8B.5 BOUNDARY LAYER STRUCTURE AND AEROSOL PROPERTIES: LIDAR RETRIEVALS AND IN-SITU MEASUREMENTS

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1. INTRODUCTION

Aerosols remain the dominant source of uncertainty in radiative forcing (IPCC, 2007). They directly affect the climate by reflecting visible radiation back to space, while absorbing aerosols may heat the air and promote dispersion of clouds ('cloud burning'). An increase in aerosol concentration affects clouds via the 'indirect' effect whereby the larger number of small droplets i) increases cloud albedo and ii) may increase cloud lifetime as coalescence is suppressed (or possibly shorten cloud lifetime as smaller drops evaporate more quickly). The effect of aerosols acting as ice nuclei for cold clouds and hence influencing glaciation and rainfall production is even more speculative. Aerosols also directly affect visibility, and some aerosols can be deleterious to health.

Detailed measurements of aerosol physical and chemical properties require highly specialised and expensive instrumentation, and are thus largely limited to dedicated field campaigns with very restricted temporal and spatial extent. More limited measurements of bulk aerosol properties are conducted continuously via long-term efforts targeted either on climate monitoring or pollution regulation; again these tend to be relatively limited in spatial coverage. On a global scale remote sensing via satellite borne lidars offers the potential for measurements covering a large fraction of the Earth's surface over a long period of time (Vaughan et al. 2004); however the interpretation of such measurements in terms of the aerosol size spectra, total concentration, and chemical properties remains ambiguous. Calibration of retrieval algorithms requires coincident measurements from both lidar and in-situ aerosol instrumentation.

In order to address some of the issues associated with interpreting lidar measurements a month-long campaign of field measurements was undertake during April 2008 at the Chilbolton Observatory in southern England. The site is well equipped with multiple lidars, details of which are given in section 2.1; for the duration of the field campaign an extensive range of additional measurements was made, including aerosol physical and chemical properties, surface fluxes, and balloon borne in-situ measurements of aerosol spectra, mean meteorology, and turbulence properties throughout most of the depth of the boundary layer.

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2. MEASUREMENTS

2.1 Lidar Measurements

Three lidars operate on a continuous basis at the Chilbolton observatory. The first, which has been operating for several years, is a simple Vaisala ceilometer which records profiles of elastic backscatter at 905 nm. This can be related to the optical depth of the aerosol if the 'lidar ratio', S, of the backscatter to the extinction is known. The second lidar, manufactured by Halo photonics, has been operating continuously since September 2006, has a wavelength of 1.55 μm and provides profiles of backscatter and Doppler velocity**.** A cross polar return channel is also available allowing measurement of the 'depolarisation ratio', P – a measure of the non-sphericity of the targets. The third lidar, manufactured by Leosphere, and installed early in 2007, operates at a wavelength of 355 nm and measures the elastic backscatter together with the cross polar return. It also detects a molecular return, the value of which is known from the air density; any reduction in this signal relative to the expected molecular return gives a direct measure of the extinction/optical depth of the aerosol, and, when combined with the backscatter, the lidar ratio (S) can be derived.

The backscatter ratio at different frequencies – the so called 'colour ratio' – depends upon the size, dielectric constant, and shape of the aerosol particles, and is particularly useful for inferring a mean size. Ansmann et al (2003, and refs therein) suggest how colour ratio, P and S may be used to infer aerosol properties with some accompanying validation from aircraft flights. For example: desert dust has an S of 50 and a P of 30%; marine aerosol an S of 20 and a P of 20%, but with rising humidity for hygroscopic aerosols both S and P fall.

In summary the following seven independent parameters are available from the lidars on a continuous basis: i-iii) Backscatter profiles at 355, 905 and 1.5um (and the colour ratios derived from them); iv) Doppler velocity at 1.5um, which reveals the vertical mixing within the boundary layer; v-vi) Depolarisation ratio (P) at 355nm and 1.5um, and vii) Lidar ratio (S) at 355nm.

Figure 1. SkyDoc aerostat balloon carrying the aerosol instrumentation.

In addition to these, a Raman backscatter lidar is also available on site, but does not operate continuously. This provides profiles of water vapour concentration. Near real-time imagery and links to other information about the Chilbolton measurements can be found at: http://www.met.rdg.ac.uk/radar/realtime/pbl.html

2.2 In-Situ Measurements

The key measurement required in order to begin calibration of the aerosol retrieval algorithms from the lidars is that of the in-situ aerosol size spectrum. Most aerosol instrumentation is relatively large, heavy, and power-hungry, restricting airborne measurements to dedicated research aircraft. Such measurements are less than ideal for comparison with lidar observations, since the time spent in the same air mass seen by the lidar is relatively short. A new instrument, designed and built at the University of Leeds, allows a tethered balloon to be used to make measurements close to the lidar sample volume over a period of several hours at a time.

The Compact Lightweight Aerosol Spectrometer Probe (CLASP) is built around a commercially available optical scatter cell; purpose built electronics include a 1024 channel pulse height analyzer and software to bin the measured particles into an arbitrary number of user defined size channels (here 16) spanning the measurement range of 0.24–18.5 μm (diameter) at a

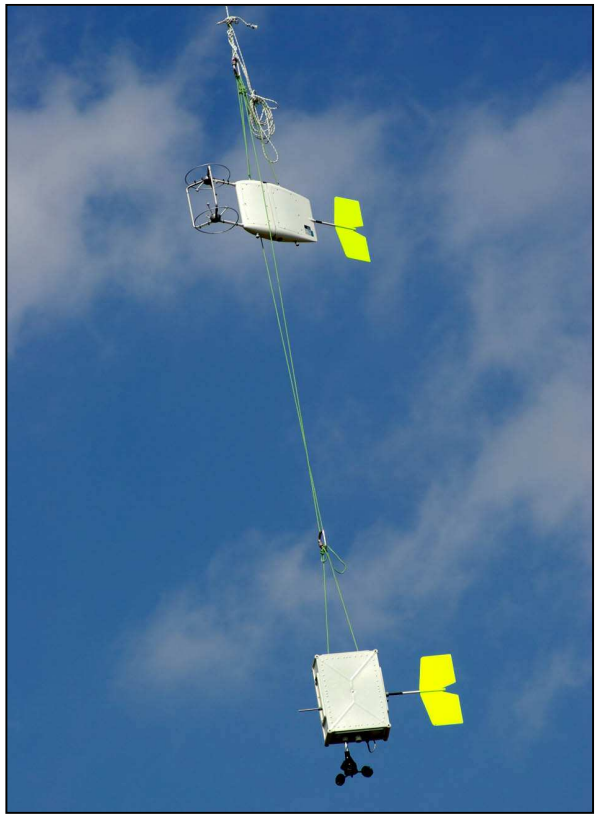

Figure 2. The aerosol and mean meteorology package (bottom) and turbulence sonde (top) suspended from the balloon.

frequency of 10 Hz. A complete description of CLASP is given in Hill et al. (2008). It has previously been used to measure fluxes of sea spray aerosol (Norris et al. 2007a, 2008a, 2008b), and aerosol spectra directly over breaking waves from a tethered buoy (Norris et al. 2007b). For this study CLASP was incorporated into a package with sensors for the measurement of mean pressure, temperature, relative humidity and mean wind speed; along with a 12V rechargeable battery pack and a small embedded computer for data logging. The whole package measured 380×280×130 mm and weighed less than 3 kg. The instrument package was suspended from a tethered aerostat balloon, approximately 4 m in diameter and with a zero wind lift of 12 kg (figure 1).

A total of 14 successful flights were conducted under a wide range of atmospheric aerosol loadings. The ascent/descent rate is determined primarily by the fixed rotation rate of the winch, and is approximately 0.17 m s^{-1} (10 m min^{-1}); this is sufficiently slow to allow stable aerosol spectra to be obtained within 10 m vertical intervals during continuous profiling.

For some of the flights a prototype turbulence sonde was flown in addition to the aerosol package. This consists of a Gill Windmaster sonic anemometer mounted in a streamlined housing (figure 2). A set of 3-axis accelerometers and rate gyros provide the information required to apply motion correction to the

raw measurements of turbulent wind components. Both the sonic anemometer and motion pack were recorded at 10 Hz. The primary purpose of the turbulence sonde was to provide measurements of eddy dissipation rate for comparison with those derived from the Doppler lidar. These do not require motion correction of the wind components and can again be made during continuous profiling. Estimates of eddy correlation fluxes during periods at fixed altitude are also of interest, but require extended periods at a fixed altitude and careful correction for motion contamination of the wind components.

2.3 Surface-based Measurements

The balloon-borne measurements provide an essential data set for calibration of the lidar retrievals, but remain limited in duration and can only cover part of the total aerosol size range. In order to extend the information available an extensive suite of aerosol instrumentation was installed in or on the roof of a laboratory cabin. Aerosol size spectra were determined from a combination of: TSI condensation particle counter (total aerosol concentration > 3 nm), PMS FSSP (1-32 μm), PMS OAP (6-155 μm), PMS PCASP (0.05-5 μm). Two volatility systems (Brooks et al. 2002, 2007) provided information on the bulk chemistry and mixing mode of the aerosol; the first utilized a PCASP (0.05-5 μm), the second a Scanning Mobility Particle Sizer to measure particles in the range 5-200 nm (radius). All the aerosol samples were drawn from a height of approximately 10m above the surface; measurements of mean wind speed, direction, temperature, humidity, and pressure were made close to the sample inlet.

An instrumented tower made measurements of the surface fluxes of momentum, heat, moisture, and aerosol at approximately 15.5 m above the surface. The instrumentation consisted of a Gill R3 sonic anemometer, a LiCOR 7500 H_2O/CO_2 gas analyzer, and a CLASP unit. This CLASP also provides a continuous surface reference for comparison with the balloon borne system.

During the analysis the combination of surface fluxes, balloon borne measurements, and lidar can be used to make an assessment of the extent of mixing throughout the boundary layer. If conditions are well mixing from the surface, then we can assume that the surface aerosol measurements are representative of the aerosol loading at higher altitude, allowing us to infer a wider size spectrum than can be measured from the balloon, and the chemical makeup of the aerosol at altitude.

3. PRELIMINARY RESULTS

The data collected on the morning of April 22nd provides an ideal case study to test the response of the lidar to changing aerosol size distribution. Following the dissipation of early morning mist, a shallow, humid haze layer, approximately 300 m deep remained, deepening rapidly after 10:30 UTC and the onset of convection. This is clearly visible in the lidar backscatter and Doppler velocity (figure 3). The aerosol and meteorology package was launched at 9:30 UTC, profiled up to 600 m by 10:45 UTC and back to the surface by 12:15 UTC by which time the mixed layer extended to about 1200 m.

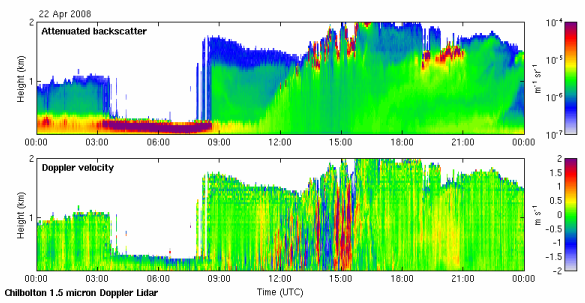

Figure 3. Lidar backscatter and doppler velocity on April 22.

Profiles of relative humidity, temperature, and wind speed are shown in figure 4, for both upward and downward legs. The downward leg displays greater small scale vertical motions due to the descent being 'stepped' at 50-m intervals rather than continuous in order to obtain better statistics at nominally fixed altitudes, coupled with stronger turbulence.

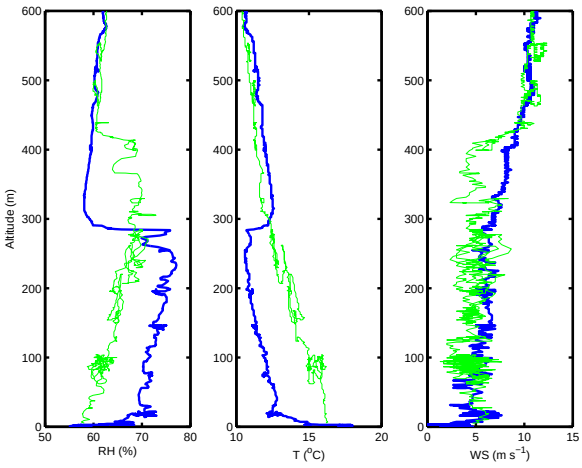

Figure 4. Profiles of relative humidity, temperature and wind speed for ascending (blue, thick line) and descending (green, thin line).

Figure 5 shows a comparison of the lidar backscatter coefficients from the Vaisala ceilometer (905 nm) and the Halo Doppler lidar (1.55 μm) with those calculated from measured aerosol spectra for a wavelength of 1.55 μm. The profile calculated from the CLASP measurements uses in-site spectra; while that calculated from the PCASP data uses surface layer measurements only, and grows the spectra to the measured ambient humidity profile assuming that the

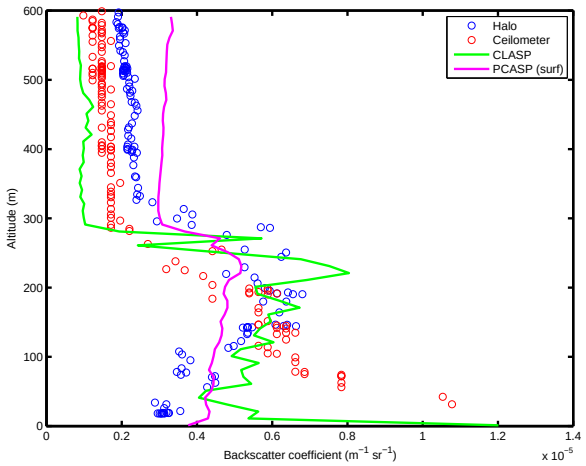

Figure 5. Profiles of measured backscatter coefficient from the Halo and Vaisala lidars, along with those calculated from the measured aerosol size spectra for a wavelength of 1.55 μm.

layer is well mixed. Backscatter within the haze layer is significantly greater than that above, primarily due to hygroscopic swelling of the aerosol, rather than greater number density. The response of the two wavelengths differs, with the longer wavelength showing backscatter profile that more closely follows the humidity structure of the layer. There is good agreement between the Halo backscatter and the profile calculate from in-situ CLASP measurements. The PCASP derived profile shows a similar structure, but the agreement with the lidar is weaker; however, the maximum particle size measured by the PCASP is probably too small to fully account for the backscatter at 1.55 μm. The Vaisala ceilometer shows a similar backscatter profile – the increased values below 100m result from contamination of the received backscatter signal in the near-field.

4. SUMMARY

14 flights of a tethered balloon with instrument packages to measure mean meteorology, aerosol size spectra (0.24–18.5 μm diameter), and turbulence intensity were made during April 2008 at the Chilbolton Observatory, UK. This in-situ data, along with additional measurements of aerosol physical and chemical properties at the surface and will be used to develop and test aerosol property retrieval algorithms for the array of lidars operating at the site. Good agreement between the measured backscatter and that calculated from the observed aerosol spectra is found.

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