

# Drones et basses couches de l'atmosphère

**Session : Projets d'envergure**

**Greg Roberts (with contributions from many collaborators)**

Centre National de Recherches Météorologiques, Toulouse, France

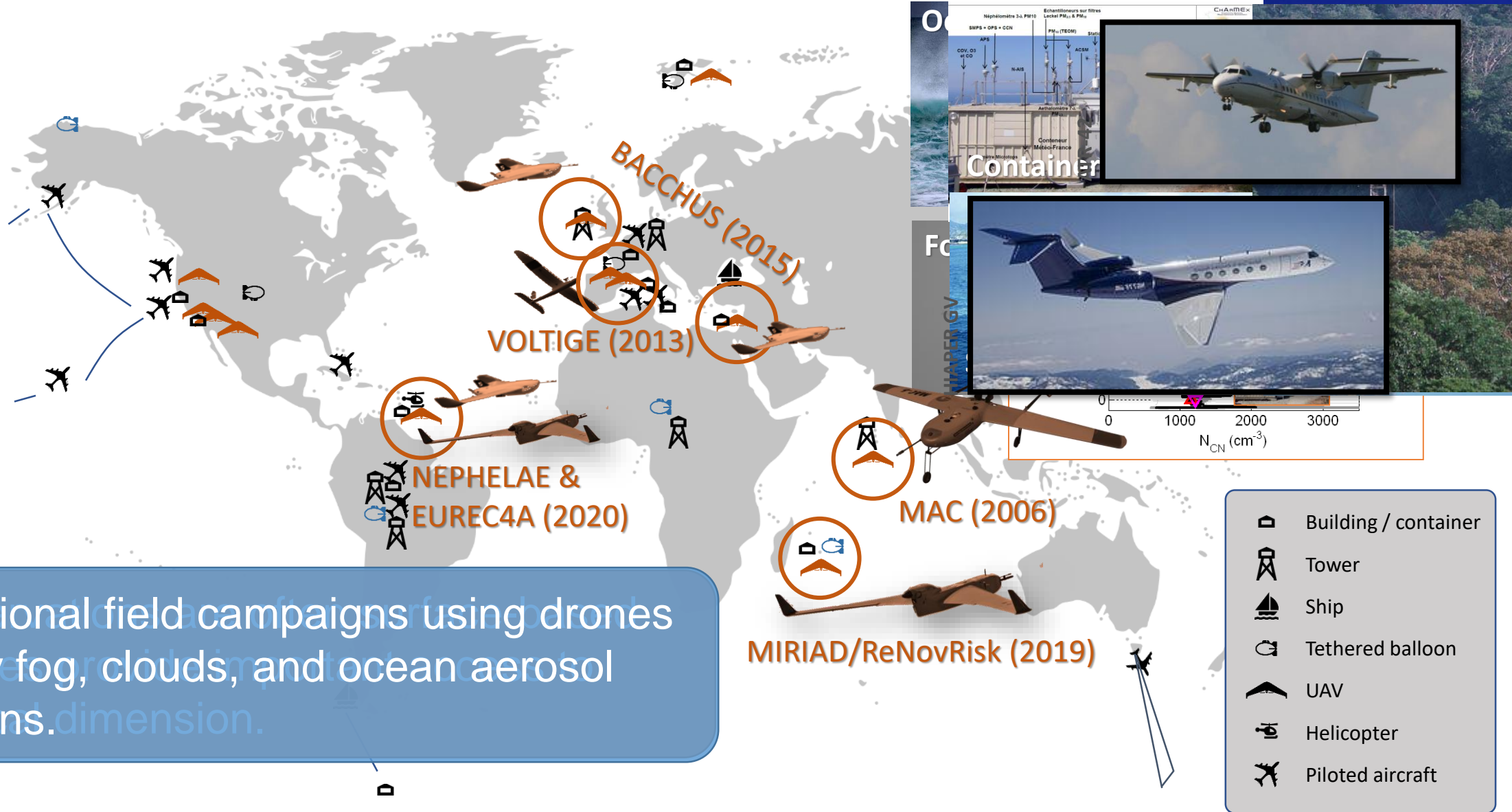
Scripps Institution of Oceanography, La Jolla, CA, USA










**DRONES  
CAP'**

1<sup>ère</sup> Édition des Journées Drones & Capteurs Embarqués  
La Vieille Perrotine, île d'Oléron  
28-30 septembre 2021

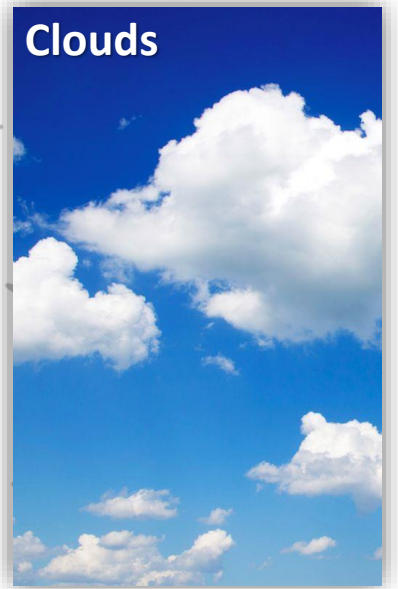
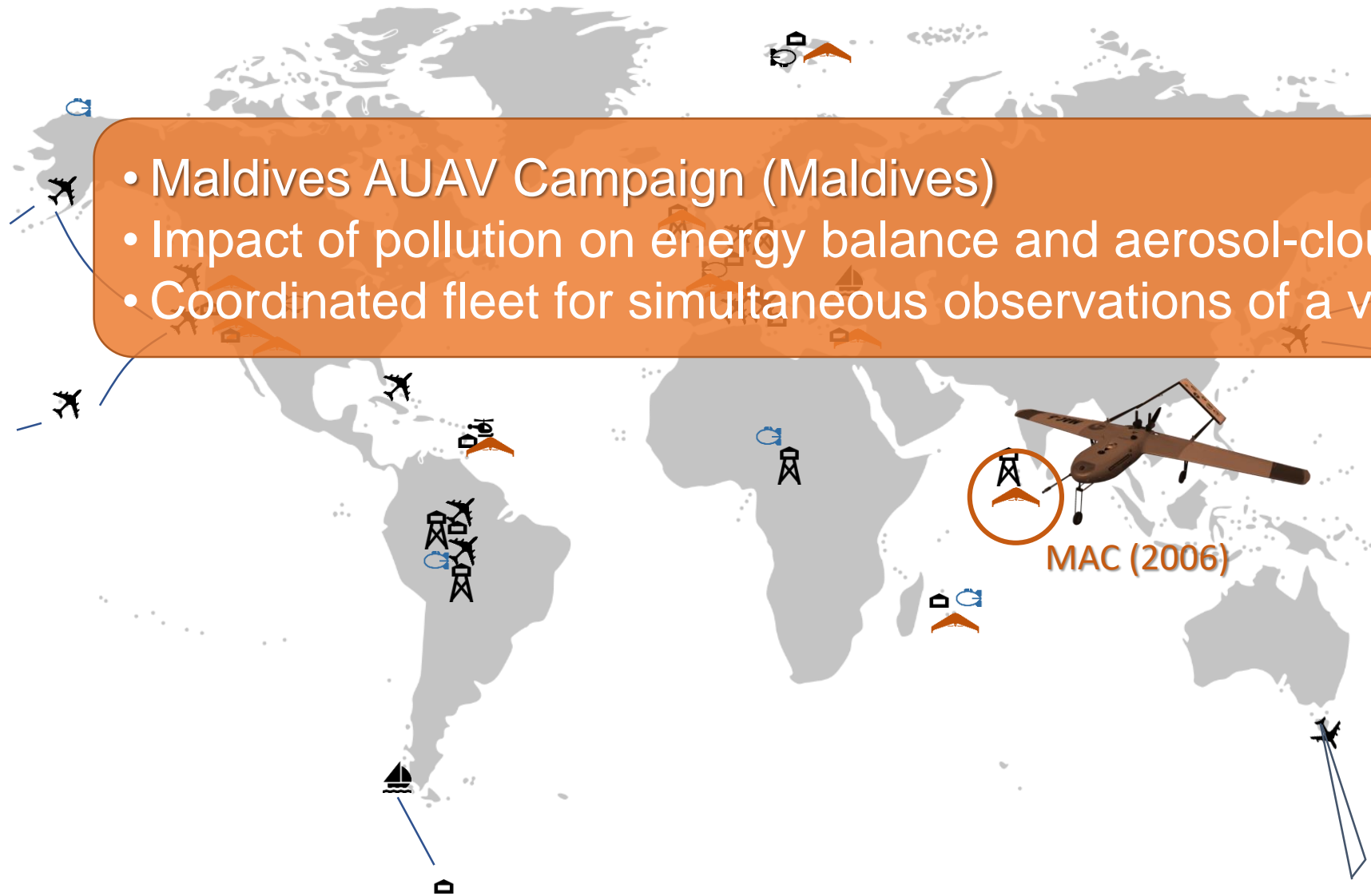
# Deploying drones for atmospheric research



International field campaigns using drones to study fog, clouds, and ocean aerosol emissions.

-  Building / container
-  Tower
-  Ship
-  Tethered balloon
-  UAV
-  Helicopter
-  Piloted aircraft

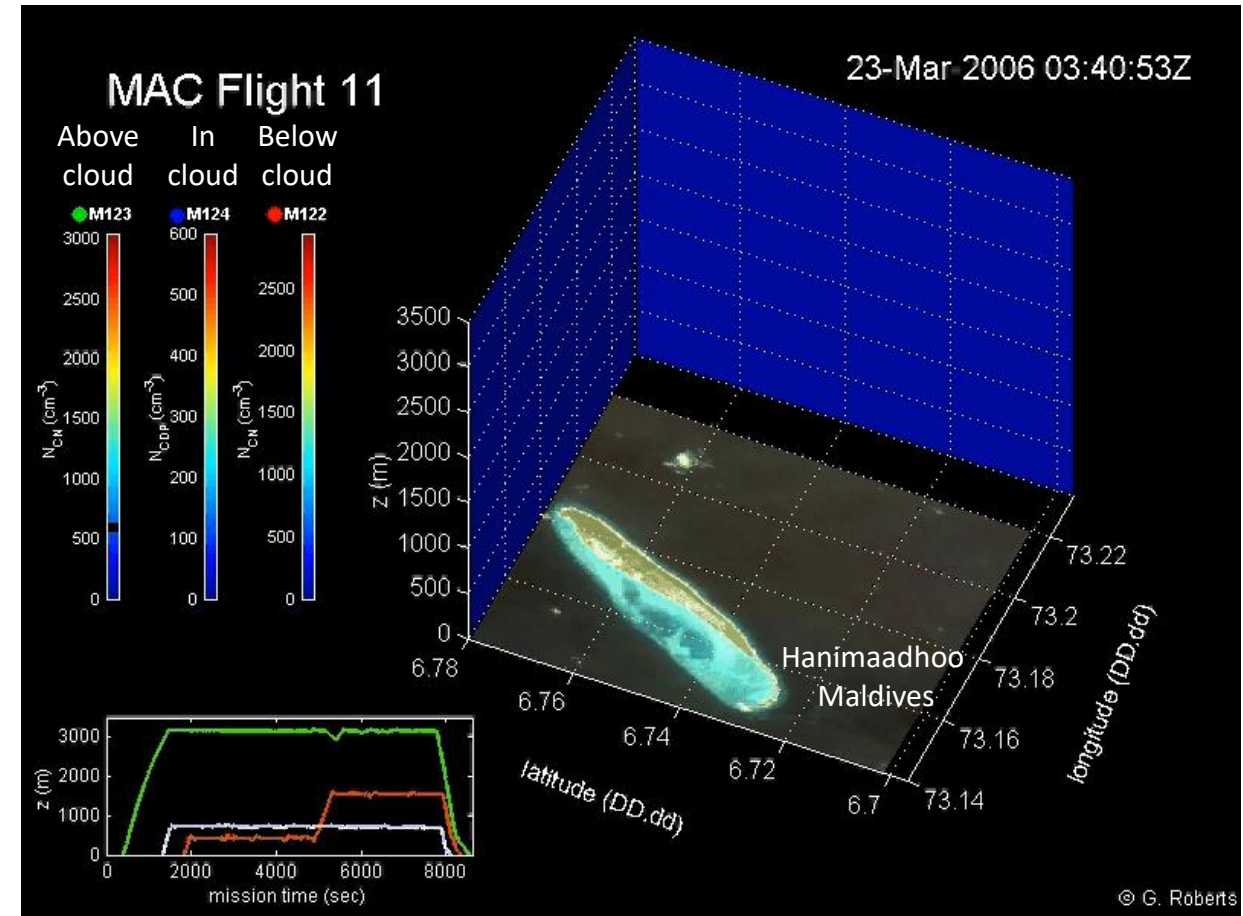
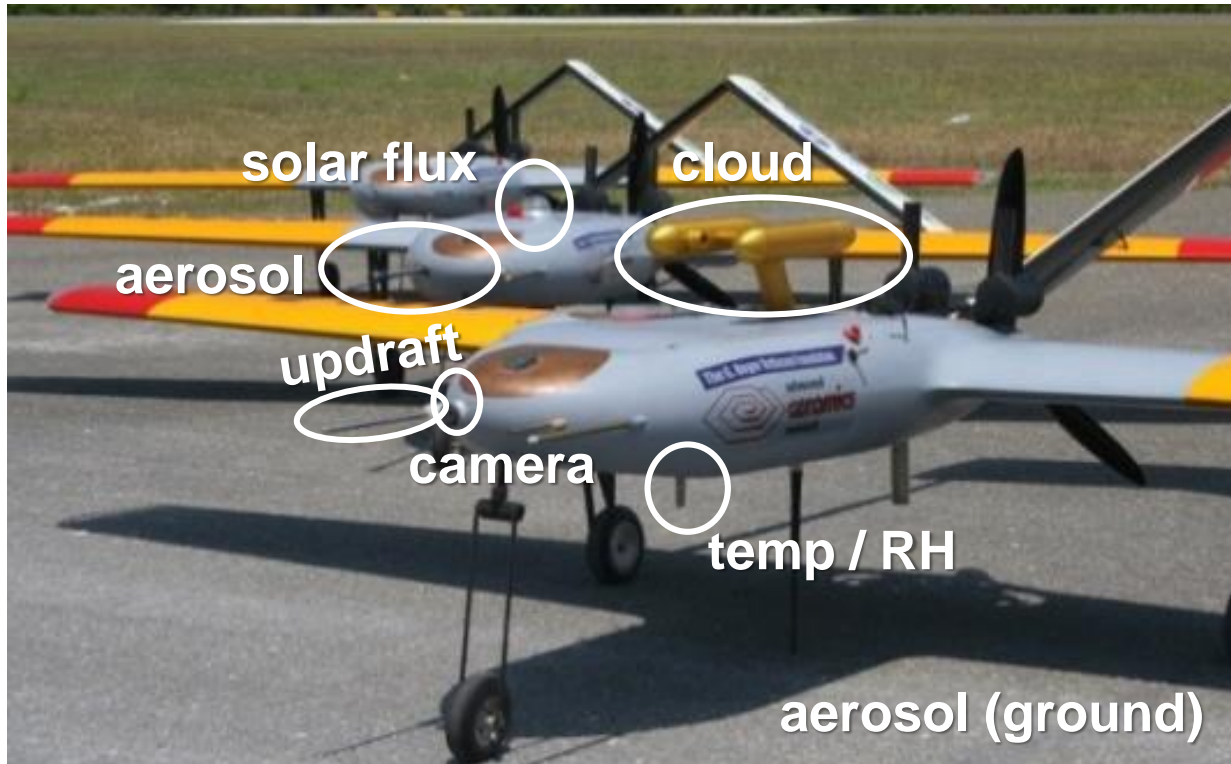
- Maldives AUVAV Campaign (Maldives)
- Impact of pollution on energy balance and aerosol-cloud interactions
- Coordinated fleet for simultaneous observations of a vertical column





# UAV fleet in stacked formation (Maldives, 2006)

Manta UAV fleet from  
Advanced Ceramics Research

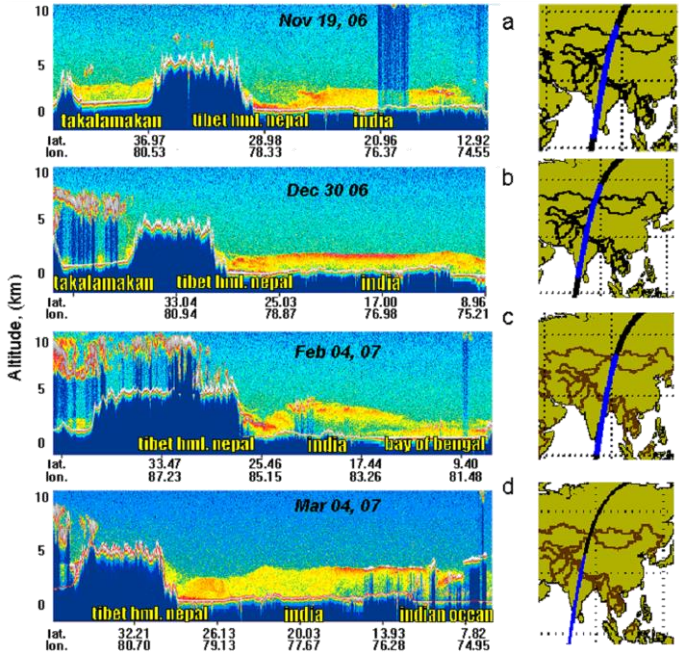


Three vertically-stacked UAVs to observe aerosol-cloud interactions  
on a cloud-by-cloud basis with 20+ hrs synchronized flights

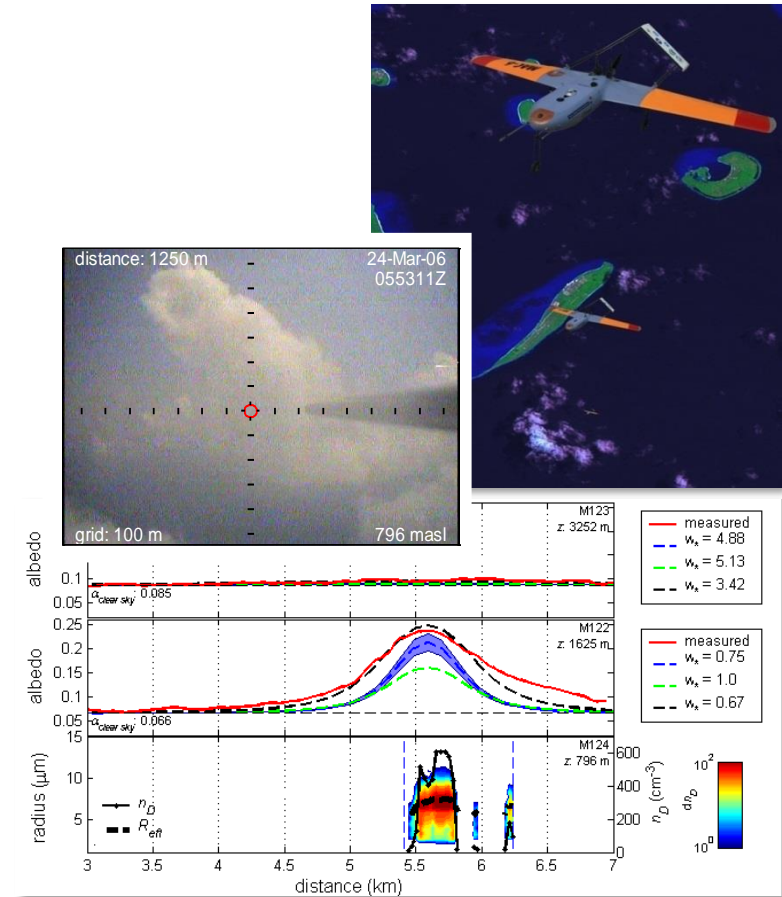


# UAV fleet to study clouds and energy budget

Ramanathan et al., Nature, 2007



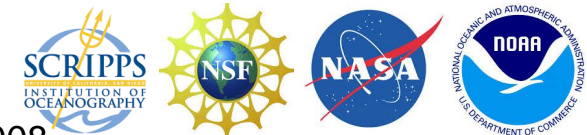
Roberts et al., PNAS, 2008



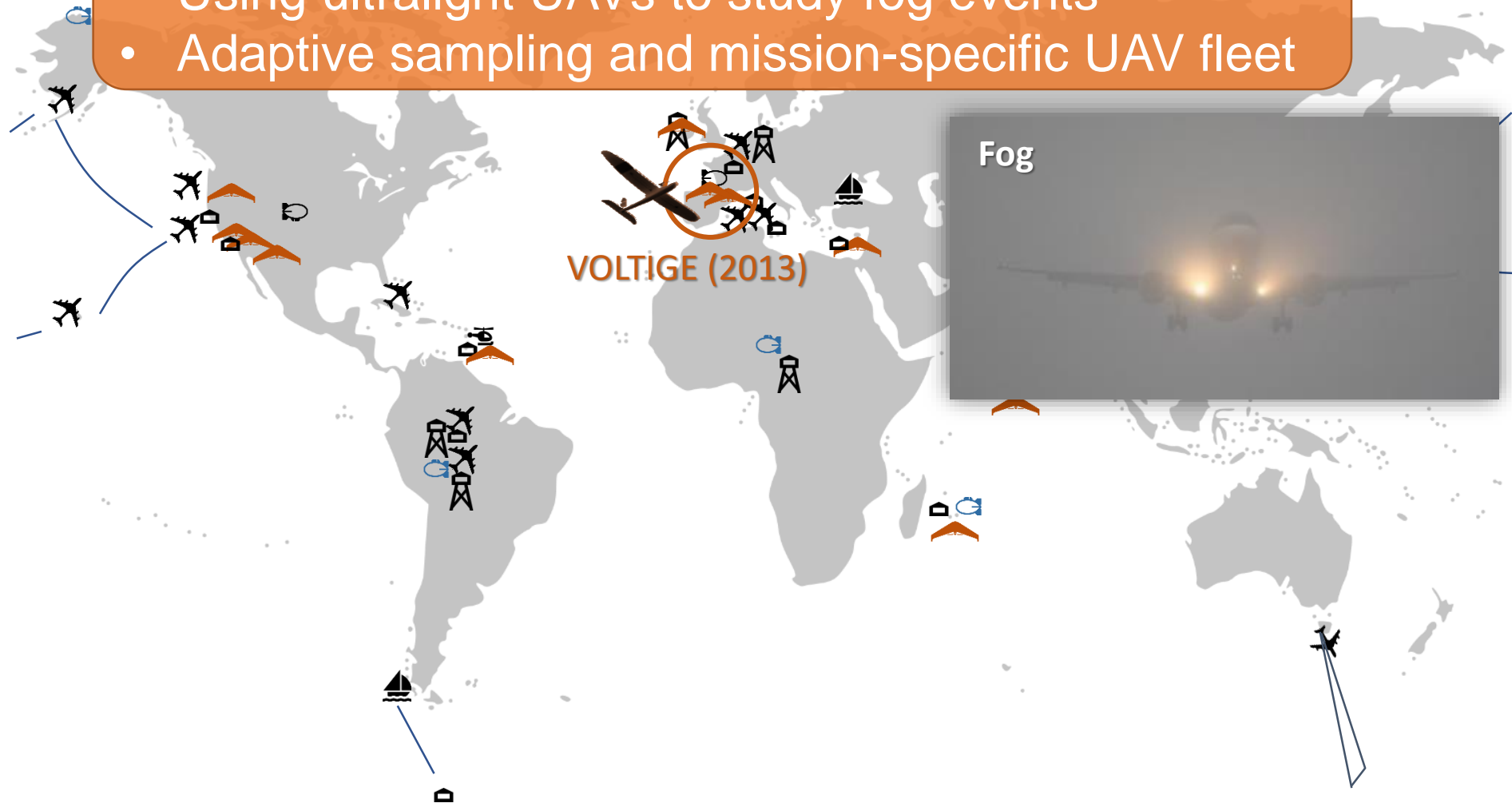
## Maldives AUAV Campaign (2006)

18 missions , 45 flights, 23 hrs synch. obs.. 350 clouds

- Synchronized, stacked fleet for measuring aerosols, clouds and albedo
- Heating of aerosol layers (regional warming ~ scale as CO<sub>2</sub>)
- Linking aerosol-cloud interactions on individual cloud scales



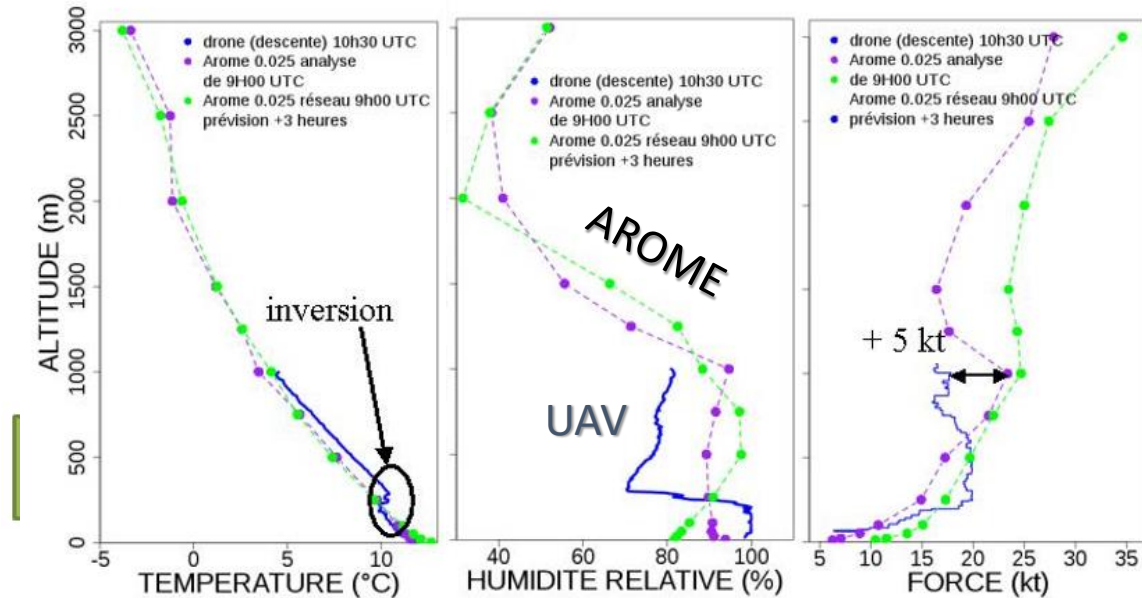
- ANR VOLTIGE (France)
- Using ultralight UAVs to study fog events
- Adaptive sampling and mission-specific UAV fleet



# Boundary layer and fog studies

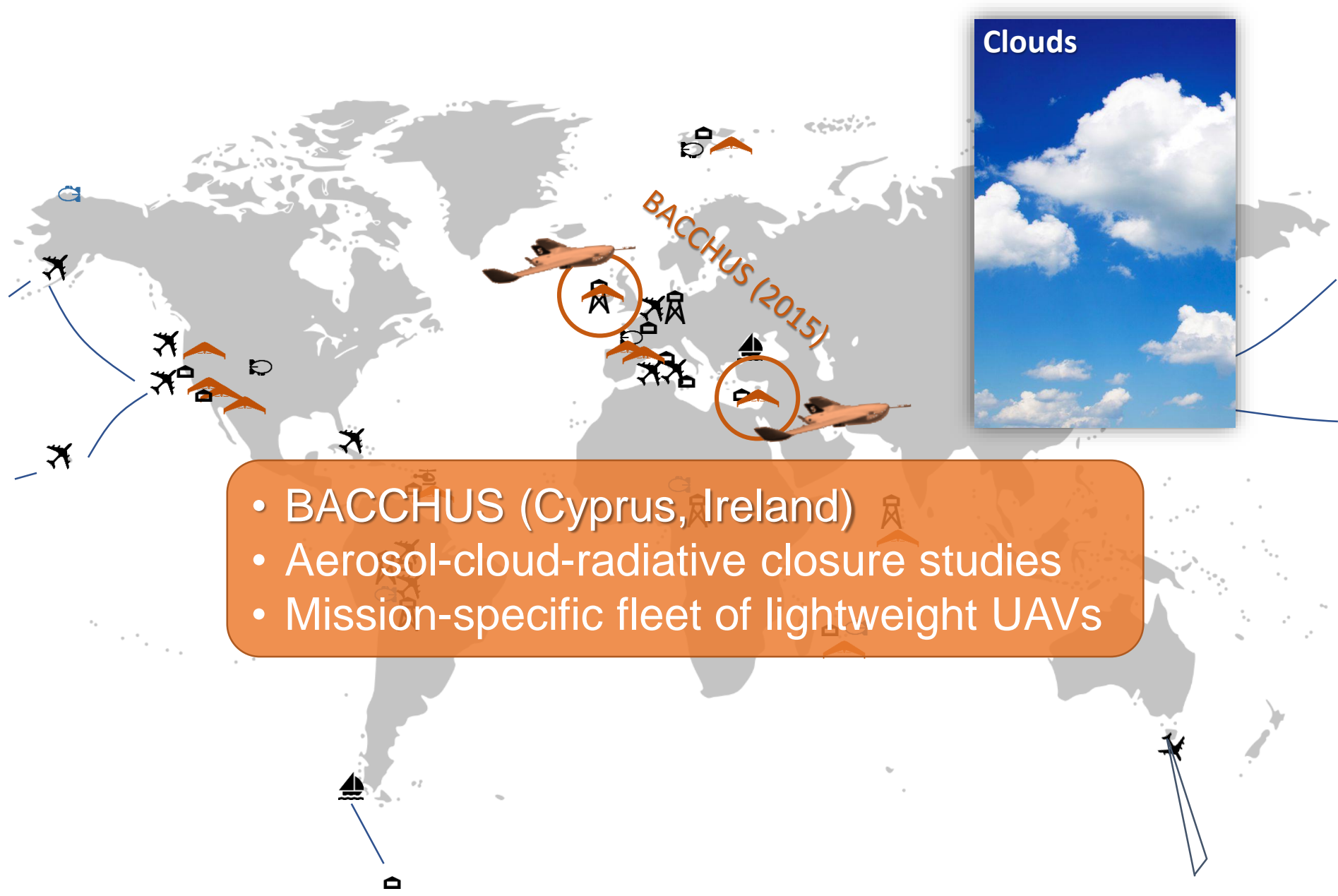


Vecteurs d'Observation de La Troposphère  
pour l'Investigation et la Gestion de  
l'Environnement (VOLTIGE)



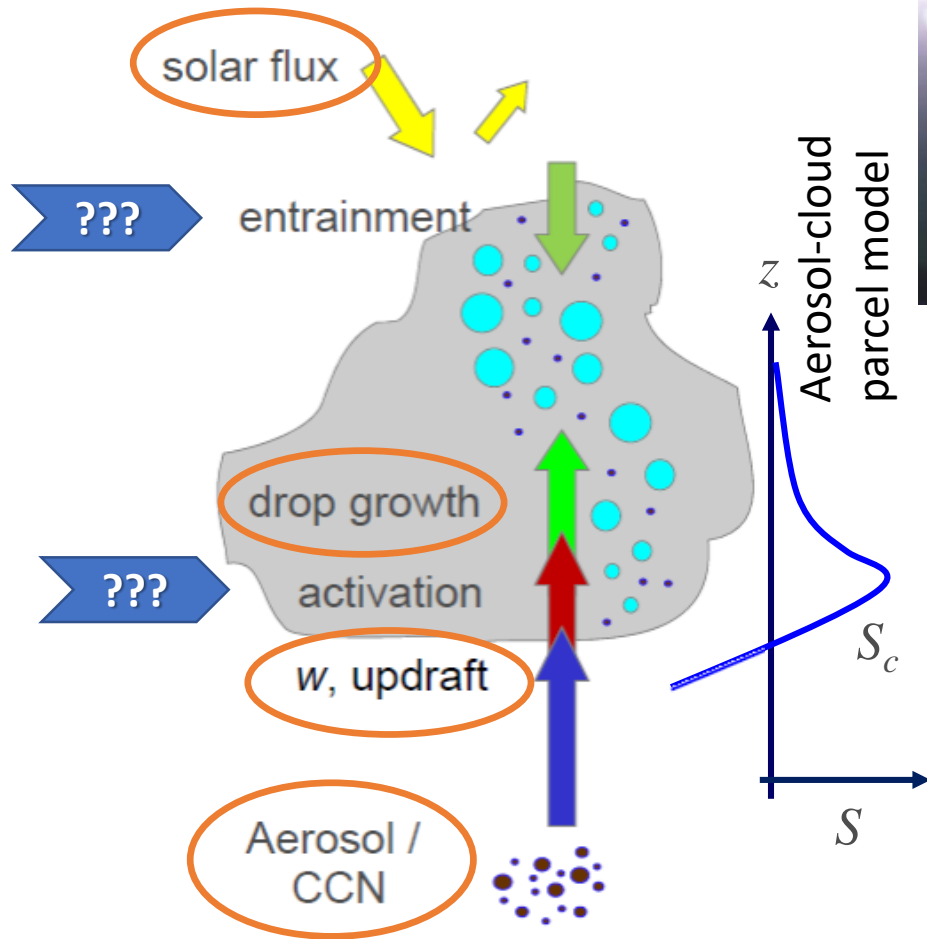
- UAV fleet for simultaneously observing the boundary layer, fog event and radiation budget.
- Temperature, humidity, wind profiles compared to AROME 2.5km operational model
- In-situ measurements show strong inversion not captured in model → in-situ observations would improve forecasts





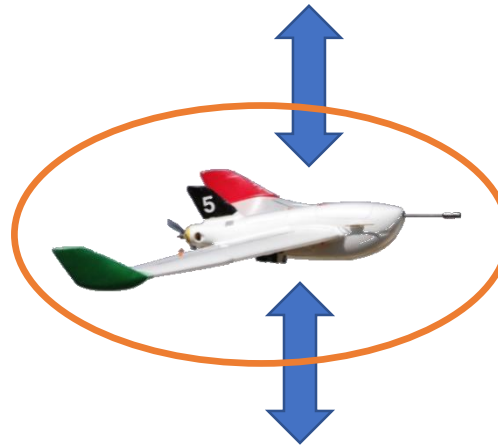
- BACCHUS (Cyprus, Ireland)
- Aerosol-cloud-radiative closure studies
- Mission-specific fleet of lightweight UAVs

# Using UAVs to link observations and models



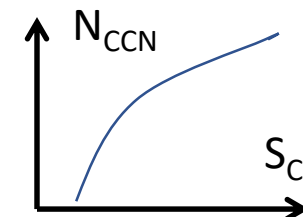
**'top-down' closure**

→ compare in-situ measurements with those derived from satellite



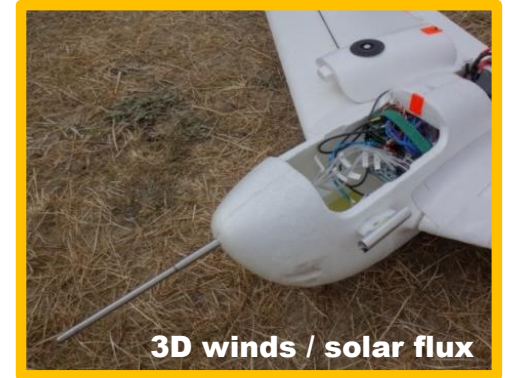
**'bottom-up' closure**

→ use measured updraft and aerosol measurements to initial cloud model and compare cloud properties



# Payloads for aerosol-cloud interactions

Standard instruments (all)	Standard Parameters
Pressure, temperature, humidity	PTU $\rightarrow$ $T_{\text{dew}}$ $\rightarrow$ Lifting condens. level
Autopilot & Pitot	$u, v \rightarrow$ horizontal winds
Video camera	$\Theta_E, Z_{\text{inversion}}$
Data acquisition	data downlink



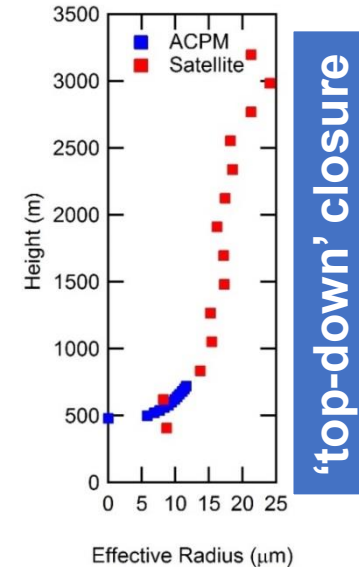
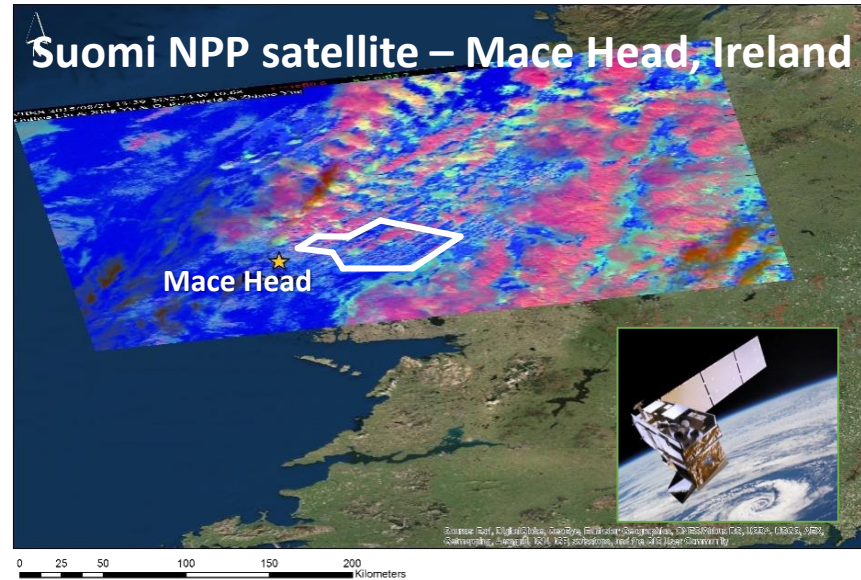
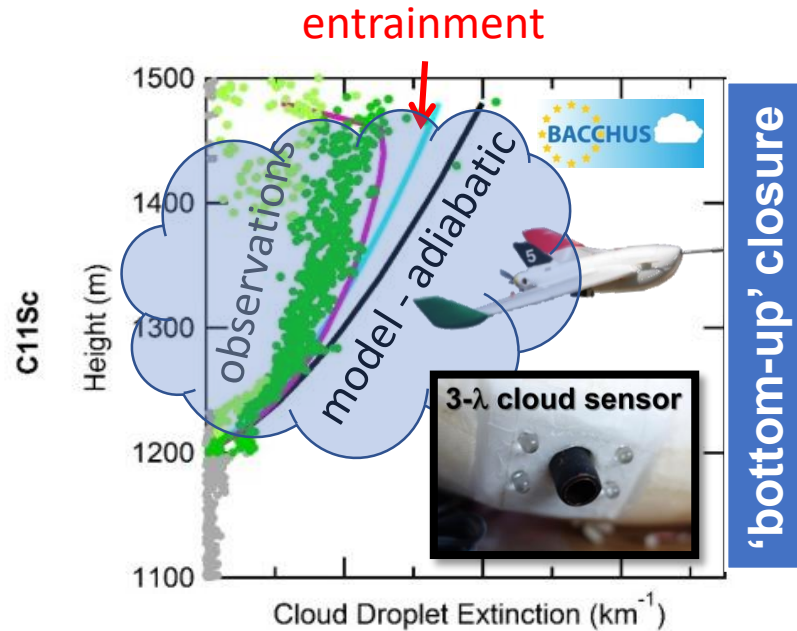
Atmospheric dynamics	3D winds and solar fluxes
5-hole probe	$w \rightarrow$ supersaturation $\rightarrow$ $n_{D\_f(\text{CCN,SS})}$
Pyranometer (up & down)	$s_e \rightarrow n_D \times r^2; F_{\uparrow} / F_{\downarrow} \rightarrow$ Albedo

Cloud / charge	Cloud microphysical properties
Cloud sensor (3- $\lambda$ )	$\sigma_e \rightarrow n_D \times r^2; R_{\text{eff}}$
Charge sensor	Atmospheric charge

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



# Coupling UAV observations with models and satellite

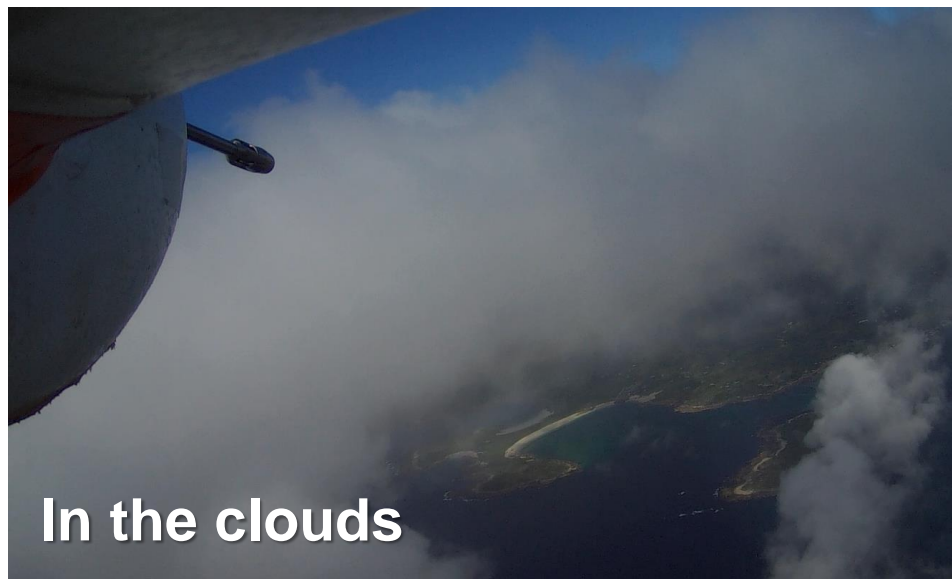


- UAVs link ground-based and satellite observations to cloud models (bottom-up and top-down closures)
- Quantified impact of entrainment on shortwave radiative cloud forcing

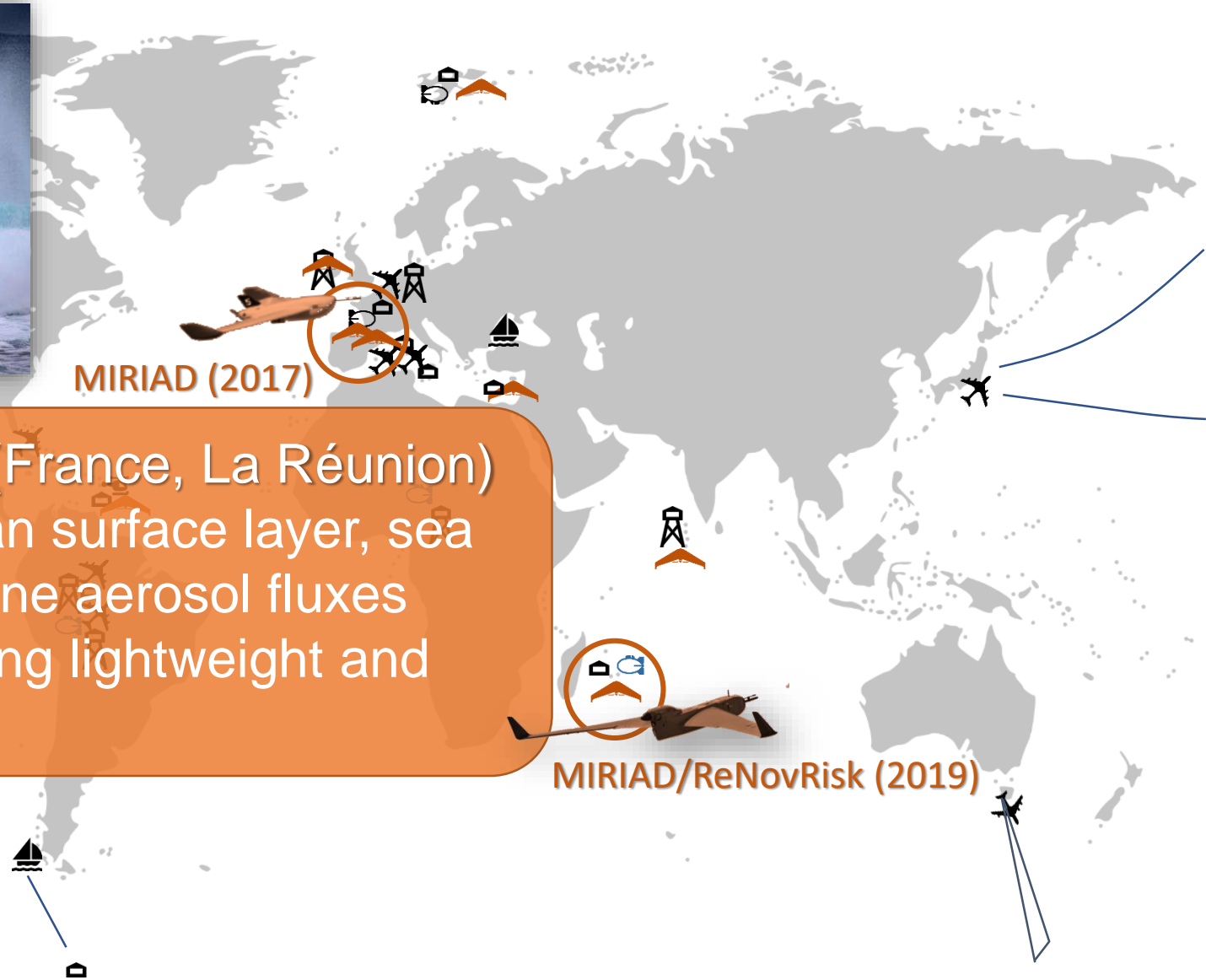
Publications related to this work:

- ❖ Sanchez et al., ACP, 2017
- ❖ Calmer et al., AMT, 2018
- ❖ Calmer et al., ACP, 2019
- ❖ Sanchez et al., GRL, 2020

# First airborne operations at Mace Head







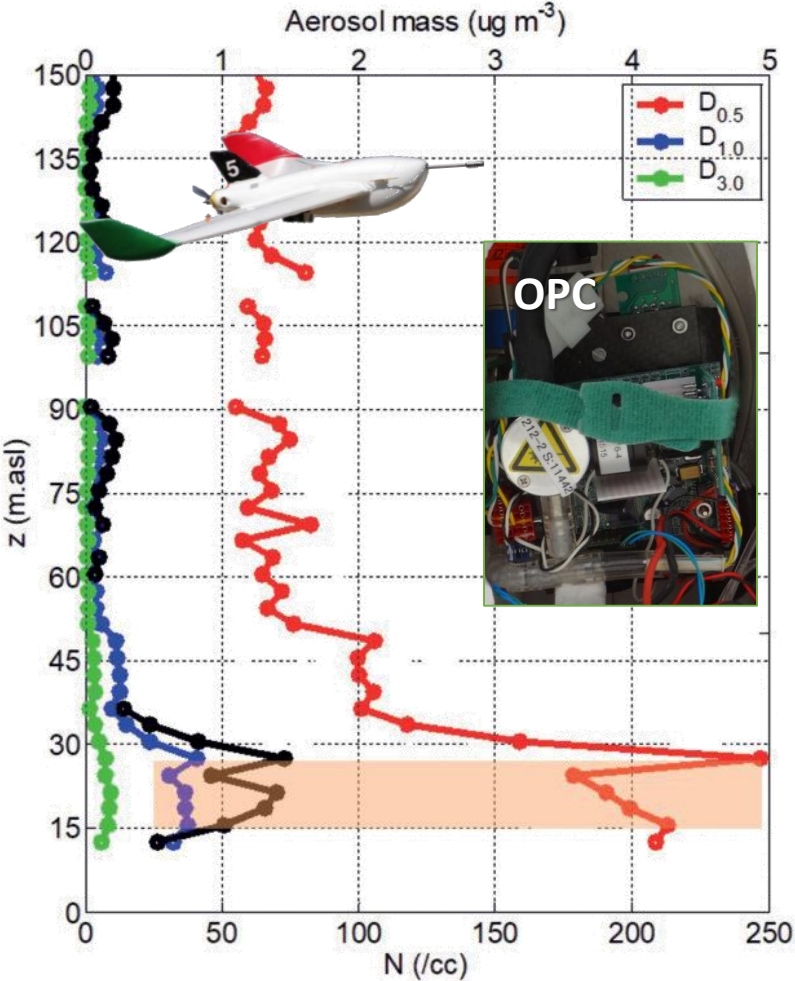
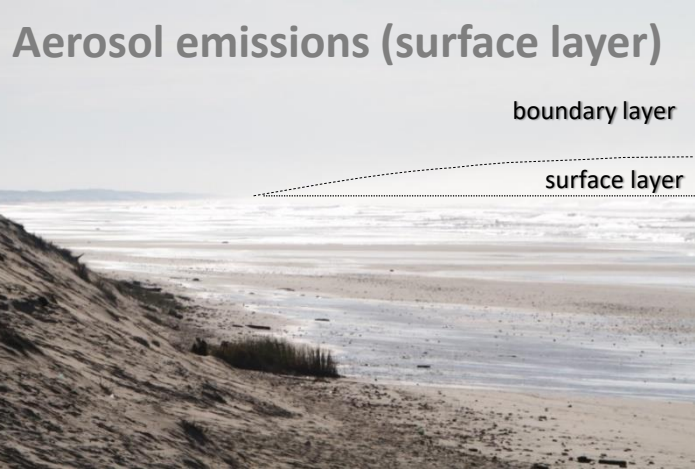
MIRIAD (2017)

MIRIAD/ReNovRisk (2019)

- MIRIAD / ReNovRisk (France, La Réunion)
- Vertical mixing of ocean surface layer, sea surface state and marine aerosol fluxes
- Low altitude flights using lightweight and long endurance UAVs



# Near-surface UAV observations to study air-sea exchange



Roberts et al., La Météorologie,  
doi : 10.4267/2042/62453

- Sea salt aerosol at Cap d' Homy (Atlantic coast, France)
- Vertical profiles from 6 to 150 m.asl with UAV equipped to measure aerosol concentration and size distributions.
- Steep gradient in aerosol between boundary layer and surface layer

**Flux estimate:**  $F = D (dC / dz)$   
 $:: \rho \sim 2 \text{ g/cm}^3; D \sim 10^{-2} \text{ m}^2 / \text{s}$   
 $\rightarrow F \sim 1 \text{ ng} / \text{m}^2.\text{s}$  (PMA surf zone)

# UAV payload for studying marine aerosol fluxes



Boreal UAV

## Marine aerosol flux parameterization

$$\frac{dF}{d \log D} = \sum_{i=1}^n \frac{F_i(Re_{H_w})}{\sqrt{2\pi} \ln \sigma_i} \exp \left( -\frac{1}{2} \left( \frac{\ln \left( \frac{D}{CMD_i} \right)}{\ln \sigma_i} \right)^2 \right)$$

Ovadnevaite et al., 2014

Sea salt flux

Wave breaking param.

$$Re_{H_w} = u_* H_s / \nu_w$$

Wind speed

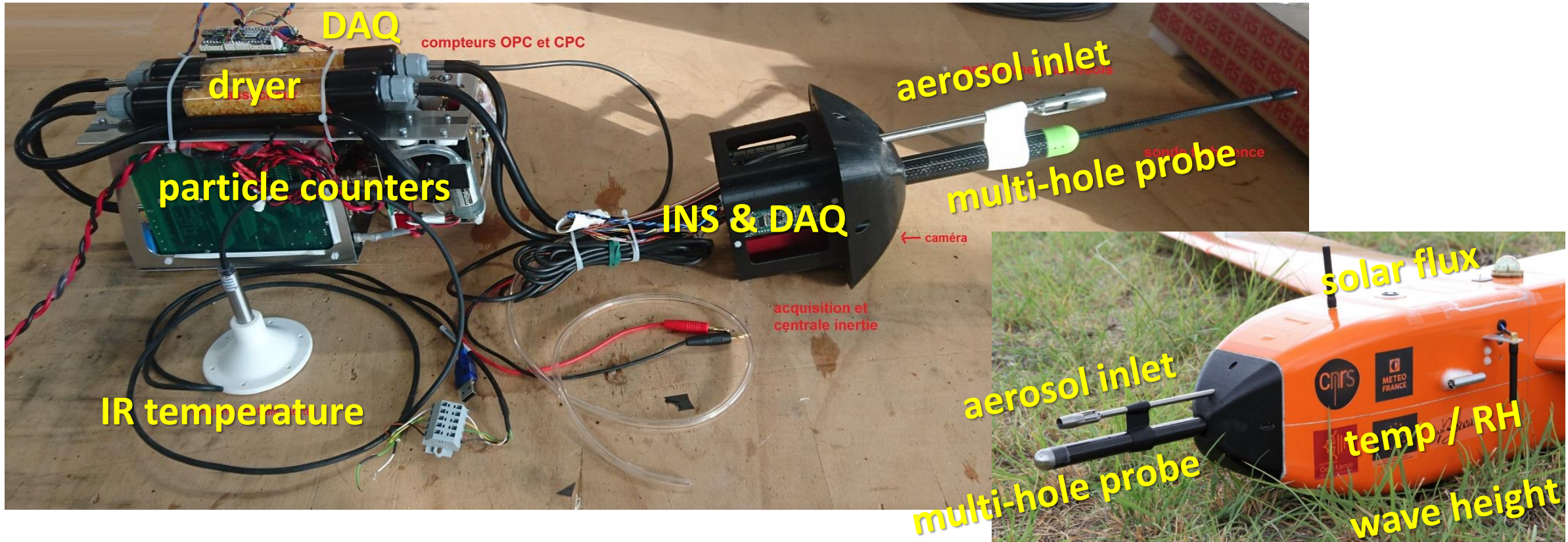
Wave height

Kinematic viscosity;  
f(SST, salinity)

Atmospheric state	
Pressure, temperature, humidity	boundary layer stability; lifting condensation level
Wind Speed & Flux	
multi-hole probe	U, V → horizontal wind speed
	w → vertical wind; eddy flux correlation
Wave Height; Sea State	
Radar altimeter	Wave height
Video camera	White cap fraction
Sea surface temperature (SST)	
IR temperature	SST → kinematic viscosity
Aerosol	
Optical Particle Counter	Number & mass concentration ( $D_p > 0.3 \mu\text{m}$ )
Condensation Particle Counter	Number concentration ( $D_p > 0.01 \mu\text{m}$ )



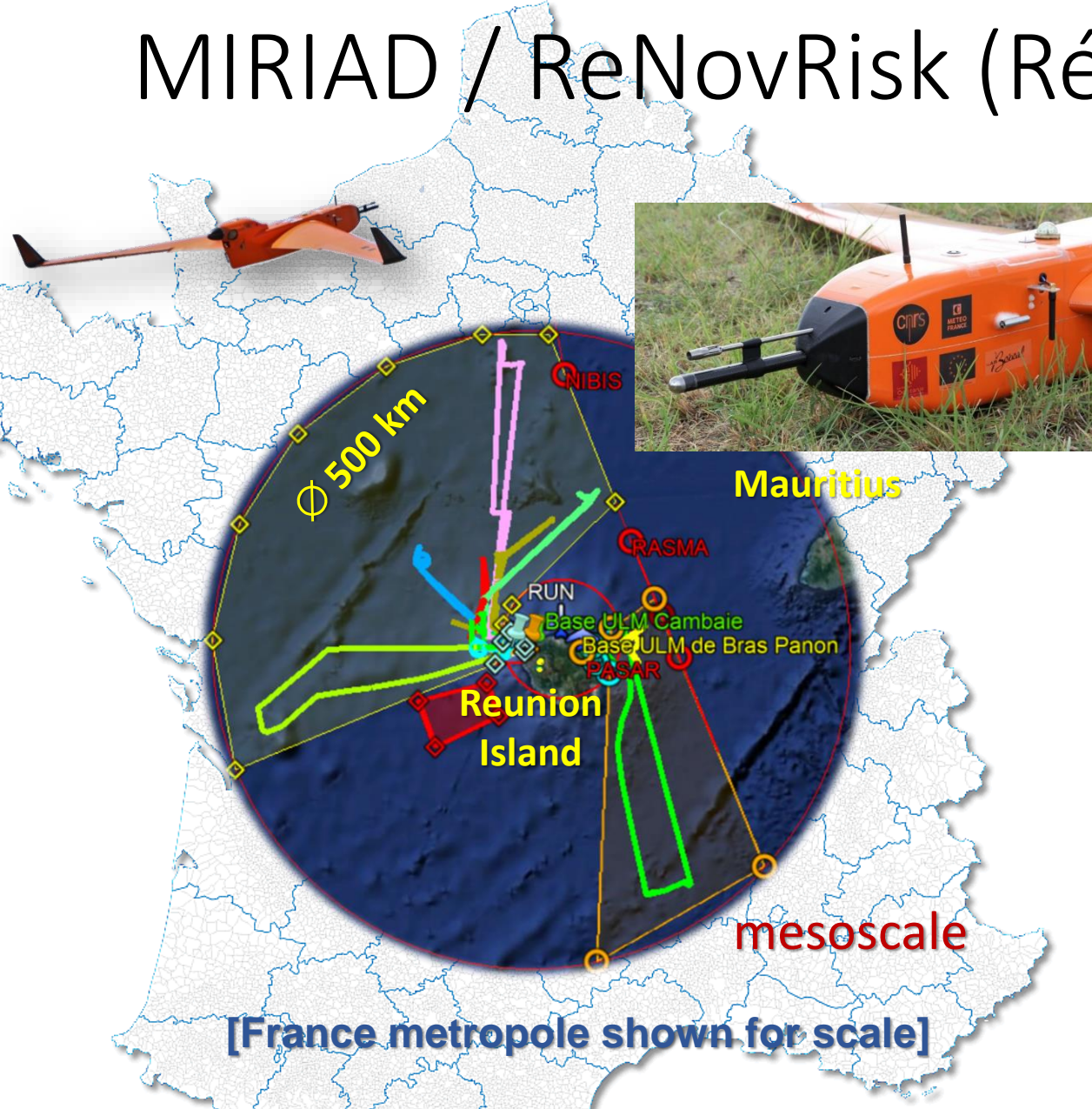
# Payload for MIRIAD / ReNovRisk



- Designed to measure air-sea interactions (4.5 kg): Aerosol concentration and size distribution, 3D winds and turbulence; sea surface temperature, wave height, solar flux, temp / RH, video
- Payload data sent to ground-station in real-time for mission planning.



# MIRIAD / ReNovRisk (Réunion Island, 2019)



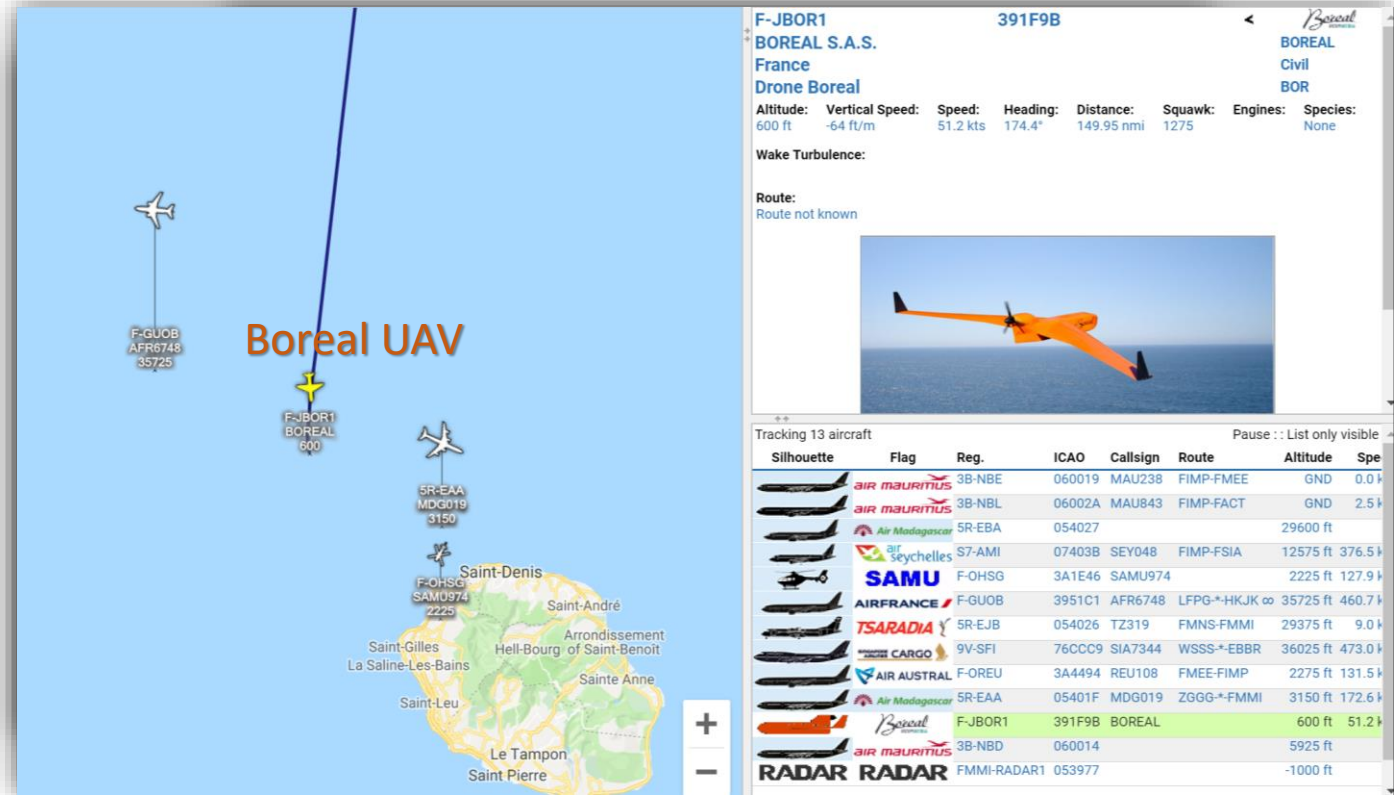
- 4 – 19 February; 21 March – 2 April 2019 during cyclone season (Indian Ocean)
- 12 research flights; 53.7 hours; 5012 km
- Airspace within 500 km diameter circle
- Surface to 1000 m.asl (w/ corridor to access international airspace)



# MIRIAD / ReNovRisk Operations

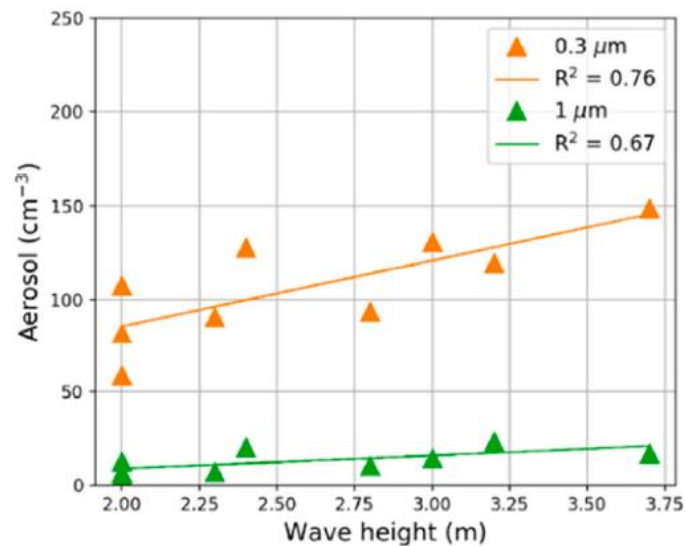
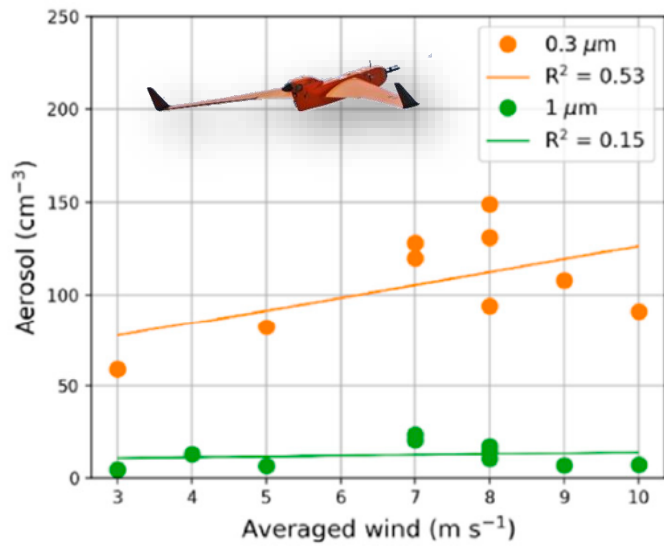


- **MIRIAD**, develop the scientific payload on Boreal UAV to study air-sea interactions
- **ReNovRisk**, study the impacts of aerosol fluxes on the development of tropical cyclones (w/ Univ. La Réunion and LACy)



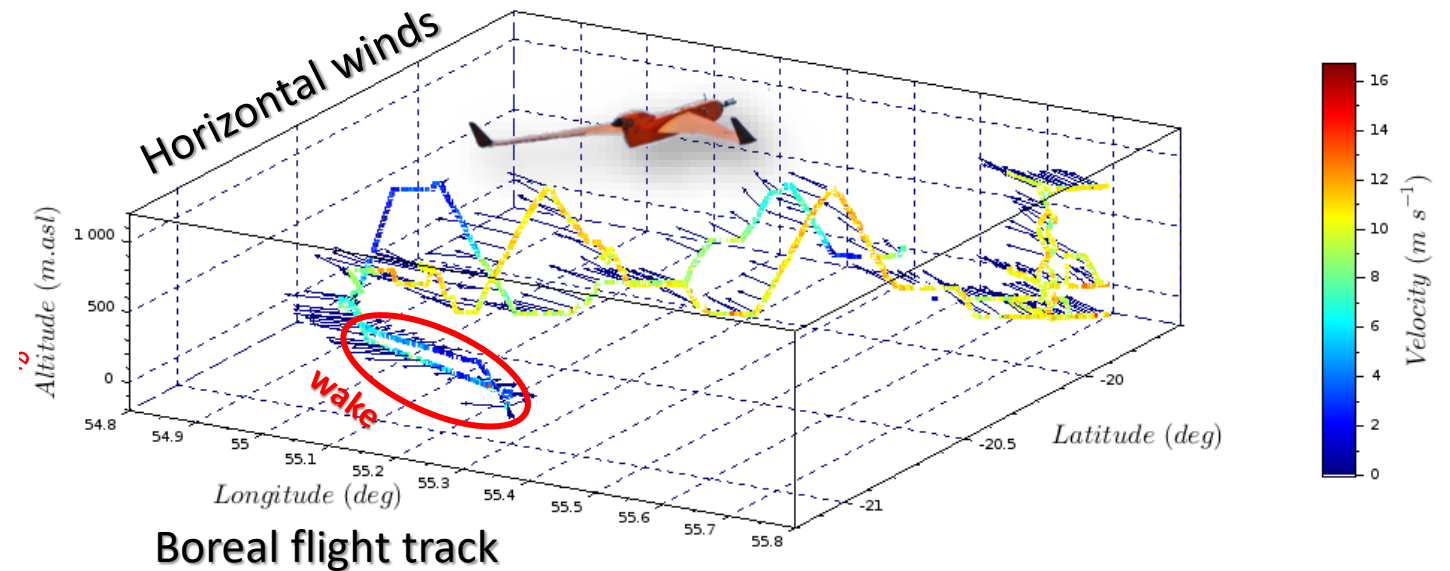
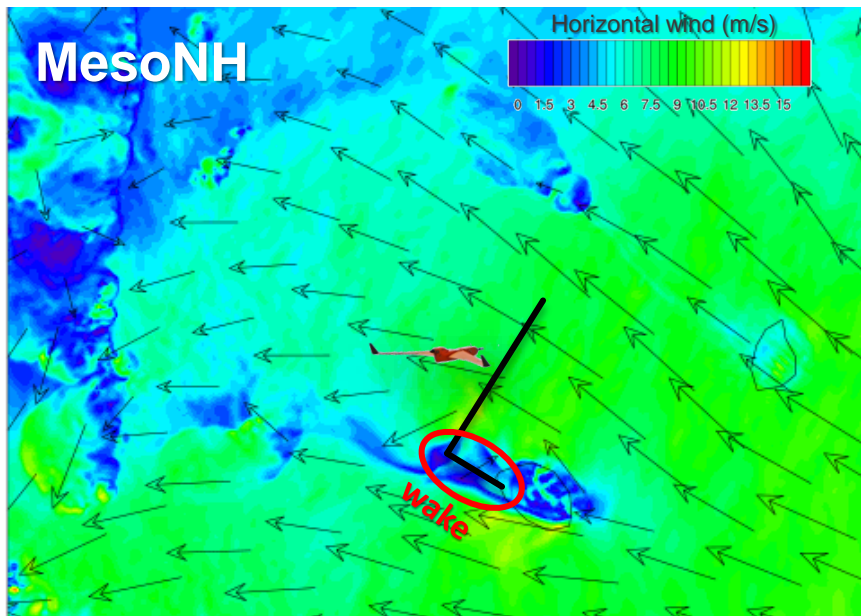
Real-time tracking of ship traffic on [mannedrains.com](http://mannedrains.com)  
S/ADS-B Transponder for integration of Boreal into civilian airspace. Screenshot from [flightradar24.com](http://flightradar24.com)

# Marine aerosol emissions and wind measurements

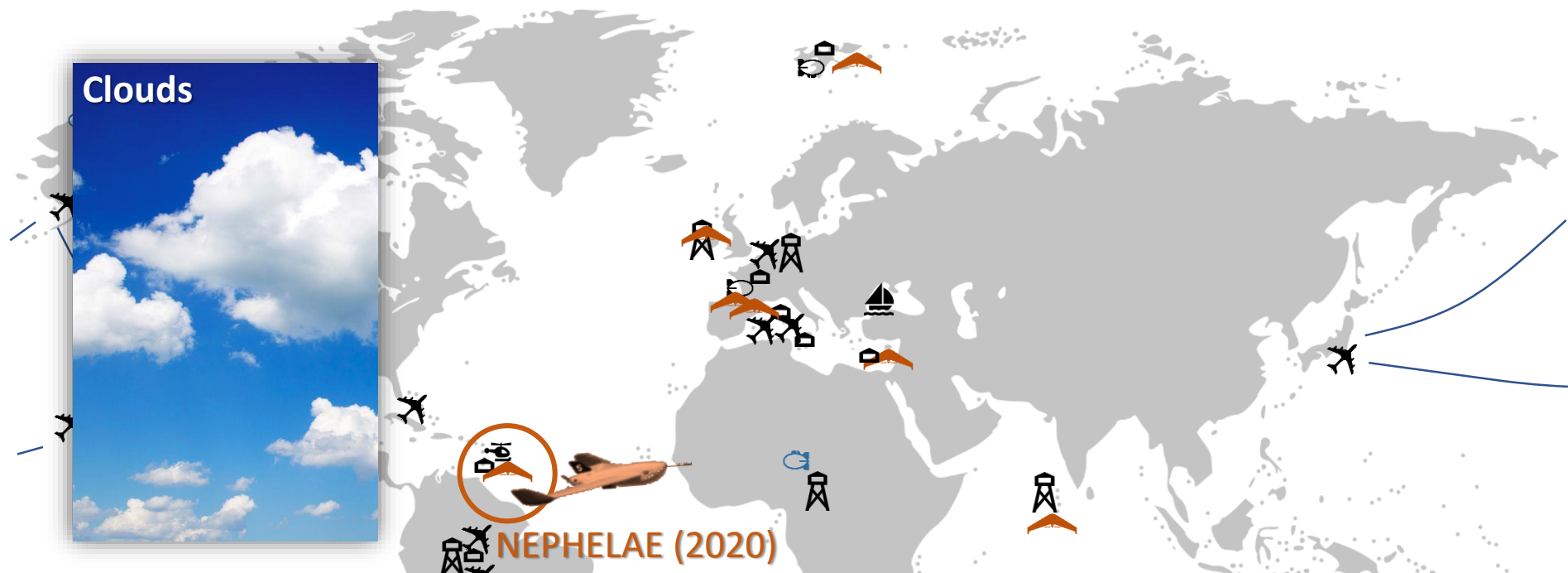


Bouquet et al., Atmos., 2021

- Aerosol concentrations ( $D_p > 0.3 \mu\text{m}$ ) relatively high – marine aerosol emission related to wind and wave height
- Réunion Island wind wake visible in measurements and MesoNH model (not seen in all models)



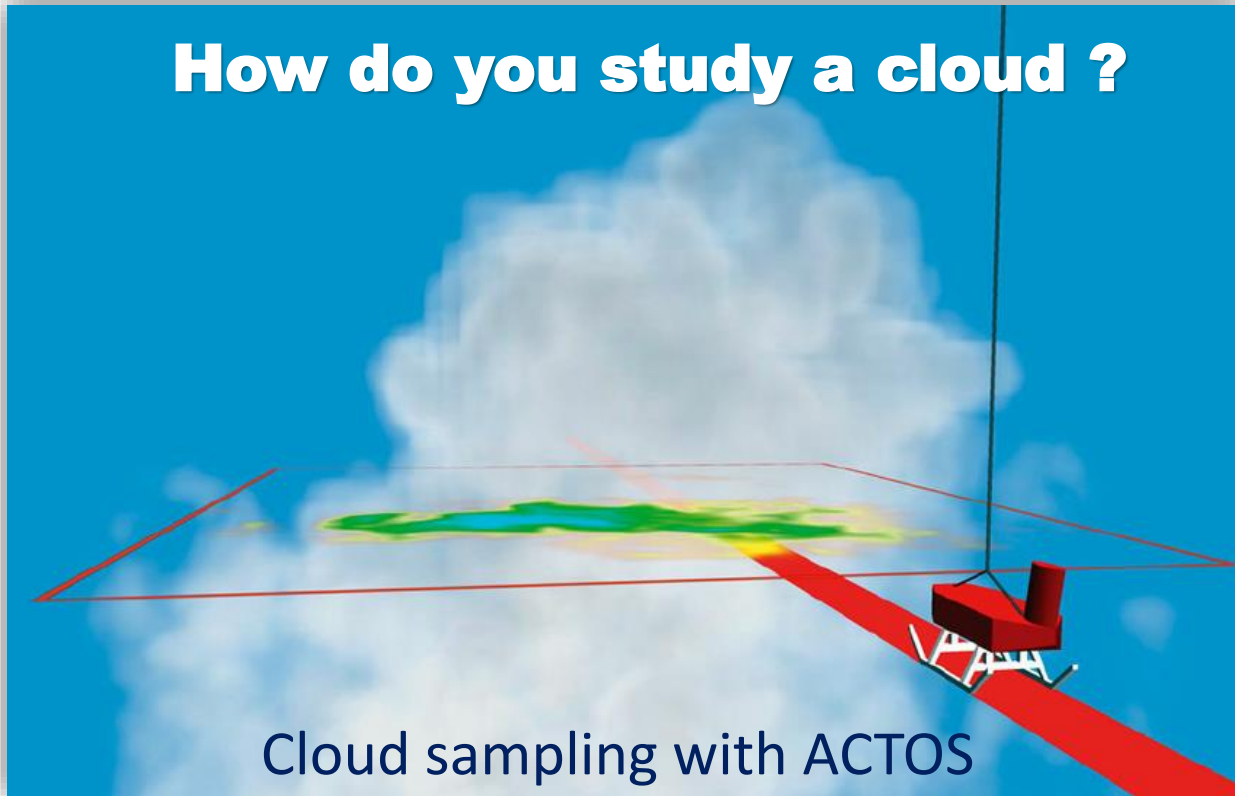




- NEPHELAE – EUREC4A (Barbados)
- Evolution of cloud life cycle using measurements of cloud optical properties  
Simultaneous observations with UAV fleet, adaptive sampling, cloud mapping

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

## How do you study a cloud ?



Hoffmann et al., 2014

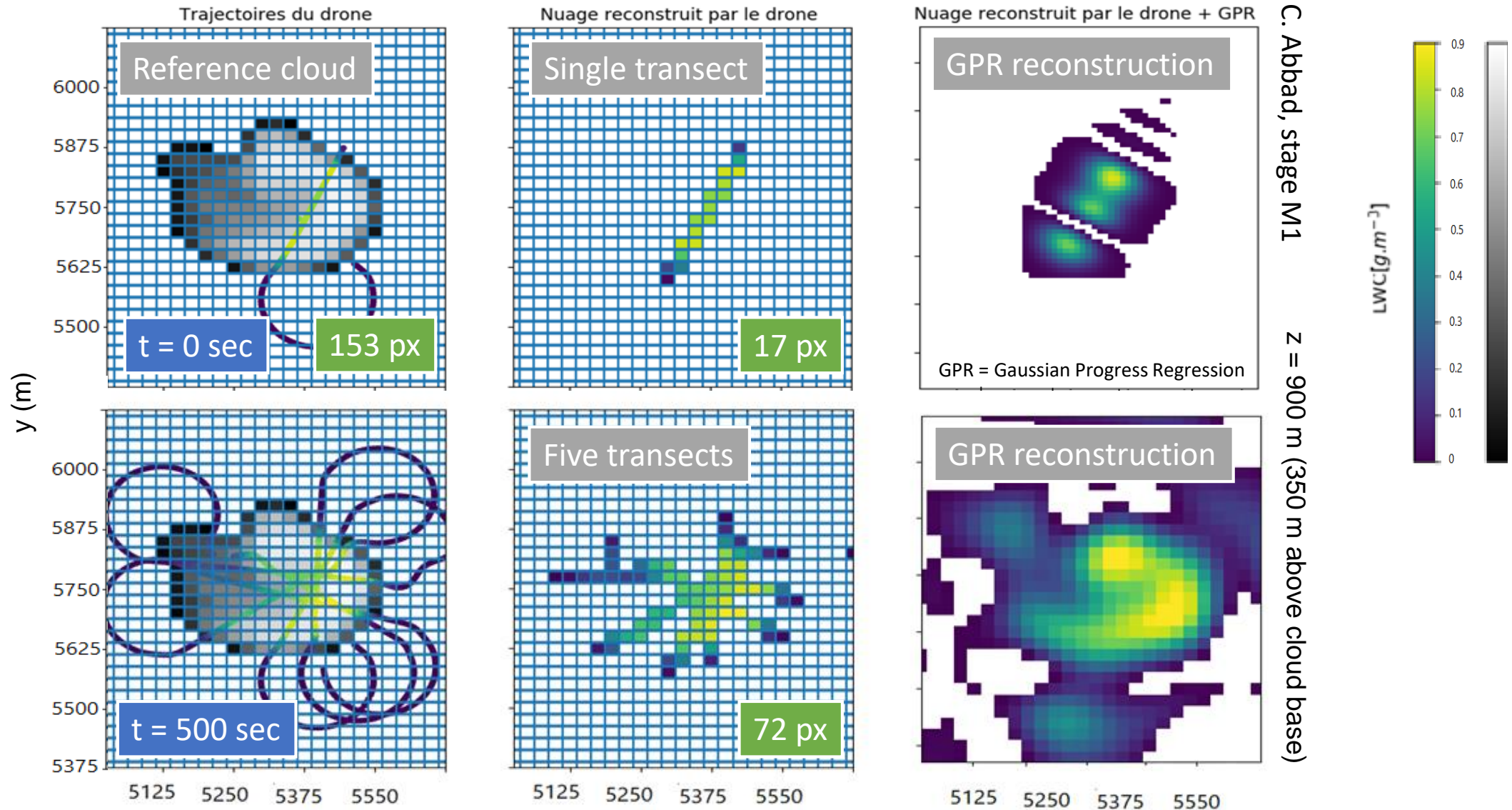
- Traditionally a cloud is sampled via a straight passage through a cloud
  - The relative amount of cloud edge (yellow) and cloud core (green) depends on the trajectory which leads to biases in inferring the structure of the cloud
- As cloud lifetime ~ 20 minutes, need to optimize trajectories and/or deploy multiple observations simultaneously



AGENCE  
NATIONALE  
DE LA  
RECHERCHE



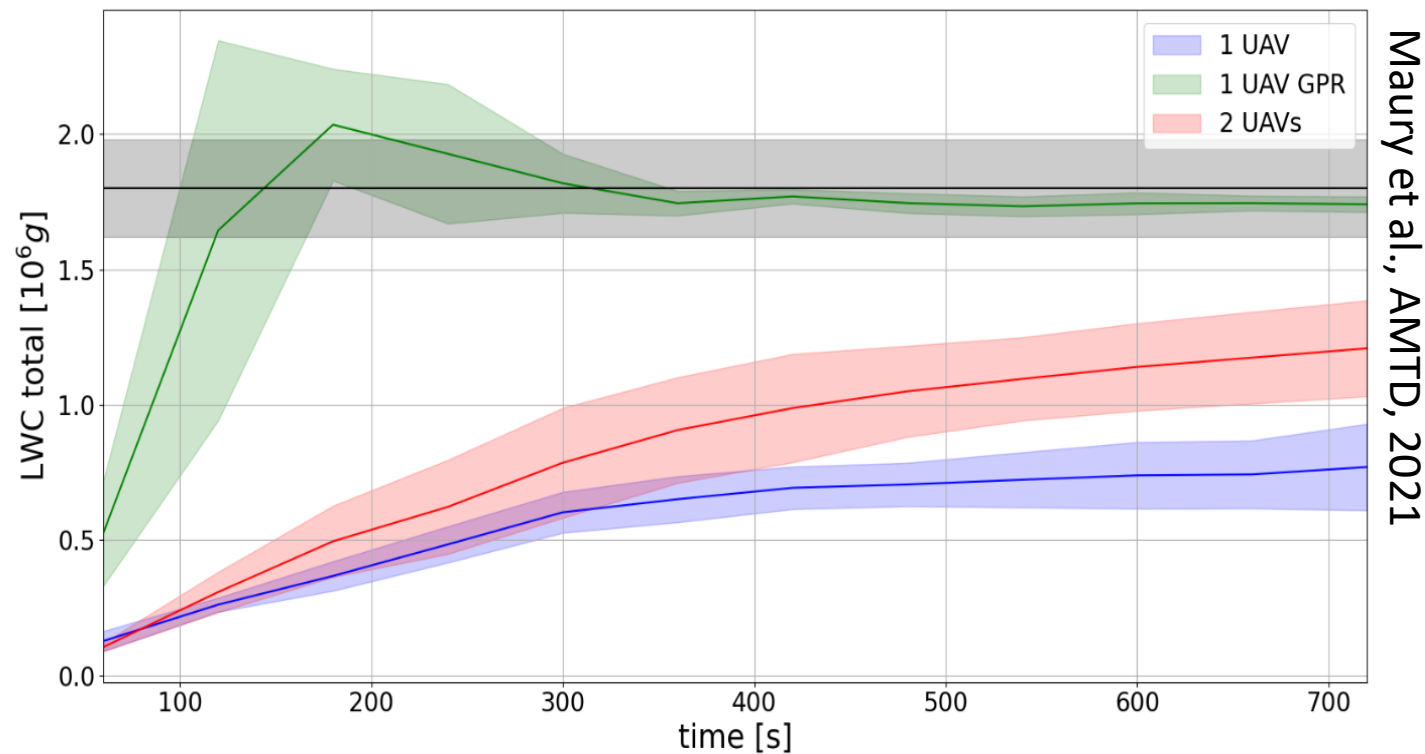
# Adaptive sampling and mapping of virtual cloud



Gaussian Progress Regression reproduces reference cloud within five transects (< 50% of area sampled).



# Cloud mapping with Gaussian Process Regression



Maury et al., AMTD, 2021

- Statistical analysis (random entries) based on 10 explorations of the same reference cloud
- Comparison of total liquid water in horizontal cross-section at 150 m above cloud base

GPR with single UAV reproduces reference cloud **1) much faster (~350 sec)** and **2) with less uncertainty** compared to observations (even with two UAVs).

# Time to catch some real clouds

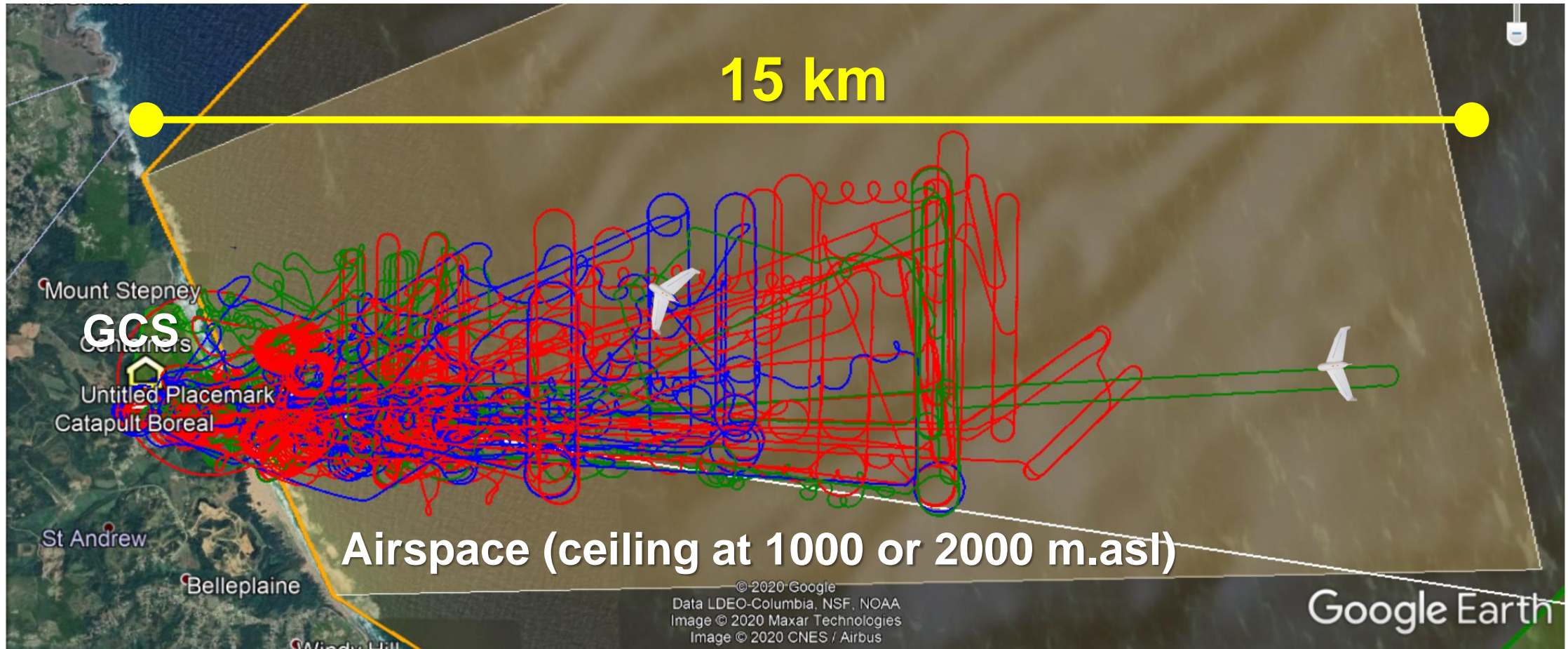


A blue banner for the EUREC4A International campaign. It features a large orange drone flying over a blue sky. Below the drone, the text 'EUREC4A International campaign' is written in white. To the right, there are logos for 'Suzanne', 'cnrs', and 'METEO FRANCE'.





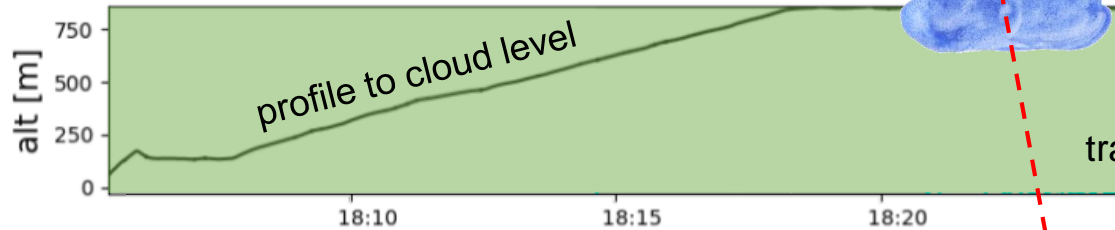
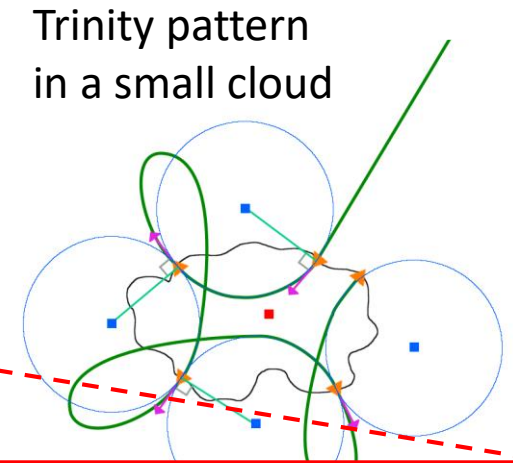
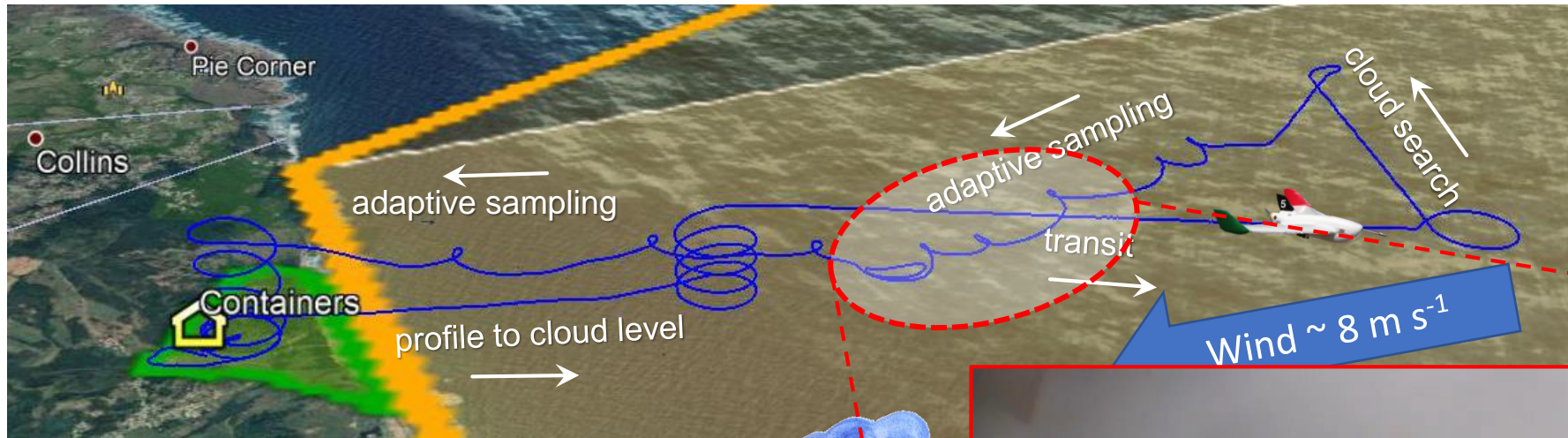
# Flight Overview – NEPHELAE - EUREC<sup>4</sup>A



- Flight operations over the ocean on the east coast of Barbados
- 50+ flights; 17 flights with adaptive sampling (following 26 clouds for more than a minute)



# Following a cloud



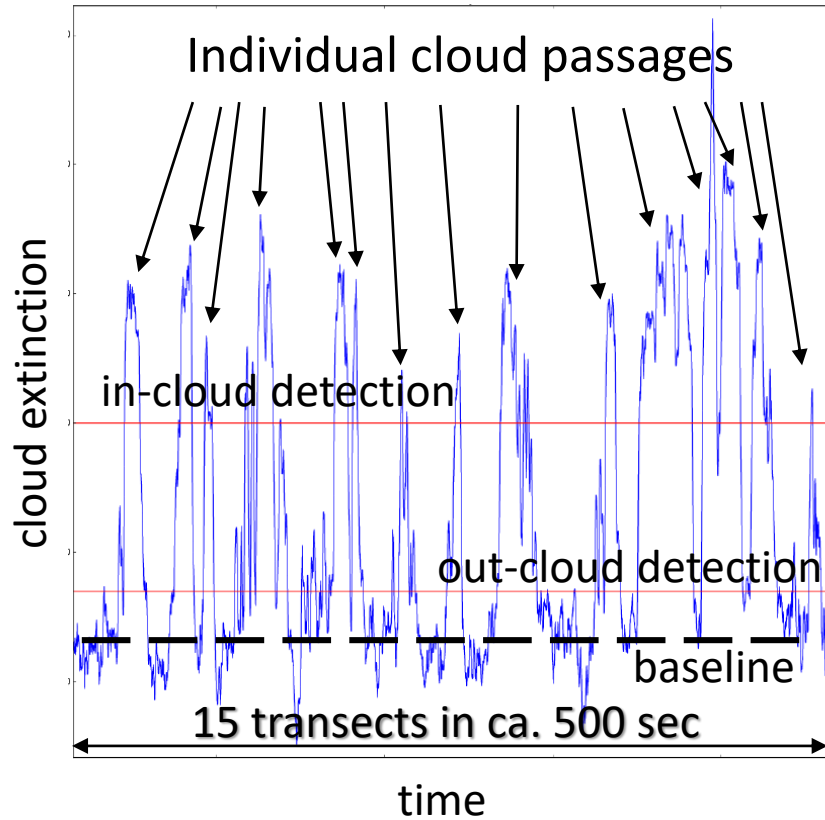
Cloud radar & ceilometer at BCO (Deep

Mission protocol:



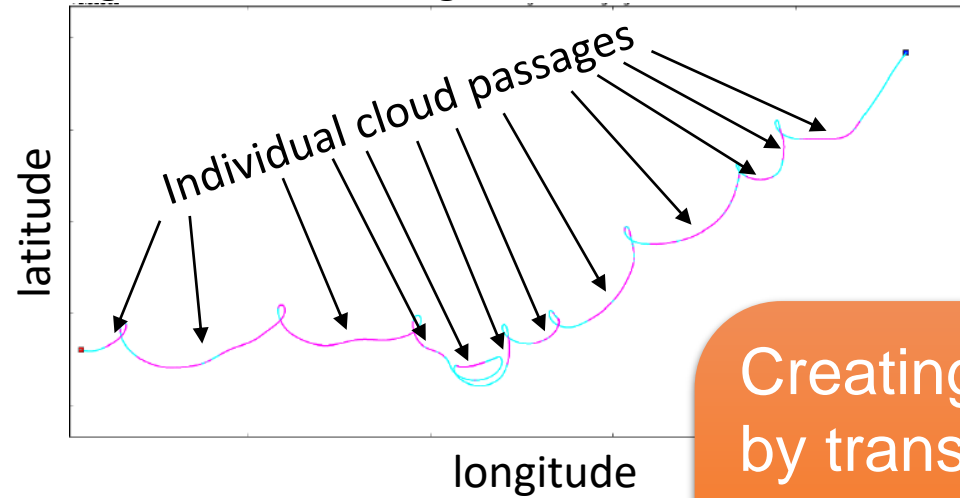
- transition to nippourime patterns per
- follow cloud (Lagrangian) using in/out

# Detection in/out of cloud and reference frame

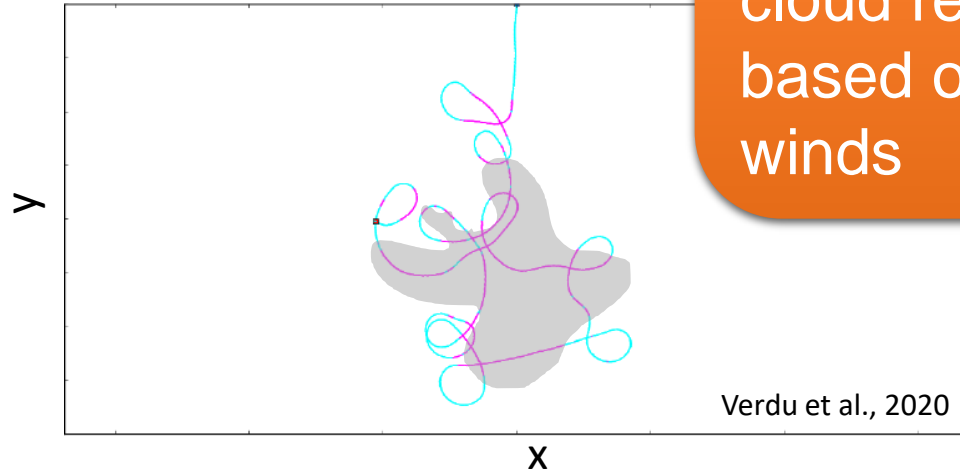


Time series of cloud sensor

flight track following a cloud

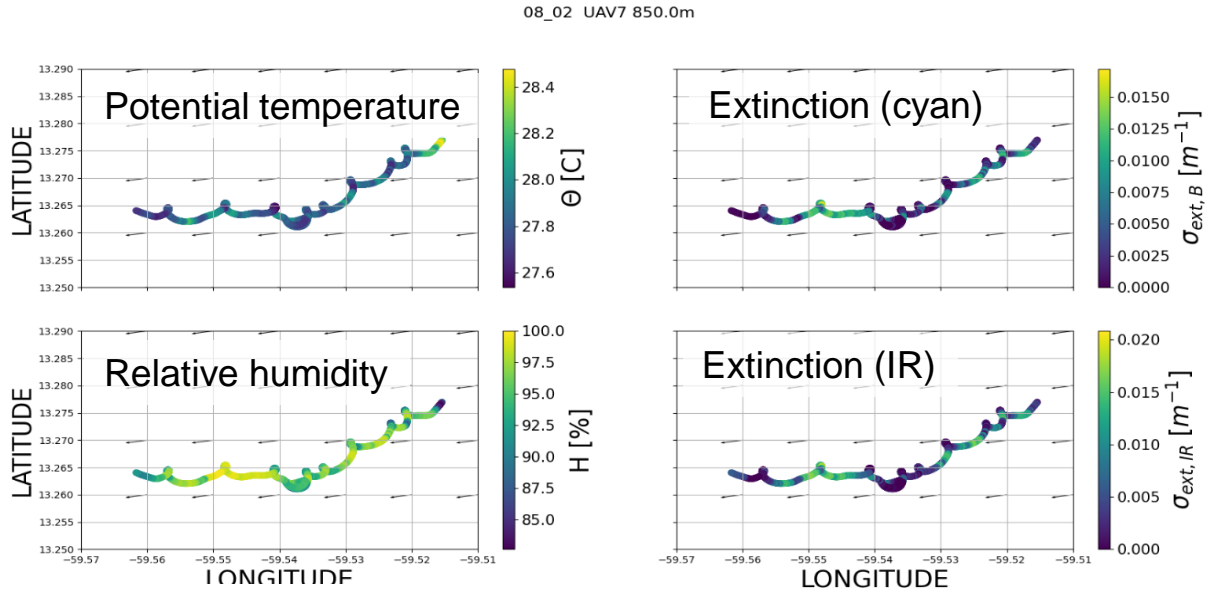
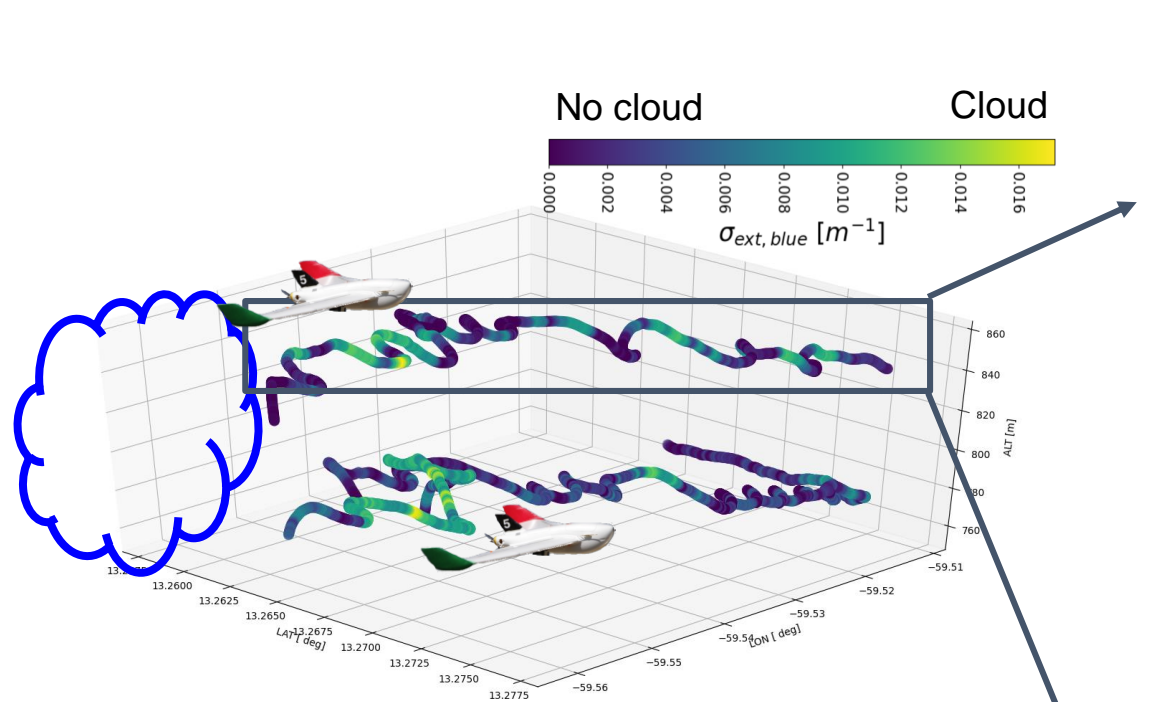


UAV trajectory in cloud frame



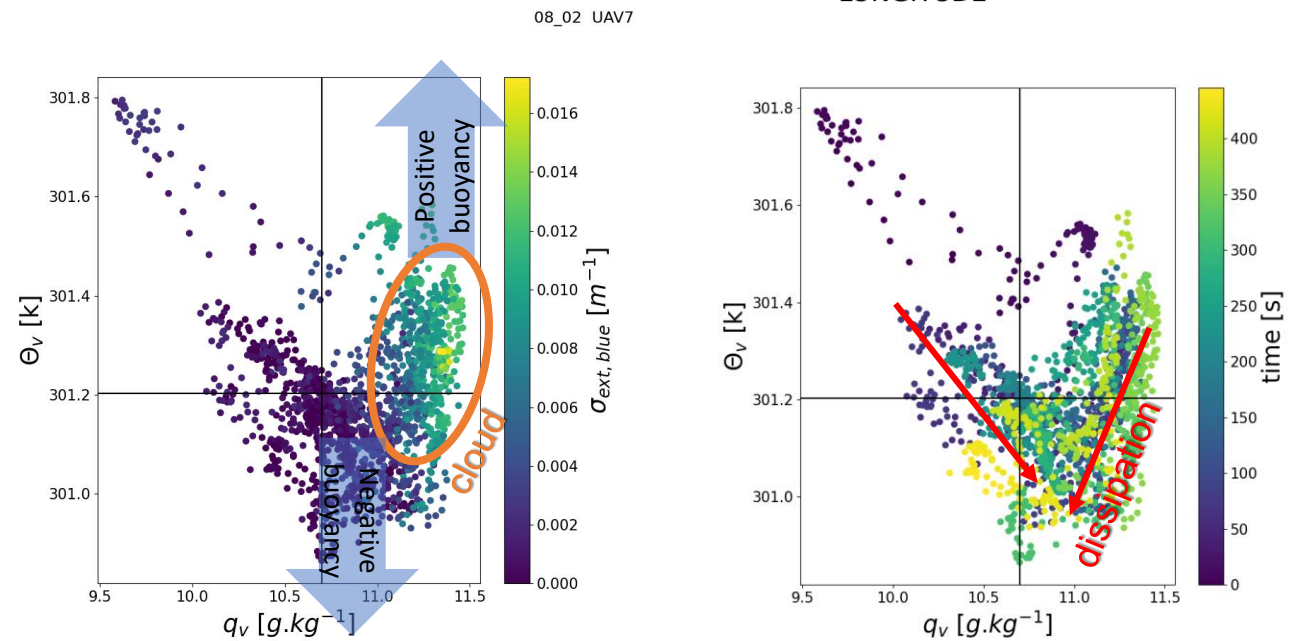
Creating cloud map by transforming earth reference frame to cloud reference frame based on horizontal winds

# Tracking a cloud in time and space



Maury et al., in prep

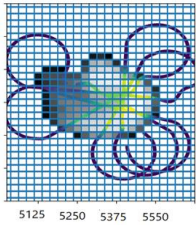
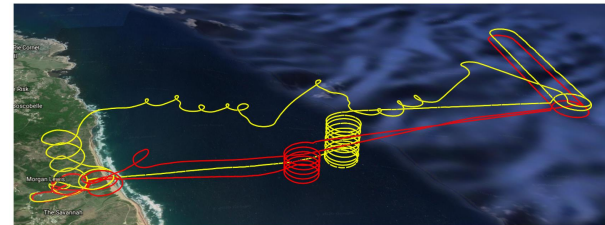
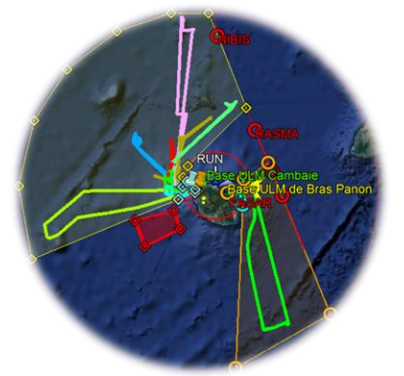
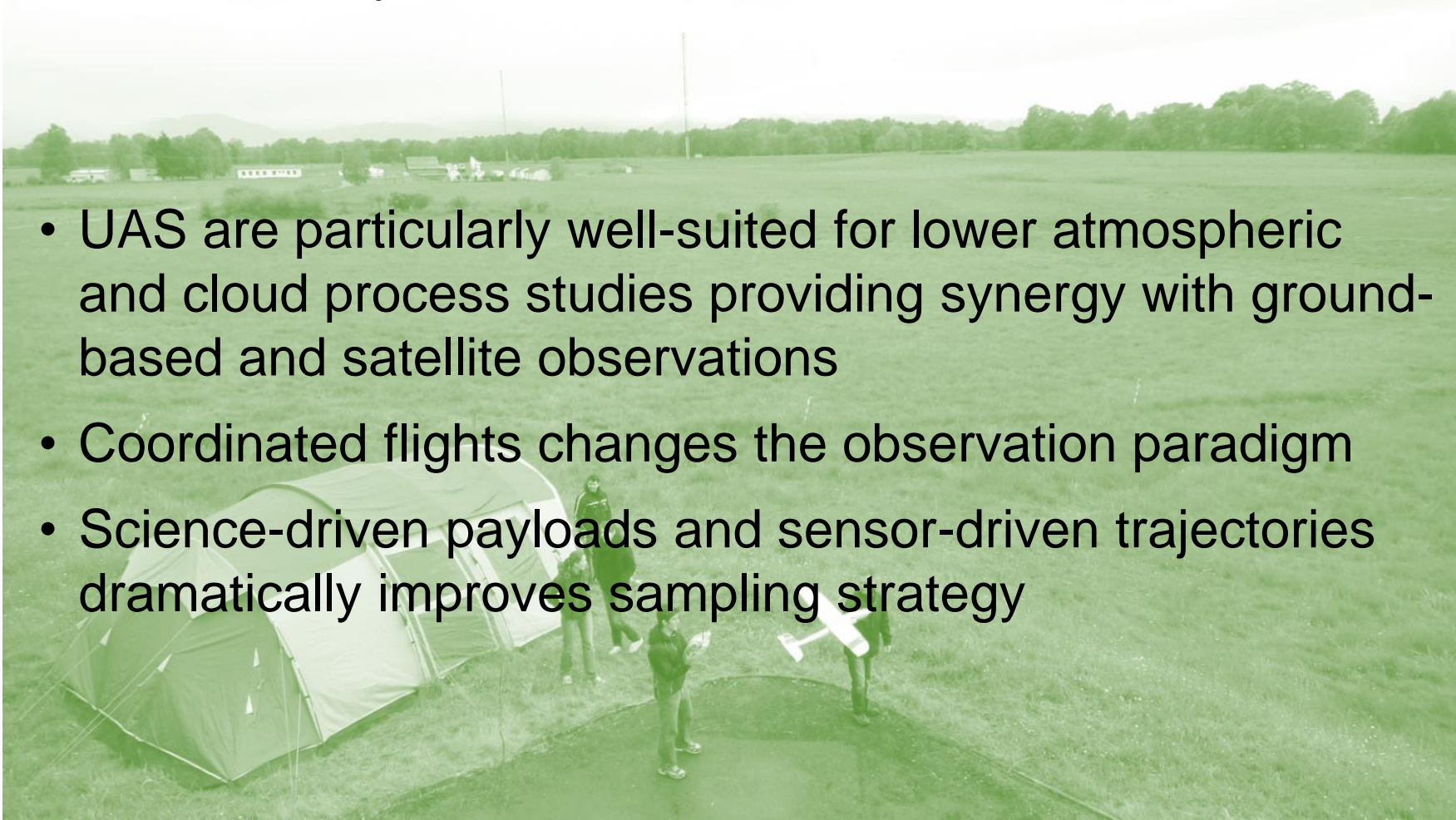
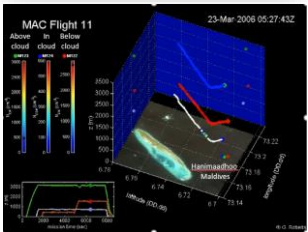
- High values of  $q_v$  and  $\theta \Rightarrow$  High values of extinction (in-cloud; positive buoyancy)
- Low values of  $q_v$  and  $\theta \Rightarrow$  Cloud edge (negative buoyancy)
- Cloud becomes negatively buoyant with time (dissipation; transition blue to yellow)





# Take Aways

- UAS are particularly well-suited for lower atmospheric and cloud process studies providing synergy with ground-based and satellite observations
- Coordinated flights changes the observation paradigm
- Science-driven payloads and sensor-driven trajectories dramatically improves sampling strategy



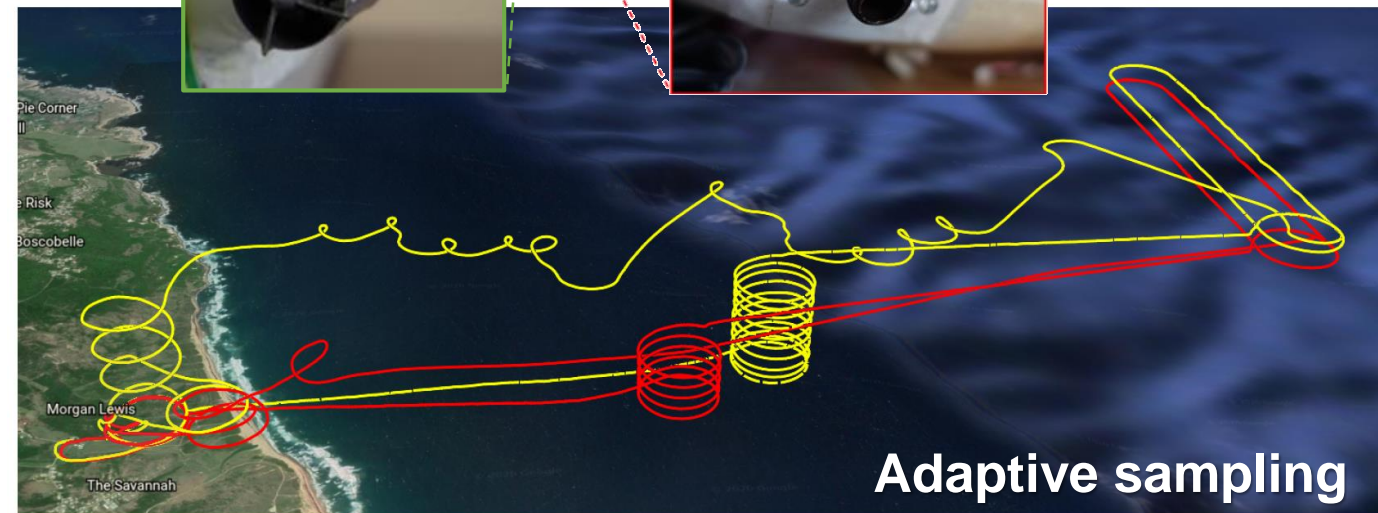
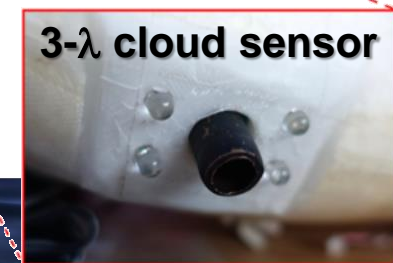
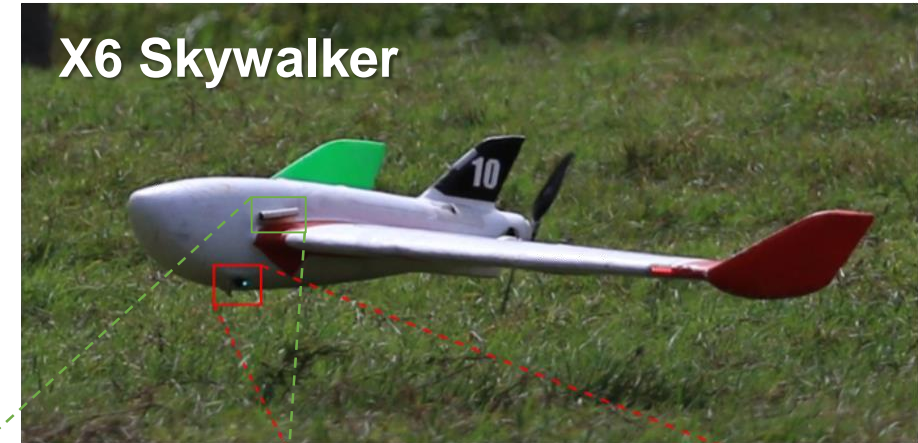
# acknowledgements





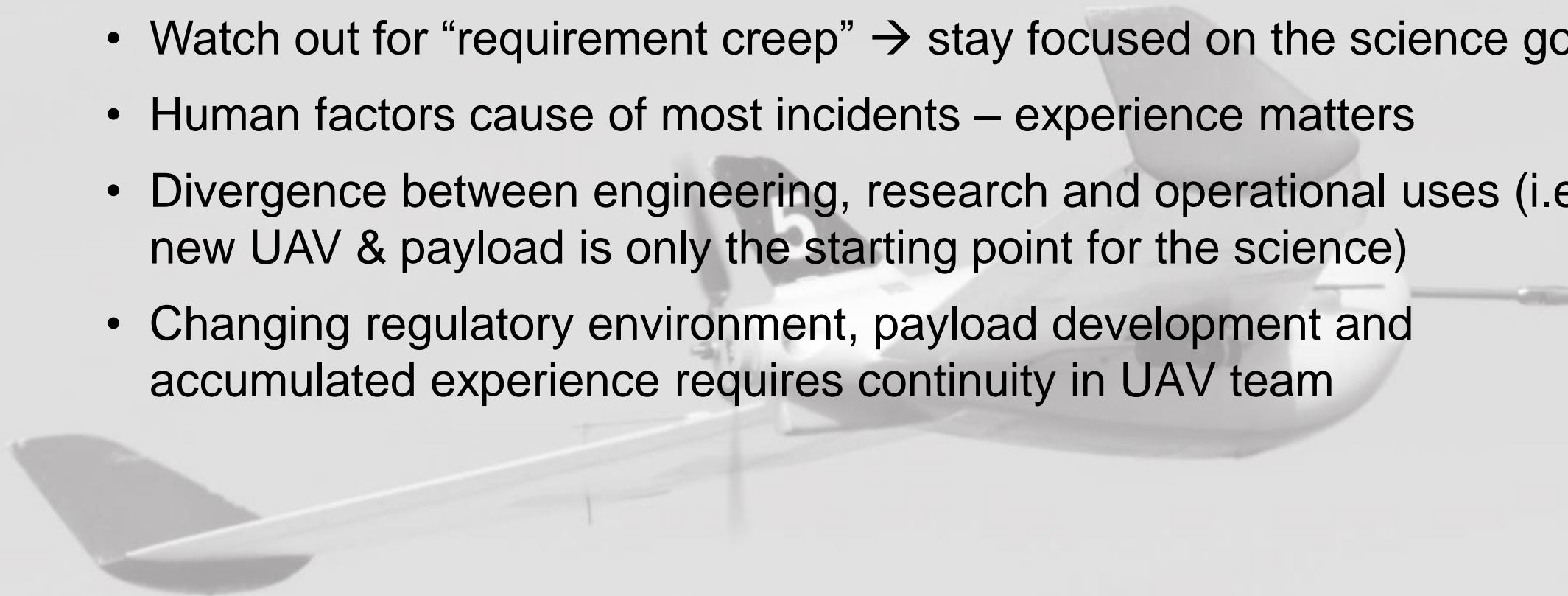


# NEPHELAE flight operations for adaptive sampling



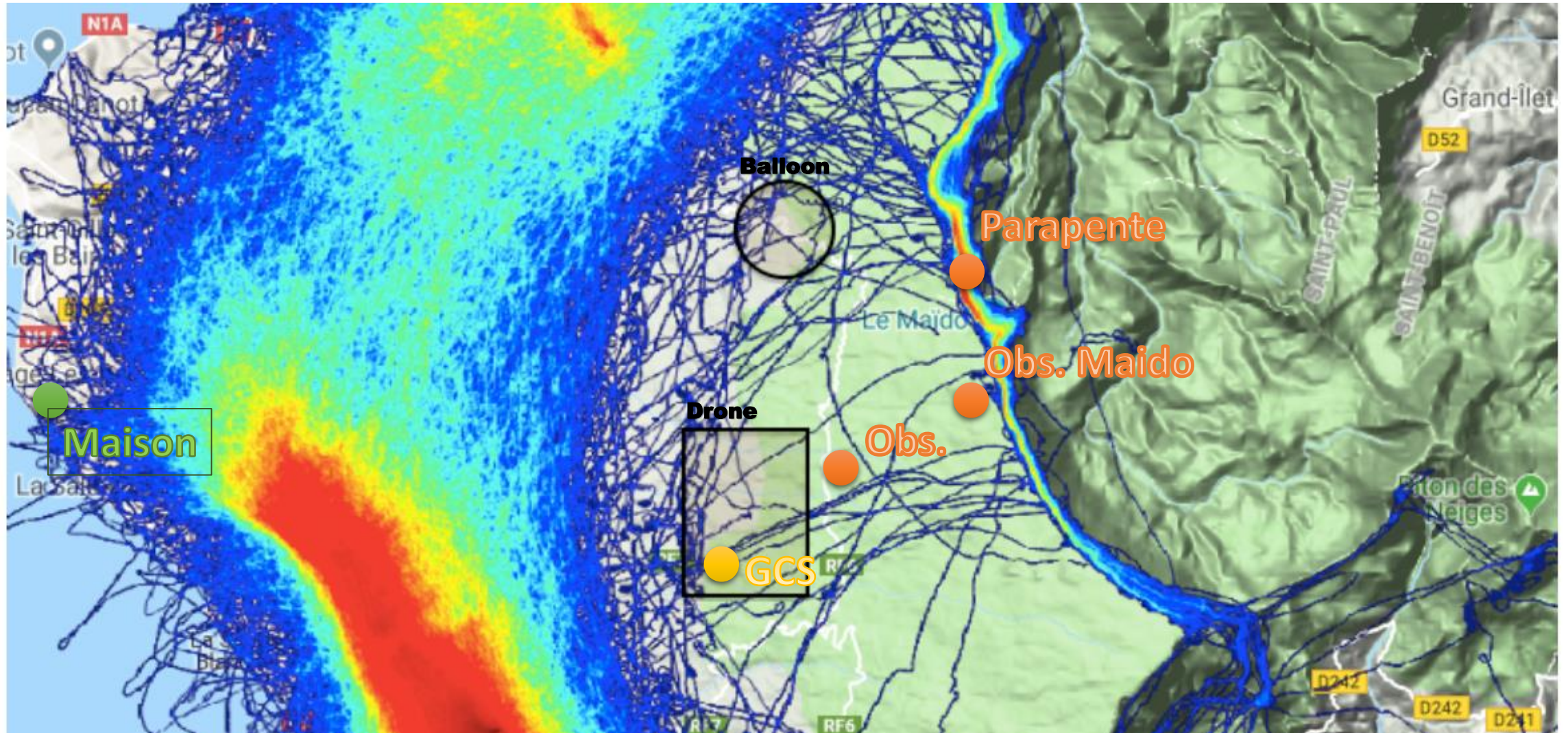
# Perspectives of using UAVs for atmospheric research

- Select aircraft around payload needs (smallest size for science mission)
- Watch out for “requirement creep” → stay focused on the science goals
- Human factors cause of most incidents – experience matters
- Divergence between engineering, research and operational uses (i.e., a new UAV & payload is only the starting point for the science)
- Changing regulatory environment, payload development and accumulated experience requires continuity in UAV team





# NEPHELAË operations in airspace





# Adaptive sampling with two UAVs simultaneously

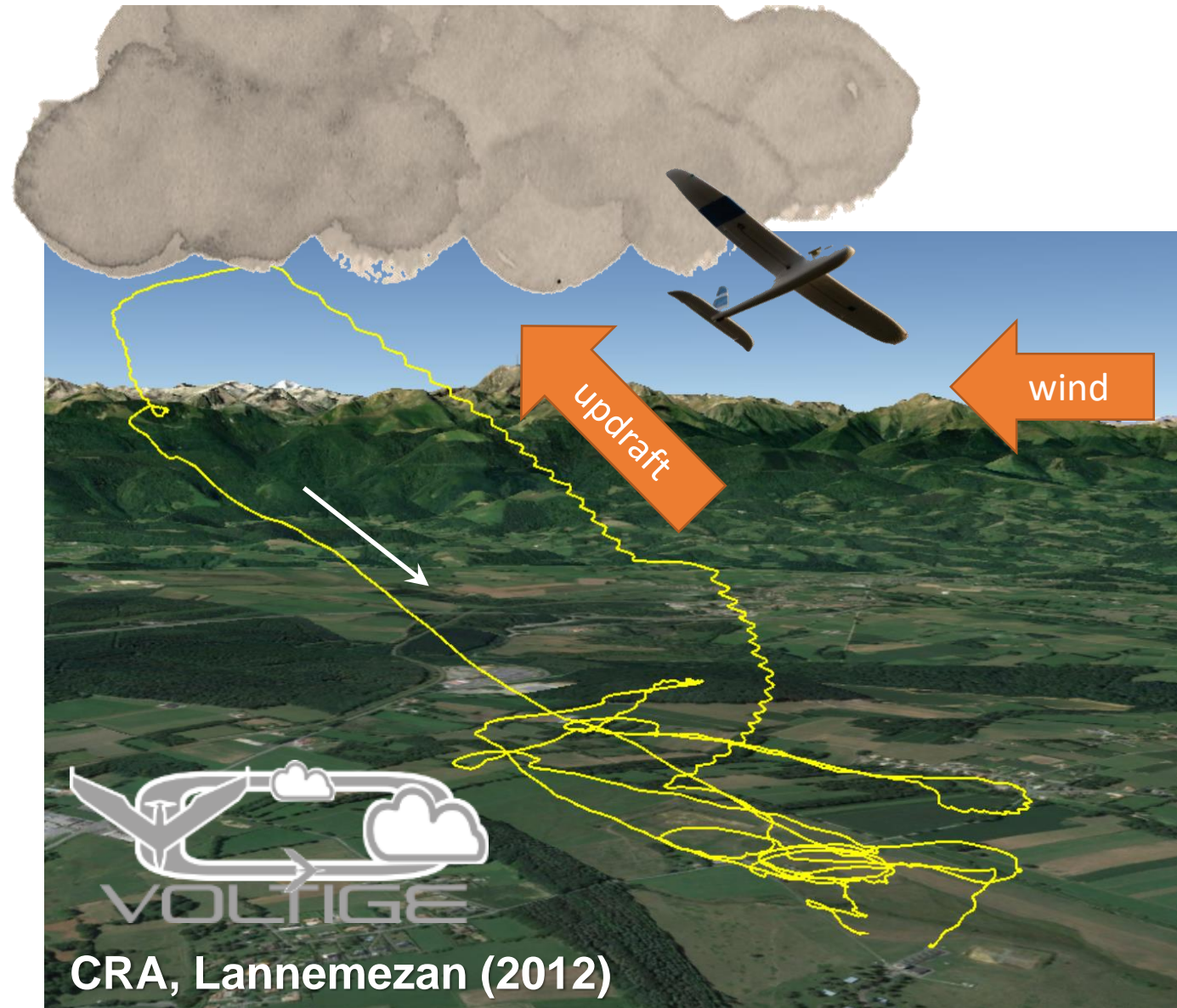


- Tracking the cloud system with two UAVs using 'trinity' pattern
- UAVs vertically separated by ca. 50 m to avoid potential collisions
- Cloud appears to be in dissipating stage; two clouds close together



# Finding an adequate platform to chase clouds

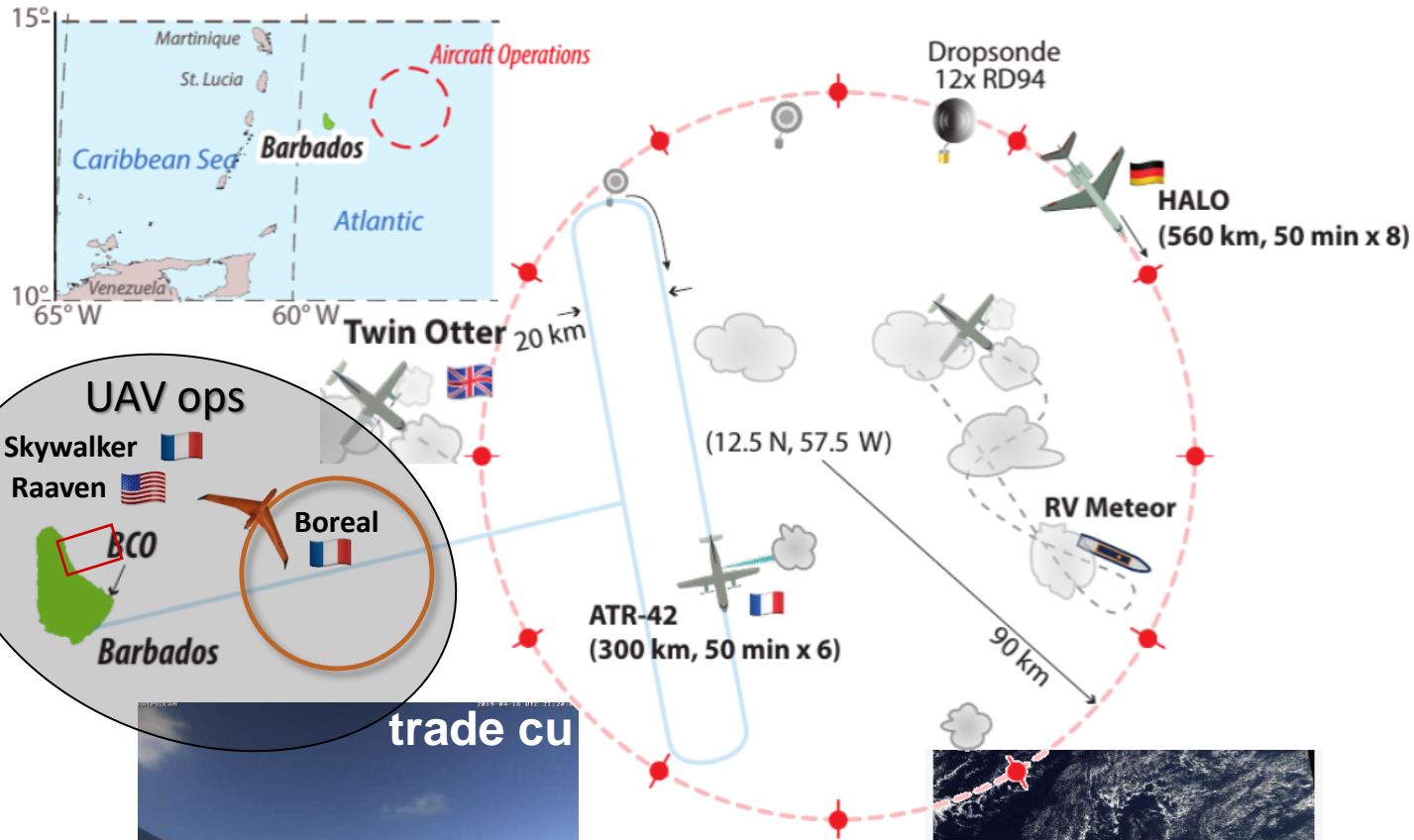
- Manta UAV: sub-contracted experienced operator; limited opportunities to test/deploy payload testing
- UAV Cost-Action 2009-2013 (J.Reuder); SUMO; PPRZ with to integrated IMU (clouds had not been possible)
- Smaller UAVs are easier operate logistically (but not too small)
- Backwards flight with EasyStar in convective cloud → need platform adapted for wind, adequate duration and payload capacity





# EUREC4A field experiment

20 January – 15 February 2020

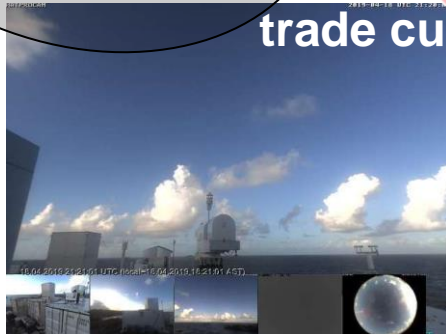


## • Science objectives :

- Role of ocean surface on mesoscale cloud field (sugar, flower, gravel, fish)
- Cloud development / dissipation
- Impact of clouds on radiative budget and precipitation

## • UAV operations

- Skywalker X6 (CNRM, France): NEPHELAE; adaptive sampling
- Raaven (Colorado, USA): turbulence in MBL and updrafts at cloud base
- Boréal (CNRM, France): air-sea interactions, aerosol emission, turbulence in MBL



trade cu



sugar clouds

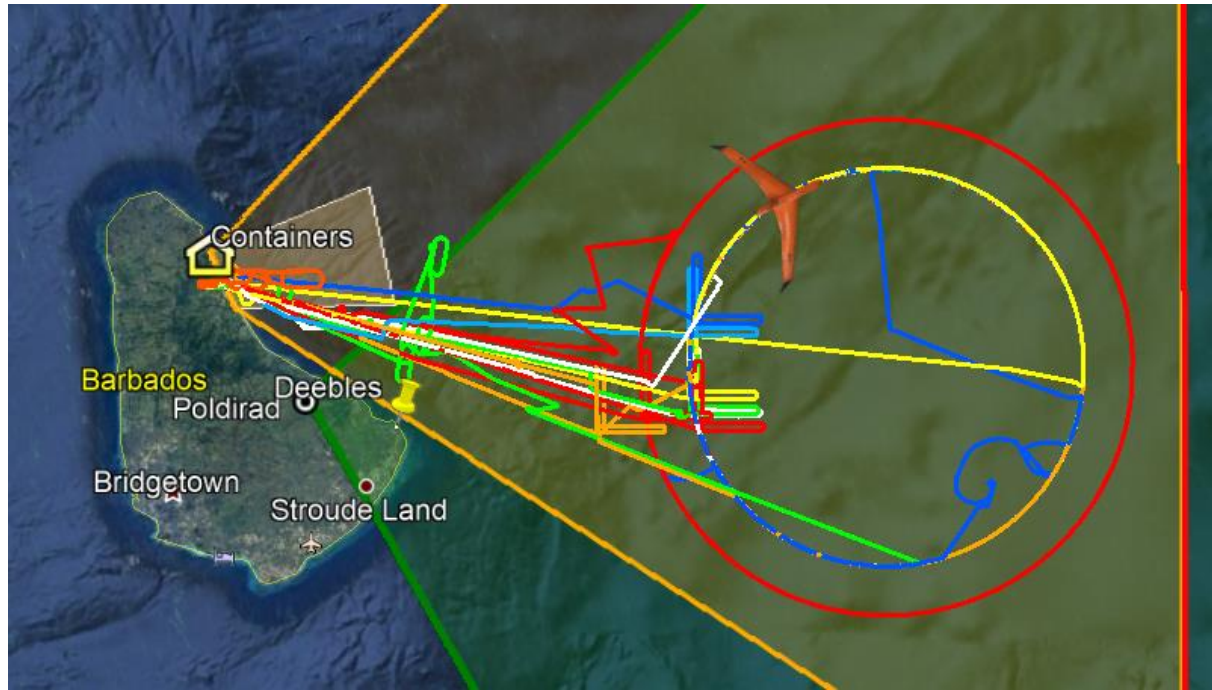
Website: <http://eurec4a.eu/>

Sandrine Bony (LMD, CNRS); Bjorn Stevens (MPI Meteorology); David Farrell (CIMH)





# Flights with Boreal during EUREC4A



- Aerosol, turbulence, sea surface temperature, wave height, meteorological
- ~20 km circle and multiple altitudes within trade wind corridor
- 10 Flights (33.7 hours)
- Data analysis underway

Flight ID	Date	Time UTC			Flight Table						Instrument Table									
		Take-off	Landing	Duration	Calibratic	Circle A	Circle B	Circle C	Circle D	Profile	Turbulence	CPC	OPC	T/RH1	T/RH2	SST	Radar	Pyrano	Camera	
F01	25-Jan-20	20:11	21:45	1:34	Test Flight															
F02	26-Jan-20	16:41	19:40	2:59	400	400				1000										
F03	28-Jan-20	17:07	21:31	4:24	400	400	100	700		1000		dry out								
F04	31-Jan-20	16:34	16:53	0:19	Onboard generator problem															
F05	2-Feb-20	12:33	18:23	5:50	400	400	100	50	700	1000										
F06	5-Feb-20	10:30	14:14	3:44	400	400				1000	rain									
F07	5-Feb-20	16:26	20:16	3:50	400	400	50			1000	rain									
F08	7-Feb-20	12:55	16:05	3:10	400	400	100			1000	rain + detour									
F09	7-Feb-20	18:12	20:15	2:03	400	400				500	detour									
F10	9-Feb-20	11:04	16:54	5:50	400	400	100	50	700	700	rain + detour									

Complete data set

Partial data set

No data

# Platform: BOREAL

## Specifications:

- Wingspan: 4.2 m; 25 kg max take-off
- Flight capacity up to 700 km with a 5 kg payload (ca. 7 hrs)
- Two-stroke gas engine
- 95 km/h cruise air speed (26.4 m/s); Range: 60-130 km/h
- Catapult take-off; belly landing

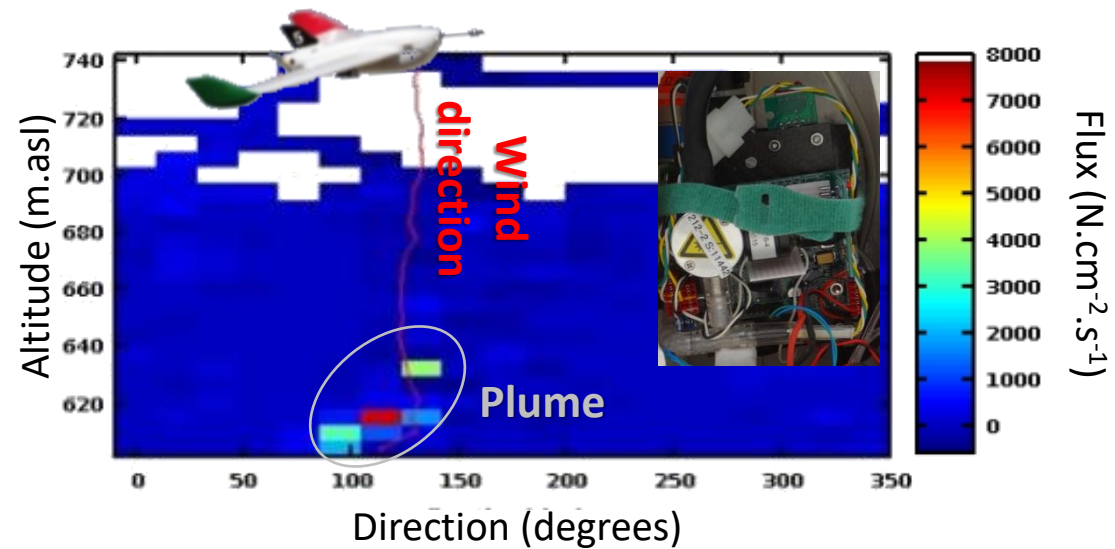


## Onboard instrumentation during ReNovRisk):

- Transponder (mode S/ADS-B)
- Strobe
- C2Link RF communication & Iridium satellite with real-time video (up to 50 km from GCS)
- Radar altimeter to measure sea state and for security
- Science payload to measure 3D winds, aerosol, turbulent fluxes



# Fire plume flux measurements using UAS



$$\text{Flux (N.m}^{-2}\text{.s}^{-1}) = \text{Speed (m/s)} * \text{Concentration (N/m}^3\text{)}$$

Wind (GPS)

Particle Counter (OPC)

- Cylindrical flight around source (1 hour up to 150 m.agl; vertical res. ~5 m; horizontal res. ~15 m)
- Measured aerosol concentration and wind vector;
- Subtract background to calculate particle flux