Transport and chemical transformations in shallow cumulus over land

Jordi Vilà-Guerau de Arellano
Wageningen University
The Netherlands
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 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

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

20\textsuperscript{th} 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)
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 20\textsuperscript{th} June: CLEAR

Diurnal ABL 21\textsuperscript{st} June: CLOUDY (Cu)

What are the implications for atmospheric chemistry?
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

⇒ Process study
⇒ 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
11.45 LT. 21st June 1997
Vertical cross section NO
Daily evolution of the surface forcing

**SH and LE fluxes**

**Friction velocity**

[Graphs showing daily evolution of surface forcing with SH and LE fluxes and friction velocity over time.]
Time evolution of cloud characteristics

Cloud base and top

Cloud cover
Vertical profiles

LES results (1-hour average) versus radisounding observations

Potential temperature

Specific humidity

CLOUD LAYER

SUB-CLOUD LAYER
Vertical profile buoyancy and scalar flux

Clouds in an initial phase
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 \textit{entrained} species (ozone)

\textbf{Clear boundary layer} \quad \textbf{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

\[ A \xrightarrow{j} B + C \quad (1^{\text{st}} \text{ order reaction}) \]

\[ B + C \xrightarrow{k} A \quad (2^{\text{nd}} \text{ order reaction}) \]

Possibility to define a photostationary state

\[ \varphi = \frac{kAB}{jC} \]
Initial conditions reactants

\[ z = z_i \]

\[ z = 0 \]
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

$1^{st}$ 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

\[ \varphi = 1 \]

\[ Da = \frac{\tau_t}{\tau_c} \approx O(1) \]
Conclusions

Importance to understand and to reproduce the influence and transition

Stable BL $\Rightarrow$ 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 stratocumulus 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

\[ \text{Diff} = \frac{A(j_{cl}) - A(j_{cs})}{A(j_{cl})} \]

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

Moderate chemistry

Fast chemistry

\[ Da \approx 0.4 \]

\[ Da \approx 4 \]