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High frequency boundary layer profiling with reusable radiosondes

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Abstract

A new system for high frequency boundary layer profiling based upon radiosondes and free balloons was tested during the field phases of the Boundary Layer Late Afternoon and Sunset Turbulence (BLLAST 2011, Lannemezan, France) and of the Hydrological cycle in the Mediterranean Experiment (HyMeX, 2012). The system consists of a conventional Vaisala receiver and a GPS radiosonde (pressure, wind, humidity and temperature) that is tied to a couple of inflated balloons. The principle of the sounding system is to permit the first balloon to detach from the rawinsonde at a predetermined altitude, allowing the rawinsonde to slowly descend with the second balloon to perform a second, new sounding. The instrumentation is then eventually recovered. The expecting landing area is anticipated before the flight by estimating the trajectory of the probe from a forecasted wind profile and by specifying both the balloon release altitude and the mean ascent and descent rates of the system. The real landing point is determined by the last transmission of the radiosonde GPS and the visual landmark provided by the second balloon. About 70 soundings were performed with a recovery rate of more than 80 %. Recovered radiosondes were generally reused several times, often immediately after recovery, which definitely demonstrates the high potential of this system.

1 Introduction

The observation of meteorological parameters through the depth of the atmosphere can be achieved from remote sensing (e.g. radars, lidars, sodars, radiometers) or through in situ measurements made by aircrafts or sounding balloons. The latter are commonly used in meteorology to collect humidity, temperature and wind data, as well as any other parameters that can be inferred from inexpensive, expendable instrumentation such as radiosondes. Free sounding balloons can collect high resolution observations throughout the troposphere in all weather conditions and are often used to achieve reference measurements for weather forecast, data assimilation or remote sensing technique validation.

When the required measurement frequency becomes too high, or when the meteorological sensors are expensive (e.g. ozone, turbulence or aerosol sensors), free sounding balloons become economically impractical, and are often replaced by tethered balloons, which allow recovery of the meteorological instrumentation. Tethered balloons nevertheless suffer from important limitations (e.g. flight clearance, limited payload and limited range of measurement) and cannot be used in all weather conditions unlike free balloons.

The intent of this paper is to present a sounding system that would account for both the flexibility of the free balloons and the ability to recover instrumentation from tethered balloons. The proposed development is based upon the pioneering research of Albert the 1st of Monaco who developed a 2-balloon system to perform soundings at sea on the ship Princess Alice (Le Roy Mesinger, 1921) in the early twentieth century. By charting the course of the ship and using a theodolite, the crew was able to ascertain the point where the instrumentation would reach the Sea so as to recover the data recorder. Other systems have also been proposed later by Mastenbrook (1966), Tennermann et al. (2004) or Douglas (2008) for passive or active recovery of meteorological sensors. The cost of the latter systems however makes their dissemination complicated and represents an important challenge that has yet to be solved.

The 2-balloon system described in this study is a low-cost device that is designed to be easily implemented on any available free balloon sounding system in order to measure all physico-chemical parameters for which sufficiently light instrumentation exists. It was first tested in 2011 in calm, clear air, conditions within the frame of the Boundary Layer Late Afternoon and Sunset Turbulence (BLLAST) field experiment (Lothon et al., 2012) before being later evaluated in a more hostile environment during the 2012 field phase of the Hydrological cycle in the Mediterranean Experiment (HyMeX, Ducrocq et al., 2013).

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The principle, components and potential applications of the dual-balloon sounding system are described in Sect. 2. A first evaluation of the system performance is presented in Sect. 3 using the 62 launches performed during the BLLAST experiment. Finally, Sect. 4 gives some examples of soundings performed during the HyMeX field phase and discusses the potential of this device for recovering prototype or expensive probes.

2 Sounding principle

2.1 Overview of the system

The principle of the two-balloon radiosounding system is shown in Fig. 1. It consists of sending aloft a couple of differently inflated balloons (referred to as the "carrier" and "slowing" balloons) in tandem, to lift up the instrumentation and perform an upward sounding (Fig. 1a). Both balloons are inflated using tares so as to set the vertical ascent/descent rates of the whole system to known preset values. The carrier balloon is tied to the rawinsonde by a wire and linked to a separation system programmed to trigger at a preset atmospheric pressure that is specified before the launch (Fig. 1b). After the carrier balloon has been released, the instrumentation goes down with the slowing balloon to perform a downward sounding (Fig. 1c). Once the probe has reached the ground (Fig. 1d), the buoyancy of the slowing balloon becomes positive. The balloon can then be used as a landmark to determine more easily the landing point and to recover the probe.

The different components of the system are shown in Fig. 2. It is composed of the carrier and slowing balloons (Fig. 2a), a meteorological radiosonde with a GPS probe for wind measurement and positioning (Fig. 2b) – the probe is surrounded by a mechanical protection system made of lightweight materials to avoid destruction of sensors upon descent and landing – a separation device tied to the carrier balloon (Fig. 2c) and a ground receiver station. The release of the carrier balloon is performed by cutting

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the wire that ties the balloon to the probe. This action can be achieved from mechanical, thermal or pyrotechnical means depending on sounding conditions and can be triggered by a timer or by a pressure sensor. The separation device is managed by microcontrollers to achieve a light weight separator.

2.2 Balloon inflation and launching

Ascending and descending speeds must be known as accurately as possible in order to properly estimate the landing area of the probe. Furthermore, commercial probe measurements are only valid for a given speed range (to properly compensate the effect of radiation on the temperature sensors, for example). The balloon inflation is thus performed to achieve two objectives: a known diameter to adjust the speed of ascent/descent and a sufficient buoyancy to ensure both the lift of the slowing balloon and its visibility from a distance once the probe has reached the ground.

2.3 Flight simulation software

Dedicated software has been developed to estimate the landing point of the probe. The anticipated location is determined by calculating the most probable trajectory of the balloons (Fig. 3) based on (i) a forecasted (or measured) vertical wind profile at the launching site, (ii) hypotheses on both the ascending/descending speed of the system, and (iii) the chosen release pressure of the carrier balloon. Performing flight trajectory simulations before the launch allows mitigating the risk of having the probe fall in areas difficult to access (e.g. water, urban areas, forests), as well as to allow the recovery team to re-position quickly after the radiosonde has landed. Performing balloon trajectory simulations also allows to set up the system so as to sample a specific area or to accomplish a particular objective. Examples of applications that would require a precise setting of the system are shown in Fig. 4. This includes modification of boundary layer properties by a surface transition (Fig. 4a), measurement on each side of a drastic change in terrain/topography (Fig. 4b) or observation of coastal breezes (Fig. 4c), but

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many other applications may be envisioned. In each of the case scenarios shown in Fig. 4, the distance travelled by the radiosonde must be known as accurately as possible in order to attain the scientific objective of the sounding. One way to do so is to play with the release height or with the ascent/descent rate of system, which is controlled by the volume of the balloons.

An example of flight trajectory simulation is shown in Fig. 5. In this example, the objective is to describe the possible modifications experienced by an oceanic air mass during its propagation from the coast to the foothills of the Massif Central (black dashed line), located ~40 km northwards of the launch site. The wind profile at the launch site that is used to estimate the flight trajectory is shown in Fig. 3. It is derived from a numerical forecast of the operational model Arome (Seity et al., 2012) valid on 21 October 2012 at 09:00 UTC. In this flight simulation the slowing balloon is inflated so as to achieve a mean descent rate of 3.4 m s^{-1}, and the release pressure of the carrier balloon is set to 600 hPa (~4200 m). The trajectories shown in Fig. 5 correspond to various ascent speed hypotheses ranging from 3 to 5 m s^{-1}. According to the simulated trajectories, the carrier balloon would have to be inflated so as to reach a mean ascent rate of 4 to 5 m s^{-1} for the radiosonde to land near the foothills. Using a slower ascent speed would likely result in a greater travelled distance and the radiosonde would possibly fall over the terrain.

2.4 Probe recovery

The instrumentation is recovered from the last known position recorded during the descent of the balloon. In cases where the last received position does not match the ground, the landing point is extrapolated from the last wind measurement. Ultimately, a label on the probe provides information allowing potential public citizens to contact operators.

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3 Test of the system during BLLAST

3.1 The BLLAST experiment

The 3 week field phase of the Boundary Layer Late Afternoon and Sunset Turbulence (BLLAST) experiment was conducted in the summer of 2011 in Lannemezan, in the French Pyrenees (Lothon et al., 2012). The overall objective of BLLAST was to collect accurate observations of the so-called late afternoon transition (LAT), which corresponds to the period when the convective boundary layer decays to an intermittently turbulent residual layer overlying a stably-stratified boundary layer. The objective of BLLAST was to better understand the physical processes that control the LAT, and to elucidate its role on both mesoscale and turbulence scale motions. This campaign brought together many complementary observation devices including UAVs, aircraft, wind profilers, sodar, lidars, tethered balloons and balloon soundings, among others, with the objective of achieving an exhaustive description of the dynamical processes in the boundary layer.

3.2 BLLAST sounding summary

The new high-frequency sounding device was tested with conventional Vaisala radiosondes (RS92) during nine Intensive Observation Period (IOP) days. A team of four people was in charge of conducting high frequency sounding activities. As soon as the radiosonde was in the air, two of the people involved in the sounding preparation had to leave the launch site to recover the probe. Soundings were performed on an hourly basis from 12:00 to 21:00 UTC with the objective to capture the evolution of the PBL during the LAT. The carrier balloon separation was set to occur below the cloud base (average 2700 m, min/max 1100 m/4500 m), but high enough to sample the whole boundary layer. The original rawinsonde batteries were replaced with accumulators. The total weight of the modified rawinsonde (release mechanism + probe + accumulators) was ~265 g, which is slightly less than the weight of the original probe

(274 g). All carrier (resp. slowing) balloons were inflated to achieve an ascent (resp. descent) rate of ~5 (resp. 3.4) $m\,s^{-1}$. Landing points were predicted using vertical wind profiles forecasted by Météo-France high resolution model AROME.

An example of sounding time series is shown in Fig. 6, which presents the vertical structure of the PBL between 13:00 and 20:00 UTC on 1 July 2011. Seven launches were performed within this seven hour period, which allowed collecting 14 boundary layer profiles. The four first launches were made before sunset, while the PBL was still unstable. The air temperature close to the ground was quite warm, as shown by the existence of a super-adiabatic surface layer between 13:00 and 17:00 UTC. According to observations, the air mass near the surface becomes stable near 18:00 UTC, but cooling continued to increase over the next few hours. The maximum depth of the CBL was observed at 13:00 UTC. As time passes, the top of the boundary layer progressively decreased from 1500 m a.g.l. at 13:00 to 12:00 m a.g.l. at 19:00 UTC. A strong capping inversion could be observed at all times. The variation of temperature and humidity across the inversion was on the order of 6 K (Fig. 6a) and 6 $g\,kg^{-1}$ (Fig. 6b), respectively. Four probes were needed to complete this time series. One of them was lost and the three others were reused later in the experiment.

3.3 Sounding statistics

Twenty radiosondes were available for the BLLAST project, which allowed performing 62 launches for a total of 104 measured vertical profiles. Sounding statistics are presented in Table 1. The release mechanism performed well in about 84 % of the time, although separation sometimes occurred at a wrong level. The total release failure rate, which corresponds to situations where the release did not occur or occurred at the wrong pressure, reached 16 %. Eighty-five percent of the released probes were visually identified within one hour after landing. Among those, 79 % were recovered and reused at least one time, sometimes immediately after recovery. Considering that 11 probes were still available at the end of the experiment, only 9 probes were thus needed to perform 104 vertical soundings of the atmosphere.

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3.4 Uncertainties on the landing point

As discussed earlier, a proper estimation of the landing point is needed to maximize the odds of recovering the probes or to achieve particular applications (Fig. 4). The two major sources of uncertainties arise from the estimation of the ascent/descent speed of the system and from the accuracy of the vertical wind profile used to estimate the flight trajectory. A couple of experiments were conducted from the BLLAST dataset in order to evaluate the impact of these errors on the determination of the landing point.

Figure 7a shows the differences between the actual landing point of each recovered radiosonde and the ones simulated using horizontal wind profiles forecasted by the Arome model at the time of soundings and (i) mean theoretical ascent and descent speeds of 5 and 3.4 $m\,s^{-1}$, respectively (red) or (ii) mean vertical speeds derived from in-situ radiosonde measurements (black). The results shown in Fig. 7 are normalized by the total distance traveled by the probe. Overall, the dependence of the error on ascent and descent rates is relatively weak and using true mean vertical speeds does not significantly improve the results. The error rate averages around 22 % in both cases (meaning that the actual distance travelled by the system is 22 % lesser or greater than that expected). This suggests that the main source of uncertainty is more likely related to the accuracy of the horizontal wind profile used to perform the trajectory simulations.

In a second step, one can try to evaluate the impact of the accuracy of the horizontal wind profile used for flight trajectory simulations. For this purpose, theoretical trajectories of each recovered probe are simulated using theoretical mean ascent and descent speeds of 5 and 3.4 $m\,s^{-1}$ and (i) true horizontal wind speeds (as measured by the radiosonde during the flight), (ii) a wind profile measured by a UHF profiler at the launch site, and (iii) a model wind forecast valid at the launch site. The difference between the actual and anticipated fall points are shown in Fig. 7b. Using exact wind speeds leads to a mean error rate of ~ 6 %. This error rate increases to 20 % when using a UHF wind profile and up to 22 % when using a model forecast. The somewhat poor score obtained with the wind profiler data is a bit surprising, but is likely related to the poor accuracy

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of wind profiler measurement under light wind conditions such as those encountered during BLLAST. Clearly, the accuracy of the horizontal wind profile used to simulate the flight trajectory is a key factor to properly estimate the location of the landing point. The residual error of 6 % obtained with true horizontal wind values likely corresponds to the error arising from hypotheses made on mean vertical velocities.

4 Test of the system during HyMeX

4.1 The HyMeX field phase

During BLLAST, this system was tested in relatively ideal conditions: light wind, clear skies, and low release altitude, just to name a few. The HyMeX[1] research program provides another opportunity to evaluate the performance of this system in more complex, hostile meteorological situations. HyMeX aims at a better understanding and quantification of the hydrological cycle and related processes in the Mediterranean, with emphasis on high-impact weather events; inter-annual to decadal variability of the Mediterranean coupled system, and associated trends in the context of global change. In the frame of this project, a special observation period (SOP) was conducted in fall 2012 to collect detailed observations of the coupled ocean-atmosphere system in various places of the NW Mediterranean basin including Southern France, Italy and Spain.

4.2 Examples of dual-balloon soundings during HyMeX

About a dozen of dual-balloon soundings were performed in Southern France during the HyMeX field campaign. The objectives of these soundings were twofold: (i) evaluate the thermodynamical properties of the low-to-midlevel flow originating from the Mediterranean Sea before it reaches the Massif Central mountains, and (ii) evaluate the possible modification experienced by this oceanic air mass during its propagation

[1] More information about this program can be found at http://www.hymex.org.

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towards the higher terrain. To achieve those objectives, soundings were launched from the coastal town of Candillargues (Fig. 5) and the release pressure was setup so as to make the radiosonde fall as close as possible from the foothills of the Massif Central.

Figures 8 and 9 show vertical profiles of potential temperature and water vapour mixing ratio achieved from dual-balloon soundings performed on 17 and 21 October 2012, respectively. Three dimensional wind and reflectivity fields inferred from the analysis of multiple-Doppler radar data at times of soundings are also shown on each figure (the reader is referred to Bousquet and Tabary (2013) for details about the construction of these fields). On both days, a couple of soundings were launched from Candillargues at a three-hour interval. The separation was set to occur at 600 hPa and the ascent and descent speeds were set to 5 and 3.4 $m s^{-1}$, respectively. The points marking the locations of balloon separation and probe landing for each of the four flights are shown in Fig. 5. Note that the distance travelled by the probes during the ascending phase is approximately two times shorter than that flown during the descent phase, which is consistent with chosen ascent and descent rates of 5 and 3.4 $m s^{-1}$.

On 17 October, the soundings were performed at 09:00 and 12:00 UTC. The total distance travelled by the radiosonde was ∼ 34 km for the first sounding and ∼ 48 km for the second one (Fig. 5). Both probes landed in cultivated areas at an altitude of ∼ 100 m a.g.l. and were easily recovered the same day. The distances travelled by the two radiosondes during the ascent phase were comparable, but were quite different during the descent phase. This indicates that the vertical wind profile north of the balloon separation point experienced significant changes between the two launches. No precipitation was present along the coast at launching times, but weak orographic precipitation extending up to a height of 6 km could be observed over the terrain at both times (Fig. 8c, d).

The potential temperature at the coast increased from a couple of K within most of the measured layer (Fig. 8a) during the 3 h period separating the two launches. The mixing ratio remained comparable except between 1 and 2 km a.m.s.l., where it decreased from up to 3 $g kg^{-1}$ (Fig. 8b). The low level moisture was somewhat moderate

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with mixing ratio values of ~11 g kg^{-1}, which is consistent with the lack of heavy precipitation over the terrain. The thermodynamical properties of the incoming southerly flow measured farther inland at 09:00 and 12:00 UTC were similar to those observed at the coast at the same times. One can notice small temperature variations of up to 0.5 K at 09:00 and 12:00 UTC, as well as moderate moisture increase between 1 and 2 km a.m.s.l. at 09:00 UTC, but the airmass clearly did not experience significant modifications between the coast and the foothills of the Massif Central.

On 21 October, two new dual-balloon soundings were performed at 12:00 and 15:00 UTC. The radar observations indicate the presence of convective precipitation over the terrain (Fig. 9c, d). The two radiosondes landed in the same area after a flight of ~35 km (Fig. 5). The proximity of the two landing points indicates that the wind profile over the area was quite uniform within the 3 h period separating the two launches. Also note that the actual landing point of the radiosonde launched at 15:00 UTC is actually very close from the one simulated before using the sounding from a Arome forecast (red trajectory).

The potential temperature profiles measured near the coast at 12:00 and 15:00 UTC (Fig. 9a) were extremely similar and did not evolve significantly during this period. Mixing ratio profiles (Fig. 9b) however indicate significant fluctuations of the moisture content within the boundary layer. Mixing ratio values increased from ~2 g kg^{-1} in 3 h close to the surface, but decreased significantly between 500 m and 2500 m a.m.s.l. Also notice that the moisture at low levels was more abundant than on 17 October (Fig. 8b), which may explain the more convective nature of precipitation over the terrain (Fig. 9c, d). Changes that occurred in theta and mixing ratio profiles between the coast and the foothills of the terrain also show contrasting behaviour. The vertical structure of the mixing ratio is almost identical at both times, except around 1 km a.m.s.l. where one can notice a slight increase of the moisture content. The temperature profile, on the other hand, decreases significantly within the boundary layer (with variations of up to 3 K at 15:00 UTC), which suggest that the low level flow experienced important modifications while propagating towards the higher terrain.

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In addition to performing conventional temperature and humidity measurements, the dual-balloon system was also used to test a prototype of a new probe called Light Optical Aerosol Counter (LOAC). LOAC is a new generation of aerosol counter, which is developed in cooperation between the company MeteoModem and several French scientific laboratories. It consists in a small optical particle counter/sizer of ∼250 g that performs measurements at scattering angles of 12° and 60°. It is used to determine the aerosol particle concentrations in 20 size classes within a diameter range of 0.3–100 µm. The ratio of the measurements at the two angles is used to discriminate between the different types of aerosol particles in the different size classes (i.e. wet and liquid particles, soil dust and soot). LOAC is designed to be deployed under all kind of atmospheric balloons. A prototype, especially developed for free balloon deployment, was tested for the first time during HyMeX.

A test flight was conducted from Candillargues, on 23 September 2012 between 09:00 and 09:45 UTC under clear sky conditions. The goal was to evaluate the performance of this new sensor against backscattering lidar measurements collected at the same location during the HyMeX field phase. The possibility to recover the instrumentation was an important consideration since this prototype of LOAC was unique and quite expensive. The balloon release pressure was set to 500 HPa and light winds were present within the entire troposphere. The prototype sensor was recovered in good conditions about 20 km away from the launching point.

Example of aerosol measurements performed during the ascending and descending phases are shown in Fig. 10. The most interesting feature is an aerosol enhancement detected above 3 km during ascent and above 2.5 km during descent. LOAC indicates that such aerosols are solid, which suggests remnants of a Saharan sand transport episode that was detected above southern France during this period. It can also be noticed that the small haze layer observed around 1 km during ascent is not present during the descent, few tens of km away.

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5 Conclusions and perspectives

A new system for high frequency atmospheric profiling based upon radiosondes and free balloons was tested during the field phases of the Boundary Layer Late Afternoon and Sunset Turbulence (BLLAST 2011, Lannemezan, France) and of the Hydrological cycle in the Mediterranean Experiment (HyMeX, 2012). The standard system consists of a conventional Vaisala receiver and a GPS radiosonde (pressure, wind, humidity and temperature) that is tied to a couple of inflated balloons. The principle of the sounding system is to permit the first balloon to detach from the rawinsonde at a predetermined altitude, allowing the rawinsonde to slowly descend with the second balloon so as to perform a second, new sounding. The instrumentation is then eventually recovered. The expecting landing area is anticipated before the flight by estimating the trajectory of the probe using a forecasted or observed wind profile and by specifying both the balloon release altitude and the expected mean ascent and descent rates of the system. The real landing point is determined by the last transmission of the radiosonde GPS and the visual landmark provided by the second balloon. Around 60 soundings were performed in light wind conditions during the BLLAST field phase. The radiosonde recovery rate attained more than 80 % and the release mechanism performed well in about 84 % of the time. Recovered radiosondes were generally reused several times, often immediately after recovery. A total of 104 vertical profiles were obtained by using only 9 radiosondes, which demonstrates the high potential of this system. A posteriori experiments conducted after the BLLAST reveal that a proper estimation of the horizontal wind profile is key in order to accurately assess the landing location of the probe. The accuracy of the vertical speed used to simulate the trajectory of the probe was found to have a more limited impact with an error of approximately 6 % that corresponds to the fluctuation of the vertical speed with height.

Additional tests were also performed under more severe weather conditions during the field phase of the HyMeX project. In particular, the dual-balloon system was used to describe the modifications possibly experienced by an air mass propagating from

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the Mediterranean coast towards the foothills of the Massif Central Mountains, located about 40 km northwards. The analysis of the soundings performed on 17 and 21 October show that this system can be easily set up to sample precise areas and monitor the space and/or time variability of given atmospheric parameters. The system was also used to test and recover the prototype of a new aerosol counter designed to be used under free balloons. Overall, soundings performed during HyMeX have demonstrated the good reliability of the system in all-weather situations as well as its value in order to retrieve expensive probes or prototype sensors.

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Table 1. Sounding statistics during BLLAST.

Probes available	20	
Launches	62	
Spotted probes	53	(85%)
Recovered probes	49	(79%)
Unrecovered probes[a]		(06%)
Lost probe		(15%)
Re-used probes	49	(79%)
True release	46	(74%)
Faulty release[b]		(10%)
No release	10	(16%)

[a] Probes visually identified but unrecoverable (trees, roofs, . . .).
[b] Release at a wrong pressure/height.

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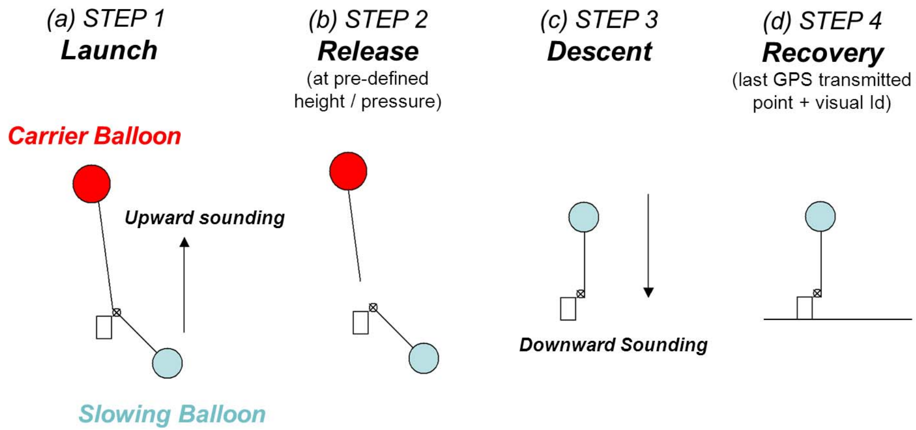

Fig. 1. Principle of the dual-balloon sounding.

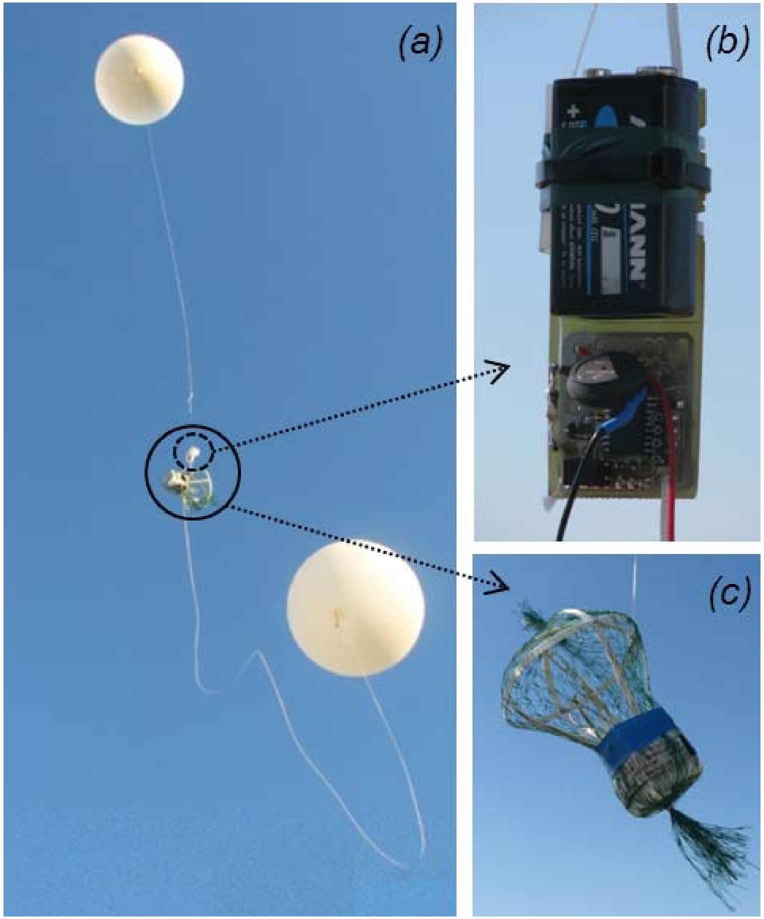

Fig. 2. Overview of the dual-balloon sounding system: **(a)** complete system, **(b)** separation device and **(c)** radiosonde protection system.

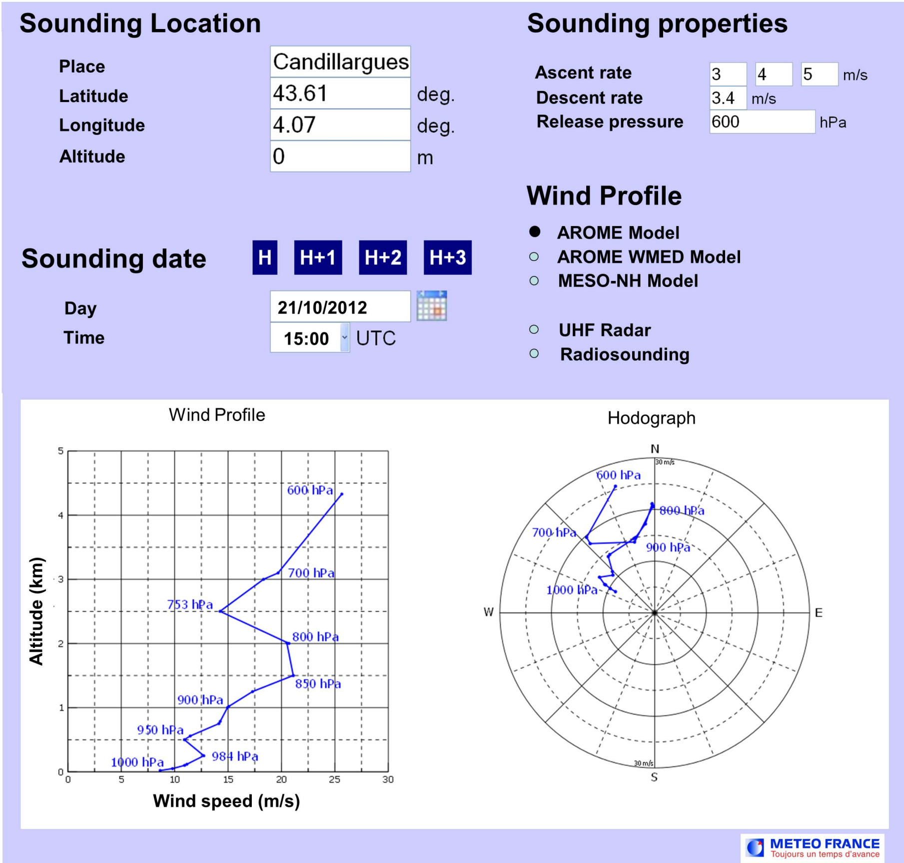

Fig. 3. Interface of the flight simulation software. Displayed wind data are used to simulate the flight trajectories shown in Fig. 5.

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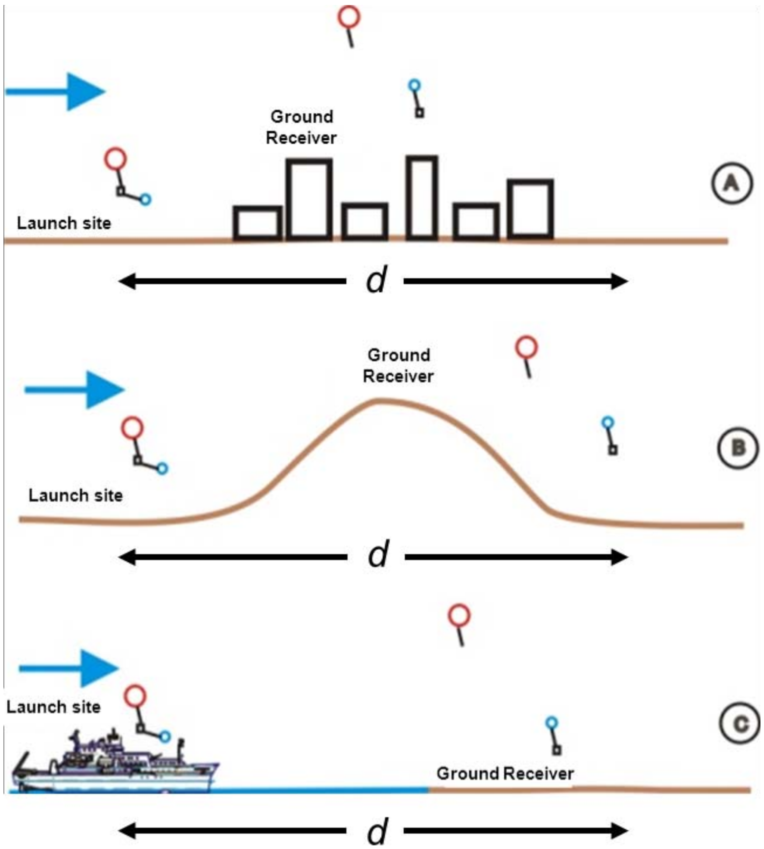

Fig. 4. Example of applications of the dual-balloon sounding system: **(a)** modification of boundary layer properties by a surface transition, **(b)** measurement on each side of a mountain, **(c)** observation of coastal breezes. Distance *d* indicates the distance that must be travelled by the radiosonde in order to achieve the objective.

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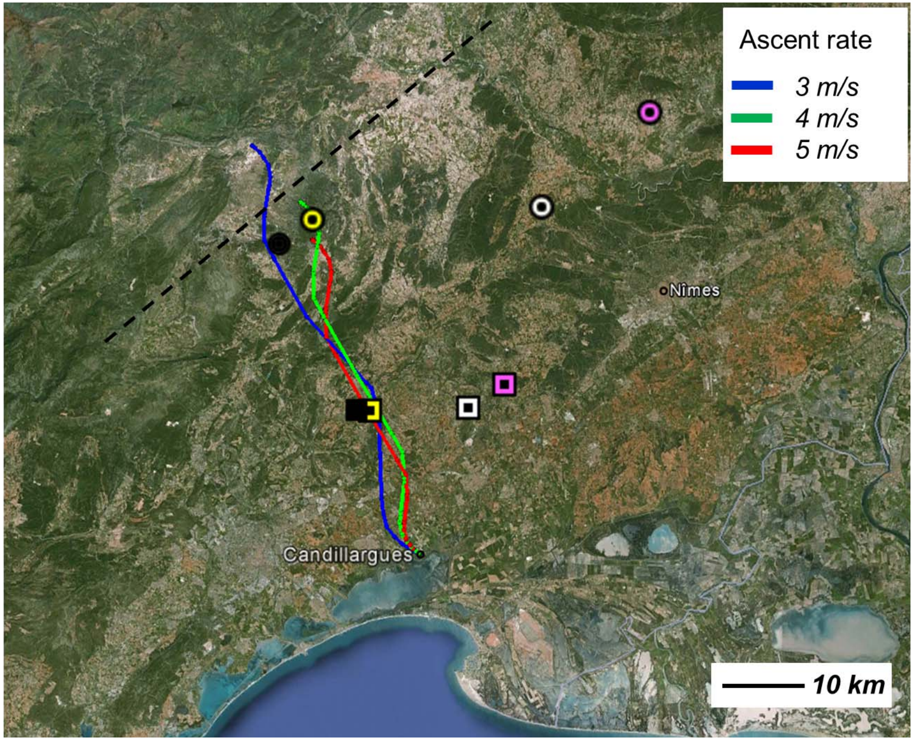

Fig. 5. Flight trajectory simulations valid 21 October 2012 at 15:00 UTC, according to the wind profile and sounding settings displayed in Fig. 3. The launch site is located in Candillargues, along the Mediterranean coast. Blue, green and red trajectories correspond to a mean ascent rate of 3, 4, and 5 $\mathrm{m\,s^{-1}}$, respectively. The circles (resp. squares) indicate the actual landing points (resp. separation point) of radiosondes launched on 17 October 2012 at 9:03 (white) and 11:55 UTC (pink), and 21 October 2012 at 10:50 (black) and 14:50 UTC (yellow). The foothills of the Massif Central Mountains are shown by the dashed black line.

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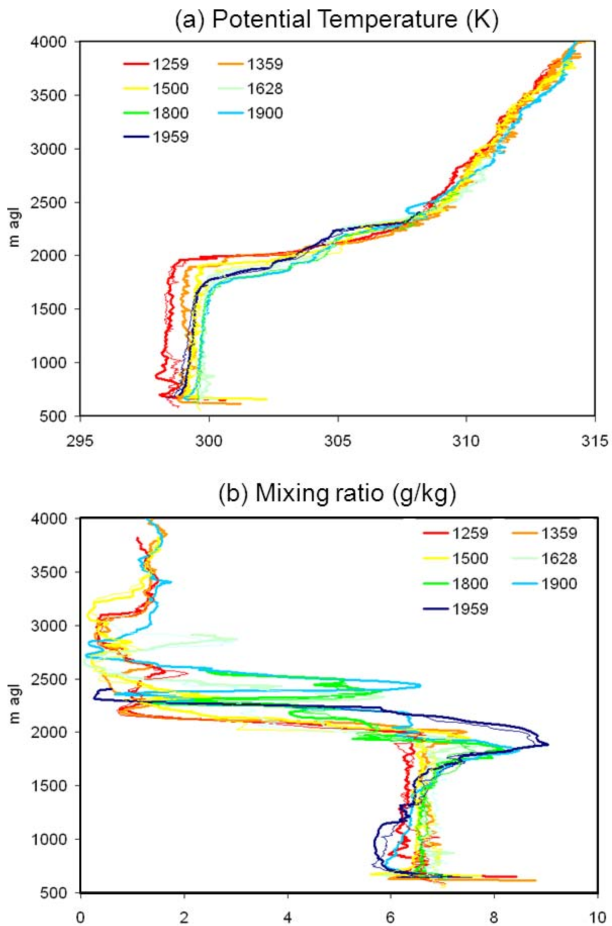

Fig. 6. Time series of hourly soundings performed on 1 July 2011 between 13:00 and 20:00 UTC. **(a)** Potential temperature (° K) and **(b)** water vapour mixing ratio ($g\,kg^{-1}$). Bold and thin lines correspond to ascending and descending soundings, respectively.

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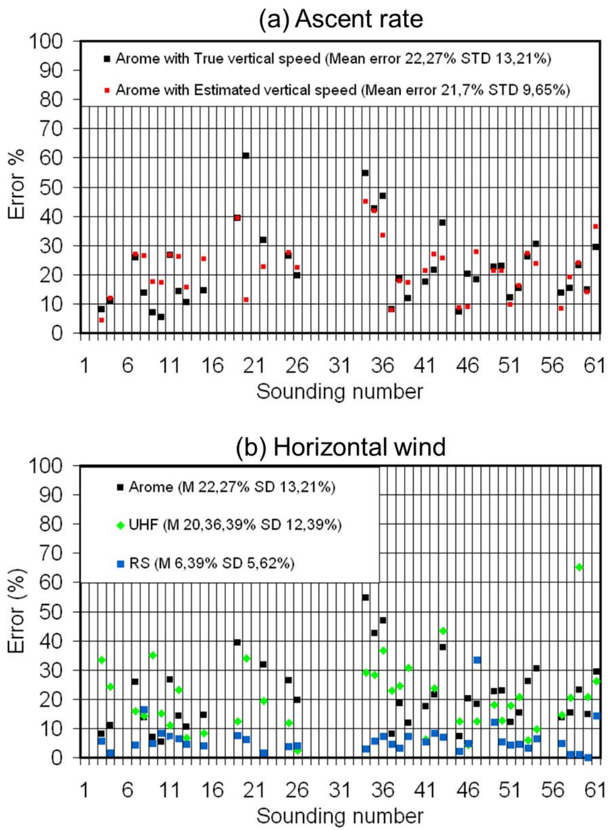

Fig. 7. Difference between actual and simulated radiosonde falling points as a function of **(a)** ascent rates and **(b)** horizontal wind profiles used to simulate flight trajectories. Scores are computed for recovered balloons only.

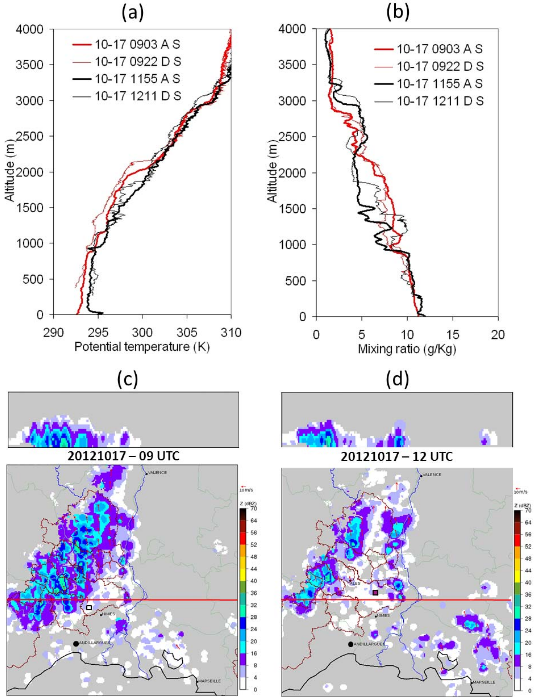

Fig. 8. Thermodynamical and precipitation data valid on 17 October 2012. Top panel: vertical profile of **(a)** potential temperature and **(b)** water vapor mixing ratio, derived from dual-balloon soundings at 09:00 (red) and 12:00 UTC (black). Thin (resp. bold) lines correspond to ascending (resp. descending) soundings. The locations of balloon separation (beginning of the downward sounding) are shown in Fig. 5. Bottom panel: Horizontal (1 km MSL) and vertical cross sections of radar reflectivity (dBZ, scale at lower right) over a domain of 200 km × 200 km (horizontal) × 12 km (vertical) centered on Nimes, valid at **(c)** 09:00 and **(d)** 12:00 UTC. The location of the cross-section is indicated by the red line. White and red squares in **(c, d)** show the landing point of corresponding radiosoundings. Red vectors show the direction of the wind derived from multiple-Doppler analysis of radar data.

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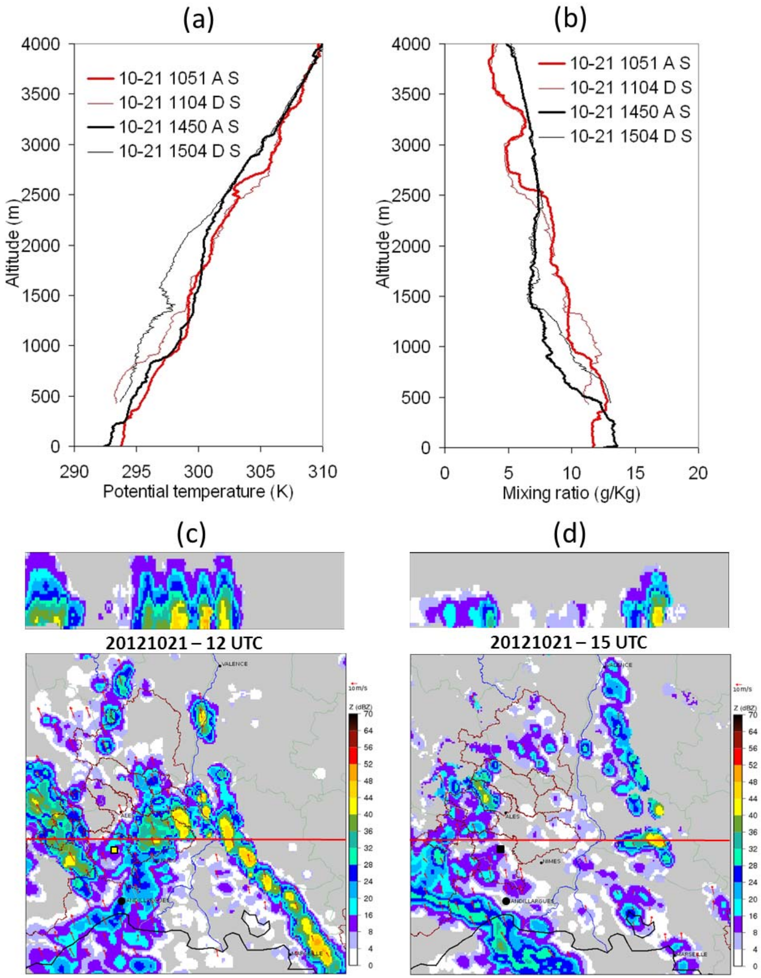

Fig. 9. As in Fig. 8, but for the 21 October 2012 at 12:00 and 15:00 UTC.

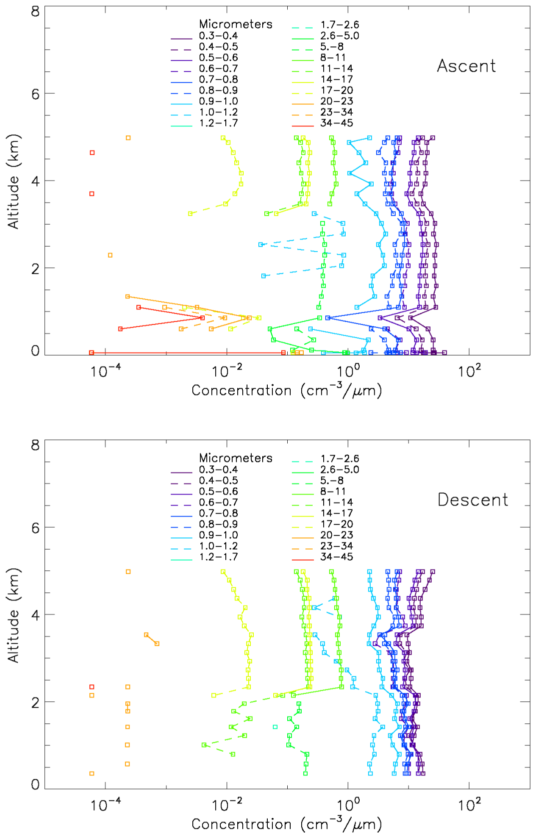

Fig. 10. Vertical profiles of aerosol concentration as a function of particle size inferred from the LOAC probe between 09:00 and 09:45 UTC on 23 September 2012. Upper (resp. bottom) panel show data collected during the ascending (resp. descending) phase of the sounding.

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