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LOAC: a small aerosol optical counter/sizer for ground-based and balloon measurements of the size distribution and nature of atmospheric particles – Part 2: First results from balloon and unmanned aerial vehicle flights

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First results from balloon and unmanned aerial vehicle flights

J.-B. Renard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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**First results from
balloon and
unmanned aerial
vehicle flights**

J.-B. Renard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

In the companion paper (Renard et al., 2015), we have described and evaluated a new versatile optical particle counter/sizer named LOAC (Light Optical Aerosol Counter) based on scattering measurements at angles of 12 and 60° that allows some topology identification of particles (droplets, carbonaceous, salts, and mineral dust) in addition to size segregated counting in a large diameter range from 0.2 up to possibly more than 100 µm depending on sampling conditions. Its capabilities overpass those of preceding optical particle counters (OPCs) allowing the characterization of all kind of aerosols from submicronic-sized absorbing carbonaceous particles in polluted air to very coarse particles (> 10–20 µm in diameter) in desert dust plumes or fog and clouds. LOAC's light and compact design allows measurements under all kinds of balloons, on-board unmanned aerial vehicles (UAV) and at ground level. We illustrate here the first LOAC airborne results obtained from an unmanned aerial vehicle (UAV) and a variety of scientific balloons. The UAV was deployed in a peri-urban environment near Bordeaux in France. Balloon operations include (i) tethered balloons deployed in urban environments in Vienna (Austria) and Paris (France), (ii) pressurized balloons drifting in the lower troposphere over the western Mediterranean (during the Chemistry-Aerosol Mediterranean Experiment – ChArMEx campaigns), (iii) meteorological sounding balloons launched in the western Mediterranean region (ChArMEx) and from Aire-sur-l'Adour in south-western France (VOLTAIRE-LOAC campaign). More focus is put on measurements performed in the Mediterranean during (ChArMEx) and especially during African dust transport events to illustrate the original capability of balloon-borne LOAC to monitor in situ coarse mineral dust particles. In particular, LOAC has detected unexpected large particles in desert sand plumes.

First results from balloon and unmanned aerial vehicle flights

J.-B. Renard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



1 Introduction

The concentration, size and properties of atmospheric aerosol particles are highly variable in both space and time due to the large variety of aerosol sources of both natural and man-made origin, and to their relatively short residence time in the atmosphere (Holton et al., 2003). The characterization and monitoring of aerosol particles in the lower and middle Earth atmosphere is important for climate studies (e.g. Kaufman et al., 2002, and Ammann et al., 2003, respectively) and near the surface for air quality issues (e.g. Brunekreef and Holgate, 2002). When very high concentrations of ashes after volcanic eruptions are present at aircraft cruise altitude, they can severely affect air traffic (e.g. Chazette et al., 2012). In the middle atmosphere, aerosols also play a significant role in stratospheric ozone chemistry through heterogeneous reactions with nitrogen and halogen species (e.g. Hanson et al., 1994, 1996). To understand and predict aerosol impacts, it is important to develop observation and monitoring systems allowing for their characterization. In particular, small instruments adapted to balloon-borne measurements are scarce and generally devoted to stratospheric aerosols (Deshler et al., 2003; Renard et al., 2008). The aim of our study was to develop a new, relatively low-cost optical aerosol particle counter that could be launched under small balloons.

In Part I of this publication, a new versatile optical counter/sizer instrument named LOAC (Light Optical Aerosols Counter) was described and evaluated. It is light and compact enough to perform measurements at the surface and on-board airborne vehicles including all kinds of balloons in the troposphere and in the stratosphere and unmanned aerial vehicles (UAVs). Meteorological sounding balloons and UAVs are in particular adapted to airborne operations on alert. LOAC uses a new approach combining measurements at two scattering angles, which allows the determination of the particle size distribution and of the dominant nature of particles (manly liquid droplets, and carbonaceous, mineral dust and salt particles) in various size classes.

First results from balloon and unmanned aerial vehicle flights

J.-B. Renard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**First results from
balloon and
unmanned aerial
vehicle flights**

J.-B. Renard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



In the companion paper we have presented the principle of measurements, the instrument calibration, cross-comparisons with other aerosols instruments, and field observations validating the “topology procedure” to estimate the main nature of the particles. In this paper, we illustrate the first airborne results obtained with LOAC on-board a UAV and under different kinds of balloons including low-altitude tethered balloons, meteorological sounding balloons, pressurized tropospheric drifting balloons, and stratospheric balloons.

2 LOAC instrument and gondola for balloon flights

A first description of the instrument is given in Lurton et al. (2014). Particles are drawn up to the optical chamber through an isostatic tube by a small pump. The air stream crosses the centre of a laser beam of 25 mW working at the red wavelength of 650 nm. The scattered light is recorded by two photodiodes at scattering angles of ~ 12 and $\sim 60^\circ$. Photons travel directly to the photodiodes through pipes (without a lens), providing fields of view with a few degrees. A total of 19 size classes are defined for diameters between 0.2 and $\sim 100 \mu\text{m}$. The size classes are chosen as a good compromise between the instrument sensitivity and the expected size distribution of ambient air aerosols. LOAC can determine up to ~ 3000 particles smaller than $1 \mu\text{m cm}^{-3}$, 20 particles greater than $1 \mu\text{m cm}^{-3}$ in dry conditions and up to 200 particles cm^{-3} in fog/cloud conditions. The uncertainty (at 1σ) is of about $\pm 15\%$ for concentrations $> 10^{-1}$ particles cm^{-3} and of about $\pm 30\%$ for lower concentrations.

A “speciation index” is retrieved by combining the 12 and 60° channels measurements. Speciation indices have been determined in laboratory for 4 families of particles including solid carbonaceous, mineral dust, and salt particles, and liquid droplets. The speciation indices obtained from LOAC observations in the atmosphere are compared to the charts obtained in the laboratory. The position of the data points in the various speciation zones provides the main nature of the particles. The identification of the nature of the particles works well in case of a homogenous medium, and is more difficult

in case of a heterogeneous medium that generally cause the speciation index to be scattered among several speciation zones.

To minimize the instrument weight, the optical chamber is in plastic Delrin[®]. The weight, including the pump, is of 300 g. The electric consumption is of 340 mA under 8 V, which corresponds to 3 W. Autonomy of about 3 h can be obtained with alkaline batteries. A gondola in polystyrene has been developed for flights under meteorological balloon. The data are sent in real-time by on-board telemetry. In its nominal configuration, LOAC uses the MeteoModem Company system for telemetry and GPS, and for temperature, pressure and humidity (PTU) measurements (<http://www.meteomodem.com/>). The total weight of the gondola (Fig. 1a), including the batteries and the PTU sounding, is of about 1 kg. The duration of a flight with meteorological balloons is of about 2 h, and can reach an altitude of 37 km with a latex balloon of 1200 g. One of the critical part of the instrument is the pumping system, which must work in extreme conditions in the middle atmosphere. At ground, the pump has a stability of about $\pm 5\%$. Tests have been conducted in the stratosphere during a meteorological flight up to an altitude of 34 km. The rotation speed of the pump and its stability are the same all along the flight, allowing us to conclude that the pump is insensitive to temperature and pressure variations.

A specific gondola has been developed for launch below low altitude drifting balloons developed by the French Space Agency (CNES; Fig. 1b). Such tropospheric balloons can stay in flight at a float altitude below 3500 m during several tens of hours (Ethé et al., 2002).

First results from balloon and unmanned aerial vehicle flights

J.-B. Renard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



3 Field measurements under uav balloons

3.1 General comments

A large number of LOAC flights under different kinds of balloons and airborne vehicles has been conducted since 2011. We present here some examples of the flight results (Table 1) and first interpretations of the measurements.

For all kinds of flights, the aerosols were rejected inside the gondola, to prevent the creation of a pollution cloud around the balloon or the UAV. Some flights under drifting and sounding balloons were conducted with a very good time and spatial coincidence (less than 1 h and less than 50 km). Both measurements at the same altitude are in good agreement, confirming that no pollution cloud was around the drifting balloon.

During ground-based and flight tests, no effect of pressure and humidity on the LOAC working was detected. On the other hand, there is a risk of condensation or ice in case of low temperature and pressure. Ice on the optical chamber would produce strong stray light contamination, and the data would be rejected. But because humidity is low in the tropopause region and in the stratosphere, these problems will not occur. They could occur only inside thick tropospheric clouds (in general the balloon will not operate or survive in such extreme environment).

3.2 Unmanned aerial vehicle flights

A possible application of LOAC consists in measurements from unmanned aerial vehicles. LOAC has been mounted on a small UAV of Fly-n-Sense Company (Fly-n-Sense, <http://www.fly-n-sense.com/uav-solutions/environment/>), as shown on Fig. 2. Tests have been conducted to ensure, first, that the sampled air is not affected by the motions of the propellers, and secondly that the electromagnetic radiations of the motors do not perturb the LOAC electronics. Figure 3 presents an example of a 20 min flight close to the ground performed in a field near the Bordeaux-Mérignac airport (South-West of France; 49°49'43" N, 0°42'55" W) on 18 December 2013 at 14:30 UT.

First results from balloon and unmanned aerial vehicle flights

J.-B. Renard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



First results from balloon and unmanned aerial vehicle flights

J.-B. Renard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Above 200 m, only carbonaceous particles were detected, confirming the likely very local origin of the mineral particles at intermediate altitude.

Permanent measurements have been conducted at the “Observatoire Atmosphérique Generali” (OAG) in the South-West of Paris since May 2013 (position in Table 1). This observatory is a recreational 6200 m³ tethered balloon (Fig. 7) operated in the public park André Citroën. The spring and summer 2013 measurements were contaminated by construction activities in the vicinity and are not considered here. The LOAC pump operates at 2.7 Lmin⁻¹ and sampling is performed through a total suspended particulate (TSP) inlet having a diameter cut-off at about 100 μm. The instrument is installed in a small ventilated metallic box fixed on the side of the balloon passenger gondola with its TSP sampling inlet pointing up. The measurements can be sorted out between measurements when the balloon is at ground level and measurements during flights. From 150 to 200 days year⁻¹ are favourable for flying this type of tethered balloon. The balloon measurements nominal maximum altitude is 120 m and many flights can be performed per day depending on wind conditions. Up to several flights per week can also be conducted with measurements up to an altitude of 270 m. The aim of these flights is to study the possible evolution of the nature and of the size of particles as a function of altitude, and to distinguish between local sources at ground level and the persistent urban pollution in the middle of the boundary layer.

Most of the time, the air was well mixed and the concentrations are almost constant with increasing altitude for particles smaller than ~ 10 μm. On the opposite, some flights conducted during pollution events exhibit different trends. As an example, the 11 December 2013 (day #345) morning flight performed during anticyclonic conditions presents a temperature inversion layer at an altitude of ~ 200 m, as shown on Fig. 8. A strong accumulation layer is detected between 180 and 220 m and was visually confirmed by the pilot of the balloon. The total concentration of particles larger than 0.2 μm in diameter is between more than 1000 particles cm⁻³. Also, a fuzzy accumulation layer of particles is detected between 30 and 90 m. The size distribution at 3 different altitudes (Fig. 9) shows that the pollution (and thus the mass concentrations, as presented

in the paper 1 detailing the instrument concept) is dominated by the smallest particles. The topology indicates a mixture of carbon and mineral particles close to the ground in the recreation park, and only carbon particles for the highest altitudes. The analyses of flights performed later during that day and in the following days show the progressive disappearance of the accumulation layers as the wind speed increased.

The Vienna and OAG examples show the interest of performing urban measurements under a tethered balloon, in order to document the size, the nature and the evolution of the particles as a function of altitude in the urban polluted boundary layer. In particular, such kind of flights can help distinguishing between local sources of pollution close to ground and accumulation/transport of aerosols in the ambient air at higher altitude in the atmospheric boundary layer.

3.4 ChArMEx tropospheric flights

LOAC was also intensively involved in the ChArMEx campaign (Chemistry Aerosol Mediterranean Experiment, <http://charmex.lsce.ipsl.fr/>). ChArMEx aims at a scientific assessment of the present and future state of the atmospheric environment over the Mediterranean basin (e. g. Menut et al., 2014; see ChArMEx Special Issue in Atmos. Chem. Phys. and Atmos. Meas. Tech.). All the LOAC balloon flights have been performed by the Centre National d'Etudes Spatiales (CNES).

A total of 13 LOAC flights under low tropospheric pressurized drifting balloons were conducted from the Spanish Minorca Island from 15 June to 2 July 2013, and from the French Levant Island from 22 July to 4 August 2013 (station positions in Table 1), mainly during well-identified desert dust transport events. Results will be detailed in a forthcoming paper. We illustrate here one flight launched from Minorca Island during the ChArMEx/ADRIMED (Aerosol Direct Radiative Impact in the Mediterranean) campaign. Except in case of precipitation or condensation, these balloons follow a near-Lagrangian trajectory (i.e. remaining in the same air mass during their trajectory in the lower atmosphere). Their float altitude was chosen before the flight in the 400–3500 m range by adjusting the balloon density with helium, depending on the altitude of the

First results from balloon and unmanned aerial vehicle flights

J.-B. Renard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**First results from
balloon and
unmanned aerial
vehicle flights**

J.-B. Renard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



posphere. Figure 13 presents the evolution of the aerosol particle concentrations for the 19 size classes as a function of time along the trajectory. The mineral nature of the particles was confirmed by the topology measurements. LOAC has detected unexpected significant concentrations of large particles inside the soil dust plume, up to 50 μm in diameter, although the plume originated from North-Africa about 3 days before (Fig. 14). Thermal anomalies from MSG/SEVIRI North Africans Sand Storm Survey (<http://nascube.univ-lille1.fr/cgi-bin/NAS3.cgi>) indicate that the dust layer sampled by the balloon was likely emitted on 14 June in the NW Algeria-N-E Morocco source region particularly active in summer (Bergametti et al., 1989). The concentrations of these largest particles remained relatively constant during the flight, suggesting no significant sedimentation of large particles during the flight or compensation by particles from above. This type of observation was found during other flights, and will need further analysis to better understand the process that can maintain such large particles in suspension during several days.

This example shows, for the first time, the time-evolution of tropospheric aerosol concentrations at constant altitude from long duration balloons.

3.5 Upper tropospheric and stratospheric flights

Thanks to its light weight and small electric consumption, LOAC can be launched under meteorological sounding balloons, allowing a large number of flights from different places. The measurements were conducted during the ascending phase of the balloon. The inlet was oriented toward the sky, thus towards the relative wind direction due to the ascent of the balloon at $\sim 5 \text{ m s}^{-1}$. In the May 2013–April-2015 period, LOAC has performed 60 flights under meteorological balloons from France (Aire-sur-l'Adour, South-West of France; Ury, south-west of Paris region; Levant Island, south of France; and Ile de la Réunion, tropic of Capricorn), from Spain (Minorca Island) and from Iceland (Reykjavik). The highest altitude reached by LOAC with this kind of balloon is 37 km.

**First results from
balloon and
unmanned aerial
vehicle flights**

J.-B. Renard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



aerosols content in the free atmosphere; this new measurements strategy is similar to the one already conducted with ozone soundings. Using forecast trajectories, the balloon trajectory can be estimated before the flight to optimize the probability of a safe recovery of the gondola. As an example, the recovery success was of 90 % for the flights conducted in France from Aire-sur-l'Adour and Ury in 2014. Thanks to LOAC robustness, the recovered instrument can be re-used several times.

The large set of measurements obtained in the various geophysical conditions presented above has allowed us to obtain original results on the aerosol content in the different parts of the atmosphere. Using tethered balloon, we have started to better document the urban pollution from the ground up to the middle of the boundary layer, and to determine the evolution of the size distribution and the nature of the particles with altitude. In the free troposphere, the balloon measurements inside several desert dust plumes have shown the unexpected persistence of large coarse particles of more than 15 μm and up to several tens of μm in diameter. The analysis of the LOAC and balloons housekeeping data during these flights indicate the presence of strong electrostatic fields inside the plume (but not outside) that slightly disrupted the electronics. Ulanowski et al. (2007) observed polarization effects in a dust plume over the Canary Island that they attributed to alignment of particles due to an electric field. These fields might explain the sustained levitation of these large particles, but this hypothesis needs further experimental studies. In the lower and middle stratosphere, LOAC has confirmed the presence of layers of carbon particles. Above 30 km, LOAC has also detected transient concentrations enhancements, but the nature and origins of particles are not yet fully determined. Finally, the large size range detection of LOAC has allowed us to detect unambiguously the presence of interplanetary grains and meteoritic debris. All these first results need further flights to better document the complex content of the aerosols content in the various parts of the atmosphere.

5 Conclusions

LOAC is simultaneously involved in different projects. The LOAC ground-based and tethered balloon measurements at the Observatoire Atmosphérique Generali (Paris) will continue. The detailed analysis of the variation in concentration and the nature of the urban aerosols with altitude is still in progress, in particular during strong pollution events. Measurements at SIRTA (Palaiseau) will also continue for the detection of fog events and the time-evolution of their size distribution, and for the monitoring of sub-urban particles.

LOAC is also involved in different projects for the monitoring and the identification of tropospheric and stratospheric aerosols, using meteorological balloons and large stratospheric large balloons (zero pressure and super-pressure). In the frame of the VOLTAIRE-LOAC project, dedicated to the long-term monitoring of stratospheric aerosols, flights under meteorological balloons are conducted every 2 weeks from Aire-sur-l'Adour (South-West of France) and Ury (South-East of Paris) since January 2014. Such a strategy of recurrent balloon flights is suitable to capture events like volcanic eruptions and to derive long-term trends in the stratospheric aerosol content. Additional flights will be conducted from Reykjavik (Iceland) and Ile de la Réunion (France, Indian Ocean) to better document the latitudinal dependence of stratospheric aerosols and to identify the evolution of their nature with altitude. Some flights will be also conducted from Iceland during dedicated campaigns for the study of the vertical transport of frequently re-suspended volcanic dust (Dagsson-Waldhauserova et al., 2013), and in case of future major volcanic events. Also, the large number of flights performed each year will allow us to better estimate the mean concentrations of large particles in the middle atmosphere. Thus we expect to provide soon an estimate of the interplanetary dust input in the upper atmosphere.

The LOAC flights on-board UAVs have started, mainly for the measurements of urban pollution and the characterization of the aerosol sources, but other applications are under study.

First results from balloon and unmanned aerial vehicle flights

J.-B. Renard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



First results from balloon and unmanned aerial vehicle flights

J.-B. Renard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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**First results from
balloon and
unmanned aerial
vehicle flights**

J.-B. Renard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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AMTD

8, 10057–10096, 2015

First results from balloon and unmanned aerial vehicle flights

J.-B. Renard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



First results from balloon and unmanned aerial vehicle flights

J.-B. Renard et al.

Table 1. LOAC balloon flights illustrated in this study.

Campaign	Launch location	Launch latitude and longitude	Launch date	Balloon type	LOAC inlet
EGU	Vienna (Austria)	48.2343° N 16.4132° E	11 Apr 2013	Tethered balloon	Metal, bevelled
OAG	Paris (France)	48.8414° N 02.2740° W	11 Dec 2013	Tethered balloon	TSP
ChArMEx	Minorca (Spain)	39.8647° N 04.2539° E	17 Jun 2013	Tropospheric pressurized balloon	Metal, bevelled
ChArMEx	Levant Island (France)	43.0265° N 6.4877° E	4 Aug 2013	Meteorological balloon	Metal, bevelled
VOLTAIRE-LOAC	Aire-sur-l'Adour (France)	43.702° N 0.262° W	20 Mar 2014	Meteorological balloon	Metal, bevelled

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**First results from
balloon and
unmanned aerial
vehicle flights**

J.-B. Renard et al.

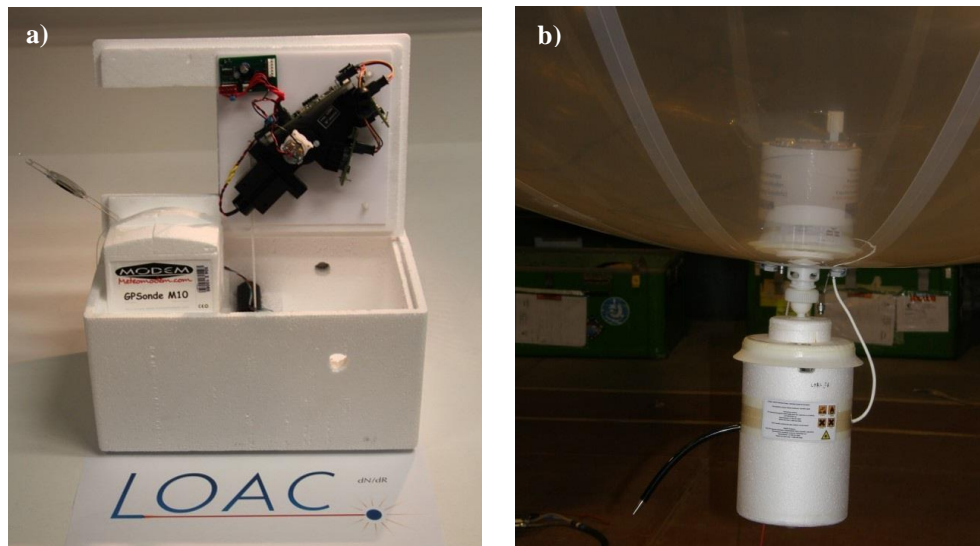


Figure 1. (a, left) The LOAC gondola with a Meteomdem Company sonde for flight under meteorological balloons; (b, right) the LOAC gondola below a low troposphere drifting balloon.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





Figure 2. LOAC on board an unmanned aerial vehicle of the Fly N Sense Company (LOAC is on the black box at the bottom of the vehicle).

AMTD

8, 10057–10096, 2015

First results from balloon and unmanned aerial vehicle flights

J.-B. Renard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**First results from
balloon and
unmanned aerial
vehicle flights**

J.-B. Renard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

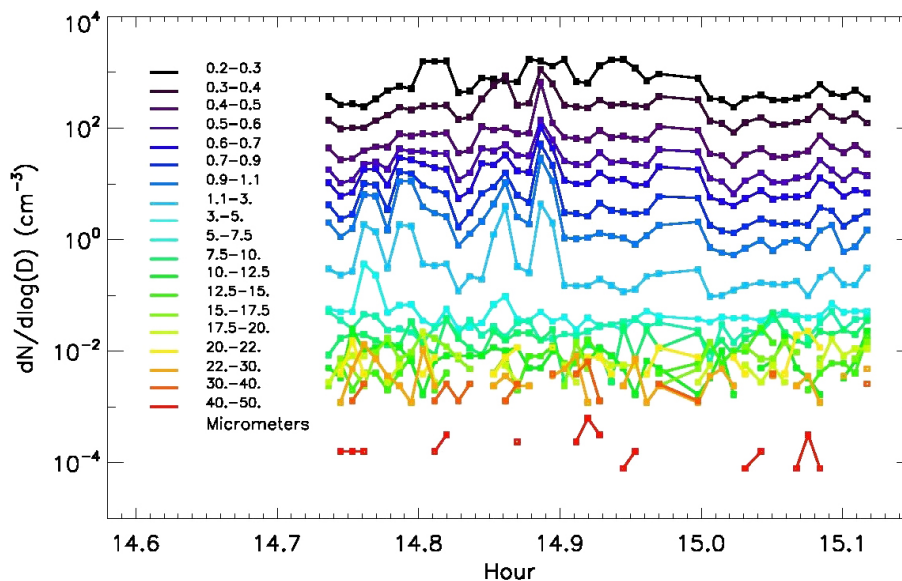


Figure 3. Aerosol particle size distribution from LOAC flight on-board an unmanned aerial vehicle flown close to the surface near Bordeaux-Mérignac (France) on 18 December 2013 at 14:30 UT.

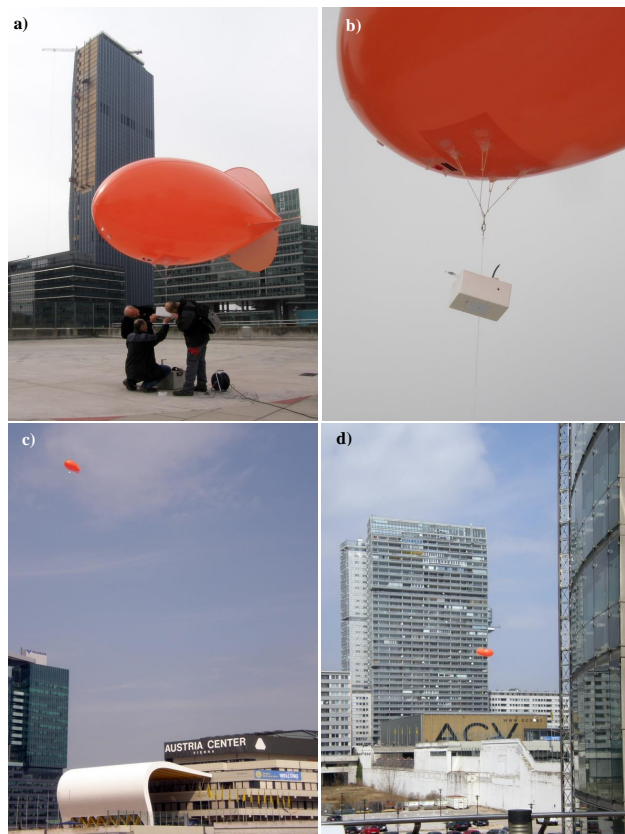


Figure 4. Pictures of the LOAC operations below a 6 m^3 tethered balloon at the Austria Center in Vienna during the 2013 European General Assembly. From left to right and top to bottom: **(a)** preparation of the launch with a view towards S on a tower under final stage of construction in the back; **(b)** view from below of LOAC in flight with its sampling inlet pointing upward; **(c)** view from the S of the balloon over the conference centre; **(d)** view from the SW of the environment of the launch site including leaving and office tower blocks and an open air car park.

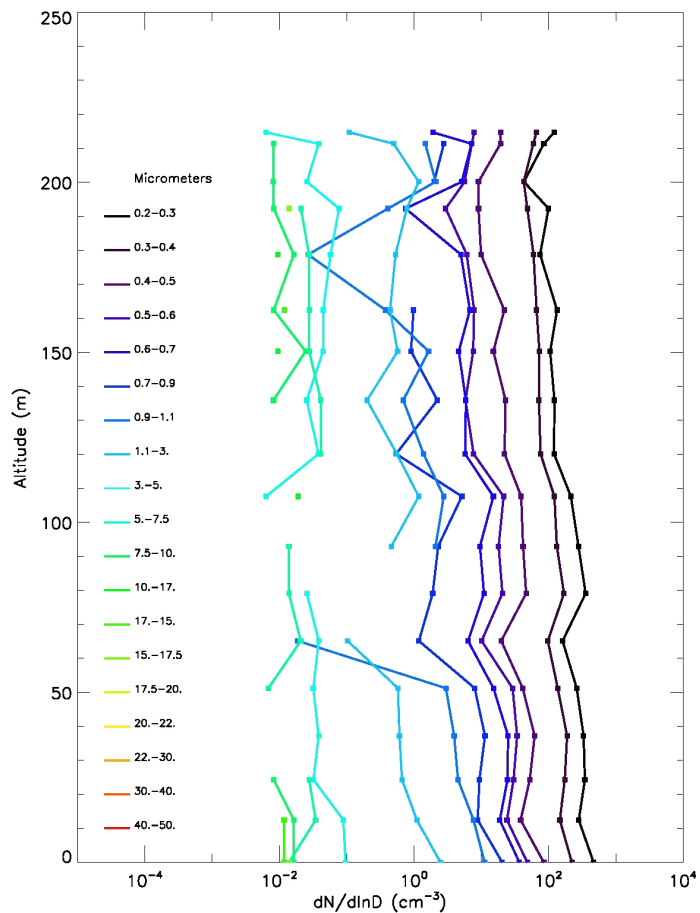


Figure 5. Evolution of the concentrations for the 19 size classes of LOAC, during a flight under a tethered balloon in Vienna (Austria) on 11 April 2013 at 11:00 UT.

First results from balloon and unmanned aerial vehicle flights

J.-B. Renard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



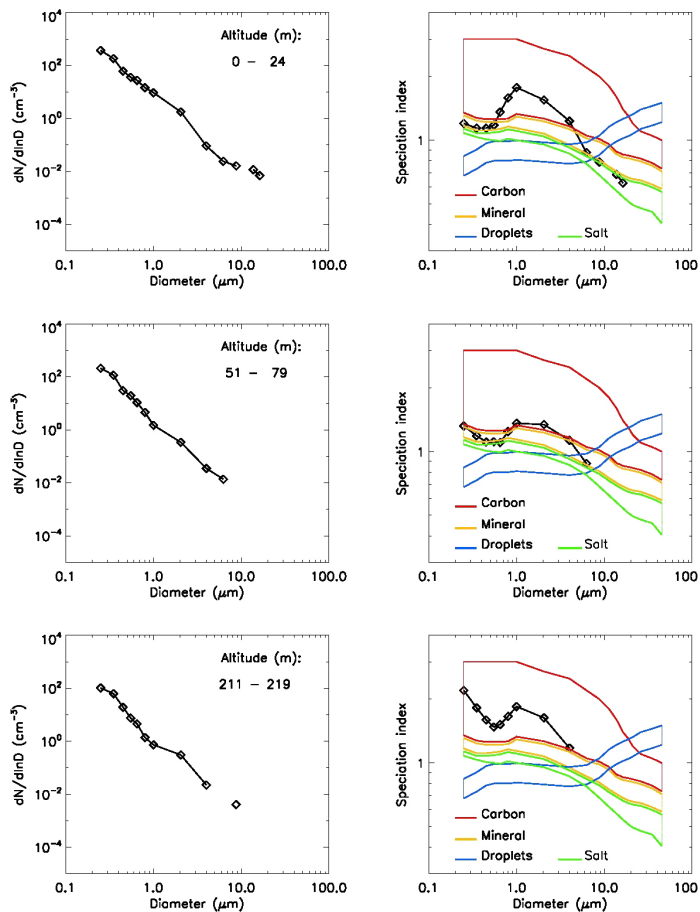


Figure 6. Size distribution and topology at 3 altitudes during a flight under a tethered balloon in Vienna on 11 April 2013 at 11:00 UT.

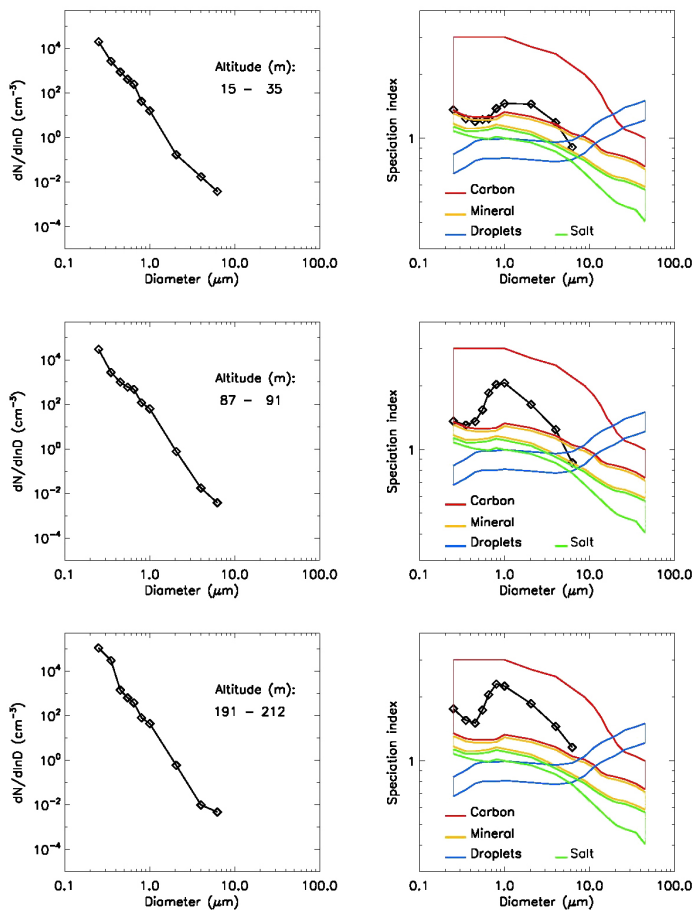


Figure 9. Size distribution and topology at 3 altitudes during a flight under the OAG tethered balloon in Paris (France) on 11 December 2013 at 10:15 UT.

First results from balloon and unmanned aerial vehicle flights

J.-B. Renard et al.

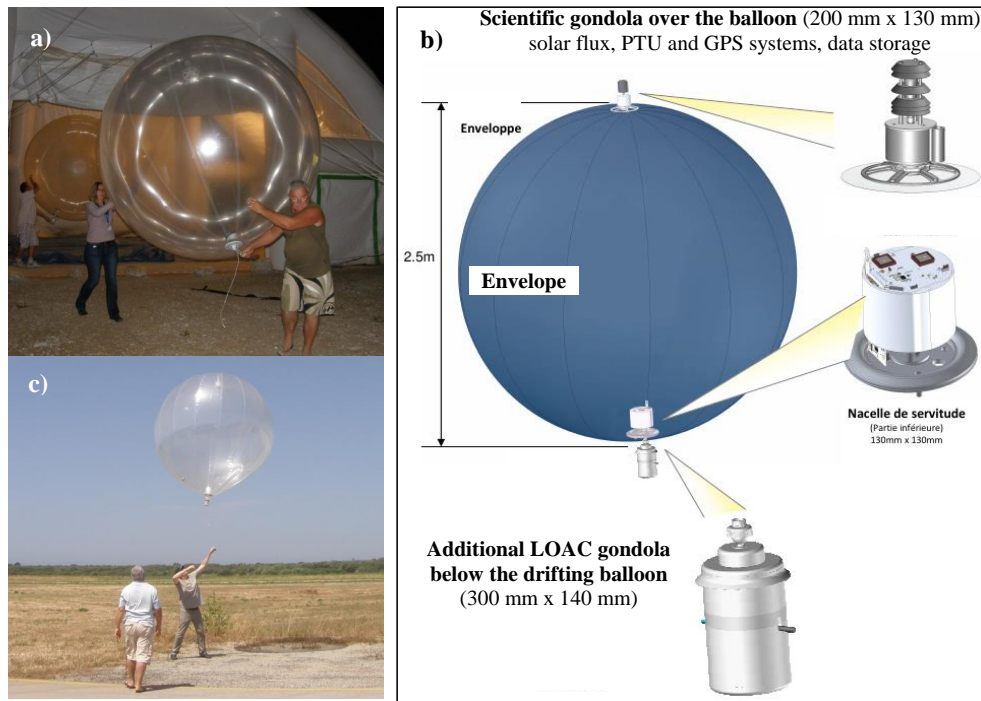


Figure 10. (a) CNES 2.5 m tropospheric pressurized balloon shortly before a night launch; (b) scheme of the pressurized balloon and gondolas; the scientific and control gondolas communicate by radio; (c) launch of balloon from Minorca on 17 June 2013, 09:45 UT.

First results from balloon and unmanned aerial vehicle flights

J.-B. Renard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

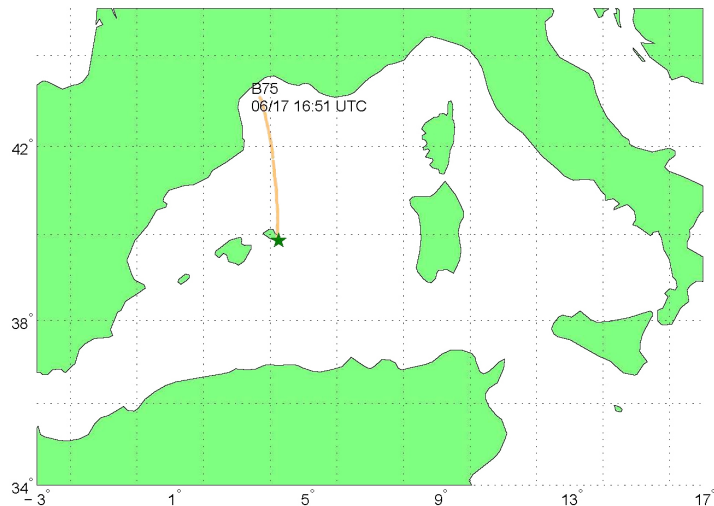
Full Screen / Esc

Printer-friendly Version

Interactive Discussion



CHARMEX SOP1 2013 – CHARMEX-S1-B75 – (B75)
Trajectory length 364.9 km, 197.0 NM – Distance from launch site 361.7 km, 195.3 NM – QDR from launch site 352.5 degree



LMD/PSL – LSCE/PSL – LPC2E – LA – CNRM & CNES

B75 Last data 06/17 16:51 UTC

Figure 11. Trajectory of the LOAC 7 h long drifting balloon flight on 17 June 2013, at an altitude of about 2000 m.

**First results from
balloon and
unmanned aerial
vehicle flights**

J.-B. Renard et al.

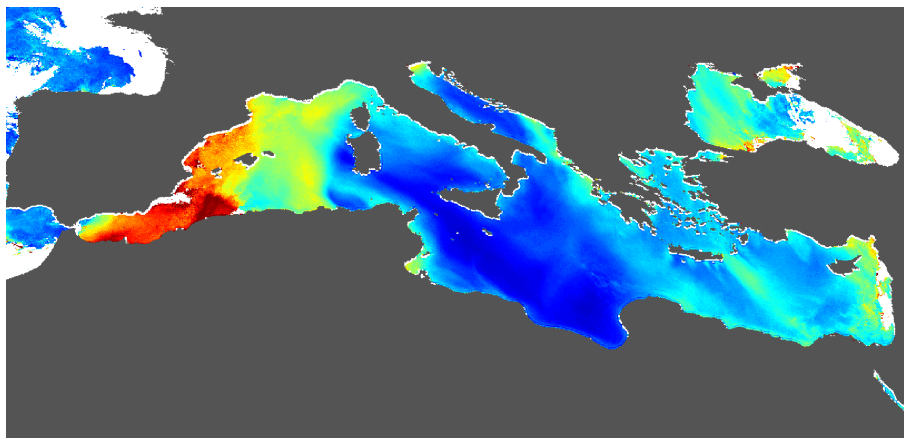


Figure 12. Daytime average aerosol optical depth at 550 nm derived from MSG/SEVIRI following Thieuleux et al. (2005) browse image courtesy ICARE/LSCE based on MSG/SEVIRI Level-1 data provided by Eumetsat/Eumetcast/LOA.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

First results from balloon and unmanned aerial vehicle flights

J.-B. Renard et al.

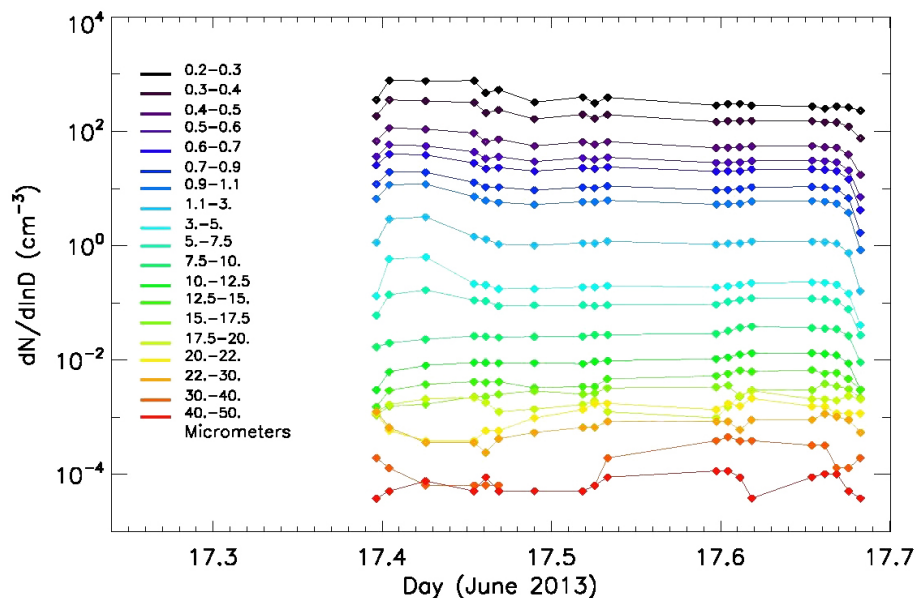


Figure 13. LOAC measurements inside a dust plume under the low tropospheric pressurized balloon during the ChArMEx campaign from Minorca, towards French coasts on 17 June 2013.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



NOAA HYSPLIT MODEL
 Backward trajectory ending at 1300 UTC 17 Jun 13
 GDAS Meteorological Data

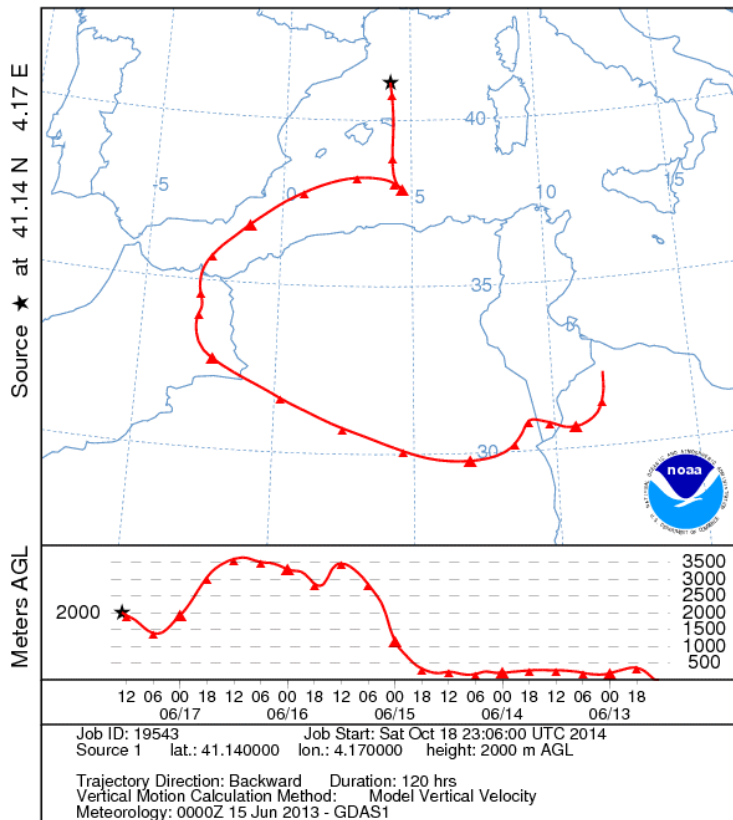


Figure 14. HYSPLIT air mass backward trajectory for LOAC balloon B75 (courtesy of NOAA Air Resources Laboratory).

**First results from
balloon and
unmanned aerial
vehicle flights**

J.-B. Renard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

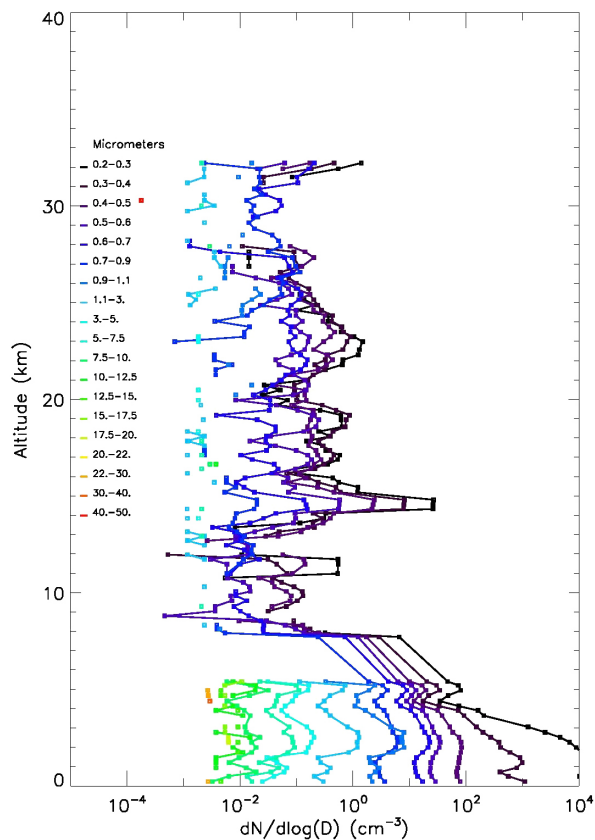


Figure 15. Particle concentrations up to 32 km in altitude from the LOAC flight under a meteorological balloon from Ile du Levant (France) during the ChArMEX campaign on 4 August 2013 between 15:30 and 17:30 UT; a sand plume is detected in the lower troposphere.

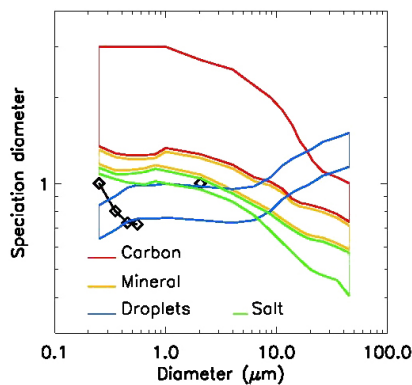
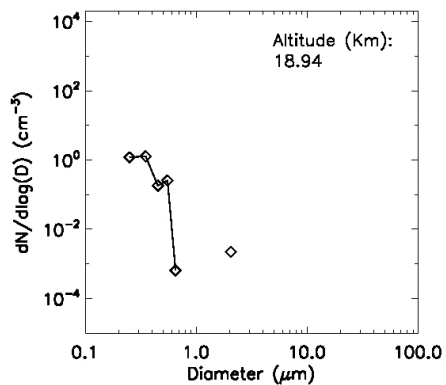
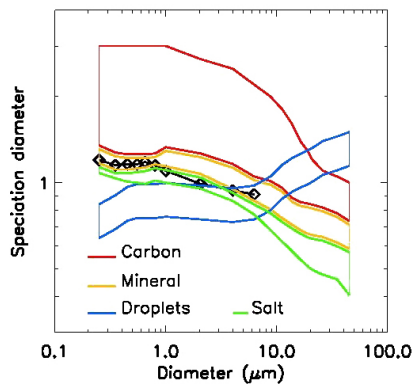
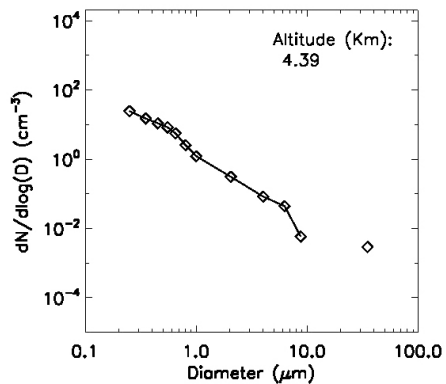


Figure 16. Examples of size distributions and topology at two altitudes for the 4 August 2014 LOAC flight from Ile du Levant (France) during the ChArMEs campaign. At an altitude of ~ 4 km the topology indicates mineral particles; at ~ 19 km, the topology indicates liquid particles.

**First results from
balloon and
unmanned aerial
vehicle flights**

J.-B. Renard et al.

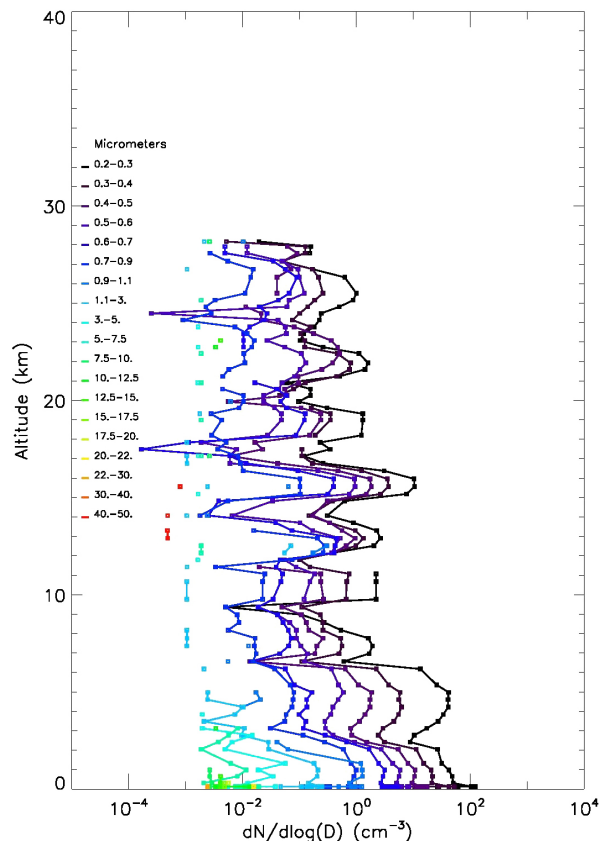


Figure 17. LOAC flight under a meteorological balloon from Aire-sur-l'Adour (France) on 28 October 2014 between 08:40 and 10:00 UT during the VOLTAIRE-LOAC campaign.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



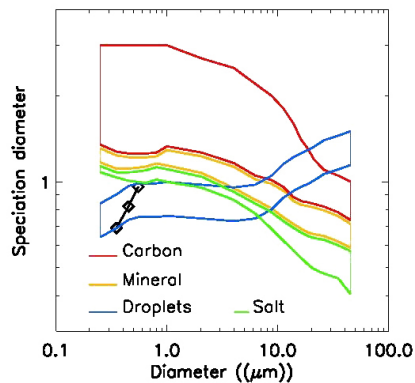
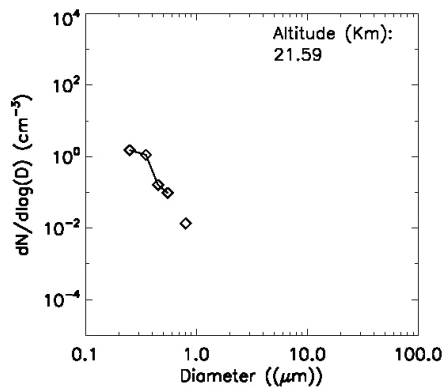
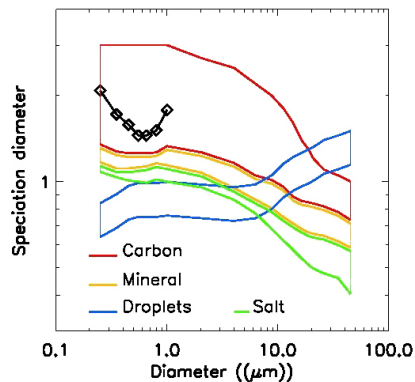
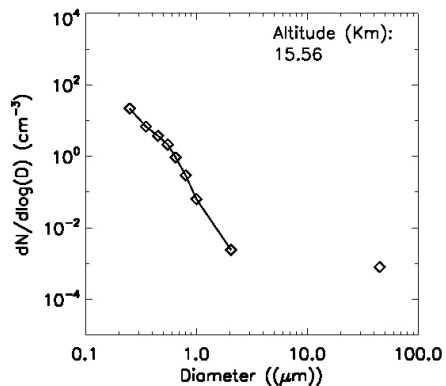


Figure 18. Examples of size distributions and topology at two altitudes for the 28 October 2014 LOAC flight from Aire-sur-l'Adour (France). At an altitude of ~ 15.5 km the topology indicates carbon particles; at ~ 21.5 km, the topology indicates liquid particles.