NEPHELAE: Network for studying Entrainment and microPHysics of clouds using Adaptive Exploration

Skywalker X6 (La Réunion)

G. Roberts\textsuperscript{1,2}, S. Lacroix\textsuperscript{4}, G. Hattenberger\textsuperscript{5}, N. Maury\textsuperscript{1}, R. Calmer\textsuperscript{1}, G. Cayez\textsuperscript{3}, F. Julien\textsuperscript{1}, J. Viviand\textsuperscript{1}, F. Couvreux\textsuperscript{1}, F. Burnet\textsuperscript{1}, P. Narvor\textsuperscript{4}, D. Lohani\textsuperscript{4}, A. Cabarbaye\textsuperscript{5}, T. Verdu\textsuperscript{5}, F. Garcia\textsuperscript{5}, M. Bronz\textsuperscript{5}, K. Nicoll\textsuperscript{6}

\textsuperscript{1} Météo-France/CNRS, CNRM/GMEI/MNPCA; \textsuperscript{2} Scripps Institution of Oceanography; \textsuperscript{3} Météo-France, INP-ENM; \textsuperscript{4} Laboratory for Analysis and Architecture of Systems, LAAS; \textsuperscript{5} Ecole Nationale de l’Aviation Civile, ENAC; \textsuperscript{6} Univ. Bath, UK

ISARRA, Lugo, Spain; July 2019
Outline

- Motivation / science questions
- Payload / platform development
- Recent campaign in La Réunion
- Cloud sampling / trajectory planning
- Towards a fleet control architecture
Motivation

Science Question:
What are the dominant mixing mechanisms in clouds?

- Difference between adiabatic and observed cloud properties
  → entrainment/detrainment or decoupled atmosphere
- Adiabatic models overestimate cloud radiative fluxes (up to 100 W m$^{-2}$ for shallow Cu)

Entrainment/Detrainment
Still an active field of research since several decades

The existing mixing models yield diverse results

Lateral mixing models
Cloud-top mixing models
**Science Question:**
What are the dominant mixing mechanisms in clouds?

Mixing between cloud air and environment occurs at cloud boundaries.
- Cloud-free air mixed into the cloud (entrainment); dilution effect.
- Cloudy air ejected outside cloud (detrainment); loss of cloud mass.

The existing mixing models yield diverse results. The lack of in-situ observations of cumulus cloud microphysical properties has left a divergence in cloud models.

Entrainment/Detrainment
Still an active field of research since several decades

Lateral mixing models
Cloud-top mixing models

Bouyancy and U-W streamlines

G. Dagan et al., 2018
NEPHELEAE Payloads

<table>
<thead>
<tr>
<th>Standard instruments (all)</th>
<th>Standard Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure, temperature, humidity</td>
<td>PTU → $T_{dew}$ → lifting condens. level</td>
</tr>
<tr>
<td>Autopilot &amp; Pitot</td>
<td>$u, v$ → horizontal winds</td>
</tr>
<tr>
<td>Video camera</td>
<td>$\Theta_E, z_{inversion}$</td>
</tr>
<tr>
<td>Data acquisition</td>
<td>data downlink</td>
</tr>
</tbody>
</table>

### Cloud dynamics

- **3D winds and solar fluxes**
  - 5-hole probe; IMU; FPGA; $\Delta P + P_{abs}$
  - Cloud sensor (3-$\lambda$)
    - $\sigma_e \rightarrow n_D \times r^2 ; R_{eff}$

### Cloud lwc

- **Cloud microphysical properties**
  - Cloud sensor (3-$\lambda$)
    - $\sigma_e \rightarrow n_D \times r^2 ; R_{eff}$
  - LWC sensor **
    - $lwc \rightarrow n_D \times r^3$

### Aerosol / irradiance

- Optical Particle Counter
  - number concentration ($D_p > 0.3 \mu m$)
- Aerosol Inlet
  - unbiased size distribution ($0.3 < D_p < 3 \mu m$)
- Pyranometer (up & down)
  - $\Delta F_{aerosol} \rightarrow W m^{-2}; F_{\uparrow} / F_{\downarrow} \rightarrow$ Albedo

⇒ Payloads based on mission specific designs for mass less than 800 g.

** LWC TBD
UAV platform under development

- Flying wing configuration
  - Inverted wing-tip:
    - Winglet
    - Vertical stabiliser / anti lacet inverse
    - balancine

- MDO (Multidisciplinary Design Optimization) design

- Adjustable battery position
- Payload compartment

- 2+ hour flight endurance
- Cruise speed: ~25 m/s
- Cruise alt: ≤ 3000 m
- Payload mass: ≤ 800 g
Cloud study at La Réunion

March – April 2019

- Aerosol/cloud flights with balloon and UAVs
- Balloon flights consisted of vertical profiles and constant altitude sampling (1000 m.agl)
- UAV flights consisted of spiral climb ascent / descent
- Operations 1400 m.asl; flight ceiling at 2000 m.agl
- 2 km max distance from GCS
UAV operations at La Réunion

- UAS operations conducted in pasture on the western slope of Maida
- Infrastructure installed / removed daily
- Bungee/ramp take-off; net landing
Overview of campaign (NEPHELAE)

• Flights on five days (2, 3, 4, 6, 7 April); between 9:00 to 18:00; four flights / day
• Flew single UAV in circular pattern in/out of clouds to study mixing at cloud interface
• 17 flights total; 15:16 total flight time
• Flights in convective clouds, precipitation, winds up to 8 m/s
Cloud profiling (Flight 4; 3 April 2019)

Boundary layer

Transition BL - FT 2.74

Compare theory and observation with LWC

Calculate mixing process in clouds
How do you study a cloud?

- Generally a cloud is sampled via a single trajectory (line through a cloud).
- The relative amount of cloud edge (yellow) and cloud core (green) depends on the position of the trajectory relative to the cloud.
- Single trajectories tend to bias the observations towards cloud core and underrepresent those of cloud edges.
- As cloud lifetime ~ 20 minutes, need to optimize trajectories and deploy multiple observations simultaneously.

Cloud sampling with ACTOS

Hoffmann et al., 2014
Cloud mapping

**Role:** compile UAV gathered data into a 3D + Time map of the cloud (i.e., LWC, 3D winds)

**Approach:**
1. Due to sparse, uncertain and dynamic nature of data: use of Gaussian Process Regression (GPR)
2. Incorporation of prior cloud knowledge (e.g., conceptual model, measurement history)
3. Building of dense layered maps with associated uncertainty
4. Extraction of macroscopic cloud properties (cloud border, surface area, volume, max. updraft)

![Gaussian Process regression simulation (MesoNH)]
Cloud mapping results

Liquid Water Content values (with border estimation)

**Linear trajectories**
- 8 lines & 4.9% coverage

**Circular trajectories**
- 6 circles & 3.9% coverage
Flight patterns for adaptive cloud sampling

- Define flight plans for zones of interest (i.e., cloud core, edge, base, top)
- Adaptive flight patterns combine cloud position and sensor feedback

Flight simulation with lace pattern determines the frontier of the cloud.
Fleet control: system overview

An intelligent perception machine dedicated to in-situ cloud data gathering

→ development of a UAS fleet with cooperative sampling
Fleet user interface

Role of GUI:
1. Inform the fleet commander of the current cloud or atmospheric state.
2. Provide a high level command interface for fleet control

Currently defining 2D and 3D interactive tracking tools with sensor data layers
Takeaways / Perspectives

• NEPHELEAE is atmospheric science driven with focus on cloud microphysical processes → identify dominant entrainment mechanism and timescale of cloud development

• Mission-specific payloads and platform designed to study the evolution and life cycle of clouds

• NEPHELEAE aims to develop a UAS fleet with cooperative sampling → adaptively plan and control fleet to maximize usefulness of gathered data

• Gaussian Process Regression and optimized trajectories to effectively map evolution of cloud structures.

• Development of flight trajectory planning and fleet GUI underway