Transport and chemical transformations in shallow cumulus over land

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Why do we need to study shallow cumulus on air pollution?

Relevant aspects in the formation of clear and cloudy boundary layers

Effect of shallow cumulus on transport and chemical transformation

Relevant aspects in the formation of clear and cloudy boundary layers

How do we view the atmospheric boundary layer?

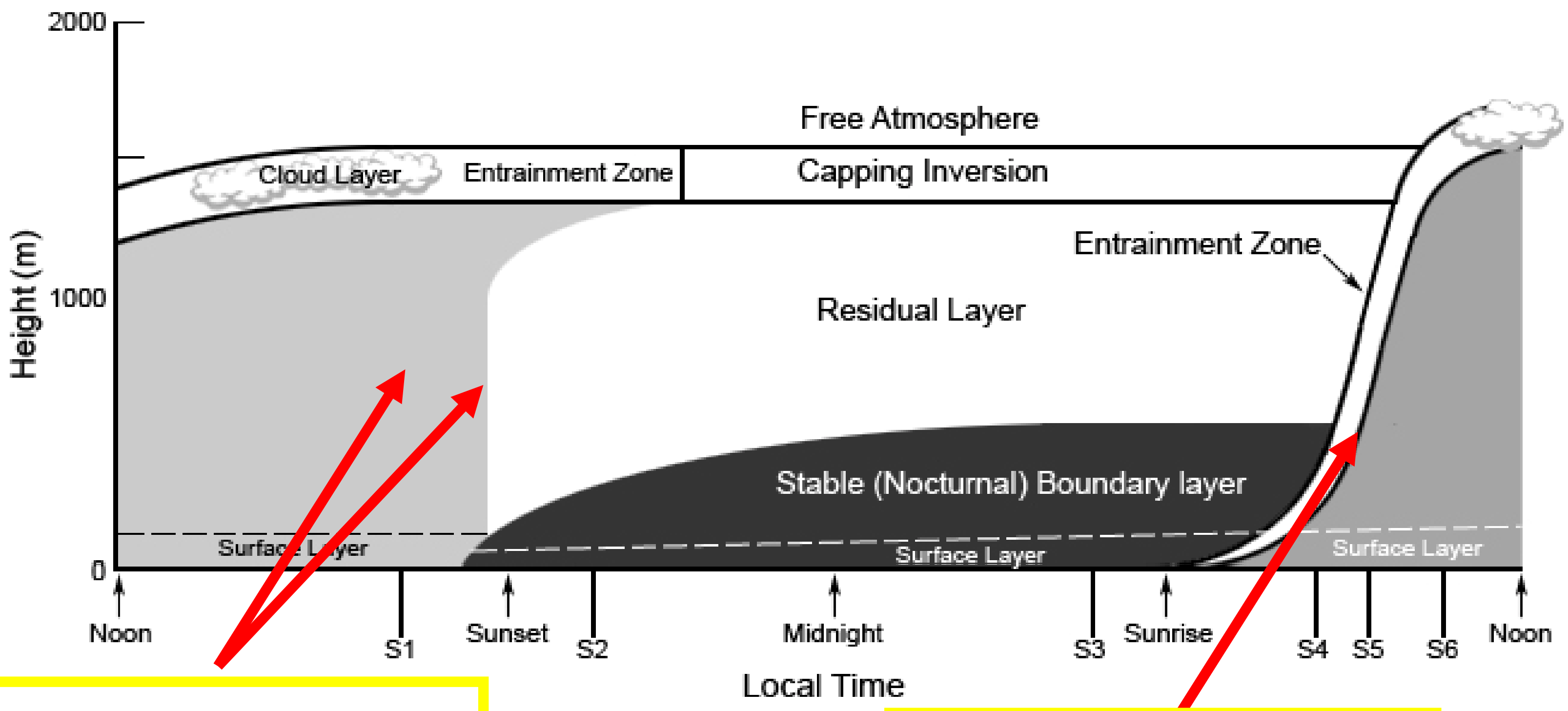
Definition of atmospheric boundary layer prototypes

Classical sketch of the ABL prototypes

Missing or overlook aspects:

Interaction of boundary layers (temporal)

Influence of scales (spatial)



2nd Part of the talk

1st Part of the TALK:

Two consecutive atmospheric boundary layers
layers were studied:

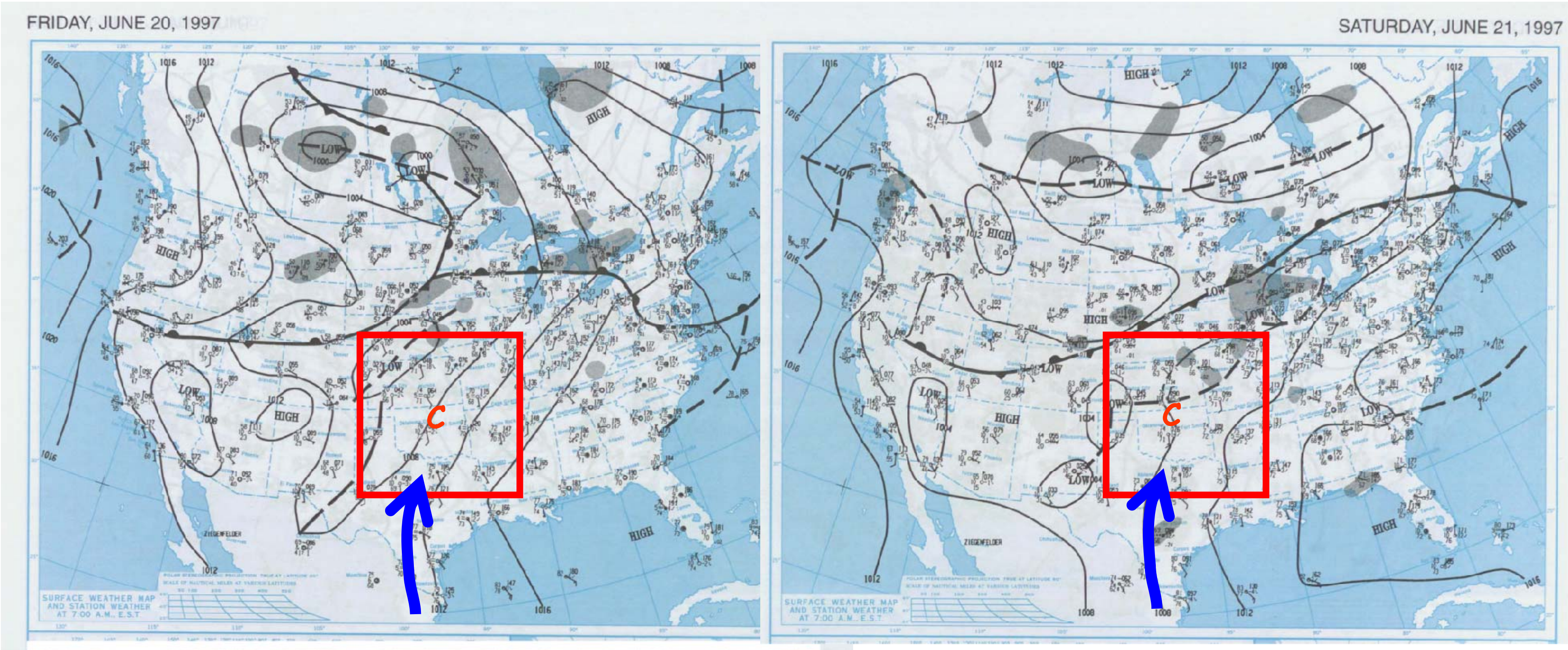
19-20 June 1997

20-21 June 1997

Focus on:

- Interaction large-small scales
- Transition nocturnal-diurnal boundary layer

Surface weather map: 20th and 21st June 07 LT



C: central facility surface/upper air measurements

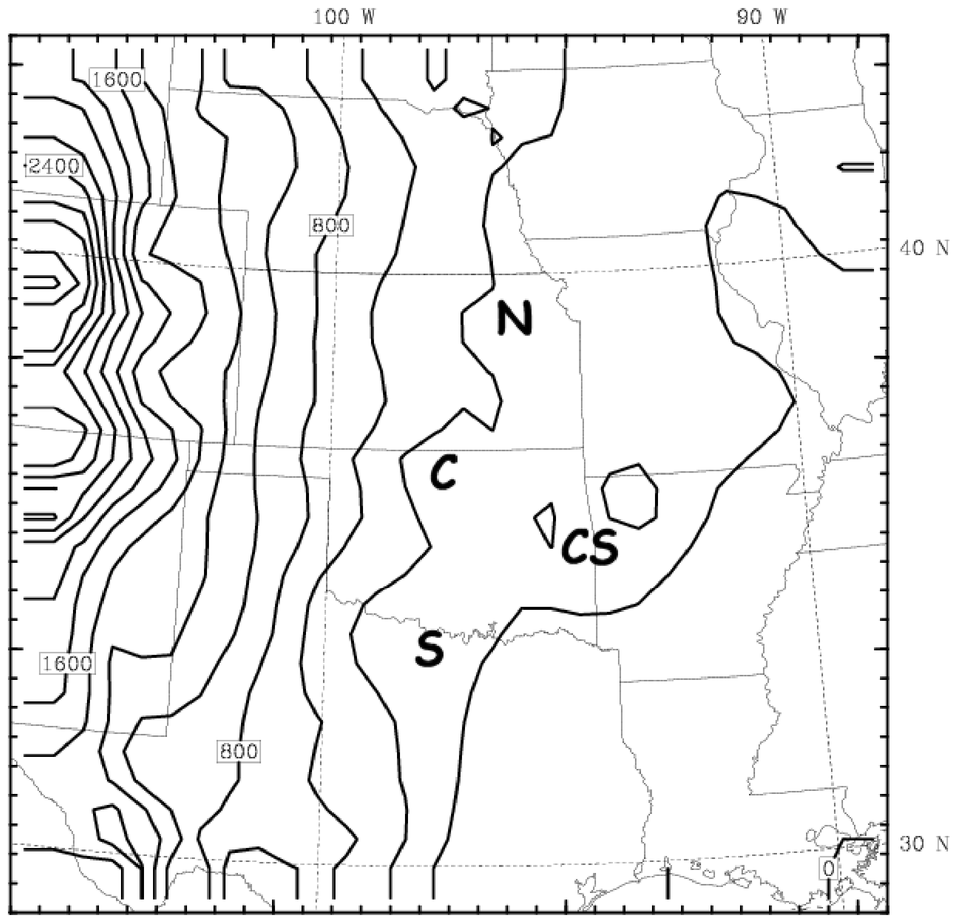
During the two consecutive nights:

-Similar surface forcing =>
 similar development of the Nocturnal boundary layer

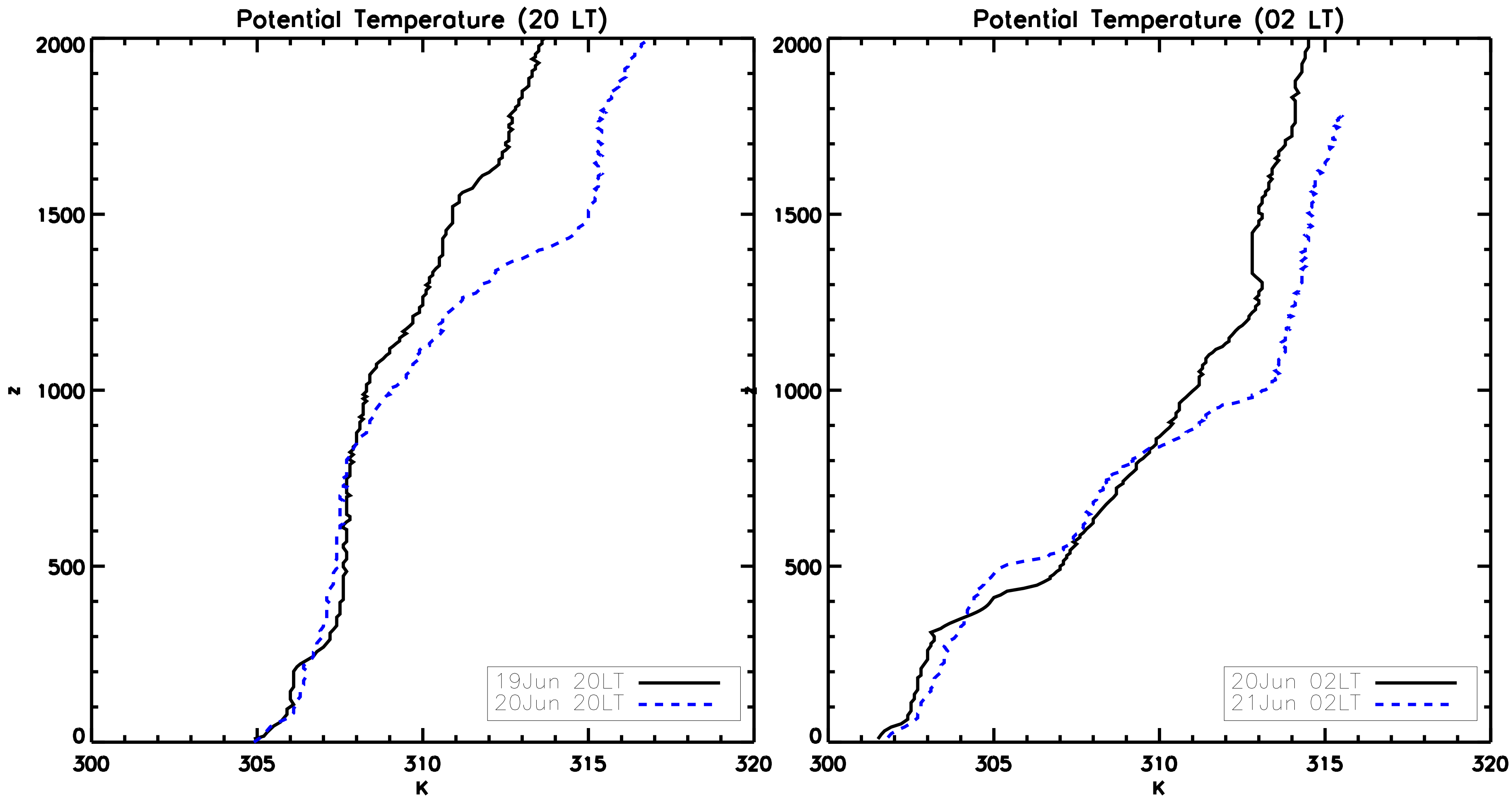
-What about the conditions in the upper layers?

Vertical thermodynamic variables at main station C: nocturnal evolution

Radisounding analysis: high temporal frequency (every 3h) and spatial coverage (4 in less than 200 km)

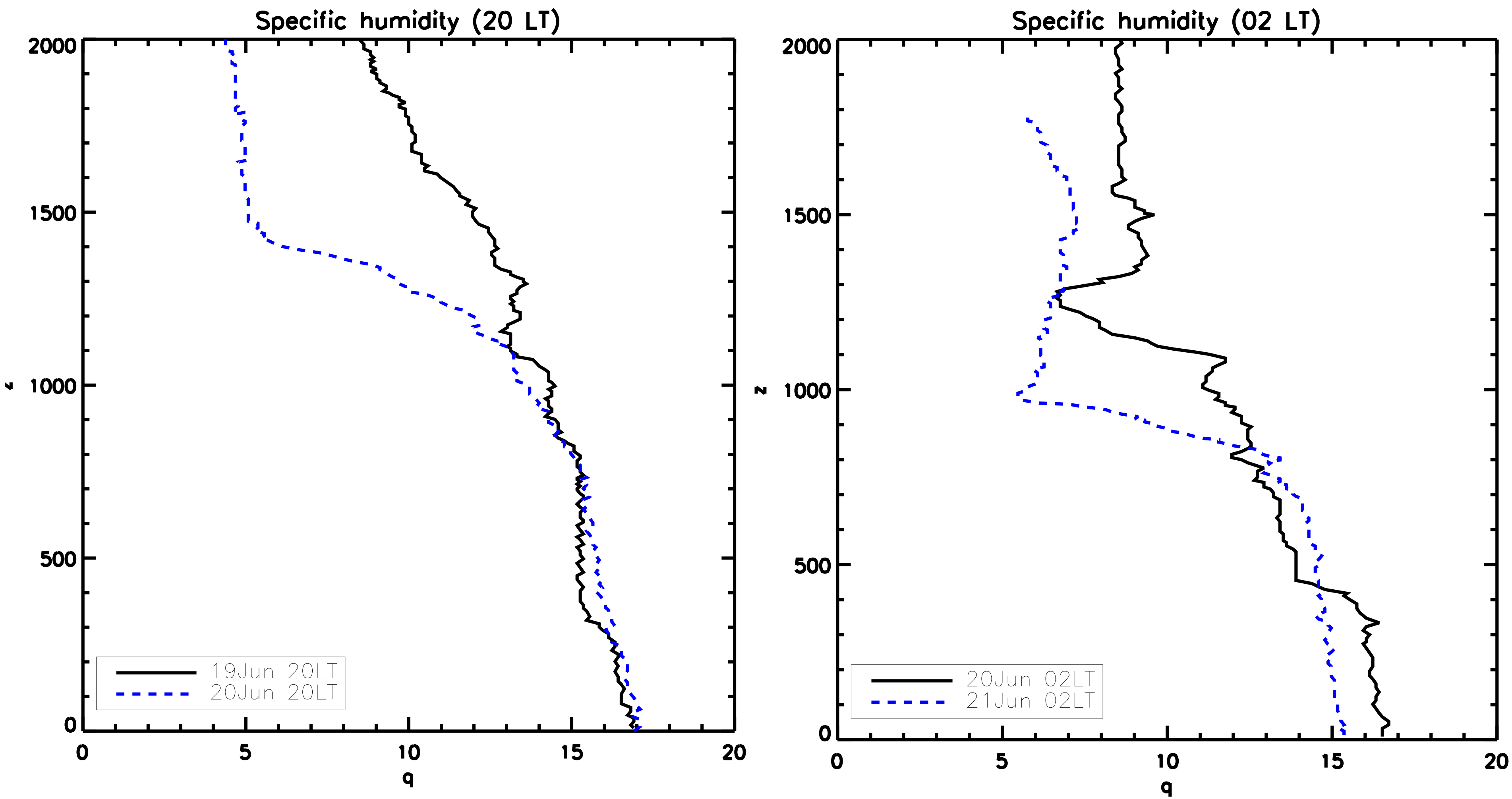


Potential temperature 20 LT and 02 LT

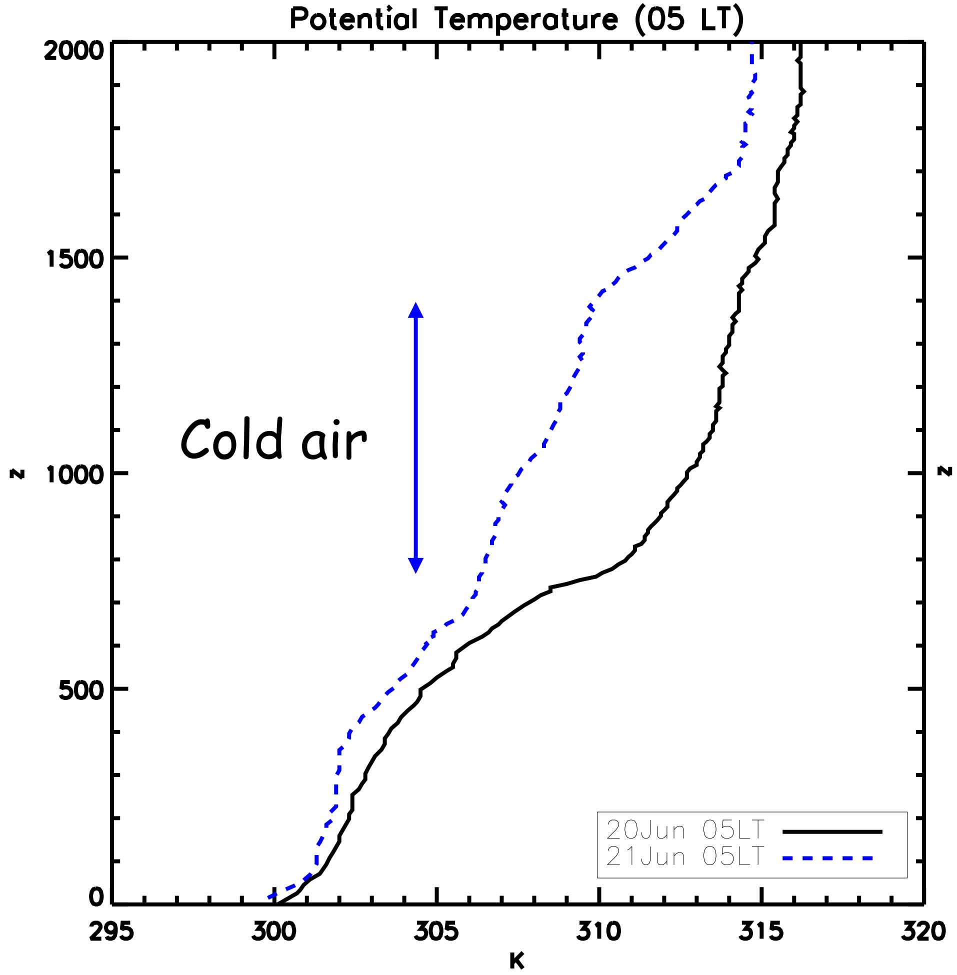


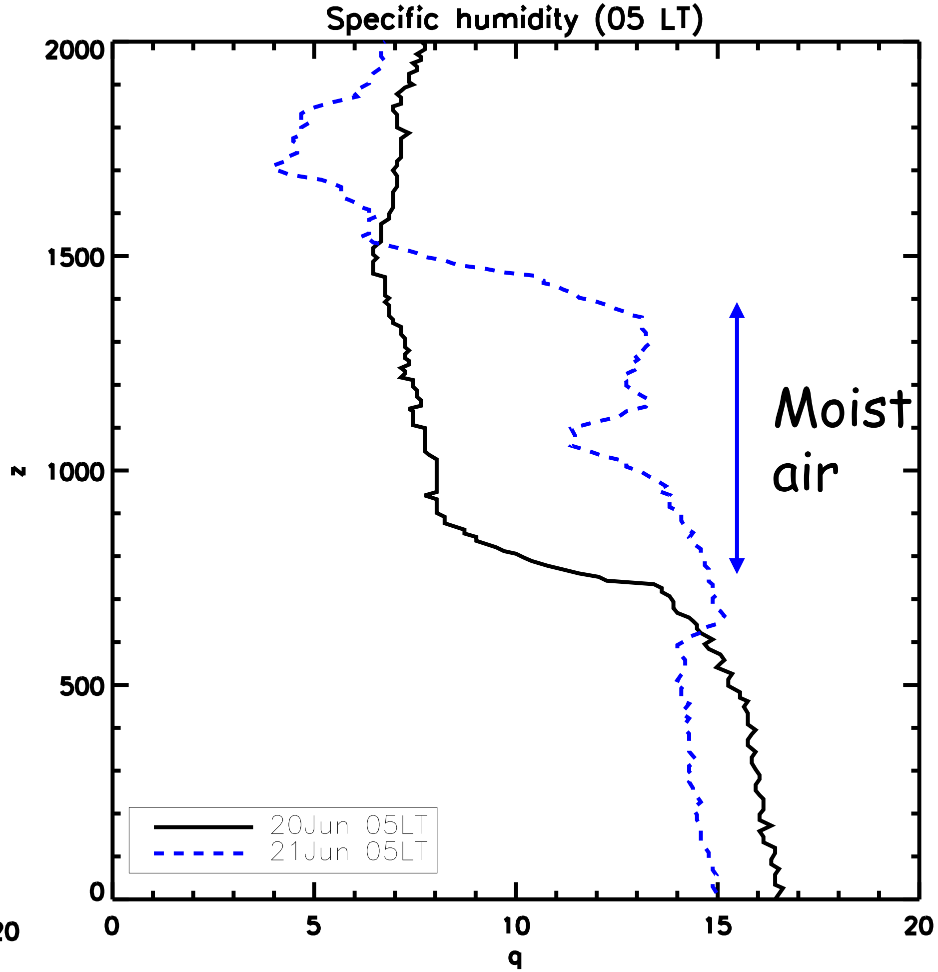
Cooling rate at the surface 0.6 K/hr

Specific humidity at 20 LT and 02 LT



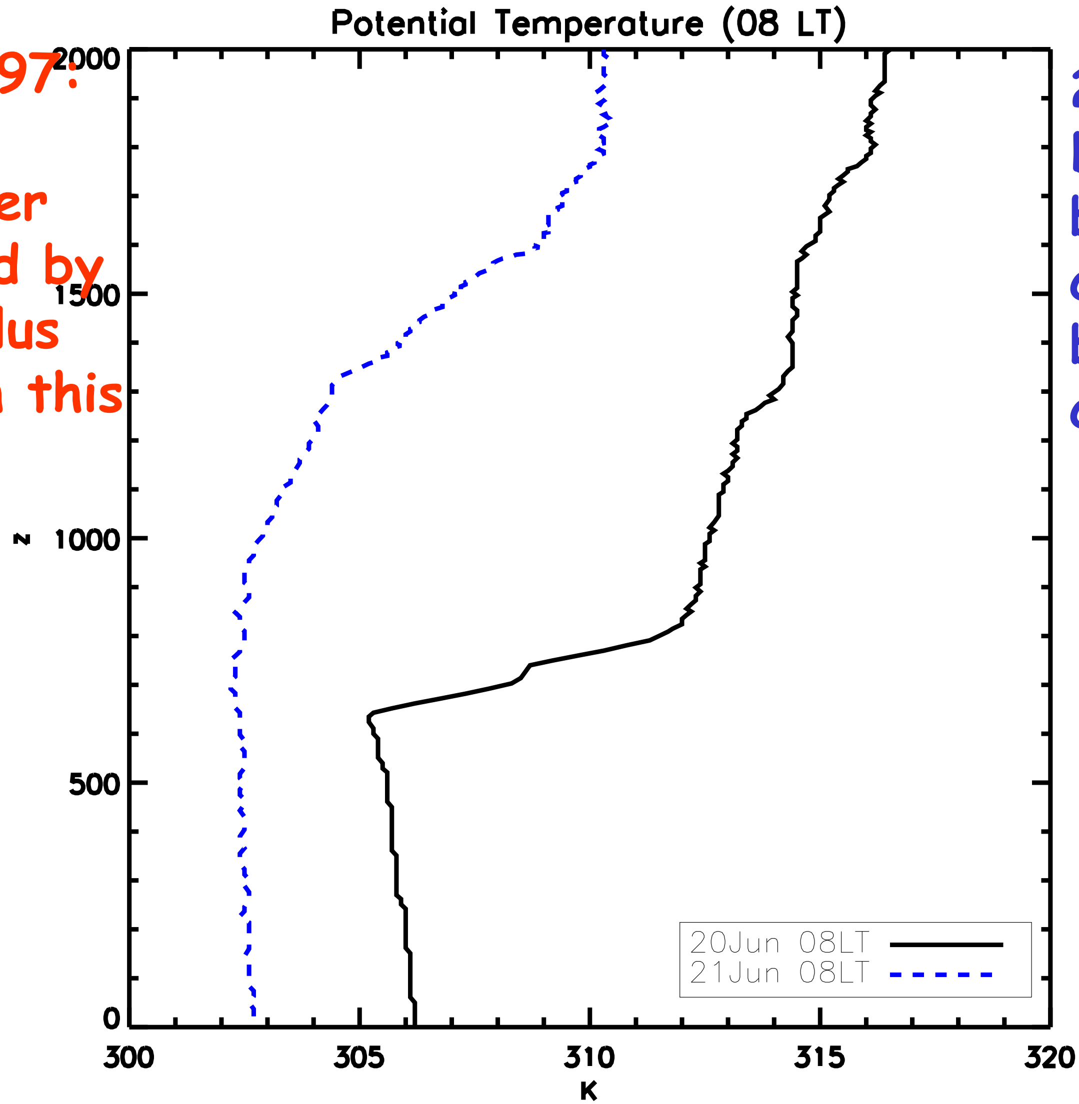
and then at 05 LT!!!!!!





Early initial morning conditions

21st June 1997: Diurnal boundary layer characterized by shallow cumulus (presented in this talk)

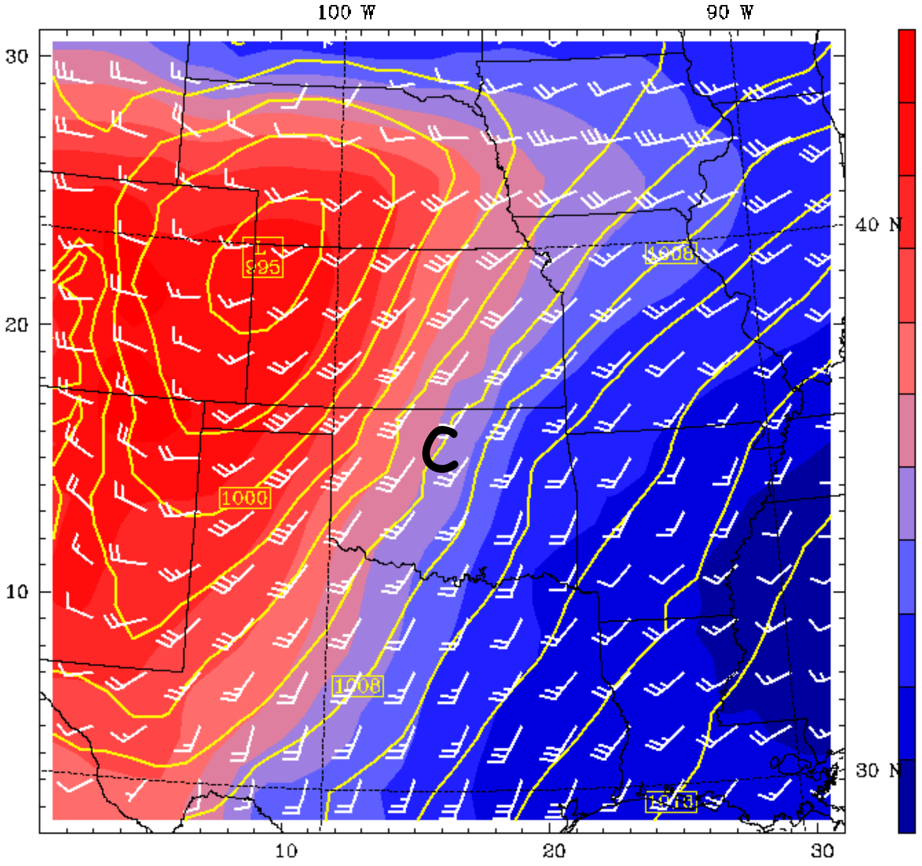


20th June 1997: Diurnal boundary layer characterized by clear convective conditions

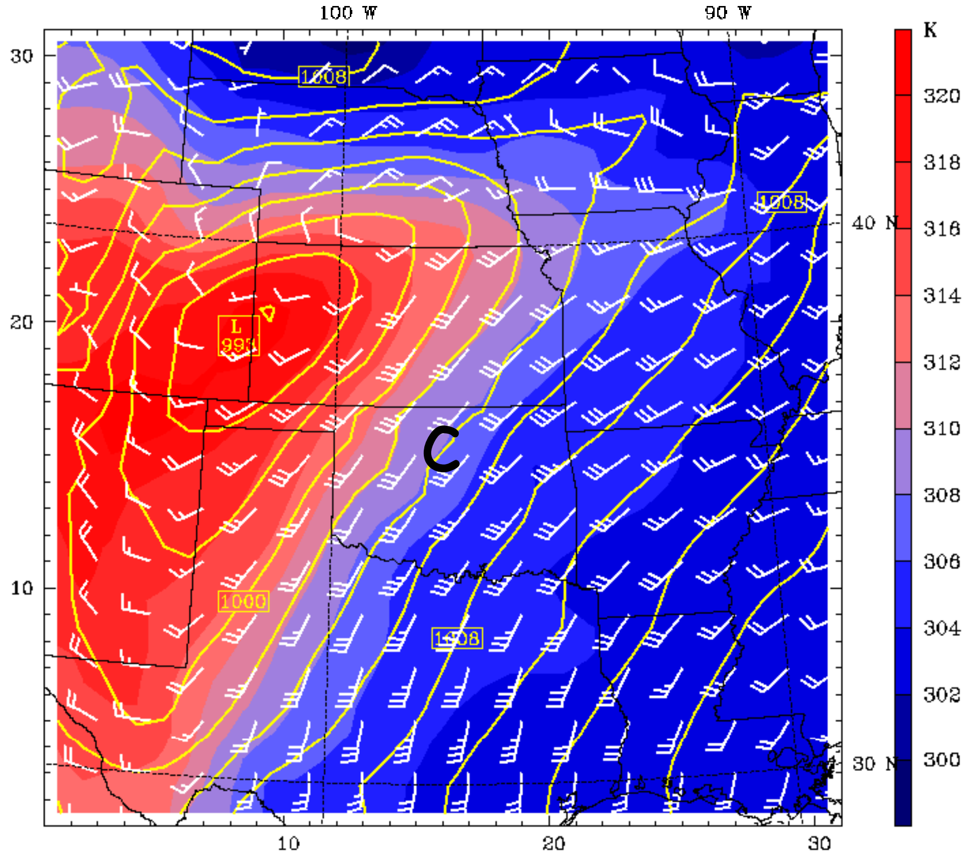
Wind fields and potential temperature (1000 m):

numerical mesoscale model (MM5)

20th June 1997 (6 LT)



21st June 1997 (6 LT)

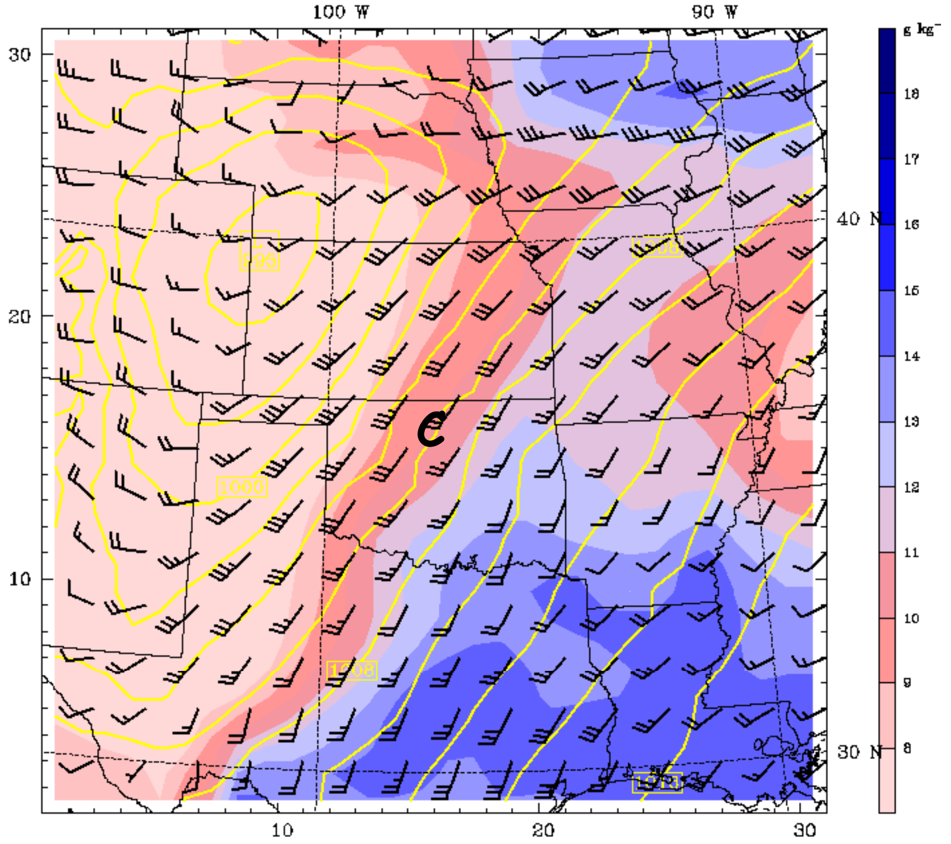


1500 km

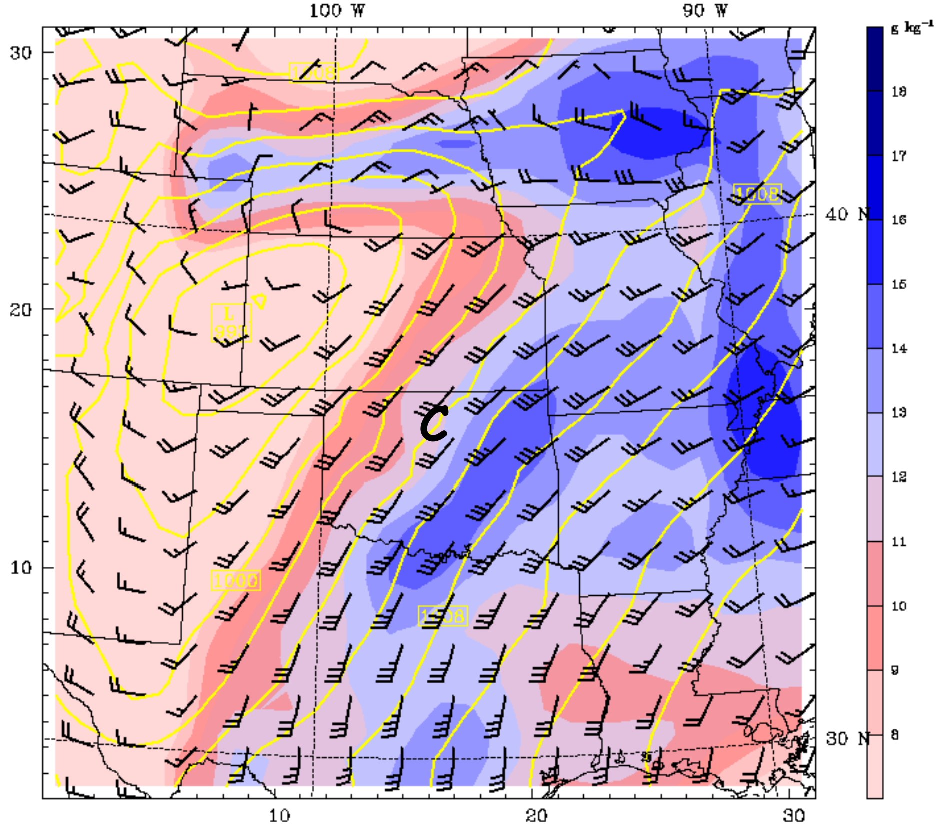
Wind fields and specific moisture (1000 m):

numerical mesoscale model (MM5)

20th June 1997 (6 LT)



21st June 1997 (6 LT)

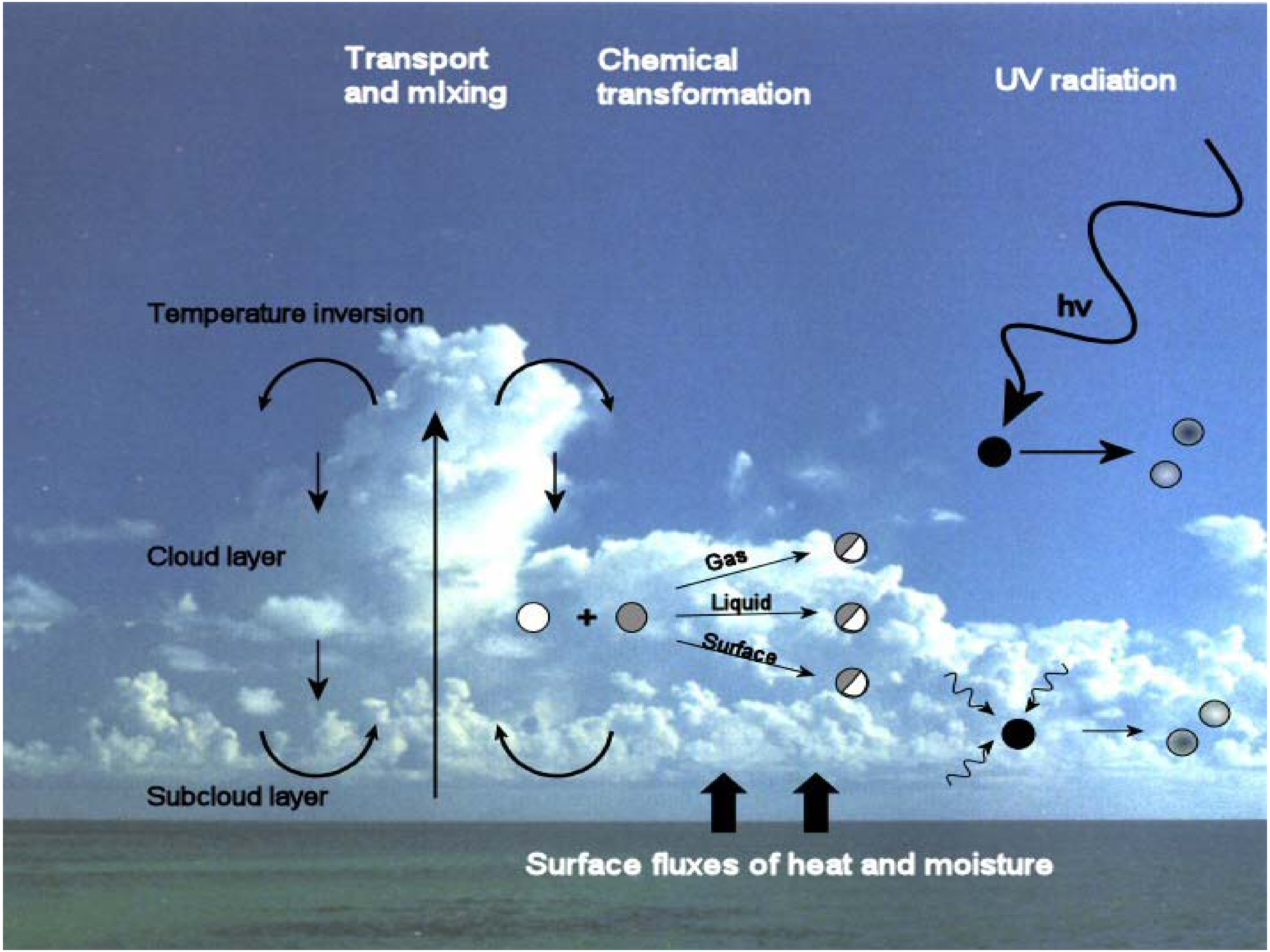


So what?

Diurnal ABL 20th June: CLEAR

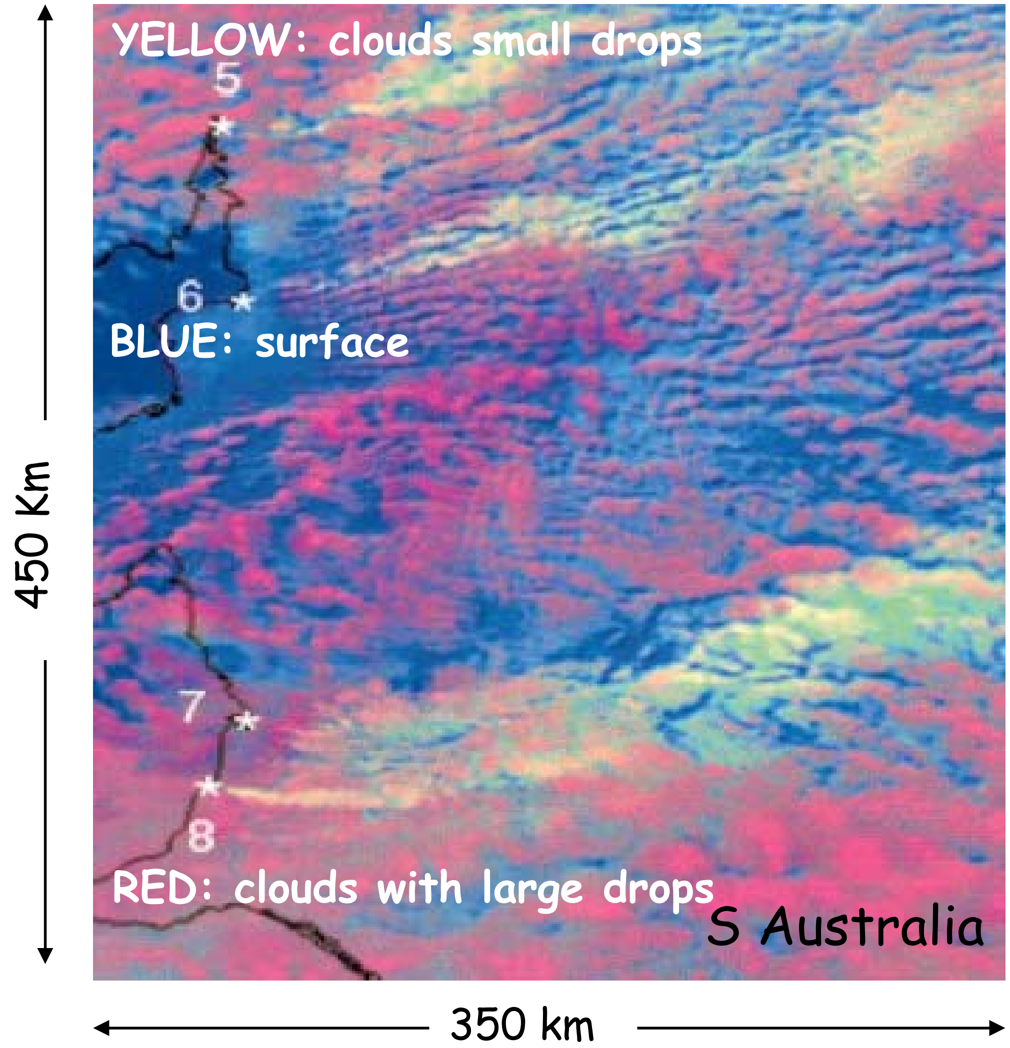
Diurnal ABL 21st June: CLOUDY (Cu)

What are the implications for atmospheric chemistry?


Transport and mixing
Chemical transformation
UV radiation
hv
Temperature inversion
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

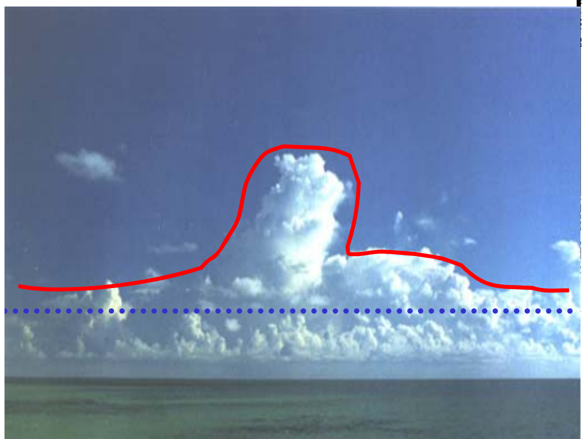


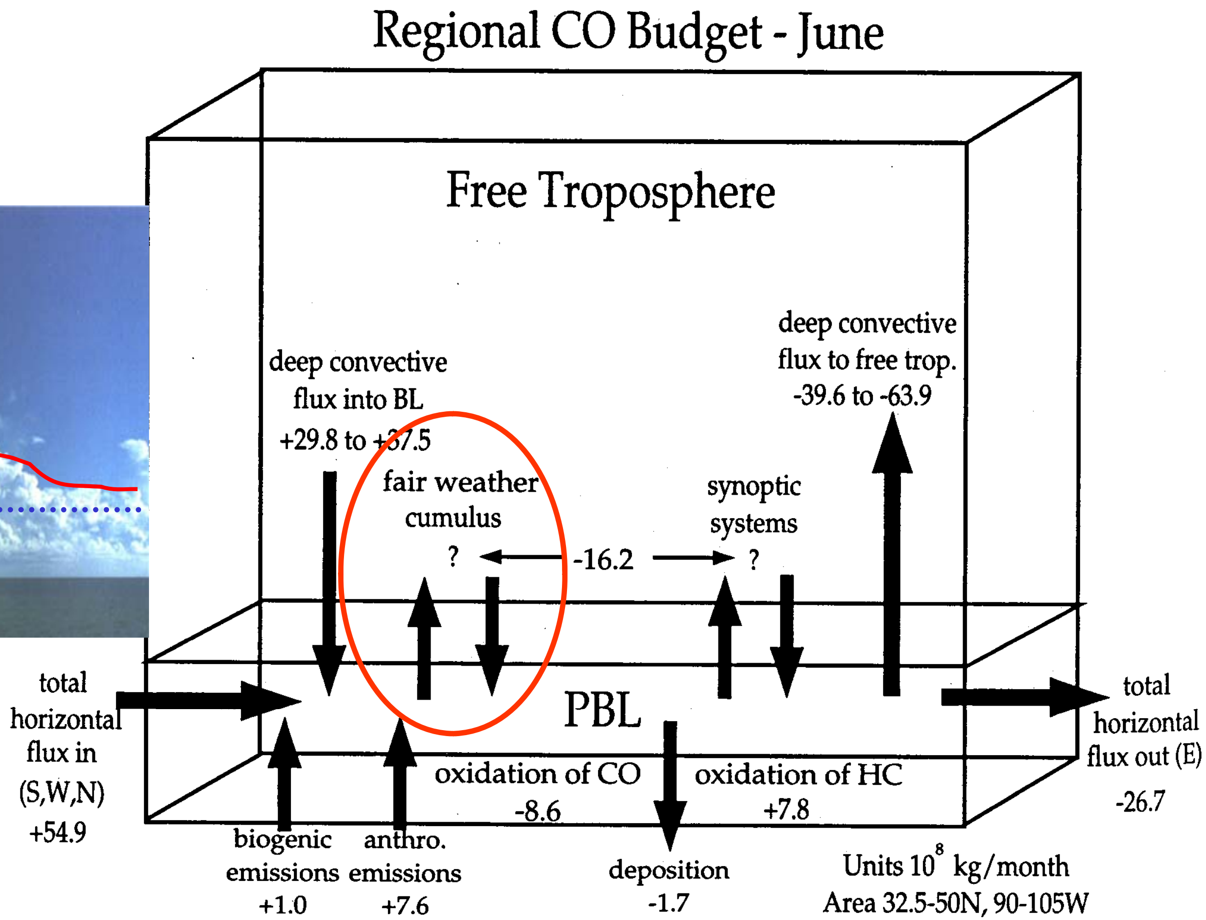
Processes

- -Dynamics
- -Turbulent dispersion
- -Radiation
- -Microphysics
- -Chemistry

AVHRR (effective radius) (Rosenfeld, 2000)

Transport of reactants by shallow cumulus
(Thompson et al., 1994)





Motivation

Reproduce by using fine scale modeling the role of cloud dynamics and physics on the reactivity

$\Rightarrow$ Process study
$\Rightarrow$ Importance of sub-grid scale processes in air quality models

Specific research issues:

- Enhancement of the vertical turbulent mixing in the boundary layer

- Controlling the mixing and the transformation of chemical species

- Perturbation of the ultraviolet radiation field below, in and above the clouds

- Chemical transformations in aqueous phase or aerosols

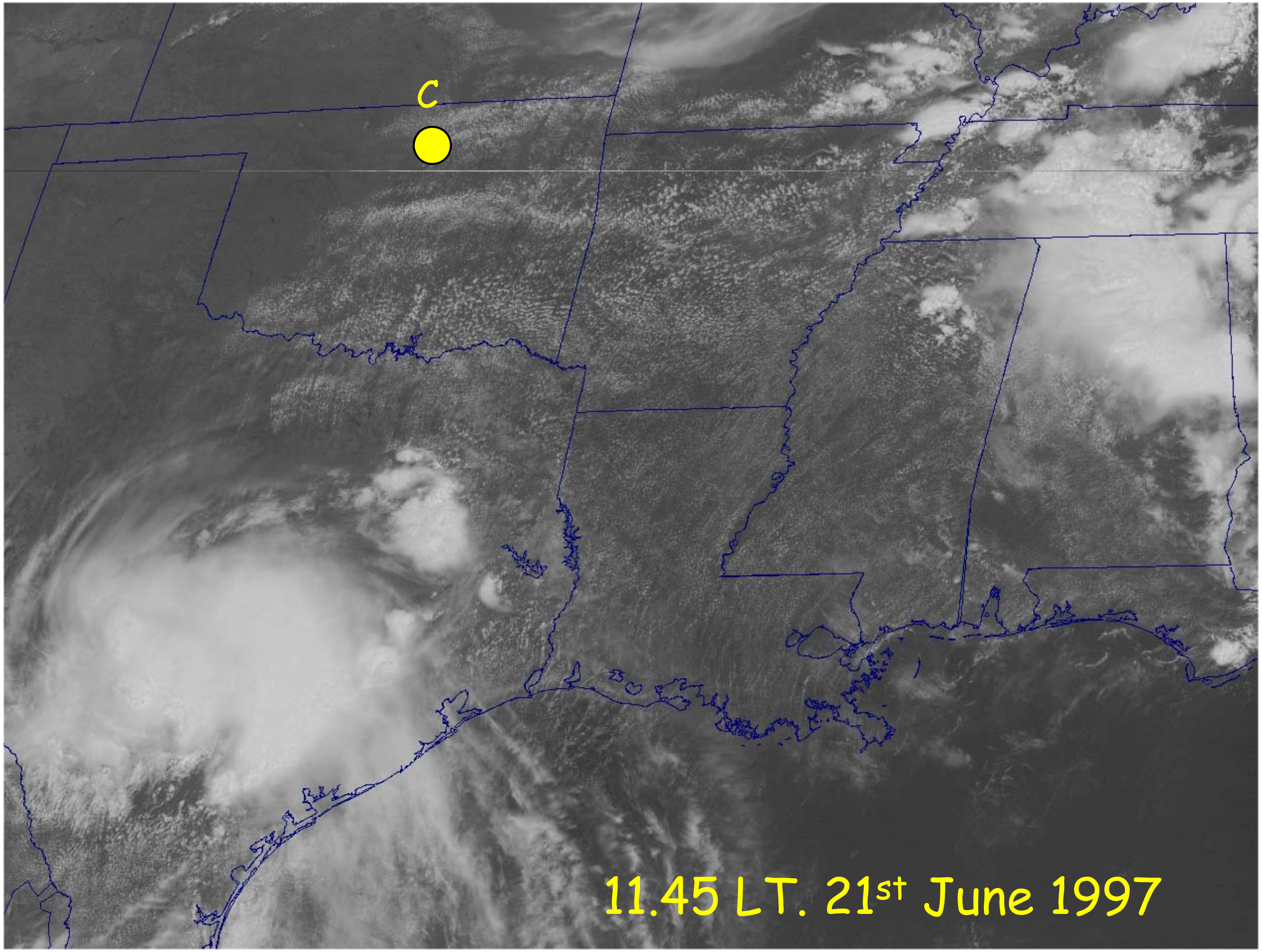
Diurnal cycle of shallow cumulus convection over land (Brown et al. 2002)

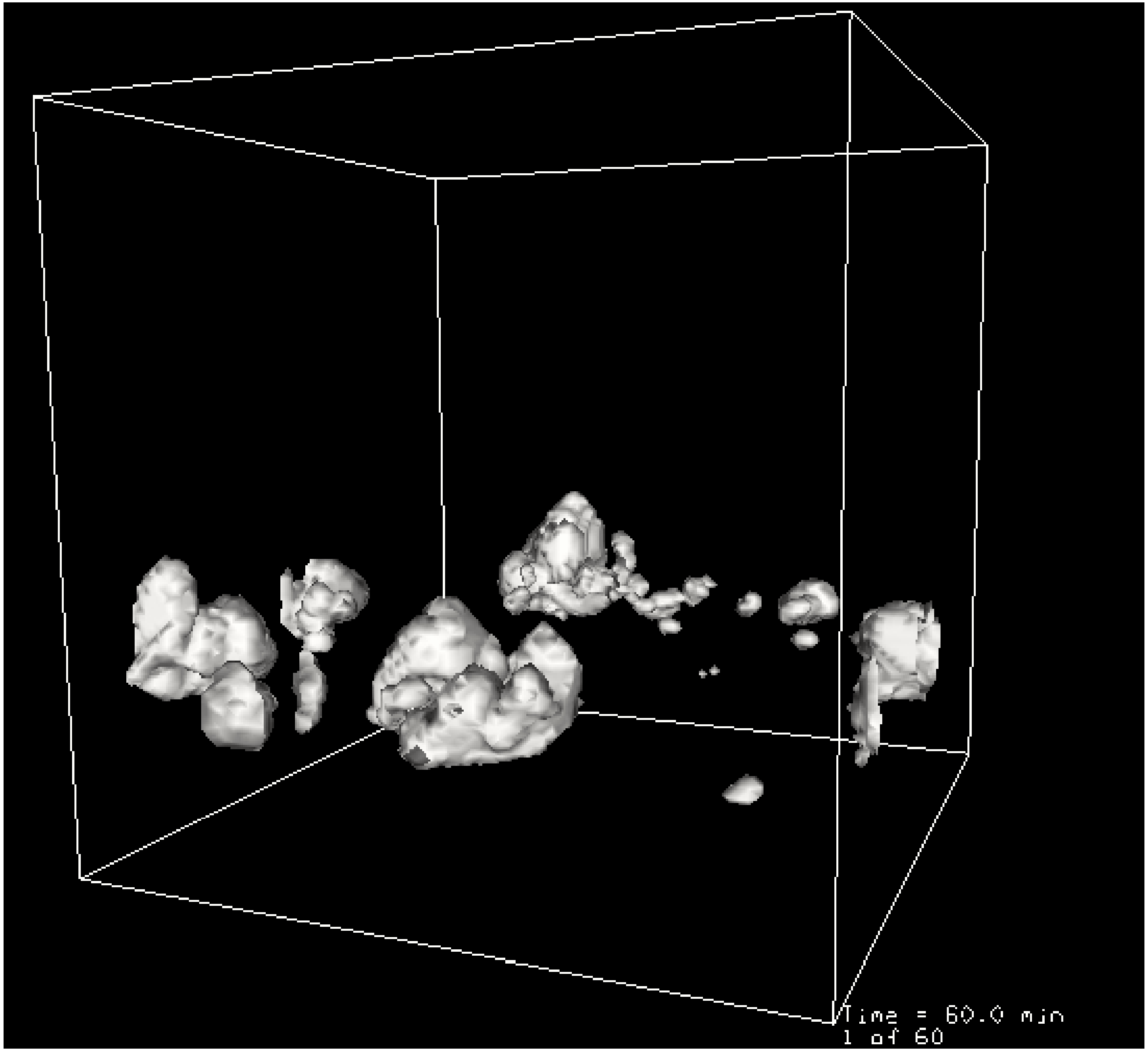
Studying this situation by means of **large-eddy simulation**. Based on an **idealization of an observed situation** at the Southern Great Plains (SGP, ARM). 21st June 1997.

External forcing:

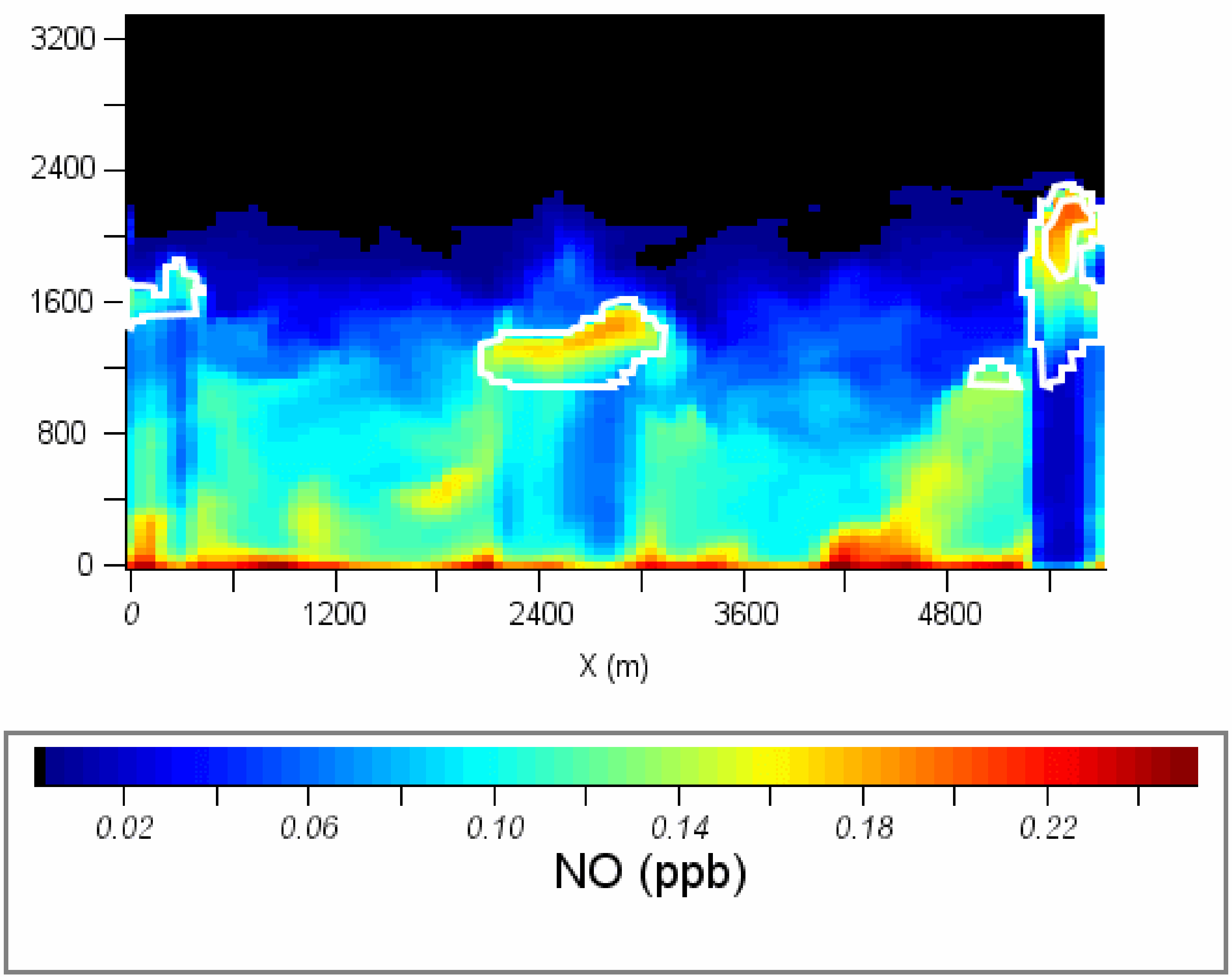
Strong diurnal variation in the evolution of the sensible- and latent-heat fluxes

Constant geostrophic wind

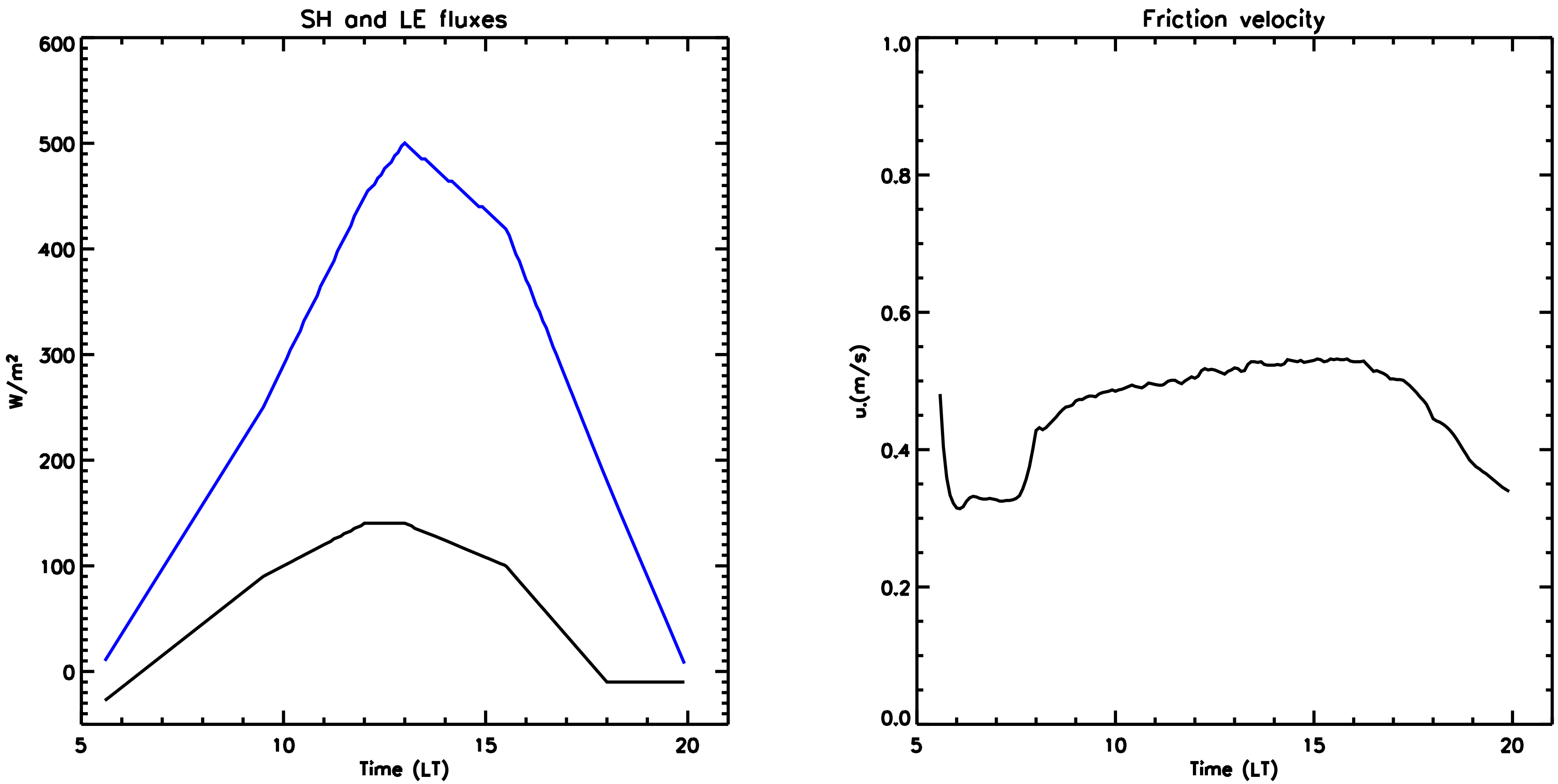

C
11.45 LT. 21st June 1997


Time = 60.0 min
1 of 60

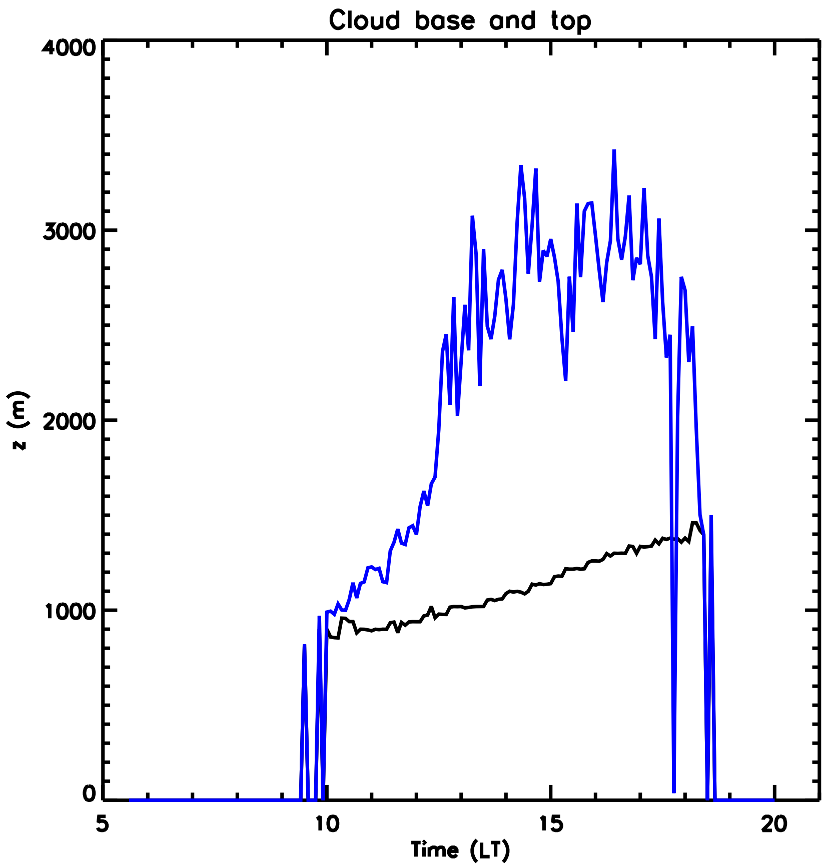
Vertical cross section NO

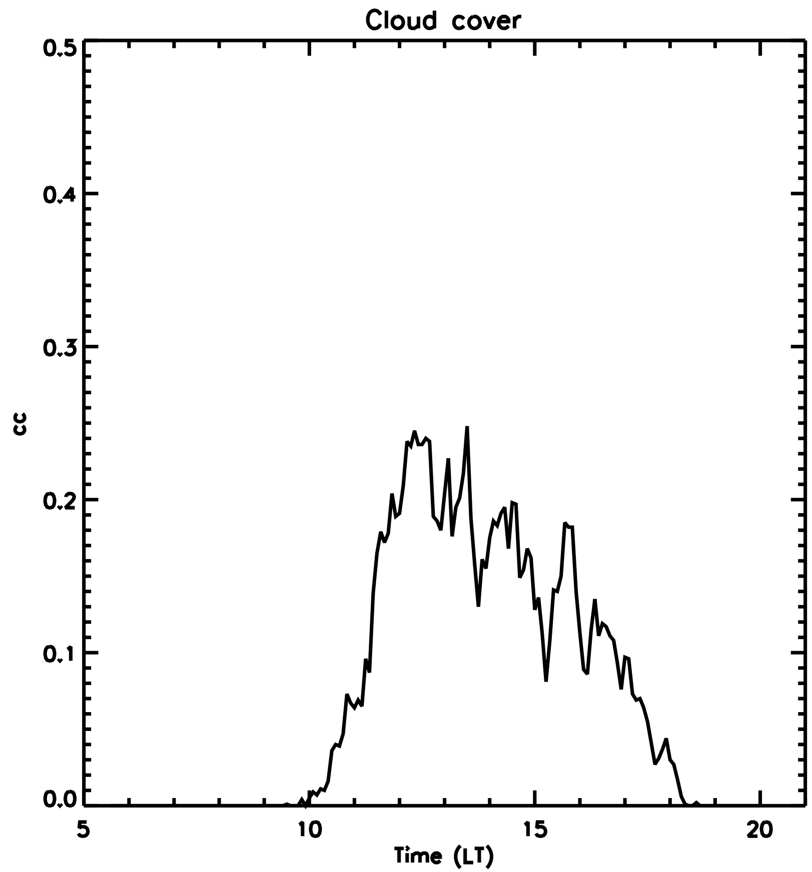


Daily evolution of the surface forcing



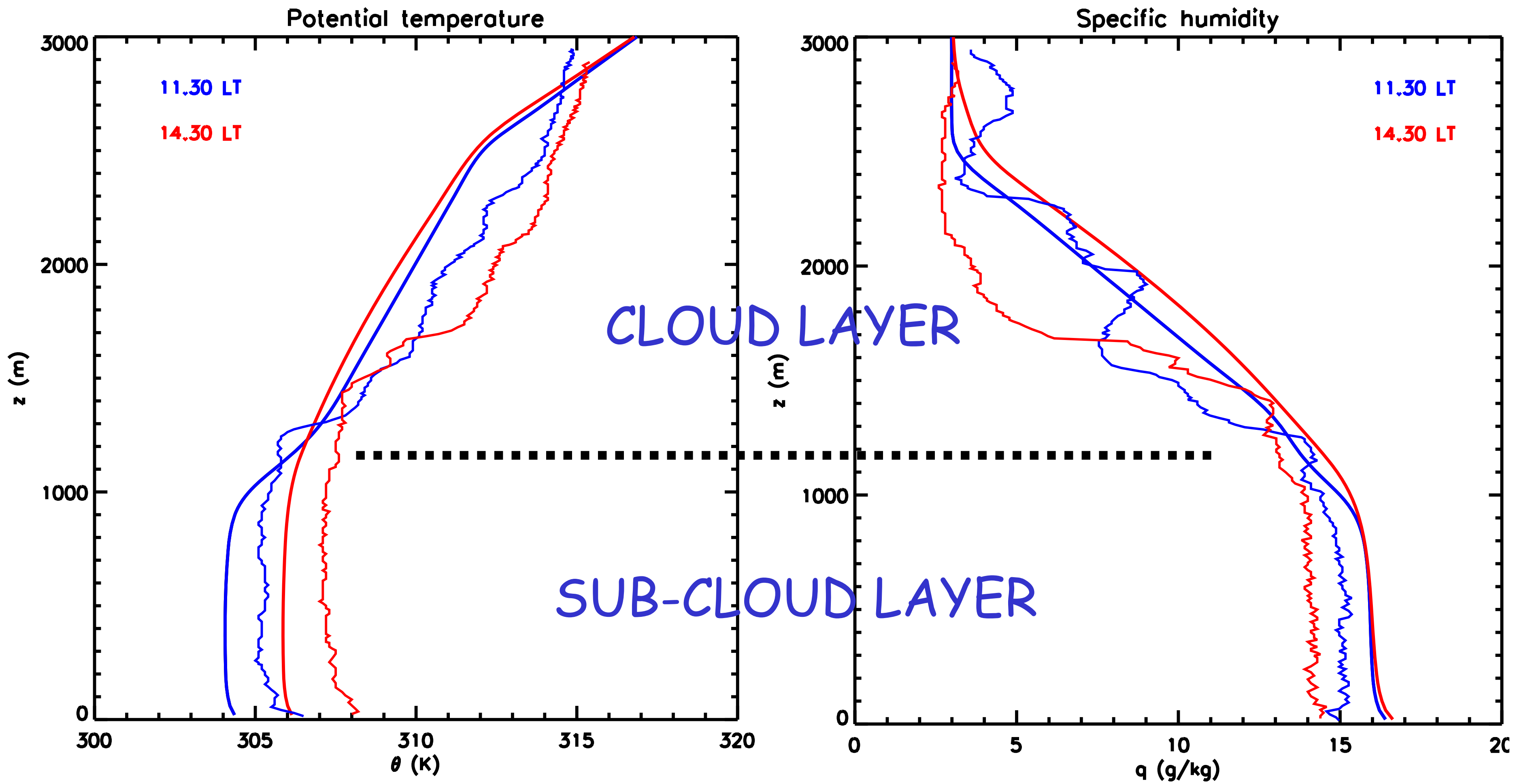
Time evolution of cloud characteristics



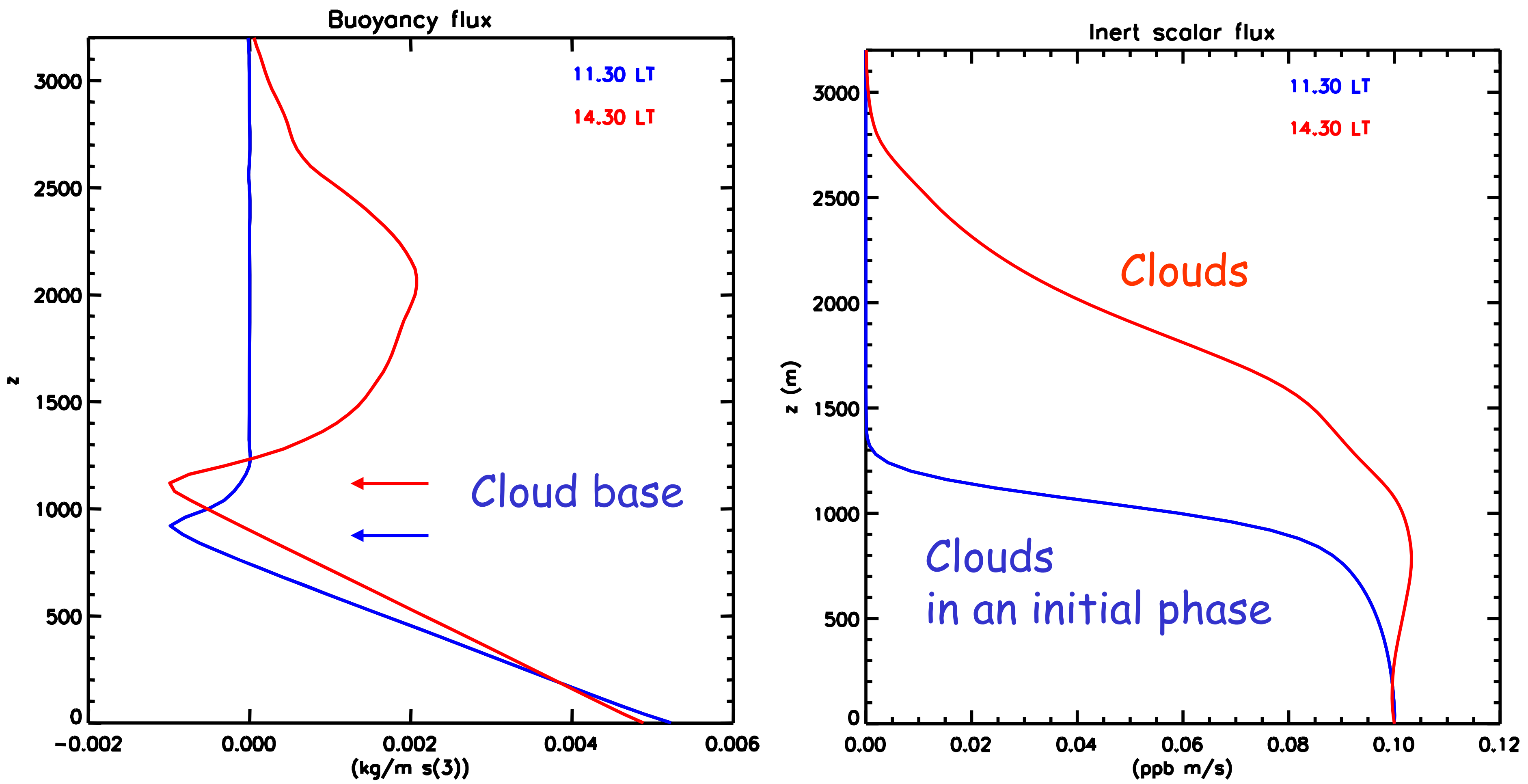


Vertical profiles

LES results (1-hour average) versus radisounding observations



Vertical profile buoyancy and scalar flux

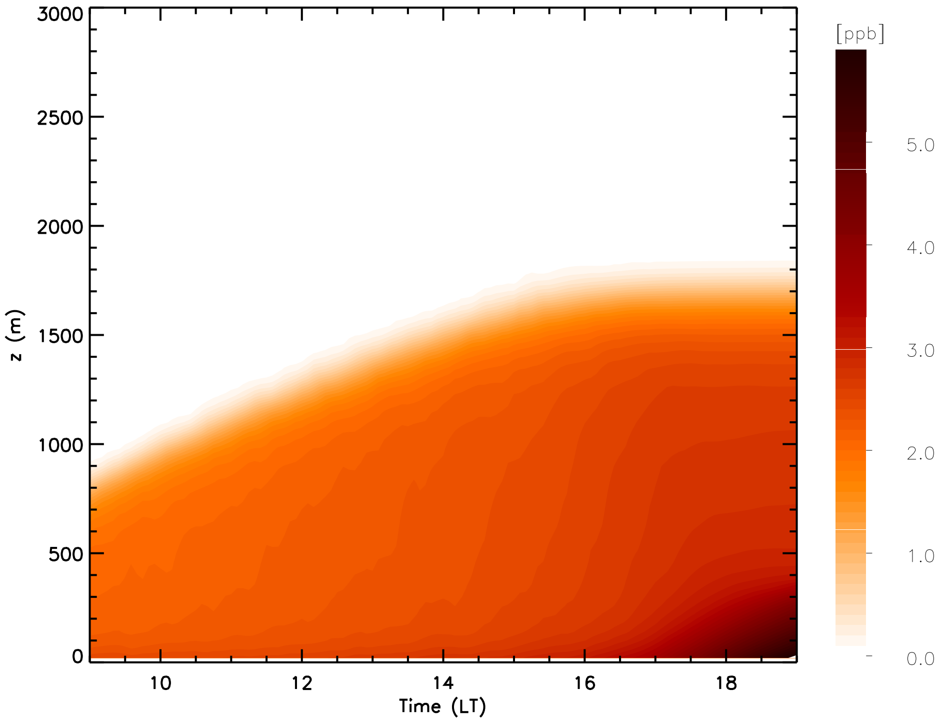


What is the difference in the temporal evolution of the vertical distribution of a scalar with and without shallow cumulus clouds?

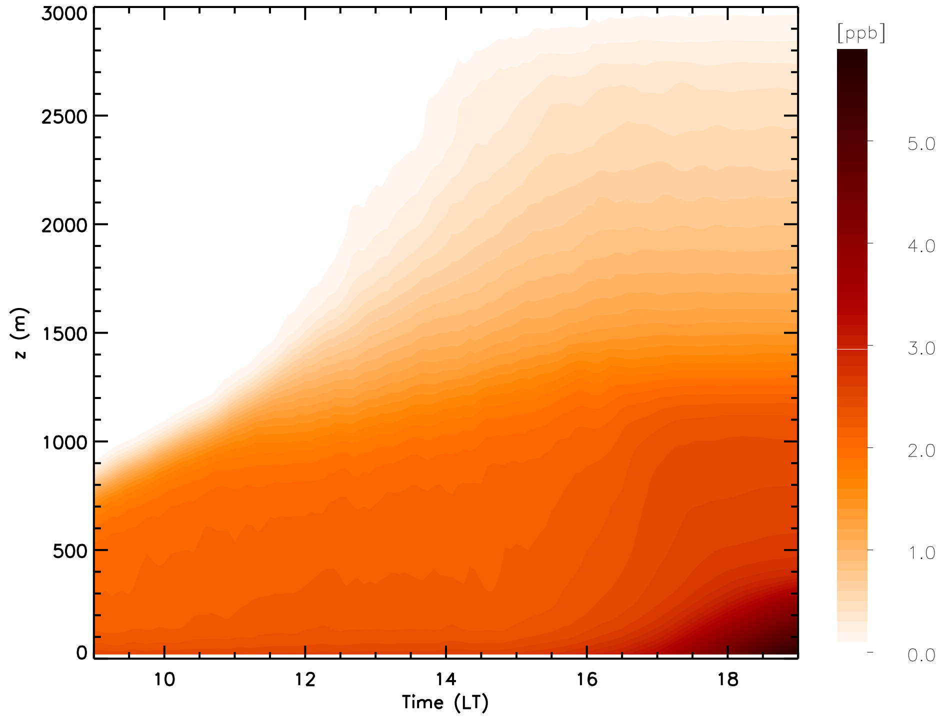
Same numerical experiment only reducing moisture content in the ABL

Vertical profile evolution of an inert emitted scalar

Clear boundary layer

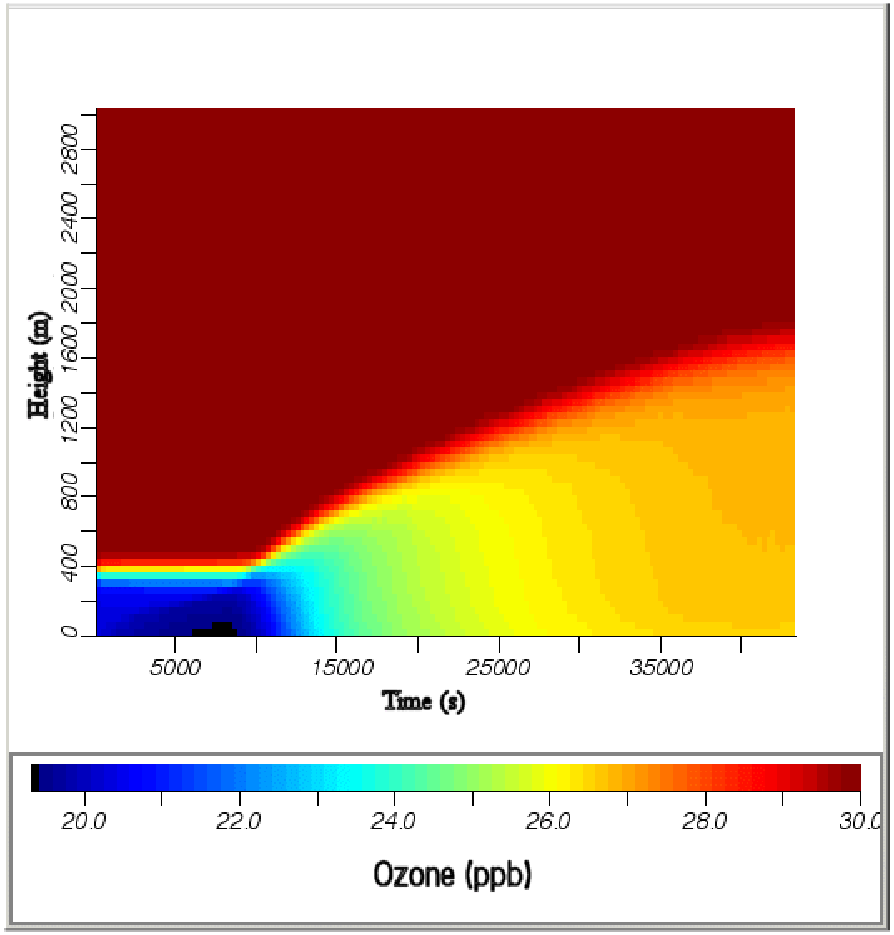


Cloudy boundary layer

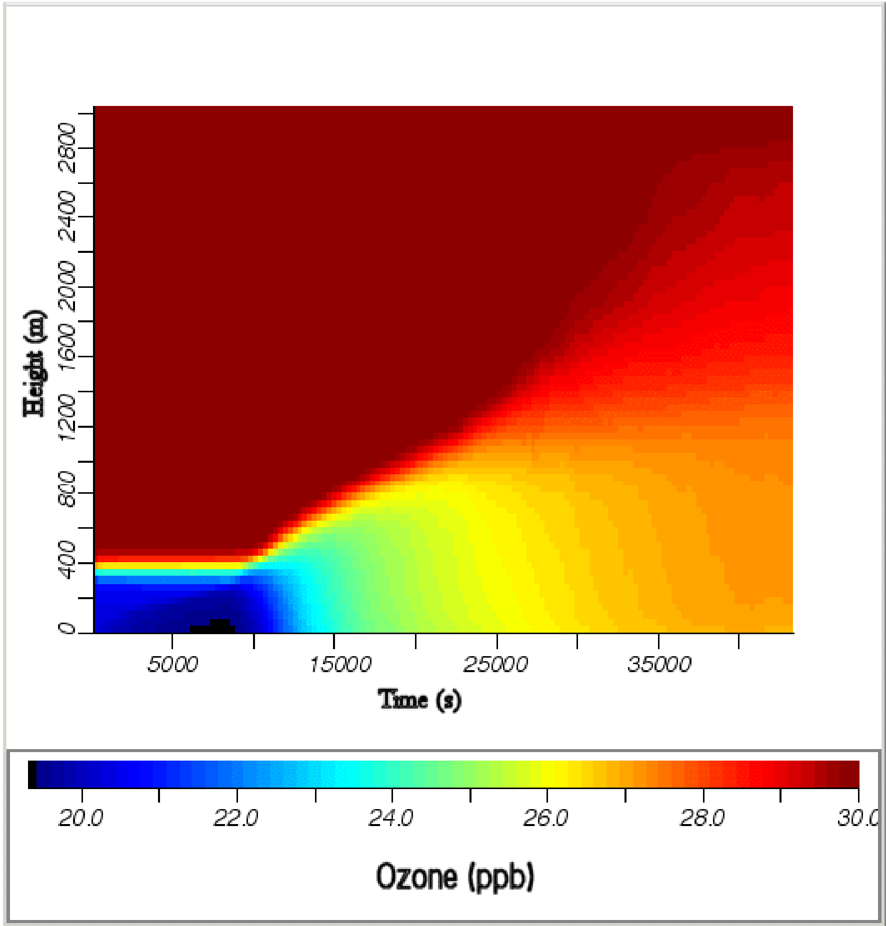


Vertical profile evolution of a reactive entrained species (ozone)

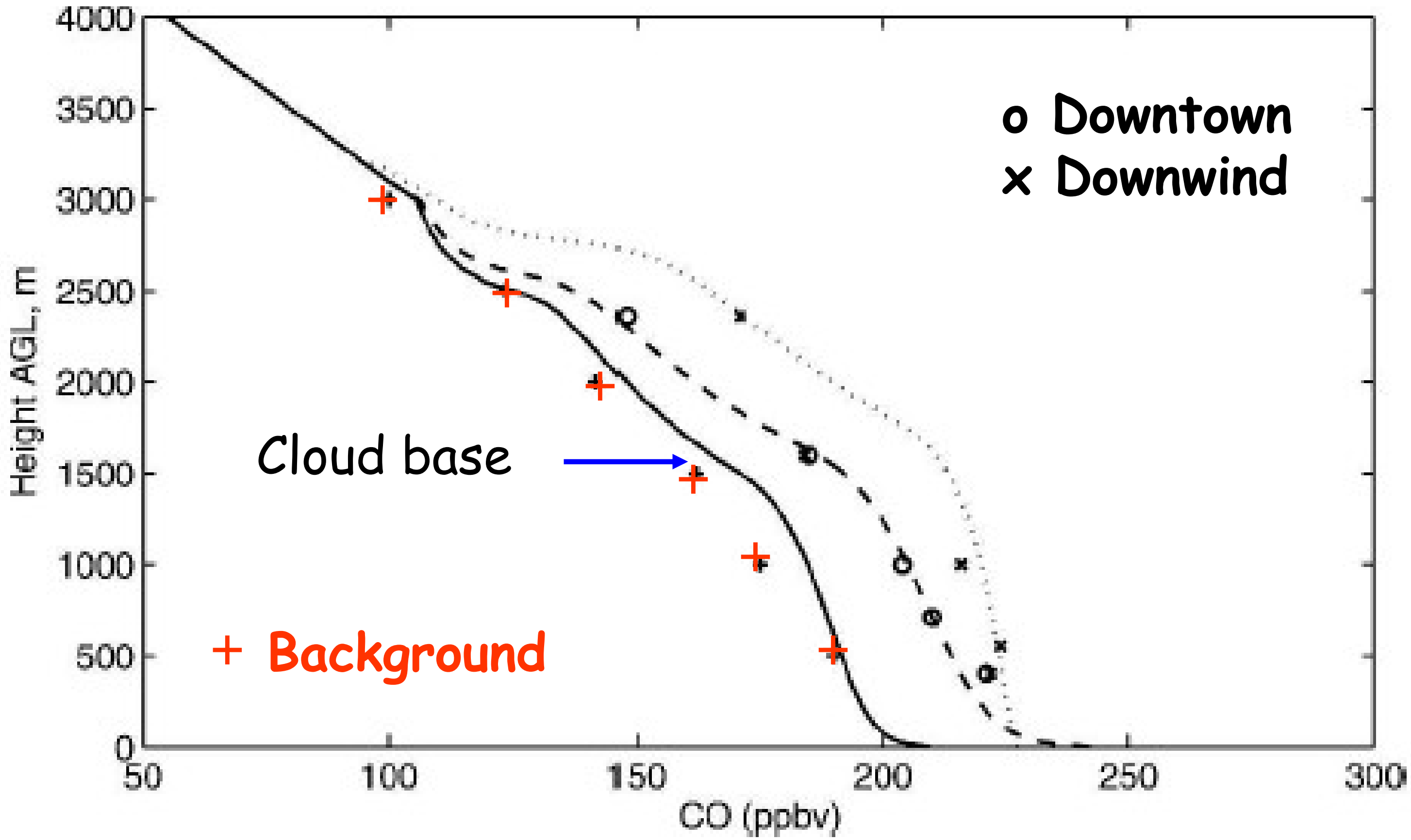
Clear boundary layer



Cloudy boundary layer



CO profiles from aircraft at Nashville
(Angevine, 2005)



What is the effect of the presence of shallow cumulus on the reactivity?

Simple chemistry

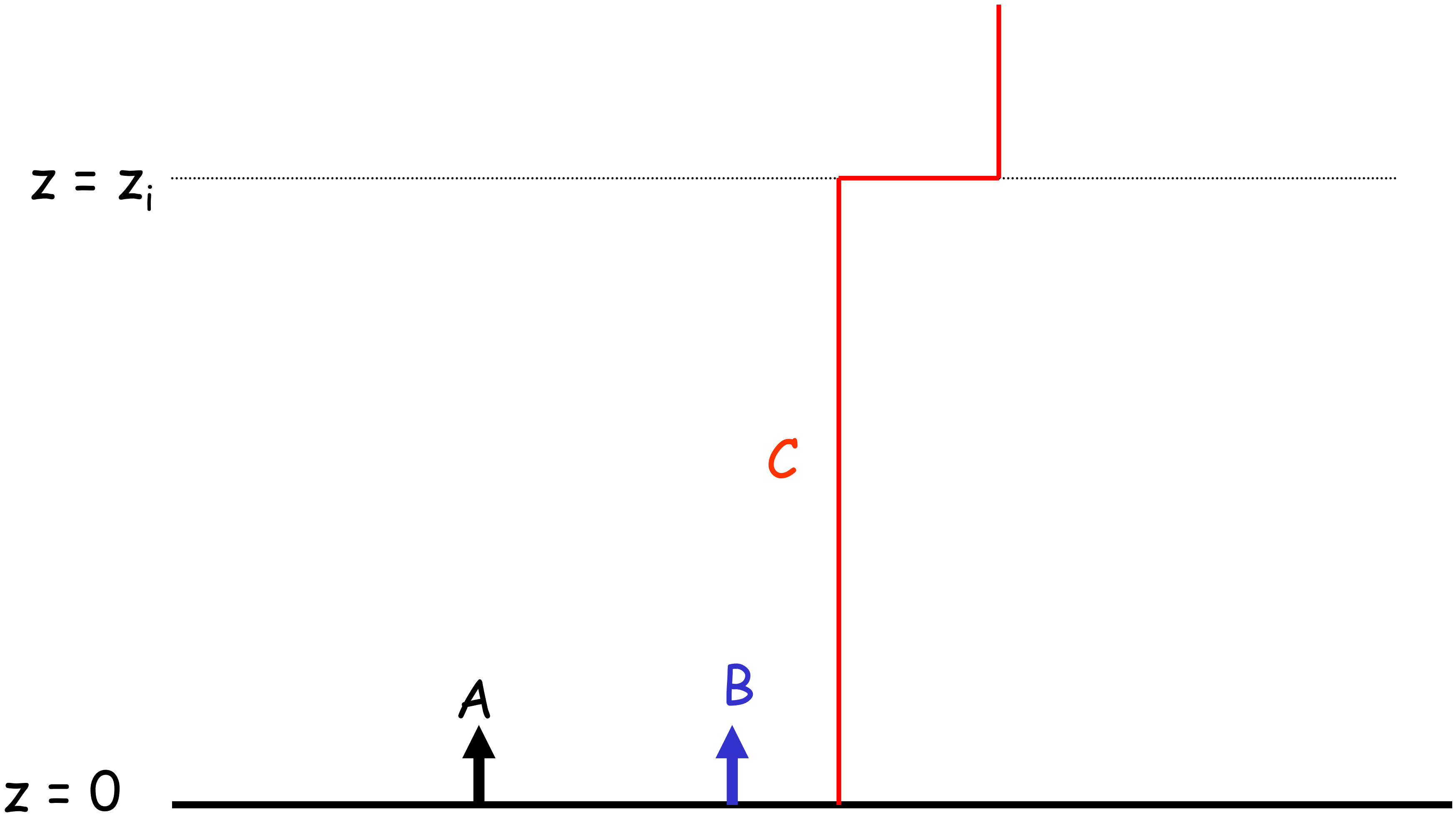
$A \xrightarrow{j} B + C$ (1st order reaction)

$B + C \xrightarrow{k} A$ (2nd order reaction)

Possibility to define a photostationary state

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

Initial conditions reactants



Influence of physical processes on chemical reactions

2nd chemical reaction

Chemical reaction rate depends on the **efficiency of turbulence** to bring species together

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

Influence of physical processes on chemical reactions

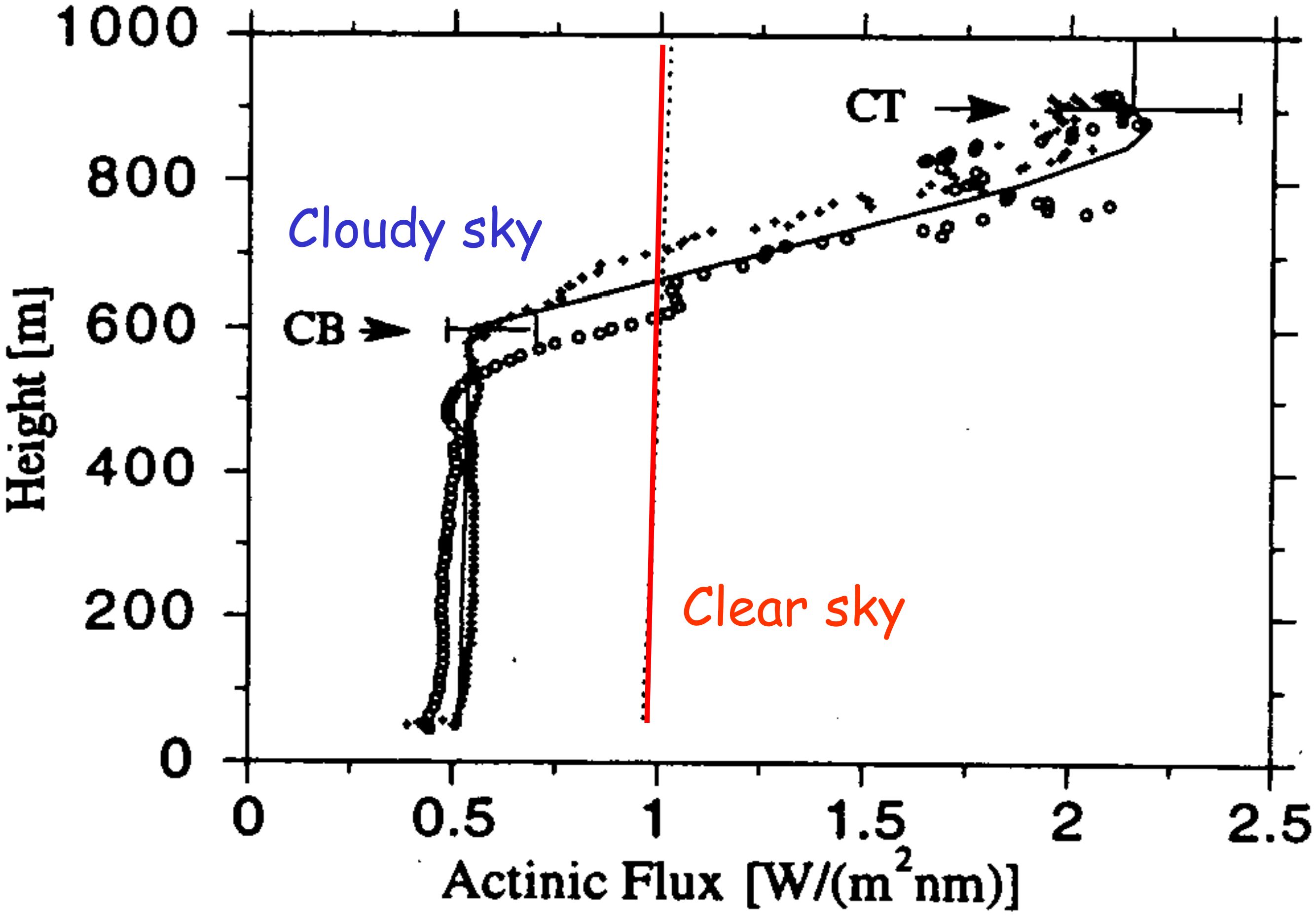
1st order reaction

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

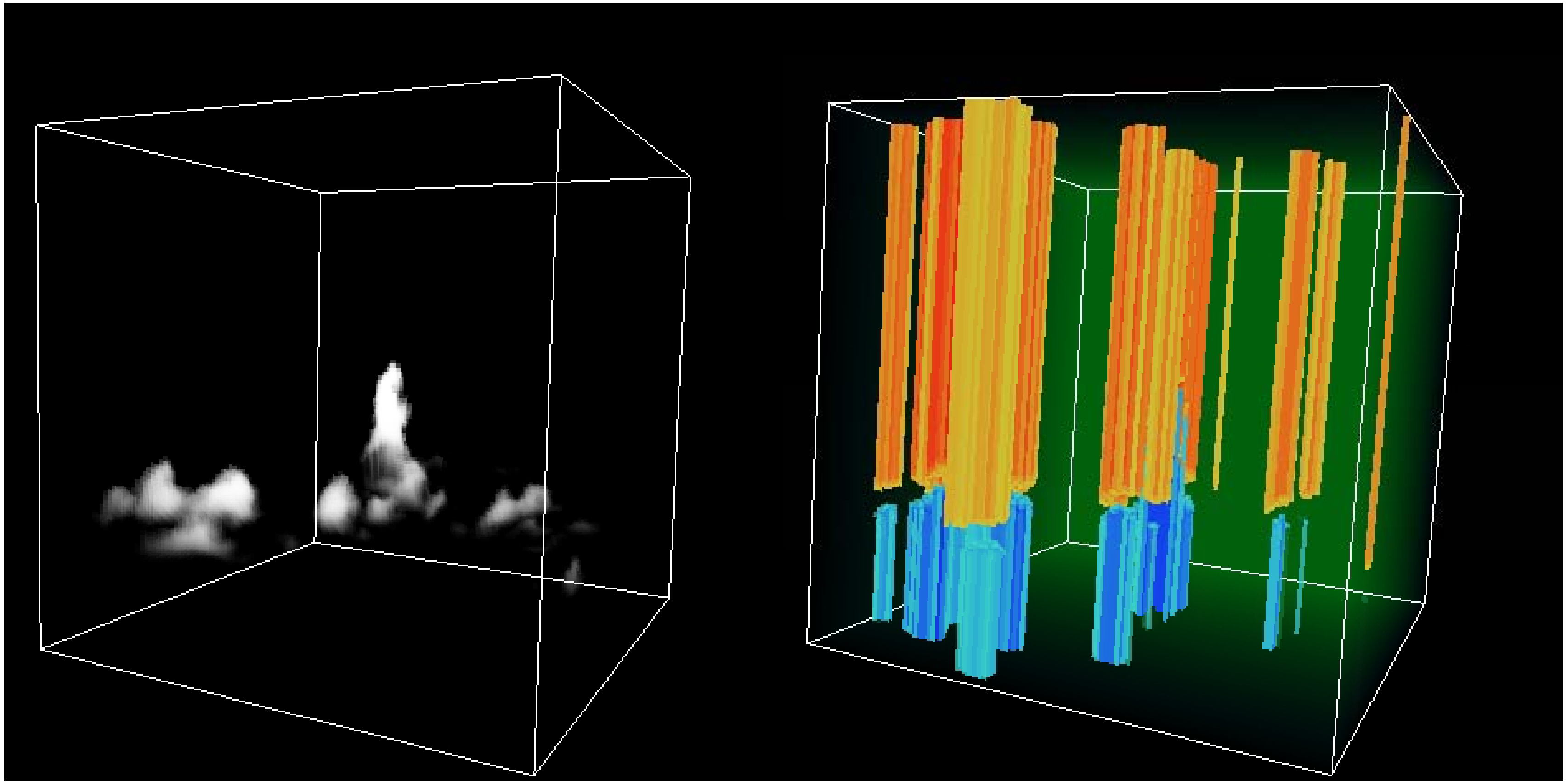
ACTINIC FLUX is largely perturbed by the presence of clouds

Vertical profile of actinic flux (Vilà et al., 1994)

Measurements collected during ASTEX (stratocumulus cloud deck)



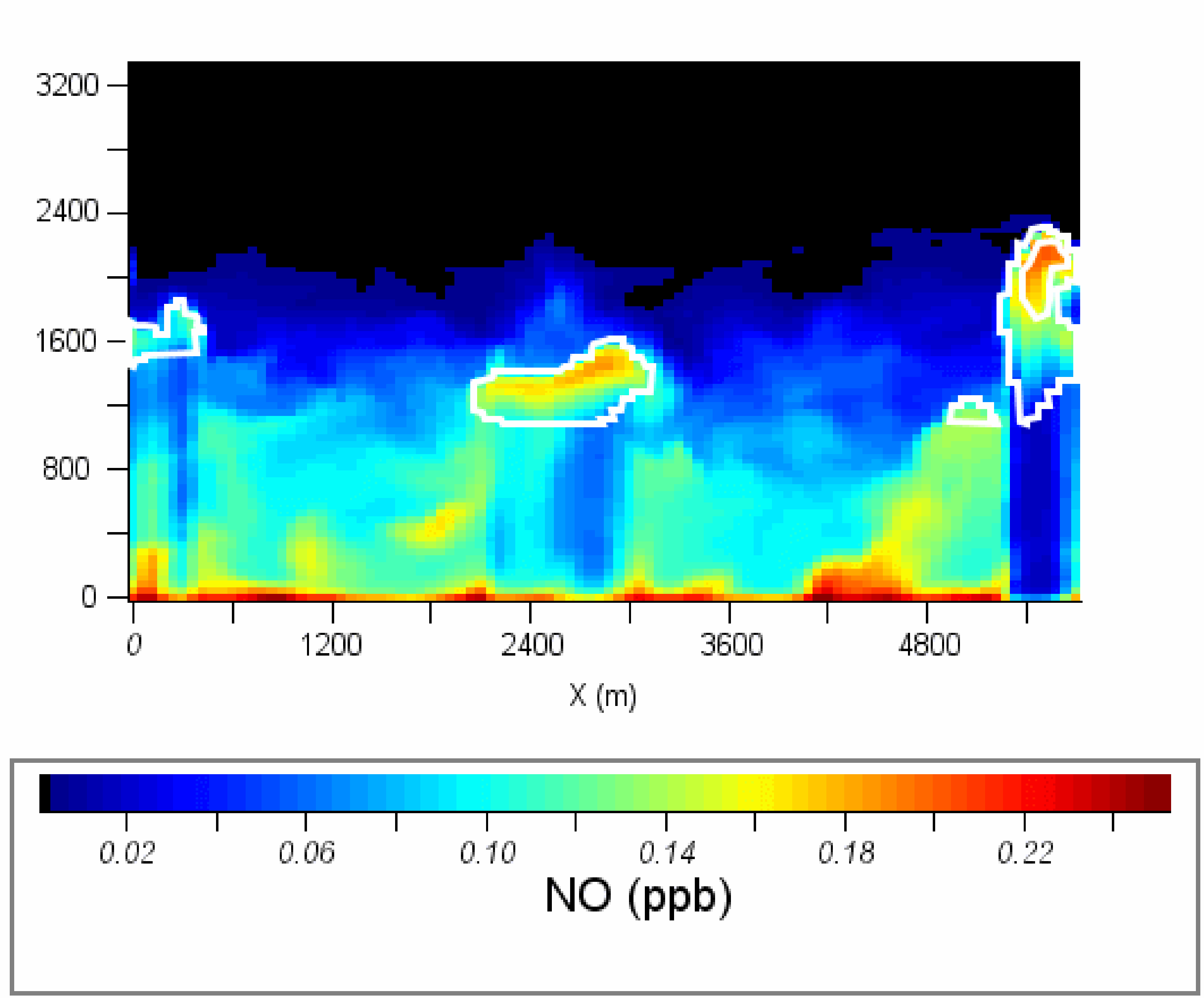
Instantaneous vertical cross section photolysis rate (j)



Parameterization depends on:

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

Vertical cross section NO



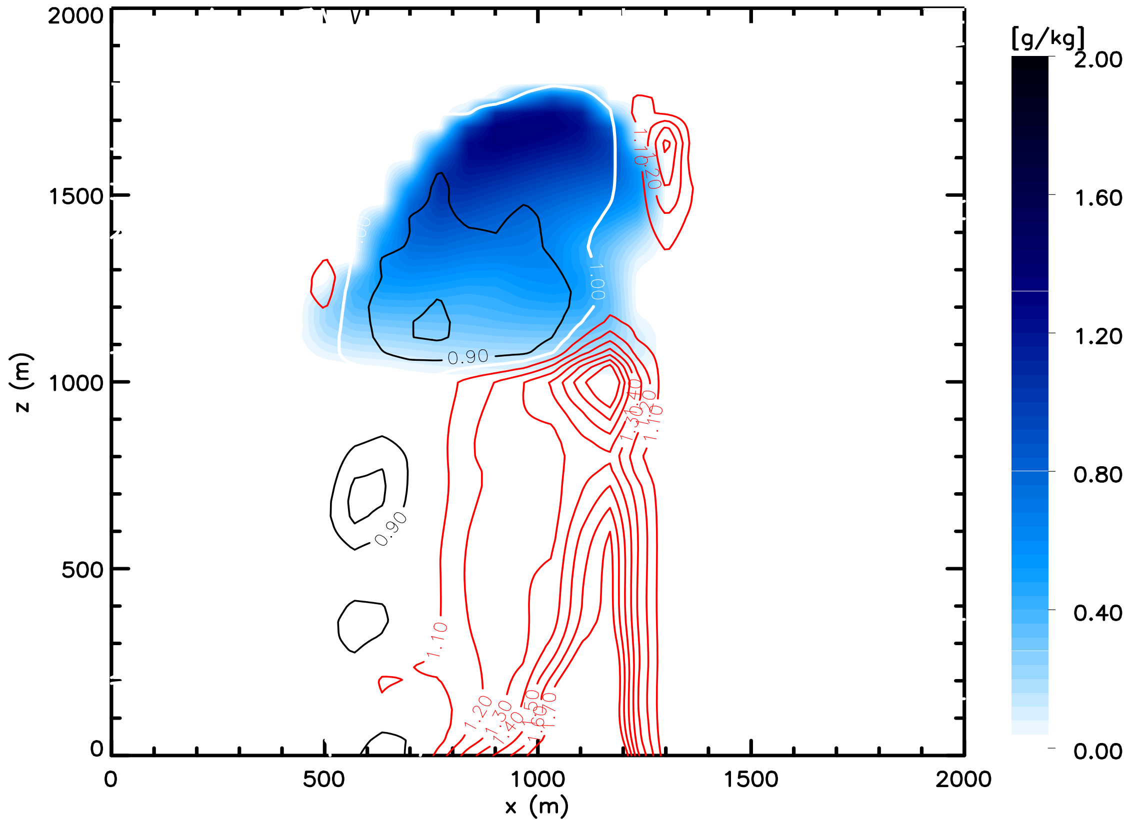
Photostationary state below, in and above shallow cumulus (instantaneous values)

$$\varphi = \frac{kNOO_3}{jNO_2}$$

Equilibrium

$$\boxed{\varphi = 1}$$

$$Da = \frac{\tau_t}{\tau_c} \approx O(1)$$



Conclusions

Importance to understand and to reproduce the influence and transition

Stable BL => Convective BL

Formation of clear/cloudy BL
(impacts on BL-dynamics and chemistry)

If shallow cumulus are formed:

Enhancement of vertical transport

Potentially larger dilution

Mixing and photolysis rate largely perturbed

Large influence in the atmospheric chemistry in the nocturnal boundary layer

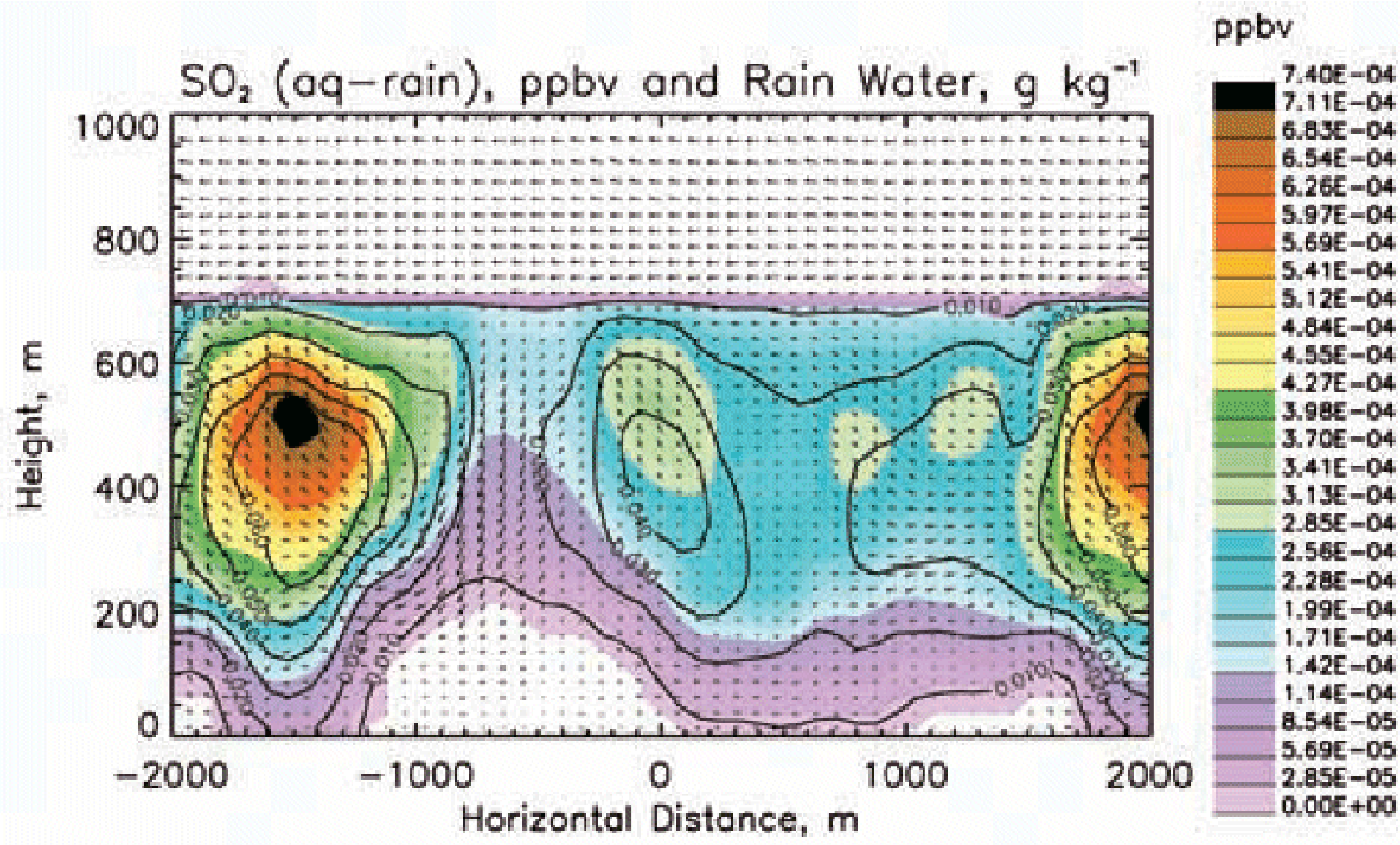
Outlook

Why do we have clear or cloudy boundary layers? Influence of the nocturnal conditions

Processes study of the interaction aerosols/cloud/chemistry

Feedbacks of aerosol processes and cloud chemistry in marine stratocumuls

LES study (Feingold and Kreidenweis, 2002)



Is able the turbulent mixing in the sub-cloud layer and the cloud layer to reduce the gradients of the species?

Damköhler number:

$$Da = \frac{\tau_t}{\tau_c}$$

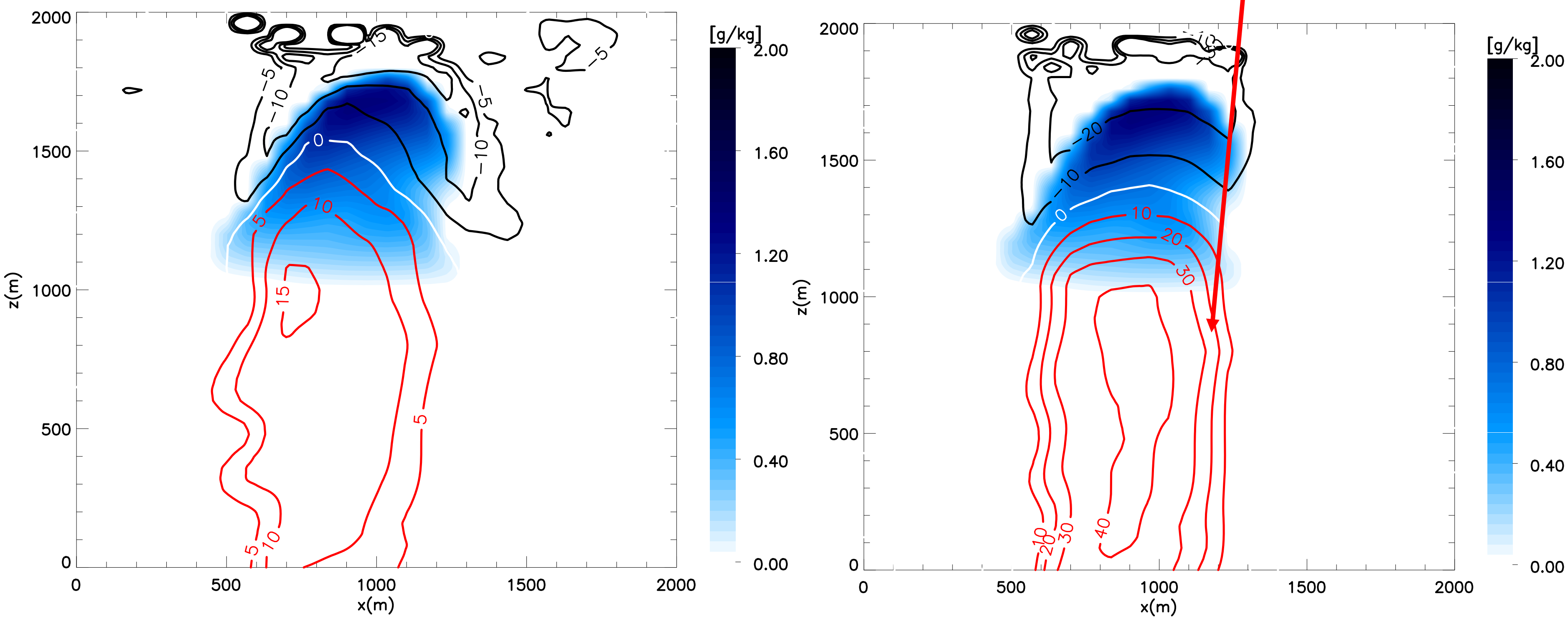
Differences in the instantaneous fields

$$Diff = \frac{A(j_{cl}) - A(j_{cs})}{A(j_{cl})}$$

Larger deviations due to the faster chemistry (transport less efficient)

Moderate chemistry

Fast chemistry



Da ≈ 0.4

Da ≈ 4