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Biogenic Aerosol - Effect on Clouds and Climate (BAECC-ERI): Extended Radiosonde Intensive Operational Period Final Campaign Summary

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ARM
CLIMATE RESEARCH FACILITY

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Executive Summary

Large-scale properties of clouds such as lifetime, optical thickness, and precipitation are all dependent on small-scale cloud microphysical processes. Such processes determine when droplets will grow or shrink, their size, and the number of cloud droplets. Although our understanding of cloud microphysics has vastly improved over the past several decades with the development of remote sensing methods such as lidar and radar, there remain a number of processes that are not well understood, such as the effect of electrical charge on cloud microphysics. To understand the various processes and feedback mechanisms, high-vertical–resolution observations are required. Radiosondes provide an ideal platform for providing routine vertical profiles of in situ measurements at any location (with a vertical resolution of a few meters). Modified meteorological radiosondes have been extensively developed at the University of Reading for measuring cloud properties, to allow measurements beyond the traditional thermodynamic quantities (pressure, temperature and relative humidity) to be obtained cost-effectively. This project aims to investigate a number of cloud processes in which in situ cloud observations from these modified radiosondes can provide information either complementary to or not obtainable by lidar/radar systems.

During two intensive operational periods (IOPs) in May and August 2014 during deployment to Hyytiälä, Finland, the Atmospheric Radiation Measurement (ARM) Climate Research Facility's Second ARM Mobile Facility (AMF2) launched a total of 24 instrumented radiosondes through a number of different cloud types ranging from low-level stratiform cloud to cumulonimbus. Twelve balloon flights of an accelerometer turbulence sensor were made, which detected significant turbulence on eleven of these flights. Most of the turbulent episodes encountered were due to convective processes, but several were associated with the transition from troposphere to stratosphere at the tropopause. Similarities in the location of turbulent layers were generally found between the balloon turbulence sensor and the Ka-band radar, but with discrepancies between the orders of magnitude of turbulence detected. The reason for these discrepancies is the subject of future work.

In addition to turbulence measurements, a series of balloon flights were made with an optical cloud droplet sensor and electrical charge sensor, to investigate charging of cloud droplets in layer clouds, as well as to detect any cloud layers that may be missed by the remote sensing methods. It was found that all clouds sampled were electrically charged, typically with charge present at the upper and lower cloud boundaries, with magnitude up to 150 pCm^{-3}. The effect of such charge on cloud microphysical processes is the subject of ongoing work and requires a combination of both modelling and further observations.

Comparison between radar reflectivity and visibility measurements from the balloon-carried optical cloud sensor demonstrated that, in particular, thin clouds can be missed by remote sensing methods such as radar. This project has demonstrated that instrumenting standard meteorological radiosondes with additional science sensors can provide a wealth of extra in situ data, which is both cost-effective and easy to achieve. By using a combination of different balloon sensors to study clouds, high-resolution information about a variety of cloud properties that are difficult to achieve by other methods can routinely be obtained.

Acronyms and Abbreviations

AMF2	Second ARM Mobile Facility
ARM	Atmospheric Radiation Measurement
BAECC-ERI	Biogenic Aerosol - Effect on Clouds and Climate - Extended Radiosonde IOP
CCN	cloud condensation nuclei
EDR	eddy dissipation rate
IOP	intensive operational period
KAZR	Ka-band Doppler zenith radar

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1.0 Background

The optical properties of liquid cloud layers are primarily dependent on their microphyiscal properties (i.e. the droplet size distribution), which is typically described in terms of number concentration and effective radius. Aerosol particles play a major role in the processes that govern the initial generation of cloud droplets at cloud base through the activation of cloud condensation nuclei (CCN) in updrafts. The vertical profile of liquid microphysical properties involves additional processes, including mixing with dry air and, potentially, precipitation processes. The effect of electrical charge on cloud microphysical processes, about which very little is known, is a particularly understudied topic. To understand the various processes and feedback mechanisms in clouds, high-vertical-resolution observations are required. Radiosondes provide an ideal platform for providing routine vertical profiles of in situ measurements at any location (with a vertical resolution of a few meters). Modified meteorological radiosondes have been developed extensively at the University of Reading for measuring cloud properties, to allow measurements beyond the traditional thermodynamic quantities (pressure, temperature and relative humidity) to be obtained cost-effectively. Sensors developed at Reading include an active cloud droplet detector (Harrison and Nicoll 2014), solar radiation sensor (Nicoll and Harrison 2012), electrical cloud charge detector (Nicoll 2013), and turbulence sensor (Marlton et al. 2014). Evaluation of these new balloon-borne sensors is required, which can be provided by active remote-sensing in the form of radar and lidar.

The aim of this project was to investigate a number of cloud processes in which in situ cloud observations from radiosondes can provide information either complementary to or not obtainable by lidar/radar systems. These include

1. investigation of electrical charging of cloud droplets in stratiform clouds (using a charge sensor, active cloud droplet sensor, and solar radiation sensor)
2. detection of cloud layers missed by lidar/radar (using the active cloud droplet sensor, solar radiation sensor, and charge sensor)
3. characterization of in-cloud turbulence (using an accelerometer turbulence sensor and solar radiation sensor).

The site chosen for the project was the Atmospheric Radiation Measurement (ARM) Climate Research Facility's Second ARM Mobile Facility (AMF2) during its deployment to Hyytiälä, Finland, as part of the BAECC campaign. This provided an unprecedented opportunity for remote sensing of clouds at multiple radar and multiple lidar wavelengths, as well as the provision of a radiosonde launching system to allow the special balloon sensors to be flown. Two intensive operational periods (IOPs) were carried out at Hyytiälä during which the radiosonde/remote sensing measurements of cloud were made. The first of these IOPs took place from 25 to 30 May 2014, the second from 8 to 15 August 2014. Radiosonde flights were made using the AMF2 operated ground station and Digicora software.

2.0 Notable Events or Highlights

A number of convective storms occurred during the second IOP, presenting an unprecedented opportunity for the first balloon flight of the turbulence sensor through a thunderstorm. Two successful launches were made into the leading edge of a cumulonimbus cloud, with significant turbulence measured throughout the depth of the cloud layer on both flights. This provided the first test of the turbulence sensor in extreme conditions and demonstrates its use for future in situ measurements of thunderstorm turbulence.

3.0 Lessons Learned

Overall both IOPs were very successful, with few problems encountered. All 24 instrumented balloons were launched successfully; however, it was noted that premature dropout of sonde data did occur on some flights. This was attributed to the heavily forested location of the field site, which can interfere with the sonde radio signal if the trees block the line of sight. In addition, an issue with two of the charge sensors was noted before launch, but has since been fixed (by a modification to the electronic circuitry). During the second IOP, there were also issues with the ARM wind profiler, which was to be used for turbulence sensor calibration measurements, but unfortunately had malfunctioned and could not be repaired in time. Although this was a slight blow for the campaign, the number of additional objectives to be achieved meant that it was not detrimental to the rest of the science.

4.0 Results

(a) Turbulence sensor measurements

Twelve turbulence sensor balloon flights were made during the second IOP in August 2014. Significant turbulence was observed on eleven of these flights, with Convective Available Potential Energy values for the majority of these flights reaching 500-1000 J kg^{-1} which is considered ample for light-to-moderate convection (Wallace and Hobbs 2006). Most of the turbulent episodes encountered were due to convective processes, but several were associated with the transition from troposphere to stratosphere at the tropopause. As part of the ARM Mobile Facility, a 35-GHz, zenith–pointing, Ka-band Doppler radar was deployed at Hyytiälä, providing a remote sensing method of turbulence detection through vertical Doppler velocity measurements. Such measurements allow the eddy dissipation rate (EDR) (a commonly used turbulence parameter) to be derived from the radar measurements (Bouniol et al. 2003). The following section presents results from a balloon ascent through a non-precipitating ice cloud on 9 August at 7:45 UTC.

Figure 1 shows the radar reflectivity image centered on the half-hour around launch time (7:45 UTC) on 9 August 2014, demonstrating the presence of a substantial, non-precipitating ice cloud layer between 5 km and 10 km. Figure 2 presents vertical profiles made by the balloon-borne sensors. The relative humidity trace shown in Figure 2(a) demonstrates the similarity between the cloud measurements from the sonde and radar data in Figure 1. Acceleration measured by the turbulence sensor is shown in Figure 3(b), where it is seen that as the sonde enters the base of the cloud at 5 km, significant accelerations (up to 4 G) are detected, and are also present at the cloud top. The EDR from the sonde (Figure 2(d)) was calculated from the standard deviation of the accelerometer data, over a 200-m height window, using a calibration from a boundary layer lidar (Marlton et al. 2014). Any standard deviations of less than 3 m s^{-2} are omitted, as these are thought to constitute the background-noise level in the accelerometer measurements due to normal swing of the balloon.

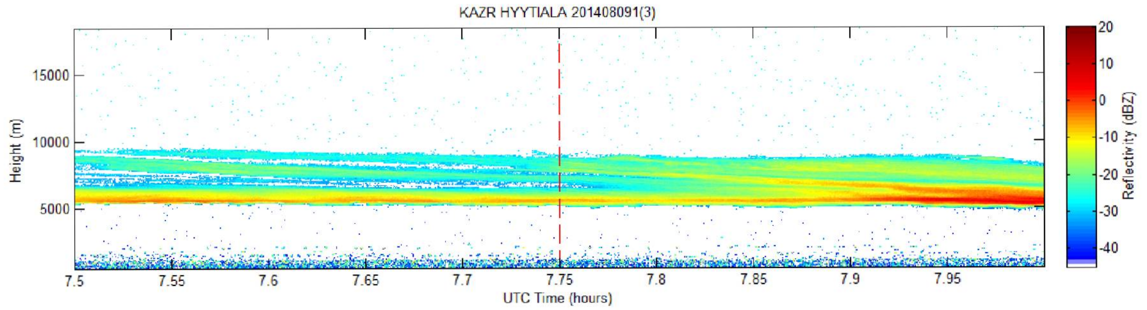

Figure 1. Radar Reflectivity from 35-GHz, Ka-band, zenith-pointing Doppler radar centered around radiosonde launch time at 0745 UTC (red dotted line) on 9 August 2014 at Hyytiälä, Finland

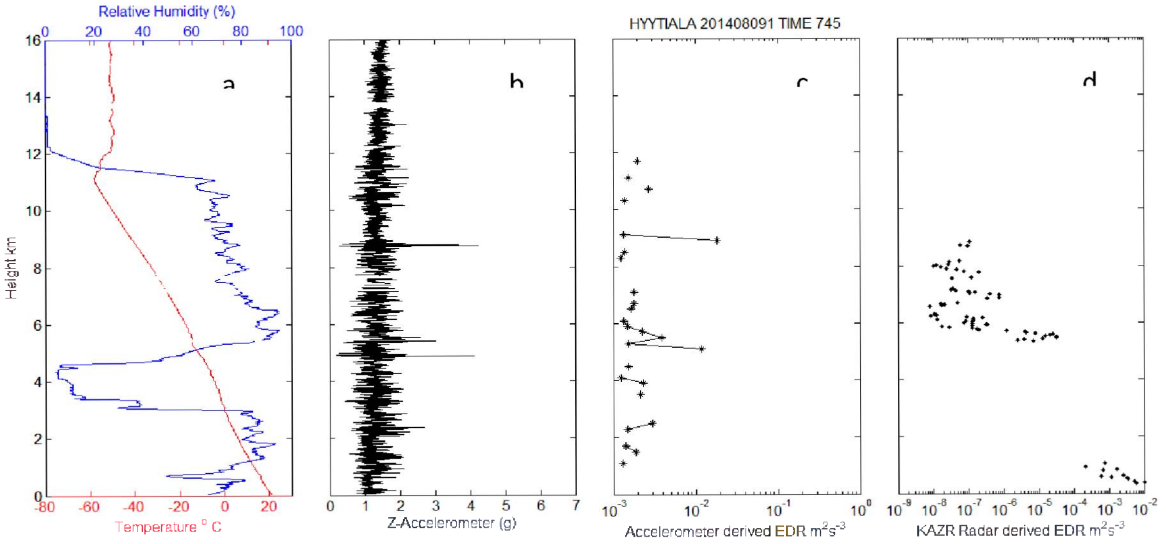

Figure 2. Vertical profile from a specially instrumented RS92 radiosonde launched at 0745 UTC from Hyytiälä on 9 August 2014. (a) temperature (red) and relative humidity (blue), (b)vertical profile of acceleration in the z-component of the accelerometer (vertically orientated) where G = 9.81 m s^{-2}, (c) EDR derived from the balloon accelerometer, (d) EDR derived from the Ka-band Doppler zenith radar (KAZR).

At both the base and top of the ice cloud, the accelerometer EDR increases to 10^{-2} m^2s^{-3}, denoting light turbulence. For the same cloud region, the Ka-band radar also detects turbulence with EDR of 10^{-4} m^2s^{-3} and 10^{-7} m^2s^{-3} at 5 km and 10 km respectively. The presence of turbulence may be expected wherever changes of state are occurring, due to the potential for very localized variations in latent cooling and heating. Generation zones at cloud-top may lead to localized patches of latent heat release, whilst at the base, ice crystals are falling into a dry region and evaporating, causing non-uniform local latent cooling. Additionally, there is the potential for strong radiative cooling at the cloud-top, similar to that experienced by liquid layers, and which may be the dominant source of turbulence. Although both techniques produce similar vertical profiles of EDR (particularly at cloud base), there are several orders of magnitude difference between their EDR values. The reason for the discrepancy in the order of magnitude for each measurement technique are at present not fully understood, but may be related to the difference in length scales between techniques. Understanding the discrepancies between the two measurement techniques will be addressed in future work.

(b) Cloud and charge sensor measurements

During both IOPs a variety of cloud/charge and solar-radiation balloon flights were made in many different cloud types, ranging from low-level stratus to cumulonimbus. Figure 3 shows results from a sonde flight through a layer of low-level stratus cloud during the morning of 30 May 2014 (launch time 0540 UTC). As well as measuring the standard meteorological data (Figure 3[a]), the sonde was instrumented with a charge sensor (Figure 3[b]), cloud droplet sensor (Figure 3[c]), and solar radiation sensor (Figure 3[e]), providing five separate measurements of cloud properties from the same balloon flight. Figure 3(e) shows radar reflectivity data from the KAZR for the period around the sonde launch, showing the presence of two distinct cloud layers with tops at ~0.5 km and 2.2 km. A vertical profile of the radar reflectivity at launch time is shown in Figure 3(d). Comparison between the radar reflectivity profile (d) and visibility (c) derived from the cloud-droplet sensor on the sonde (see Harrison and Nicoll 2014 for details) shows good similarity between the two techniques in terms of the altitude of the cloud layers detected (although the base of the lowest cloud layer is missed due to the height limitations of the radar). It is obvious that the balloon-borne cloud sensor provides much higher resolution data about the cloud structure than the radar, however, and also detects a third, very narrow cloud layer (20 m thick) at ~1.5 km altitude that is not measured by the radar. Figure 3(b) and (c) also show the detail with which the charge sensor and cloud-droplet sensor are able to measure the cloud layer, particularly the upper and lower cloud edges, which can be resolved to the nearest 5 m.

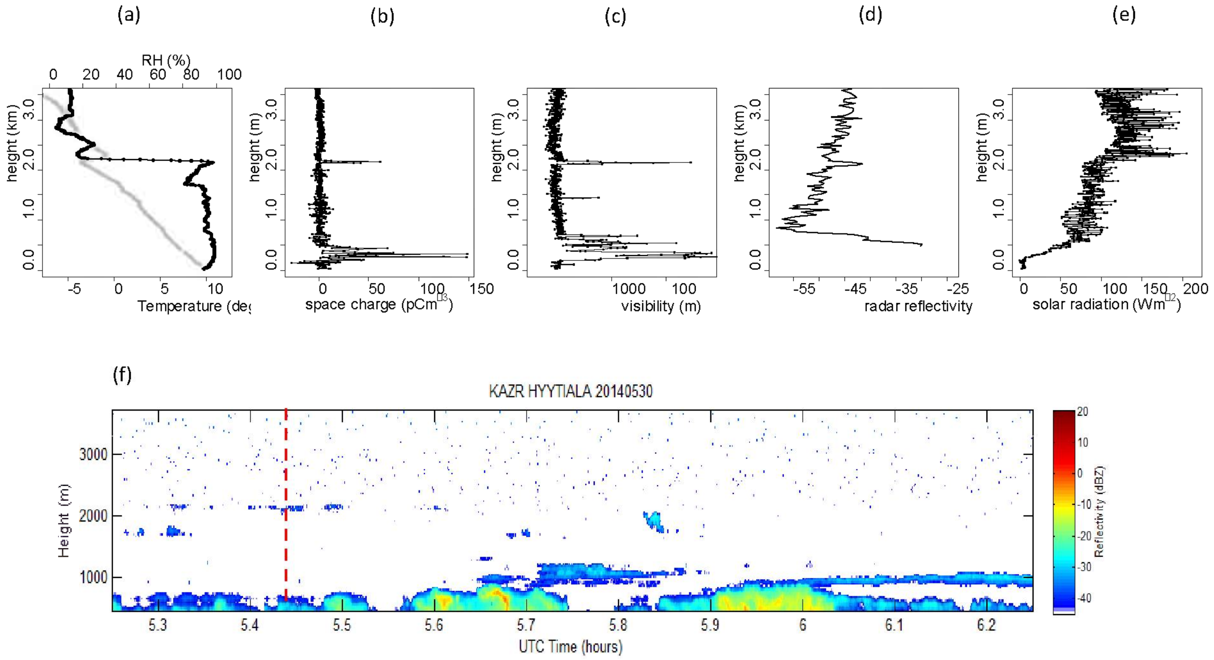

Figure 3. Vertical profile from a specially instrumented RS92 radiosonde launched at 05.43UTC from Hyytiälä on 30 May 2014. (a) temperature (grey) and RH (black) measured by the radiosonde, (b) space charge measured by the charge sensor, (c) visibility derived from measurements by the cloud sensor, (c) downward pointing solar radiation, (d) (e) radar

reflectivity from the KAZR radar at Hyytiala – the red dashed line denotes the sonde launch time.

In summary, the data revealed that all clouds sampled were electrically charged, typically with charge present at the upper and lower cloud boundaries, with magnitudes up to 150 pCm^{-3}. Understanding the effect of such charge on cloud microphysical processes is the subject of ongoing work and requires a combination of both modelling and further observations

This project has demonstrated that instrumenting standard meteorological radiosondes with additional science sensors can provide a wealth of extra in situ data, and is both cost-effective and easy to achieve. By using a combination of different balloon sensors to study clouds, high-resolution information about a variety of cloud properties can be obtained routinely that is difficult to achieve by other methods. Comparison between radar reflectivity and visibility measurements from a balloon-carried cloud sensor demonstrate that, in particular, thin clouds can be missed by remote sensing methods such as radar. In addition, turbulence measurements from a balloon-carried accelerometer show a discrepancy between the radar-derived turbulence and in situ balloon measurements, the origin of which will be the subject of future work.

5.0 Public Outreach

Since this was a very small project with funding only provided for two short field campaigns, no public outreach has yet been undertaken.

6.0 BAECC-ERI Publications

6.1 Journal Articles/Manuscripts

Nicoll, KA and RG Harrison. 2015. "Quantifying cloud edge charging through observations," to be submitted to *Quarterly Journal of the Royal Meteorological Society.*

6.2 Meeting Abstracts/Presentations/Posters

Marlton, G, RG Harrison, KA Nicoll, PD Williams. 2015. "Balloon-borne accelerometer observations of atmospheric turbulence," *EMS Conference*, Sophia, Bulgaria.

Nicoll, KA. August 2014. "Measuring cloud, aerosol and atmospheric electricity from airborne platforms," University of Helsinki, Finland.

Nicoll, KA, RG Harrison. October 2014. "Developments in optical sensors for cloud detection from radiosondes," *Radiosonde Users' Workshop*, University of Reading, UK.

Marlton, G, RG Harrison, KA Nicoll, PD Williams. October 2015. "Using a balloon borne accelerometer to make in situ measurements of atmospheric turbulence," *Radiosonde Users' Workshop*, University of Reading, UK.

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