Formation of fog due to stratus lowering:
experimental and numerical study of the life cycle

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National Center for Meteorological Research

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07/06/2022 - SOFOG3D meeting
FSTL: • poorly studied compared to RAD
  • difficult to predict.

Numerical weather prediction (NWP):
  • AROME => difficulties to correctly forecast stratus lowering.

During winter 2011 at Paris-CDG, (17 RAD, 20 FSTL et 3 ADV)

AROME simulated about 70% RAD and 30% FSTL (Philip et al. (2016)).

Better understanding for better forecasting. What are the processes involved?
Life cycle of a stratus lowering

Stratus

Lowering

Fog

Subsidence

Oliver et al. (1978)
Pilié et al. (1979)

Radiative cooling

Entrainment

Advection

Koracin et al. (2001)

Turbulent transport

Collection

Sedimentation

Dupont et al. (2012)
Wagh et al. (2021)

Evaporation

LE, H

IR
What are the main processes leading to stratus lowering?
Objectives

Better understand the processes leading (or not) to stratus lowering.

1st objective

- Are stratus lowering driven primarily by local processes (such as microphysics) or non-local (large-scale conditions or mesoscale circulations)?

2nd objective

- What are the main characteristics of stratus lowering fogs (thermodynamics, microphysics)?
Methodology

Observations (BURE campaign)  
Burnet et al. (2016)

- 2 winters 2015 et 2016
- Atmospheric station of the OPE (388 m) of ANDRA (Observatoire Périenne de l'Environnement)

✓ 29 Radiative fog (RAD)  ✓ 18 Fog stratus lowering (FSTL)  ✓ 19 No fog stratus lowering (NFSTL)

Modeling

Lac et al. (2018)
Introduction

Methodology

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- **IOP2** : One FSTL case sampled  
  *(1st and 2nd December 2016)*

Methodology

Modeling

*Lac et al. (2018)*

- ✓ **LIMA** : 2-moment scheme (mixing ratios and prognostic droplet concentration)  
  *Vié et al. (2016)*

- • High resolution numerical simulation (100m) with **LIMA**
- • Process study
**Methodology**

### Observations (BURE campaign)  
*Burnet et al. (2016)*

- 2 winters 2015 et 2016
- Atmospheric station of the **OPE** (388 m) of ANDRA  
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- **IOP2 :** One **FSTL** case sampled  
  *(1st and 2nd December 2016)*

- Statistical analysis of OPE events

### Modeling  
*Lac et al. (2018)*

- **✓ LIMA :** 2-moment scheme (mixing ratios and prognostic droplet concentration)

- High resolution numerical simulation *(100m)* with **LIMA**
  - Process study

- Characterize the **FSTL** versus **NFSTL**
Presentation outline

1. Introduction

2. Experimental study of IOP2 (FSTL observed December 1 - 2, 2016)

3. Numerical study of IOP2

4. Conclusion and perspectives
Presentation outline

1. Introduction

2. **Experimental** study of **IOP2** (**FSTL** observed December 1 - 2, 2016)

3. Numerical study of **IOP2**

4. Conclusion and perspectives
Overview of the case study: IOP2 1st and 2nd December 2016

In-situ measurements

**Instrumented mast**

- 120 m visibility
  - T, RH, U
- 50 m Cloudy water
  - T, RH, U
- 10 m visibility
  - T, RH, U
- 2 m

**Remote sensing**

- cloud base height
- Integrated cloud water on the vertical
  - Martinet et al. (2020)

**Turbulence**

**Deposition measurements**

- Tav et al. (2018)

Intensive observation period

- Tethered balloon
- Turbulence probe
- Radiosondes

Canut et al. (2016)

Droplet size from 2 to 50 μm in diameter.

Martinet et al. (2020)

**Deposition measurements**

- T, RH, U, TKE

**T, RH, U**
Overview of the case study: IOP2 1st and 2nd December 2016

In-situ measurements

Instrumented mast

120 m
- Visibility
- T, RH, U

50 m
- Cloudy water
- T, RH, U

10 m
- Visibility
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2 m
- T, RH, U

Remote sensing

Cloud base height

Integrated cloud water on the vertical

Martinet et al. (2020)

Turbulence

Deposition measurements

Tav et al. (2018)

Intensive observation period

Tethered balloon

Canut et al. (2016)

T, RH, U, TKE

Turbulence probe

CDP

Droplet size from 2 to 50 μm in diameter.

Radiosondes

Martinet et al. (2020)
Overview of the case study: IOP2  1\textsuperscript{st} and 2\textsuperscript{nd} December 2016

Satellite products

Cloud type

01/12/2016 1800 UTC  02/12/2016 0000 UTC  02/12/2016 0600 UTC  02/12/2016 1200 UTC

Source (E. Fontaine (CEMS))
Overview of the case study: IOP2 1\textsuperscript{st} and 2\textsuperscript{nd} December 2016

- **Stratus**
- **Drying period**
- **Fog**

### Graphs

- **(a)** LWP (g.m\(^{-2}\))
- **(b)** LWD (W.m\(^{-2}\))
- **(c)** Height (m)

1. **1\textsuperscript{st} stratus**
2. **1\textsuperscript{st} lowering**
3. **2\textsuperscript{nd} stratus**
4. **2\textsuperscript{nd} lowering**
5. **Fog**
Analysis of stratus lowering

1\textsuperscript{st} lowering

- Humidification

2\textsuperscript{nd} lowering

- Cooling

\begin{itemize}
  \item RH (\%)
  \item \(\Theta\) (\degree C)
\end{itemize}

\textbf{Introduction}  
\textbf{IOP2}  
\textbf{Statistic}  
\textbf{Conclusion}
1st lowering

- Dissipation of stratus
- Drying
- Warming

2nd lowering

Drying period

- RS

LWC (g.m⁻³)

RH (%)

Θ (°C)

1st lowering:
- Approx. 250 m lower than 400 m

2nd lowering:
- CBH
- No data

Introduction

Analysis of stratus lowering

Conclusion
Analysis of stratus lowering

1st lowering

1st lowering

2nd lowering

2nd lowering

Introduction

Conclusion
Microphysical properties during lowering

1st stratus
1st lowering

2nd stratus
2nd lowering

Adiabatic gradient

Quasi-adiabatic

Nc~300(cm⁻³)
Microphysical properties during lowering

1st stratus

1st lowering

2nd stratus

2nd lowering

--- Adiabatic gradient

Quasi-adiabatic

Nc~300 (cm$^{-3}$)

Over-adiabatic

Bi-layer structure
Microphysical properties during lowering

Small droplets
10 μm
Microphysical properties during lowering

Small droplets 10 μm

Large droplets 22 μm
Introduction

Microphysical properties during lowering

Statistic

Conclusion

Large droplets

Small droplets

Large droplets

Small droplets
Microphysical properties during lowering

Sedimentation

Small droplets 10 μm

Large droplets 22 μm
Microphysical properties during lowering

Sedimentation

Activation
2nd stratus

Fog

Sedimentation

Bimodal spectrum

Activation

Introduction

Statistic

Conclusion
of the previous observations
Pinnick et al. (1978)
Egli et al. (2015)
Intermediate conclusion

Supply cold and humid air

Supply warm and dry air

1\textsuperscript{st} lowering

2\textsuperscript{nd} lowering

2115

23

00

drying period

≈ 250 m

≈ 400 m

230

04

05

06

07

08

0230

Stratus over-adiabatic
Bimodal spectrum

droplets > 20 μm coalescence

Sedimentation

Fog

Activiation

Fog

Bimodal spectrum

Burnet et al, in prep
Presentation outline

1. Introduction

2. Experimental study of IOP2 (FSTL observed December 1 - 2, 2016)

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4. Conclusion and perspectives
Reference simulation with Meso-NH and LIMA at high resolution

- Horizontal grid resolution: 500 m et 100 m with two-way nested grids.
- 150 vertical levels: 0 to 3250 (from $\Delta z = 1.5$ to 50 m)
- Initial/coupling: AROME analysis (1.3 km)

- Turbulence:
  - 1D at $\Delta x = 500$ m and mixing length BL89
  - 3D at $\Delta x = 100$ m and mixing length DEAR

  Prognostic equation for (Cuxart et al, 2000)

- Microphysics: LIMA (two-moment scheme)
- LIMA with modified activation according to Vié et al. (2022)

- Aerosol initialization from ground aerosol measurements (3 modes).
- Constant aerosol concentrations over the vertical.
Validation of the reference simulation

Stratus formation at 23 UTC instead of 18 UTC in the observations.

Delay of a few hours between the simulation and the observations.
Validation of the reference simulation

OPE  CBH

Stratus formation at 23 UTC instead of 18 UTC in the observations.

AROME forecast (network 0h)

Delay of a few hours between the simulation and the observations.
Validation of the reference simulation

OPE  CBH

Stratus

Drying period

Lowering

Fog

4-hour delay in the simulation
Validity of the reference simulation

Introduction

OPE CBH

Stratus

Drying period

Lowering

OBS Stratus Drying period Fog
Validation of the reference simulation

REF reproduces well the cloud life cycle (3 phases)
Validation of the reference simulation

Measurements with CDP under the tethered balloon

Stratus

Fog

Differences between stratus and fog fairly well reproduced
Hour fog formation

- Effect of advection (northeast to southwest).
- Effect of orography: late or no fog in the valleys.
Advection of stratus from northeast to southwest. 
Lowering: 1: NE, 2: OPE, 3: SW.

- Stratus progressively thicker.
Analysis of stratus cloud lowering

Budgets to better characterize the processes leading to stratus lowering

\[ \frac{d}{dt}(K \cdot h^{-1}) + \frac{d}{dt}(g \cdot kg^{-1} \cdot h^{-1}) + \frac{d}{dt}(g \cdot kg^{-1} \cdot h^{-1}) \]
Analysis of stratus cloud lowering

Budgets to better characterize the processes leading to stratus lowering

Lowering

\[ \frac{d}{dt}(K_h) + \frac{d}{dt}(g_{kg^{-1} h^{-1}}) \]

\[ \frac{d}{dt}(g_{kg^{-1} h^{-1}}) \]

\[ \frac{d}{dt}(g_{kg^{-1}}) \]

Introduction

IOP2

Statistic

Analysis of stratus cloud lowering

Budgets to better characterize the processes leading to stratus lowering

Lowering

time

NE

0750 UTC - 0920 UTC
Analysis of stratus cloud lowering

Budgets to better characterize the processes leading to stratus lowering

<table>
<thead>
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<th>Destruction</th>
<th>Production</th>
<th>Cooling</th>
<th>Warming</th>
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Cloudy water

Temperature

Advection
Microphysics
Turbulence
Radiation

Tendency

NE
0750 UTC - 0920 UTC
Analysis of stratus cloud lowering

Budgets to better characterize the processes leading to stratus lowering

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- **Advection**
- **Microphysics**
- **Turbulence**
- **Radiation**

**NE 0750 UTC - 0920 UTC**

**Advection of cloudy water**
Analysis of stratus cloud lowering

Budgets to better characterize the processes leading to stratus lowering

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- **Sedimentation**
- **Advection of cloudy water**

\[\frac{d \theta}{dt} (K \cdot h^{-1})\]
\[\frac{drc}{dt} (g \cdot kg^{-1} \cdot h^{-1})\]
\[\frac{drc}{dt_{micro}} (g \cdot kg^{-1} \cdot h^{-1})\]
Budgets to better characterize the processes leading to stratus lowering.
Bilans pour mieux caractériser les processus menant à l'affaissement de stratus

NE

0750 UTC - 0920 UTC

Tendency
Advection
Turbulence
Microphysics
Radiation

OPE

0750 UTC - 1010 UTC

Sedimentation
Advection +CCN act
Riming
Adjustment
Sedimentation

Advection of cloudy water

SW

0750 UTC - 1100 UTC

Advection of cold air

Advection of warm air

\[ \frac{d r_c}{dt} \text{ (g.kg}^{-1} \text{.hr}^{-1}) \]
\[ \frac{d r_c}{dt} \text{ (g.kg}^{-1} \text{.hr}^{-1}) \]
\[ \frac{d \theta}{dt} \text{ (K.hour}^{-1}) \]
Analysis of stratus cloud lowering

Budgets to better characterize the processes leading to stratus lowering

The advection of cloud water into stratus and cold air under stratus is the primary process driving the STL on this case.
Impact of microphysics

Hour fog formation

**REF**

72 % of the domain

**NOSED**

(Without droplet sedimentation)

47 % of the domain

Sedimentation is the second process that favors the stratus lowering
Better understand the processes leading (or not) to stratus lowering

Life cycle of stratus and its lowering

Stratus

Dryer period

Fog

Advection of cloudy water

Advection of warm and dry air

Advection of cold air

time

Introduction

IOP2

Statistic

Conclusion
Better understand the processes leading (or not) to stratus lowering

Life cycle of stratus and its lowering

- **Stratus**
- **Dryer period**
- **Fog**
- **Lowering**

**Non-local processes 3D**
- Advection of cloudy water
- Advection of warm and dry air
- Advection of cold air

IOP2
Statistic
Conclusion
Better understand the processes leading (or not) to stratus lowering

Life cycle of stratus and its lowering

- **Stratus**
- **Fog**
- **Dryer period**
- **Lowering**

**Non-local processes 3D**
- Advection of cloudy water
- Advection of warm and dry air

**Local processes 1D**
- Sedimentation
- Evaporation
- Activation condensation

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1. Introduction

2. Experimental study of IOP2 (FSTL observed December 1 - 2, 2016)

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1er objective

- What are the main processes leading to stratus lowering?

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<th>Local processes</th>
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<td>Advection Cold air</td>
<td>Sedimentation</td>
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<tr>
<td>Advection Of cloudy water</td>
<td>Evaporation</td>
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Subsidence Radiative cooling

2ème objective

- What are the main characteristics of stratus lowering fogs?

- Cloud water production in the fog phase.
- Thicker FSTL but with lower water content near the ground than RAD.
Post-doc: FSTL during SOFOG3D:

microphysical properties and processes study

- Document the evolution of boundary layer properties during the stratus to fog event from in situ measurements and remote sensing.

- Perform numerical simulation of 2-3 case studies with the Meso-NH model in LES mode and validate with the available observation.

- Conduct budget analysis to investigate local and non local contributions of the processes leading to the fog formation by stratus lowering.
Post-doc: FSTL during SOFOG3D: microphysical properties and processes study

- Document the evolution of boundary layer properties during the stratus to fog event from in situ measurements and remote sensing.

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- Conduct budget analysis to investigate local and non local contributions of the processes leading to the fog formation by stratus lowering.
Thank you for your attention
Caractérisation des FSTL par rapport aux RAD

- **LWC at 10 m**
  - FSTL < RAD
  - 13 cases < 15 cases

- **NC at 10 m**
  - FSTL ≈ RAD
  - 13 cases ≈ 15 cases

- **LWP**
  - FSTL > RAD
  - 7 cases > 11 cases

- Variability between the different cases of FSTL and RAD
- FSTL have less liquid water on the ground than RAD
- FSTL are thicker than RAD