Disposable radiosondes for tracking Lagrangian fluctuations inside warm clouds

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Abstract – **Clouds are a weak link in modelling atmospheric circulation as they depend on interdisciplinary processes ranging from collisions of micron-sized droplets and particles to airflow dynamics on the kilometre scale. The uncertainty in cloud representation and hence climate modelling and weather prediction justifies the need for more explorative observations. A new way of tracking Lagrangian fluctuations inside warm clouds has been proposed as part of the Horizon 2020 Innovative Training Network ClOud-MicroPhysics-turbuLEnce-TElemetry project. Part of the project aims to design a new kind of ultralight radio probe capable of floating in stratocumuli clouds. The probes presented in this paper will be environmentally friendly and will allow the generation of a Lagrangian database for small-scale fluctuations inside warm clouds.**

1 INTRODUCTION

Atmospheric circulation is driven by the interaction of ‘warm’ clouds and raindrops with incoming radiation. [1] Warm clouds have a cloud top that is below freezing point and are responsible for approximately 31% of the total amount of rain on the planet. [2] Consequently, they play a key role in climate change and climate sensitivity as small changes in droplet population can significantly affect the cloud albedo and therefore the formation of precipitation. Hence, the correct representation of cloud microphysics and the assessment of the role of turbulence in cloud formation is imperative.

Clouds are a multi-scale natural phenomena and one of the largest sources of uncertainty in weather prediction and climate modelling. This is rooted in their dependence on a wide range of physical and chemical processes. The main challenge is to establish a connection across this range of scales from aerosol and particle microphysics to macro-scale turbulent dynamics in clouds. However, there is limited knowledge on the in-cloud turbulence and the consequences of spatial distribution of turbulence on humidity, mixing and temperature transport in clouds. This is in part due to the uncertainties in the droplet nucleation and growth in warm turbulent clouds emphasized by the difficulty in measuring clouds at small scales. [3] In addition, turbulence experimentation relies on estimated averages of statistical moments that is rendered difficult in cloud environments where the boundary conditions are continuously evolving.

As part of the Horizon 2020 Innovative Training Network Cloud-MicroPhysics-Turbulence-Telemetry (ITN-COMPLETE) project, a new kind of ultralight radio probe with a possibility of embedding processors, capable of floating in stratocumuli clouds is being developed. The project aims to characterize direct interactions between cloud dynamics, thermodynamics and microphysics as well as develop new telemetry methods for in-situ measurements of aerosol concentrations and turbulence. In addition, Direct Numerical Simulation (DNS) models as well as in-field and laboratory experiments will be used to improve the cloud interfaces to better predict mixing efficiency, temperature inversion, clear air entrainment and moist air detrainment. The probes conceived within the context of the COMPLETE project will provide an insight into Lagrangian fluctuations inside warm clouds over land and alpine environments.

2 RADIOSONDES

There are many high-performance satellites in orbit providing a global view of the Earth’s atmosphere [4]. However, in part due to atmospheric attenuation and clouds, chemical species and meteorological parameters below 16-18 km altitude cannot be easily observed by these satellites. This altitude range is very important as human impact on the atmosphere is greatest in the troposphere (8-15 km) and ozone depletion is carried out in the lowermost stratosphere, which expands up to 50-60 km [4]. Additionally, with a limited lifetime, satellites do not allow long-term monitoring of the atmosphere composition (except ozone) which is key in understanding the relation between cloud chemistry and climate. Moreover, several chemical species could not be derived from satellite remote sensing techniques as their vertical resolution is limited to 1-2 km.

Common operational methods for obtaining in situ information on natural phenomena such as rain, hail or hurricanes are based on drop sondes or manned and unmanned aircraft flights [5] [6]. These perform direct monitoring operations of atmospheric parameters during strong winds or precipitation. Typically, these are designed to match a maximum of the fluid-

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dynamic properties of the observed precipitation. They acquire and send data to a receiver located on the ground as they are falling [5] [6]. However, these can be expensive and the time in which they are able to sample the atmospheric parameters is of very limited duration.

2.1 Balloons and Lagrangian experiments

Contrastingly, balloons provide opportunities for measurements using a variety of in-situ and remote sensors up to about 40 km in altitude. They are relatively low cost and flights can be performed within fast time frames, allowing the possibility to conduct multiple repeated experiments as well as quick experiments on a new idea or concept. They provide insight into numerous complex processes within the atmosphere allowing for more accurate numerical models to be constructed. Furthermore, with the addition of GPS receivers and satellite cellular communication, real-time measurements of low-altitude air masses can be taken around the world.

Langrangian measurements are the most adequate for studying clouds: in principle, they consider a frame that moves with air. Lagrangian experiments offer several advantages over Eulerian studies where measurements are performed on a fixed site. Firstly, the lateral flow in and out of the volume is negligible in comparison with a Eulerian volume as the mean wind in the Lagrangian frame of reference is approximately zero [8]. This allows the consideration of an isolated air parcel if it is required. Additionally, and perhaps more importantly in this context, the size of the Lagrangian volume is small compared to its trajectory length. Consequently, researchers can direct their resources to the volume and obtain more data on the behaviour of a species within it rather than on the entire region of potential interest [9]. Finally, Lagrangian experiments allow for an easier comparison of experimental data with Lagrangian models, which are of particular importance within the COMPLETE project.

3 DESIGN PRINCIPLES

The low cost and light mini radio-sondes contain microprocessors and both solid-state analogue and digital sensors for the measurement of different physical quantities, for instance, velocity, acceleration, vorticity, pressure, temperature and humidity fluctuations. They are initially designed to float on an isopycnic level within clouds requiring them to be 20 times lighter than the National Center for Atmospheric Research (NCAR) drop-sondes and 100 times lighter than the National Oceanic and Atmospheric Administration (NOAA) smart balloons [8]. A feasibility study has been carried out using an in-house state of the art mini electronic board designed for remote sensing applications in an environmental context [5].

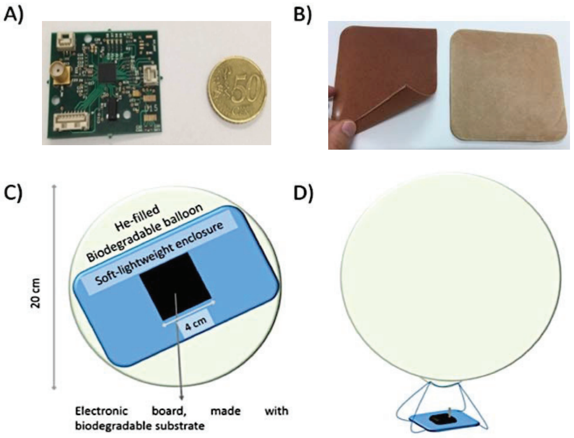

Figure 1. A) Early prototype electronic board [10] [11] B) (Left) Red beetroot bio-elastomer and (right) red beetroot and starch compound. C) Ultra-lightweight model for probe design in which the electronics is placed into the gas-inflated balloon. D) Alternative probe design where the electronics hang outside.

3.1 Weight optimization and requirements

The total target weight of the probes is around 15 g depending on the sensors included. This proceeds from preliminary work where it was determined that without weight optimisation, the mini board weighs 6.2 g and is smaller than 4 × 4 cm (Figure 1A). More information on these probes designed to mirror rain can be found in [5].

Atmospheric data (with γ= 6.5 K/km)					Balloon Dimensions	
Z [m]	T [K]	P $\times 10^4$ [Pa]	ρ [kg/m^3]	μ $\times 10^{-5}$ [kg/ms]	V [m^3]	R [cm]
0	288	10.0	1.22	1.79	0.010	13.5
500	285	9.5	1.17	1.78	0.011	13.8
750	283	9.3	1.13	1.77	0.011	13.9
1000	282	9.0	1.11	1.76	0.011	14.0
1250	280	8.7	1.08	1.75	0.012	14.1
1500	278	8.5	1.06	1.74	0.012	14.2
2000	275	7.9	1.01	1.73	0.013	14.5
3000	269	7.0	0.90	1.70	0.014	15.0

Table 1: Balloon dimensions at altitude Z in the atmosphere. The temperature T, pressure P, density ρ and the viscosity μ at a given altitude are reported.

The hydrophobic balloon must contain a printed circuit board (PCB), an almost omnidirectional antenna for data transmission to the receiver, a battery, a low consumption microcontroller, a flash memory and a configurable set of sensors (e.g. temperature, humidity, pressure, triaxial accelerometer) depending on the variables to be investigated. The balloon is filled with a gas (e.g. Helium) to obtain a buoyancy force equal to the weight of the system. The pressure is adjusted to be slightly lower or equal to the atmospheric pressure corresponding to the altitude at which the balloon will be released (Figure 1C and 1D). The relative volume and consequently radii of the balloon at various altitudes within the atmosphere are reported in table 1. The values are calculated assuming a constant lapse rate γ equal to 6.5 K/km which corresponds to the rate at which the atmospheric temperature decreases with increasing altitude.

3.2 Sensors

There are two basic configurations that can be developed; a simpler one containing basic features and a more complex configuration which includes different sets of sensors to facilitate the extraction of the probe trajectory. The former arrangement includes a common CR2354 battery, a frequency generator, a frequency stabilizer circuit and a PCB. In the second case, optional sensors such as a triaxial accelerometer to monitor speed and directional changes can be added. Additionally, temperature, humidity and pressure sensors are envisaged and in some cases, it can be thought to include a GPS receiver to correctly ascertain the balloon's position. However, the inclusion of a GPS receiver would result in a heavier probe. Initially, both configurations have a target weight of approximately 15 g or less with the goal of decreasing it with the optimization of various components. Furthermore, a special version of the probes will be equipped with small size Differential Optical Absorption Spectroscopy (DOAS) or with optical/infrared scatterometers to measure the fluctuation of the organic aerosol concentration.

The autonomy of the probes is aimed to be around 24 hours in the minimal configuration. The flash memory allows the measured data to be temporarily stored before being transmitted to the receiver in short bursts, minimizing the power consumption of the probe [5] [7]. The probes send radio signals using the frequency bands around 350 MHz or 169 MHz to a data acquiring system on Earth and they can be monitored over time as they float through the warm clouds. This assures a good propagation link in the atmosphere and a low attenuation as well as allows the probe to transmit at a lower power.

For the first prototype, the PCB of both configurations can be realised with a 0.3 mm thick FR4 material and the balloon will be made of latex. Furthermore, the antenna will be designed with an irradiation diagram that will be as omnidirectional as possible. The sampling period of temperature, pressure and humidity will de $TS_{sensors} = 2$ s as $\gamma = 0.0065$ K/m. [12] On the other hand, to accurately extract the probe trajectory, an initial sampling period, for the triaxial accelerometer of $TS_{accelerometer} = 0.1$ s is chosen. The receiver (not described in this work) is required to be able to receive signals up to a distance $r = 20000$ m and have a sensitivity of approximately $P_{RX} = -130$ dBm. Each probe must transmits a minimum power of $P_{TXprobe} = -30$ dBm if sufficient high gain antennas (at least G=30 dB) are used at the receiver. The most critical value is $P_{TXprobe}$ as the probe is powered by a battery of limited lifetime. Hence, it is essential to maintain the probe power consumption as low as possible. Low power consumption techniques will be adopted to keep sensors in sleep mode when possible. The microcontroller activates them only when they must perform a measurement or when the transmission system is required to transmit data to the ground receiver.

3.3 Smart materials

Ultimately, the goal is to design disposable probes that need to be biodegradable to minimise their environmental impact. Hence, it is foreseen to use MaterBi and a biodegradable bioelastomer substrate for the balloon and electronics (Figure 1B). The bioplastics are envisaged to be made of vegetable waste such as the red beetroot powder incorporated into starch-based bio-elastomers as described in [13]. These hydrophobic, biodegradable bio-elastomers resist disintegration upon immersion in water despite them containing about 70% starch granules in weight. Pristine starch is known to be brittle, have poor waterproof properties, low tensile strain and low thermal stability. These properties can be modified by mixing synthetic or natural polymers during the synthesis. [13] However, the feasibility of red beetroot powder as a substitute for the synthetic polymers was originally considered as part of a project for food packaging. This was based on previous work where corn starch granules (up to 80%) were mixed into polydimethylsiloxane (PDMS) matrices, which showed excellent mechanical stress relaxation and energy dissipation properties [14]. The addition of red beetroot powder to the bio-elastomer polymer matrix increased the Young's Modulus of the substance while maintaining the original elongation properties. Additionally, bioplastics are lightweight and have relatively low conductivity, which make them ideal candidates to replace the substrate onto which the circuit is printed.

Furthermore, biomass is rich with cellulose, the most abundant renewable polymer in nature. Cellulose is ideal for the formation of strong fibers as it is a crystalline, straight-chained polymer. A method whereby a solution of trifluoroactic acid (TFA) is used to cosolubilize cellulose from edible vegetable residues with other contained organic matter has been developed in the Italian Institute of Technology (IIT) in Genova. [15] This method allows the generation of cellulose-based bioplastics from vegetable and cereal waste with diverse bio-origins without the need for cellulose regeneration. The main drawback of these materials, particularly in this context, is their low hydrophobicity. However, it has been found that certain waxes, such as carnauba wax can significantly improve the hydrophobicity of bioplastics and hence their use could be envisaged for the radio-sondes [16].

4 CONCLUSIONS

In this paper, we have introduced innovative, light, bio-compatible radio-probes to be released in warm clouds. The required sensors and initial configuration of the circuits has been presented with a focus on the transmission of data from the probe to the receiver. Nevertheless, the receivers on Earth, not mentioned in this paper, will equally be optimized and tailored to the experiments. Additionally, the progressive replacement of components with biodegradable counterparts is envisaged.

The advanced spectral and statistical data acquired with the probes, will be analyzed and compared to numerical simulations. The aim is to generate a Lagrangian database of different physical quantities, velocity and acceleration fluctuations inside warm clouds over land and alpine environment. These will contribute to shaping the current understanding of microphysical processes in clouds allowing for more accurate models to be developed for weather prediction and climate modelling.

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