ATMOSPHERIC SCIENCE LETTERS
Atmos. Sci. Let. **15**: 252–258 (2014)
Published online 25 March 2014 in Wiley Online Library
(wileyonlinelibrary.com) **DOI:** 10.1002/asl2.496

RMetS
Royal Meteorological Society

Measurement of boundary layer ozone concentrations on-board a Skywalker unmanned aerial vehicle

Sam Illingworth,[1] Grant Allen,[1] Carl Percival,[1] Peter Hollingsworth,[2] Martin Gallagher,[1] Hugo Ricketts,[1] Harry Hayes,[1] Paweł Ładosz,[2] David Crawley[3] and Gareth Roberts[2]

[1] *The Centre for Atmospheric Science, The School of Earth, Atmospheric and Environmental Science, The University of Manchester, M13 9PL, UK*
[2] *The School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, M13 9PL, UK*
[3] *The School of Electrical and Electronic Engineering, The University of Manchester, M13 9PL, UK*

**Correspondence to:
S. Illingworth, The Centre for Atmospheric Science, The School of Earth, Atmospheric and Environmental Science, The University of Manchester, Oxford Road, Manchester M13 9PL, UK.
E-mail: samuel.illingworth@manchester.ac.uk*

Received: 12 August 2013
Revised: 24 February 2014
Accepted: 26 February 2014

Abstract

This study demonstrates novel measurements of *in situ* ozone (O_3) concentrations and thermodynamics sampled on-board an instrumented Skywalker Unmanned Aerial Vehicle (UAV). Small spatial and temporal gradients were observed over a localized region, which nearby ground-based *in situ* measurements lack the ability to resolve. It was found that the UAV-measured O_3 concentrations provided a useful additional indicator of O_3 variability at the sub-urban scale. The ability to sample subtle variability over a localized area highlights the important and novel capabilities of UAVs to rapidly characterize local area micrometeorology and chemistry.

Keywords: **UAV; ozone; urban scale; atmospheric chemistry; micrometerology**

1. Introduction

Unmanned Aerial Vehicles (UAVs) are remotely or autonomously piloted aircraft. While UAVs have recently been most associated with military applications, their use in the field of atmospheric science and environmental monitoring is rapidly growing, from the monitoring of carbon dioxide (CO_2) concentrations (Watai *et al.*, 2006) to observing the spatial distribution of evapotranspiration (Rauneker and Lischeid, 2012). With the continued miniaturization of highly accurate and precise sensors, their potential effectiveness to make low-cost measurements at high spatial resolution is the subject of much scientific and technological interest.

For smaller UAVs the limiting factor in their utility is typically the availability of high quality, miniaturized sensors necessary for their reduced payload capacity, as well as relatively short-duration flight times (typically of the order 1–2 h); while one of the biggest current challenges for larger platforms concerns permission to fly by the appropriate regulatory bodies, such as the Civil Aviation Authority (CAA) for UK airspace.

Low Altitude, Short Endurance (LASE) UAVs are relatively simple to operate, with simple ground-control stations and control mechanisms, requiring only a small crew (Watts *et al.*, 2012). Their small size means that they can be hand-launched from a variety of terrains, and in the UK UAVs with an operating mass of 7 kg or less are exempt from the majority of the regulations that are normally applicable to large and manned aircraft (CAA, 2010). In the atmospheric sciences, UAVs have now been used for a variety of purposes, from making in situ measurements of thermodynamic properties in the planetary boundary layer (Houston *et al.*, 2012) to studying emissions at active volcano sites (Diaz *et al.*, 2010). Measurements of reactive gases such as ozone (O_3) from UAVs offer a novel opportunity to sample the three-dimensional (3D) spatial and temporal variability of such gases to enable process analysis.

Although only about 10% of all atmospheric O_3 is located in the troposphere, it is a principal driver of the photochemical processes regulating many of the gases that are emitted into the atmosphere by either natural or anthropogenic processes. In addition to this, tropospheric O_3 is itself a pollutant with impacts on human health and the environment. In Europe alone it is estimated that O_3 contributes to over 20 000 premature deaths per annum (EEA, 2007). Tropospheric O_3 is also a greenhouse gas and has been reported to contribute a net warming effect to the climate system, with a radiative forcing estimated at 0.35 $W\,m^{-2}$ (Forster *et al.*, 2007).

Tropospheric O_3 is not emitted; rather it is produced in the atmosphere from reactions involving precursor pollutants such as volatile organic compounds (VOCs) and NO_X (nitrogen oxide and nitrogen dioxide). These rapid chemical interactions can result in large spatial and temporal gradients of O_3 in urban environments, which usually peak in sub-urban areas downwind, with the O_3 production rate generally increasing with NO_X concentrations (Fowler, 2008). However, in urbanized centres, characterized by even higher concentrations of atmospheric NO_X, O_3 production can be inhibited, as a result of the reaction of O_3 with NO and the formation of NO_y (i.e. the sum of NO_X plus the reservoirs of NO_X, such as nitric acid and peroxyacetyl nitrate). Thus, in an urban environment, a reduction in NO_X concentrations can often lead to an increase in tropospheric O_3. With future estimates of NO_X emissions in the UK predicting reductions of 45% over the next decade (Hall *et al.*, 2006), an even greater emphasis might be placed on monitoring urban hazardous O_3 concentrations on the local scale.

Ozone concentrations depend strongly on the spatial distributions of NO_X and VOCs (and their associated emission sources), which vary both from one city to another as well as within the urban environment itself. Prevailing meteorological conditions can also vary rapidly, and mixing by micrometeorological processes such as the urban heat island effect and street-canyon-scale dynamics all act to modulate the chemistry and transport of ozone and its tracers across a range of temporal and spatial scales. Ground-based *in situ* measurements such as the Automatic Urban and Rural Network (AURN) in the UK operated by the Department for Environment, Food and Rural Affairs (Defra) can provide surface-level O_3 concentrations, although such fixed *in situ* measurements are limited in their spatial coverage. AURN currently has 103 active sites across the UK (Figure 1), which while providing high-resolution hourly information, is not able to provide information about surface-level O_3 concentrations on the sub-urban scale. Measurements from ground-based monitoring sites such as AURN are often used as validation datasets for regional air quality models such as the Met Office Air Quality Unified Model. Clearly, the inability of such sites to inform on the sub-urban scale can lead to a poor interpretation (and validation) of urban environments (Savage *et al.*, 2012).

An alternative to ground-based measurements of tropospheric O_3 can be to use aircraft. Typically, airborne measurements around urban environments are made using large aircraft. However, such flight campaigns are not only expensive, but still also lack the required spatial resolution for many applications, e.g. Manchester city centre has a diameter of approximately 2 km, which combined with the science speed of the UK's atmospheric research aircraft ($\sim 100\,\mathrm{m\,s^{-1}}$), means that a typical 1 Hz instrument would only be able to make approximately 20 measurements during an overpass of the city. Large research aircraft are also restricted by the CAA, which often means that they are unable to fly around urban centres or within the lower boundary layer.

However, UAVs offer an ideal alternative at such scales, bridging the gap between ground-based and traditional airborne methods, with the potential to deliver detailed, high-resolution, and precise measurements of tropospheric and near-surface O_3 concentrations at the local scale. Potentially synergistic instruments such as the CityScan ground-based NO_2 remote sensing system (Roland Leigh, pers. comm.) in development at the University of Leicester could be used in conjunction with UAV sampling to fully characterize the sub-urban scale.

In this paper, we present measurements of planetary boundary layer O_3 concentrations measured *in situ*, thereby demonstrating the development of a system with the capabilities of providing high spatial and temporal resolution sampling, which can be deployed in urban environments. This work describes this development and the first field measurements at a site near to Manchester city centre.

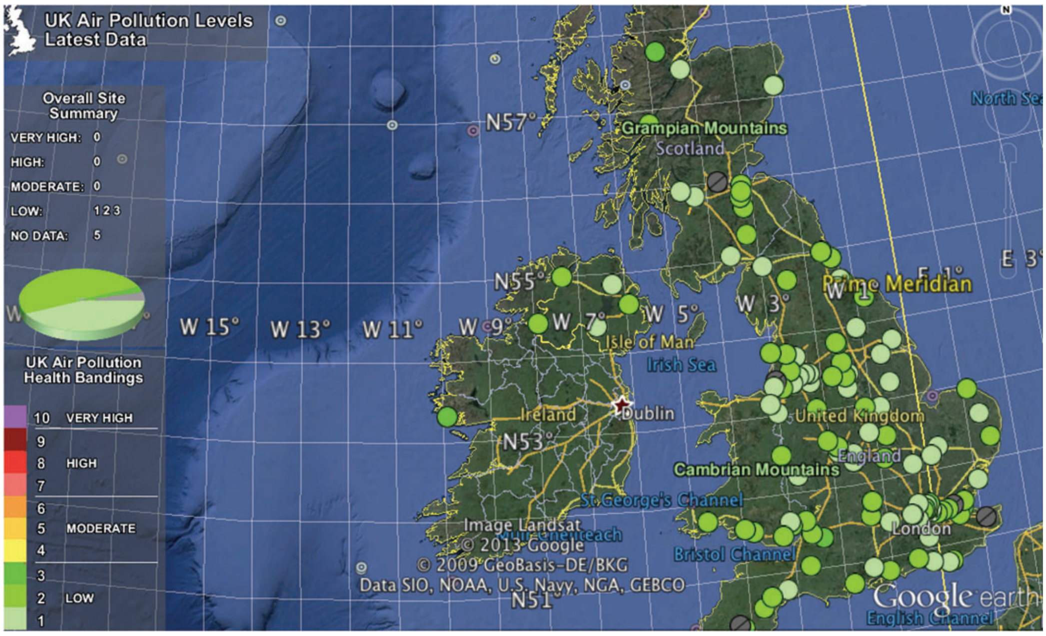

Figure 1. Locations of AURN sites in the UK plotted on Google Earth (Source: 'UK' 53°16′44.20″N and 2°43′36.48″E. Google Earth. April 10, 2013. July 7, 2013). Pollution levels correspond to measurements taken on Friday 7 July 2013; data courtesy of Defra (http://uk-air.defra.gov.uk/)

Table I. Accuracy and precision of the Vaisala RS92-KE radiosonde, when operating from 1080 to 100 hPa.

Quantity	Accuracy	Precision
Pressure (hPa)	1.5	0.1
Temperature (°C)	0.2	0.1
RH (%)	5	1

Table II. Specifications of Skywalker UAV.

Specifications	Skywalker
Length	1100 mm
Wingspan	1880 mm
Payload Bay	3450 cm^3
Maximum take-off weight	3.0 kg
Typical cruising s	45 km h^{-1}
Endurance (10 000 mAh battery)	1 h minimum

2. System design

In this study, we have adapted an Electrochemical Concentration Cell (ECC) ozonesonde to fly on a fixed-wing LASE UAV. We now describe the components and integration of this system.

The ECC ozonesonde (manufactured by Science Pump Ltd) comprises a motor, a Teflon pump, and the ECC module. The cell is made up of two chambers (anode and cathode) containing electrodes made of bright platinum and a potassium iodide solution with differing concentration in each cell. Both half-cells also contain potassium bromide in equal concentrations as a buffer. The electrodes quickly polarize, but when O_3-rich air is bubbled through the cathode solution, an electromotive force and current are induced which is proportional to the O_3 partial pressure. Data from the ozonesonde were relayed to a Vaisala RS92-KE radiosonde that simultaneously measured pressure, temperature, and Relative Humidity (RH). These data were transmitted continuously during the flight via

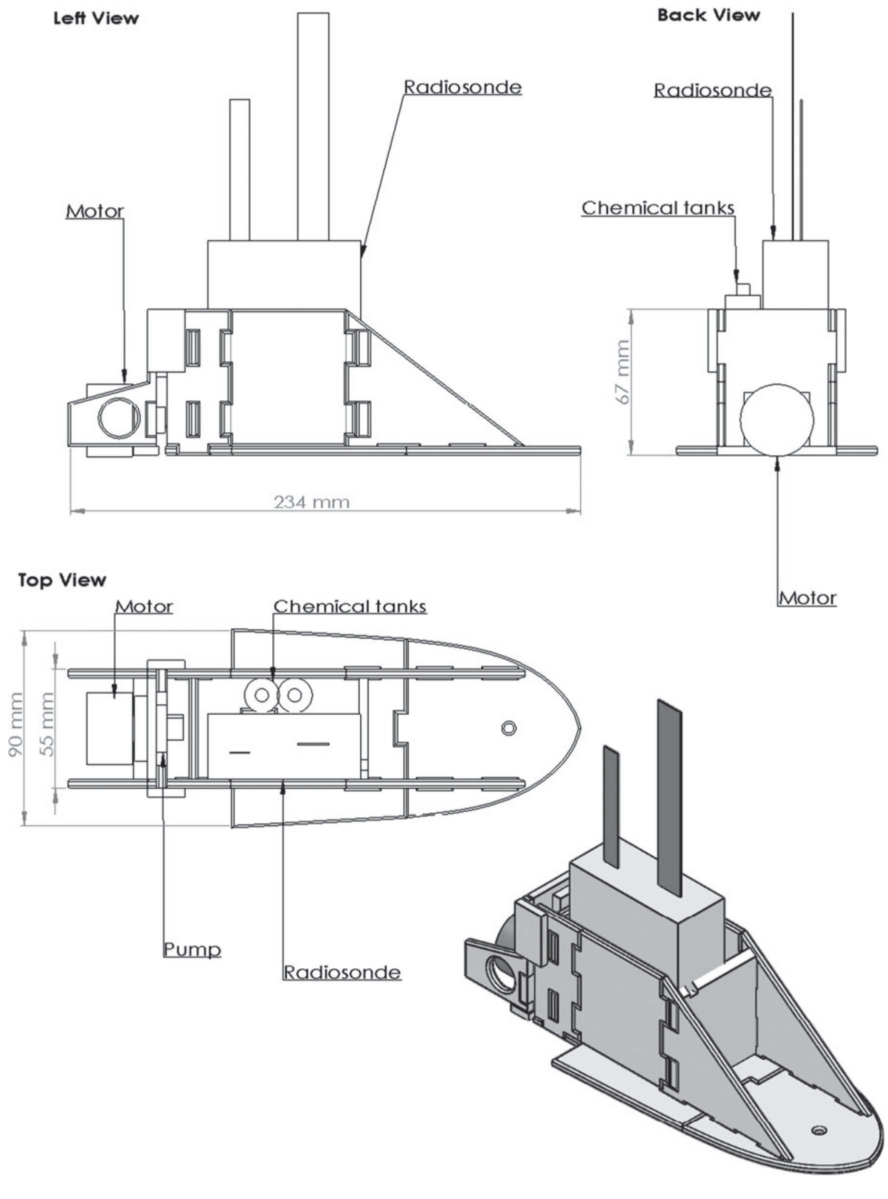

Figure 2. Drawing of final ozonesonde integration configuration.

Figure 3. A picture of the integrated ozonesonde and Skywalker airframe at the Hough End Fields site.

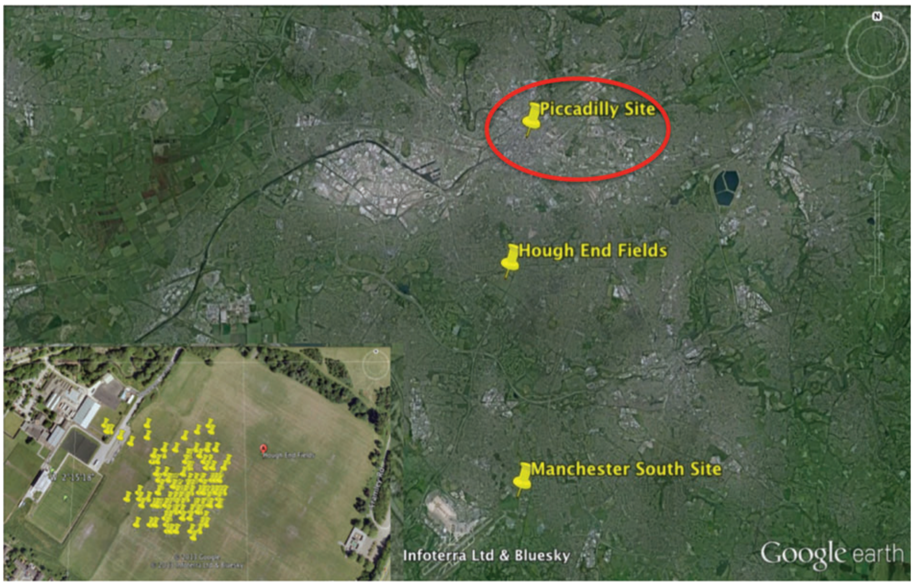

Figure 4. Google Earth (Source: 'UK' 53°25′59.48″N and 2°14′59.19″W. Google Earth. February 6, 2009. October 29, 2013.) image showing location of Hough End Fields site in relation to Manchester city centre (red ellipse). Inset: GPS locations of measured O_3.

radio to a dedicated ground station. The accuracy and precision for these measurements are given in Table I.

Tropospheric O_3 concentrations measured using this system have a typical relative precision of $\pm 3-6\%$ (Smit and Sträter, 2004), corresponding to $\sim 1-2$ ppb at concentrations measured here, with a sampling frequency of 0.5 Hz. This was also confirmed in the laboratory before flight. Anode and cathode solutions for the ECC were prepared in the laboratory at known concentrations in triple-distilled water, and the cell current was calibrated and validated for these solutions under ambient and high (saturated) O_3 concentrations. A calibrated Thermo Scientific TE49C photometric ozone analyser measured the ambient concentration in the lab, and a Science Pump Ltd TSC-1 ozoniser unit generated saturated flows. For a further description of the ozonesonde and radiosonde system, see Skrivankova (2004) and references therein.

The Skywalker airframe (the fuselage and wings) was designed and manufactured by Skywalker Technologies, before being assembled at the University of Manchester; its specifications are summarized in Table II. As well as providing the frame onto which the ozonesonde was attached, the UAV also provided GPS information.

Combining an ozonesonde with a UAV controlled via radio therefore allows the collection of real-time O_3, GPS, pressure, temperature, and humidity data.

When integrating the ozonesonde into the UAV, the electro-mechanical integration of the payload equipment needed to be taken into consideration. In addition to incorporating the ozonesonde, the final payload had to house the inlet pump motor to draw air into the ozonesonde for measurement, as well as discrete voltage sources for both the pump motor and ozonesonde. The final integration of the Vaisala probe and Skywalker airframe is shown in Figures 2 and 3.

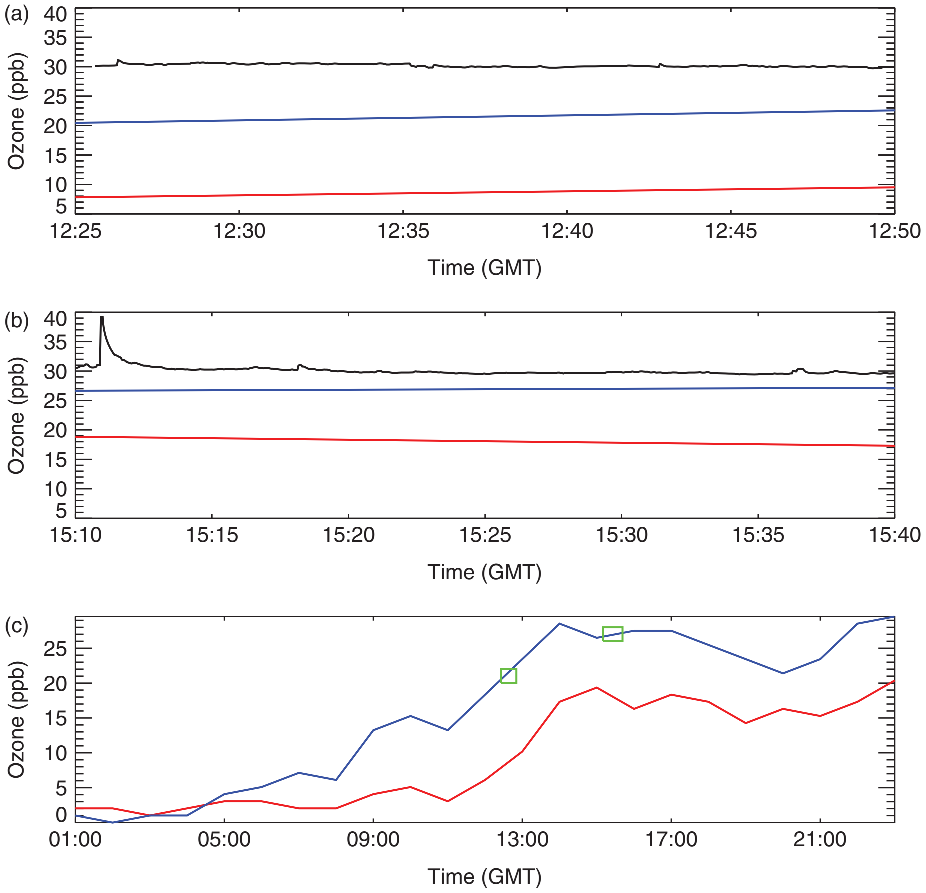

Figure 5. (a) Measured O_3 concentrations from 12:25 until 12:50. UAV measurements are given in black, Piccadilly Gardens AURN site measurements in red, and Manchester South AURN site measurements in blue. (b) Same as (a) but for 15:10 until 15:40. (c) AURN site measurements for the 28 June 2012 between 01:00 and 23:00. The Piccadilly Gardens site is shown in red, and the Manchester South site in blue. The green boxes indicate the data shown in (a) and (b).

3. Results

Test flights were carried out at Hough End Fields, Manchester on 28 June 2012 at midday, with partially cloudy conditions and gusting winds of up to 10 mph as recorded by a handheld anemometer. While the Skywalker UAV (including ozonesonde payload) weighs less than the 20 kg for which a certificate of airworthiness becomes a prerequisite, there are still a number of restrictions that are enforced by the CAA for those UAVs without an approved detect and avoid capability (as was the case here), namely that: the UAV is not allowed to fly in controlled airspace; the UAV can not be flown at an altitude exceeding 400 ft; the UAV cannot be flown within 150 m of any congested area of a city or town, or within 30 m of any person; and that a direct line of sight (500 m maximum range) must be maintained (CAA, 2010). Working under these restrictions, the Hough End Fields site, which is an existing model flying location (Figure 4), was chosen.

The ozonesonde sampled for two flying periods: from 12:25:36 to 12:50:26 and 15:09:50 to 15:41:30. These data are shown in Figure 5, with the corresponding meteorological data (pressure, temperature, and RH) shown in Figure 6. As seen from these plots, the O_3 appears to be reasonably well mixed in the lower boundary layer with a mean and standard deviation across this data set being 30.11 and 0.70 ppb, respectively. From Figure 6, the periods where the pressure was constant at roughly 1005 hPa (e.g. at approximately 12:40) indicate the periods of time when the UAV was grounded.

Peak concentrations of approximately 39 ppb were observed at 15:10. This peak was associated with a short-term shift in the prevailing wind direction to a more north-easterly direction, bringing air from the nearby main road (A5103, Princess Road) and Manchester 'city centre'. Such changes in wind direction were measured on this day using a handheld anemometer and were noted to be coincident with turbulent downdrafts associated with passing non-precipitating cloud. Our ability to sample this variability illustrates the potential for future process studies that relate to air quality, micrometeorology, and local dynamics in regions of strong local sources.

For comparative purposes, the data from two Manchester-based AURN sites is also shown in Figure 5. These sites are situated in Manchester city centre (Manchester Piccadilly: 53.481520°N −2.237881°E), and near to Manchester airport (Manchester South: 53.369026°N −2.243280°E).

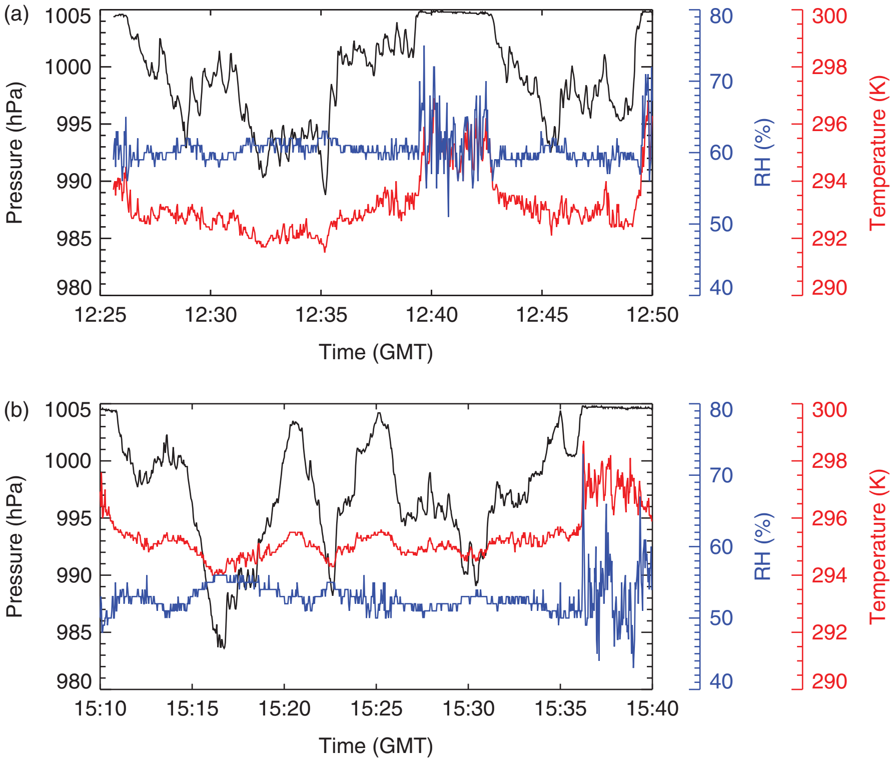

Figure 6. Meteorological data (pressure, temperature, and relative humidity) from (a) 12:25 until 12:50 and (b) 15:10 until 15:40.

Figure 5 illustrates the importance of being able to make numerous measurements of O_3 at a high spatial and temporal resolution for process studies and air quality model validation, because while the AURN sites provide a well-calibrated and consistent dataset they are only able to inform on concentrations of O_3 in their immediate vicinity, at a relatively poor temporal resolution (1 h). Furthermore, as shown in Figure 5(c), the AURN stations show rising ozone concentration throughout this day, especially between the two periods of measurement used in this study (green boxes in Figure 5(c)). Unlike at the AURN sites, the Skywalker measurements do not show a consistent increase in O_3 concentration between the midday and mid-afternoon measurement periods. These large local differences and gradients in species such as O_3 illustrate the need for dense sampling in order to inform and validate air quality models on the sub-urban scale.

Back trajectories can serve to provide information about the general airmass history of air sampled in a particular location. To probe the history of the air masses encountered by the Skywalker system, we used multiple single-particle 3D (vertical motion enabled) back trajectories from the offline Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Rolph, 2003), initialized using the National Centre for Environmental Prediction (NCEP) reanalysis meteorological wind fields at 1° spatial resolution, at 200 m vertical intervals between the ground and 2 km. 48-h back trajectories (with half-hourly outputs) were calculated with endpoints corresponding to the Hough End Fields site (Figure 7).

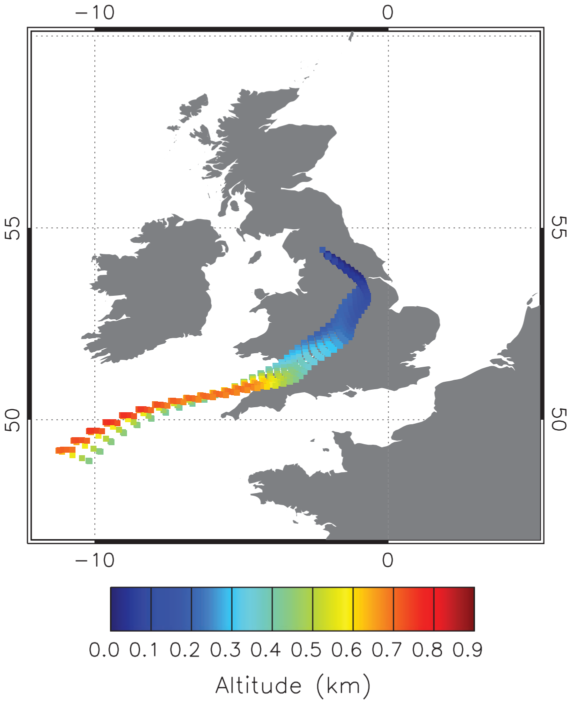

Figure 7. Forty eight-hour ensemble 3D back trajectories from the HYSPLIT Lagrangian model, ending at Hough End Fields at midday on 28 June 2012, initialized at 200 m vertical intervals between the ground and 2 km.

We would expect that the observed variability in O_3 over the relatively short timeframe of the measurements in this study would be driven more by local emissions, chemistry, and dynamics than regional scale transport, with the trajectories shown in Figure 7 demonstrating

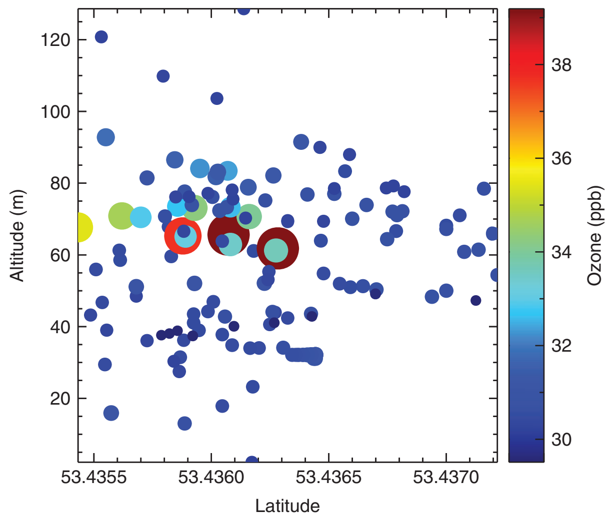

Figure 8. Plot of O_3 along the latitudinal flight track of the UAV. For ease of reference, the sizes of the plotted circles are proportional to the O_3 concentration.

that the prevailing wind direction at the time of measurement was approximately south-easterly (consistent with observations noted at Hough End Fields at the time of flight). This suggests that air sampled at Hough End would have passed near to the Manchester South AURN site; however, the poor sampling resolution (1 h) of the AURN site (and the lack of information between the two sites) means that we are unable to comment on any localized chemistry, although this might be possible in the future using simultaneous measurements of other active chemical species with UAVs.

The use of the UAV also enabled a spatially dense map of surface-level and lower boundary layer O_3 concentrations to be generated, as shown in Figure 8. It should be noted that not all of the data shown in Figure 5 is plotted in Figure 8, as there was a period of time for which the GPS data was not recorded due to a logging fault. The red colours (larger symbols) in Figure 8 show the enhancement in O_3 associated with the change of wind direction noted earlier. This highlights the potential for sampling 3D variability that may enable micrometeorological process analysis in the future using simultaneous measurements of thermodynamics and other trace gases from UAVs.

4. Conclusions

This work has presented the design, data, and analysis of a Skywalker UAV system incorporating an ozonesonde and thermodynamic measurement capability. These measurements demonstrate the capabilities of UAVs to make high-density, 3D measurements of tropospheric O_3, and (more widely) other trace gases on a sub-urban scale. The measurements recorded in this study demonstrate the localized spatial and temporal variability that exists in urban environments, and the difficulty that traditional ground-based instrumentation has in capturing these gradients at sufficient resolution.

Simultaneous measurements of pollutant trace gases are necessary to inform and validate air quality models to provide real-time data for monitoring, and to alert the public to dangerous levels. UAVs equipped with such a suite of instruments could conceivably help to provide such a network, giving vertical as well as ground-based information, and enabling a much clearer 3D picture to be developed.

Acknowledgements

We would like to thank NERC for funding the summer placement of Harry Hayes. We would also like to thank the Royal Meteorological Society for equipment and travel support of the project through their Legacies Fund. We also thank Defra for access to the AURN database.

References

CAA. 2010. Civil Aviation Authority CAP 722 Unmanned Aircraft System Operations in UK Airspace – Guidance, Directorate of Airspace Policy (http://www.caa.co.uk/).

Diaz JA, Pieri D, Arkin CR, Gore E, Griffin TP, Fladeland M, Bland G, Soto C, Madrigal Y, Castillo D. 2010. Utilization of in situ airborne MS-based instrumentation for the study of gaseous emissions at active volcanoes. *International Journal of Mass Spectrometry* **295**(3): 105–112.

Draxler R, Rolph G. 2003. HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) model access via NOAA ARL READY website, NOAA Air Resources Laboratory, Silver Spring, MD (http://www.arl.noaa.gov/ready/hysplit4.html).

EEA. 2007. Air pollution in Europe 1990–2004, *European Environmental Agency Report No 2/2007*. Copenhagen (http://www.eea.europa.eu).

Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G. 2007. Changes in atmospheric constituents and in radiative forcing. *Climate Change* **20**: 129–234.

Fowler D. 2008. *Ground-Level Ozone in the 21st Century: Future Trends, Impacts and Policy Implications*. The Royal Society: London.

Hall J, Dore A, Heywood E, Broughton R, Stedman J, Smith R, O'Hanlon S. 2006. Assessment of the environmental impacts associated with the UK Air Quality Strategy.

Houston AL, Argrow B, Elston J, Lahowetz J, Frew EW, Kennedy PC. 2012. The collaborative Colorado-Nebraska unmanned aircraft system experiment. *Bulletin of the American Meteorological Society* **93**(1): 39–54.

Rauneker P, Lischeid G. 2012. Spatial distribution of water stress and evapotranspiration estimates using an unmanned aerial vehicle (UAV), Paper presented at EGU General Assembly Conference Abstracts.

Savage N, Agnew P, Davis L, Ordóñez C, Thorpe R, Johnson C, O'Connor F, Dalvi M. 2012. Air quality modelling using the Met Office Unified Model: model description and initial evaluation. *Geoscientific Model Development Discussions* **5**(4): 3131–3182.

Skrivankova P. 2004. Vaisala radiosonde RS92 validation trial at Prague–Libus. *Vaisala News* **164**: 4–8.

Smit HG, Sträter W. 2004. JOSIE-2000: Jülich ozone sonde intercomparison experiment 2000: the 2000 WMO international intercomparison of operating procedures for ECC-ozone sondes at the environmental simulation facility at Jülich, WMO.

Watai T, Machida T, Ishizaki N, Inoue G. 2006. A lightweight observation system for atmospheric carbon dioxide concentration using a small unmanned aerial vehicle. *Journal of Atmospheric and Oceanic Technology* **23**(5): 700–710.

Watts AC, Ambrosia VG, Hinkley EA. 2012. Unmanned aircraft systems in remote sensing and scientific research: classification and considerations of use. *Remote Sensing* **4**(6): 1671–1692.