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The use of aircraft for meteorological research in the United Kingdom

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ABSTRACT: Atmospheric observations from aircraft have played an important role in meteorological research for many years; this paper presents an overview of meteorological research done with research aircraft in the United Kingdom. Key developments from throughout the history of meteorological research flying in the United Kingdom are presented, along with highlights of UK atmospheric research flying done in the last decade using the Facility for Airborne Atmospheric Measurements (FAAM) BAe-146 aircraft. The work presented includes research into thermodynamics, cloud processes, atmospheric aerosol, radiative transfer and atmospheric chemistry. Research aircraft provide a unique platform for the observation of atmospheric processes, allowing targeted measurement of specific parameters at a range of altitudes throughout the atmosphere. These measurements have improved greatly the understanding of the Earth's atmosphere, and the impact of these measurements has been seen through improvements in the representation of physical processes within numerical weather prediction (NWP) and climate models. Research aircraft have also been used extensively for the calibration and validation of remote sensing measurements, providing a unique test-bed for satellite observations. This research has led to improved use of satellite observations that have enhanced greatly how the atmosphere is viewed. Many developments in atmospheric research would not have been possible without the use of aircraft measurements, and these measurements will continue to play a key role in future developments of meteorological observation and prediction, as the complexity and resolution of weather and climate models increases.

KEY WORDS forecasting; modelling; remote sensing

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1. Introduction

In order to predict the weather accurately, it is vital to understand the complex meteorological atmospheric processes taking place in the atmosphere. This understanding can come from experiments using well-designed models; however, observations of the atmosphere provide an important source of information for the validation of such models, and are used to improve the understanding of how atmospheric processes work.

A key source of atmospheric observation for many years has been data from research aircraft; such aircraft host instrumentation to measure a range of parameters and can be directed to provide detailed observations of these parameters. Since 1942 the Met Office has used research aircraft to provide such observations, and these have helped to improve the understanding of a wide range of atmospheric processes (McBeath *et al.*, 2012).

An overview of the main developments of Met Office research which have relied on data from research aircraft in the United Kingdom is included in Section 2. This overview is by no means comprehensive but provides a flavour of the range of applications that research aircraft have supported over the years.

Section 3 provides an overview of some of the recent airborne meteorological research done by the Met Office and by researchers in the UK university community since 2003. Much of this research is driven by the requirement to better understand atmospheric processes, such as clouds, aerosols and chemistry, allowing these to be better represented in forecast models.

Work is also done to support the exploitation of satellite observations, with calibration and validation work for a range of satellite sensors undertaken using the Facility for Airborne Atmospheric Measurements (FAAM) research aircraft.

Worldwide, many countries make use of research aircraft to support a range of atmospheric research. Some examples of collaboration between FAAM and researchers from other countries are presented in Section 4.

Section 5 presents conclusions, including an overview of the role that aircraft have played and continue to play in meteorological research.

2. Selected key developments: 1942–2003

The idea of using aircraft to measure atmospheric properties is not new: William Napier Shaw proposed in 1907 that instruments for the measurement of air motions and other meteorological variables could be mounted on aircraft (Shaw, 1907), and during the 1st World War Flight Commander B. C. Clayton from the Royal Naval Air Service produced 'Records of temperature at altitude' which was commented on by Shaw (Clayton, 1917).

The events of the 1st and 2nd World Wars led to the rapid development of aircraft technology accompanied by the need for improved meteorological understanding. Dedicated meteorological flights were established across the United Kingdom to

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Figure 1. The nose boom installed on the Canberra aircraft used by MRF.

provide daily profiles of temperature and pressure. The aim of these aircraft was to provide meteorological observations during these data-sparse periods and demonstrated the potential of aircraft-mounted measurement.

It was during the 2nd World War that the use of aircraft for meteorological research applications (rather than routine observations) began in the Met Office.

2.1. Dynamics and thermodynamics

During the 2nd World War, a common problem for RAF pilots was the formation of condensation trails (contrails) in the wake of their aircraft. Such trails provided the enemy with visual confirmation of the pilots' position and made them more vulnerable to attack. In order to solve this problem, Alan Brewer, a scientist from the Meteorological Office, was sent to the High Altitude Flight (HAF) at Boscombe Down to lead research into what was causing these trails to form.

Brewer's work led to the development of the Dobson–Brewer frost-point hygrometer, which provided a massive improvement in the ability to measure the low frost point values observed at high altitude (Dobson *et al.*, 1943). These improved measurements allowed Brewer to understand that the frost-point temperature, rather than the dew-point temperature, was key to contrail formation and allowed pilots to avoid flying in areas with high frost-point values so as to reduce contrail formation (Brewer, 1946).

The measurements made using this hygrometer mounted on research aircraft also led to developments in the understanding of the lower stratosphere and atmospheric circulation, which allowed Brewer to identify the Dobson–Brewer circulation (Brewer, 1949).

This work demonstrated the value of research aircraft to the Meteorological Office, and in 1946 the Meteorological Research Flight (MRF) was established at the Royal Aircraft Establishment (RAE) Farnborough, with a selection of aircraft dedicated to meteorological research.

During the 1970s an inertial navigation system (INS) was installed on the Canberra aircraft used by the MRF, which allowed the aircraft's velocity and attitude to be measured at high frequency. This information could then be combined with measurement of the aircraft's ground speed data, enabling the accurate measurement of both horizontal and vertical wind components at the same frequency: thus, turbulent fluxes could be measured.

The measurement of the wind speed and direction was done using instruments attached to a long nose boom (shown in Figure 1); this allowed the wind speed and direction to be measured ahead of any disturbance to the airflow caused by the aircraft. These measurements led to important developments in the understanding of clear air turbulence (Axford, 1968, 1972).

Figure 2. The nose boom installed on the C-130 Hercules aircraft used by MRF. The aircraft radar has been relocated above the cockpit to accommodate the nose boom's installation.

A similar measurement system was installed on the C-130 Hercules aircraft (shown in Figure 2), and this system was used extensively during the 1974 Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE) field campaign (Kuettner, 1974). These measurements formed part of an important reference dataset of tropical convection which supported the development of tropical convective schemes for many years following the campaign.

2.2. Cloud physics studies

One of the key areas of work done with research aircraft is research into clouds and the physical processes that control their formation, growth, and dissipation. A range of impactor methods was used for cloud and precipitation measurement from the late 1940s through to the 1960s, which measured cloud droplets and rain drops by exposing a specially coated slide to air for a brief period and examples of these instruments are shown in Figure 3. An example of one of the slides used for these measurements is shown in Figure 4, this shows pits collected in magnesium oxide during a flight in stratocumulus. These slides were examined manually post-flight and the number and size of the droplets recorded. These studies were

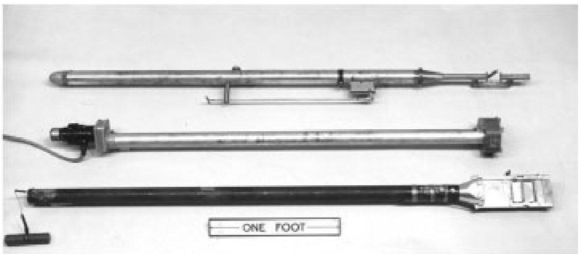

Figure 3. Three examples of cloud particle samplers used on board MRF research aircraft. Top: cloud droplet type, an oiled slide would be fired across the gap on the right. Middle: raindrop sampler, small electric motor (left) drove drums in the head (right) which moved a thin aluminium foil across the aperture. Bottom: raindrop sampler using sooted gauze method, gauze was placed in the holder (right) and the aperture controlled manually by the handle (left).

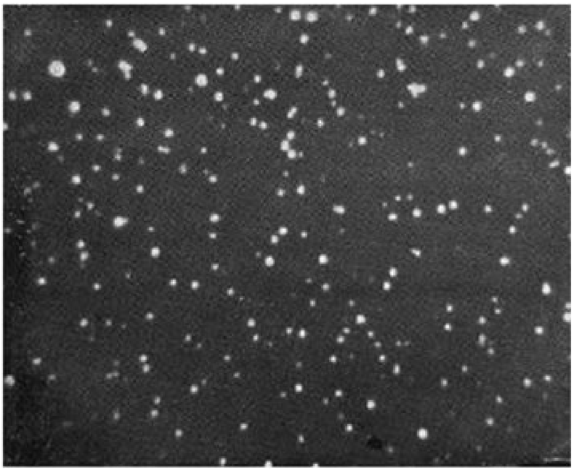

Figure 4. Cloud particle pits on a magnesium-oxide slide. Sample taken in stratocumulus cloud at 2000 ft, 13 May 1948. Image from (Firth, 1948).

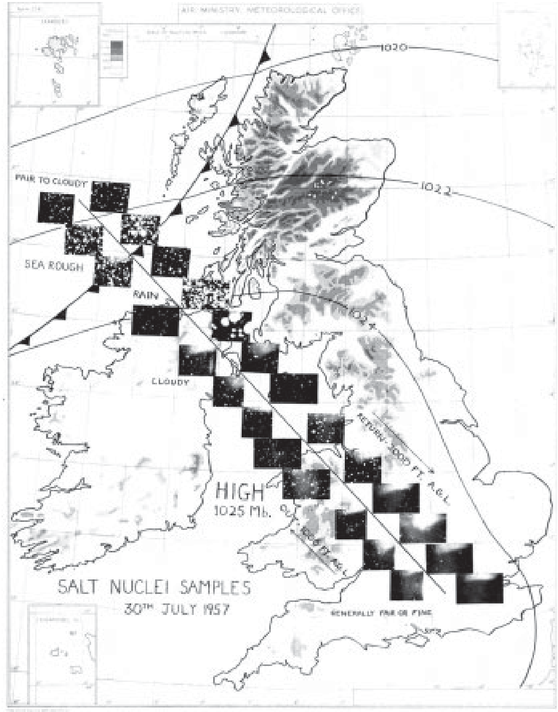

Figure 5. Salt nuclei samples obtained from a flight on 30 July 1957, overlaid on the approximate flight track along with surface pressure data.

written up in various papers throughout this period (e.g. (Durbun, 1959; Singleton and Smith, 1960)).

During the latter part of the 1960s, Cornford investigated sampling errors in measurements from impactor methods using Poisson statistics (Cornford, 1967, 1968). Cornford found that, while such methods can provide a representative measurement of small droplets, they under-sample larger droplets and were unsuitable for such measurements. While this could be seen as a setback, it was an important discovery. This work led to the development of different sampling techniques, the representativeness of which has been assessed using methods similar to that shown by Cornford.

In the late 1960s Knollenberg developed new probes for the measurement of cloud particles: these relied on optical scattering and shadowing techniques (Knollenberg, 1969, 1972), and were less susceptible to the sampling errors uncovered by Cornford. The operational principles of these probes are still used in cloud physics measurements in 2013, although there have been various developments and improvements in the measurement techniques over the years.

2.3. Aerosol measurement

Early work on aerosol–cloud interactions was done by scientists in the MRF during the 1950s, using an impactor method similar to that used for the measurement of cloud particles. An example of salt nuclei samples from a flight in 1957 is shown in Figure 5, and numerous flights were flown in a range of conditions in order to sample a variety of different air masses. Measurements of chloride particles around the United Kingdom and their interactions with cloud particles are described by Singleton and Durbin (1962).

As with the measurement of cloud particles, the use of impactor slides for aerosol measurements was later replaced by light scattering probes, which provide faster and more representative measurement of these particles than impactor methods.

Some aerosol impacts were also observed when examining data from early airborne radiometers, with variation in the upwelling terrestrial radiation observed downwind of urban areas (McBeath *et al.*, 2012).

The work on aerosol research has expanded over the years with a great deal of it on the properties of desert dust during the 1990s with the SHADE campaign; this work helped to attribute biases in satellite measurements of terrestrial radiation to absorption and scattering by desert dust (Tanré *et al.*, 2003) and this information has been used to improve satellite retrievals of meteorological parameters.

2.4. Atmospheric radiation measurement

The understanding of how solar and terrestrial radiation interacts with the atmosphere is an important part of understanding the atmosphere. The measurement of such parameters from the aircraft has been a key area of interest for the Met Office since the 1950s, and in 1952 an infrared radiometer from the Cavendish Laboratory, Cambridge, was flown on a Mosquito aircraft by the MRF. The installation and operation of this radiometer is described by Yarnell and Goody (1952), which also discusses the importance of making solar radiation measurements away from the ground: ‘Much of the future advance, both of meteorology and astronomy, is bound to be dependent upon the success of attempts to observe from above, and at various levels in, the atmosphere’. This statement pre-dated the use of satellites for atmospheric radiation measurements by many years.

In 1973, prior to the launch of the National Aeronautical and Space Administration (NASA) Nimbus-5 satellite, a prototype of their Selective Channel Radiometer (SCR) was flown by the MRF on a Canberra aircraft, providing valuable ground truth data to support analysis of the satellite data (McBeath *et al.*, 2012). This was one of the many radiometers that have been flown on research aircraft by the Met Office in support of satellite observations, and this area of work has grown as the use of satellite data for meteorological observation has increased.

Validation of satellite measurements can include the measurement of cloud, aerosol and chemistry within the atmosphere and the use of research aircraft for this work has provided an excellent platform for the multiple measurement types required for this validation. The ability to measure meteorological variables accurately from satellite platforms has had a significant impact on forecasting skill, and these measurements now provide a wealth of information about the atmospheric state and cover areas of the globe which were lacking in previous meteorological observations.

2.5. Atmospheric chemistry

Ozone measurements from the aircraft have been made since the early Met Office airborne research work during the 2nd World War: instrumentation for the measurement of carbon dioxide and helium were flown during the war, and ozone measurement equipment was developed and flown by MRF in the years that followed.

This work supported the development of Brewer’s global circulation theory which was published in 1949 (Brewer, 1949). Ozone measurements were made quite regularly by Met Office scientists using high altitude aircraft such as the Canberra, providing regular stratospheric ozone measurements until this aircraft was retired in 1981 (McBeath *et al.*, 2012).

During the 1970s and 1980s collaborative work was done by Met Office scientists in the MRF and researchers at the Central Electricity Research Laboratory (CERL) to examine the transport of pollution and production of acid rain. This work led to an expansion of the chemistry instrumentation on board the aircraft and these measurements improved greatly the understanding of how pollution is transported and transformed in the atmosphere, particularly the role that clouds can play in this process (Kallend, 1995).

3. Current meteorological research flying

In 2001 the Met Office and the Natural Environmental Research Council (NERC) established a joint facility named the Facility for Airborne Atmospheric Measurements (FAAM) in order to provide a platform that met the needs of the entire UK research community and also to reduce the operating costs associated with research aircraft use (McBeath *et al.*, 2012).

The FAAM research aircraft, a BAe146-301 aircraft (shown in Figure 6) came into service in 2004 and has been UK’s primary atmospheric research aircraft ever since. Funded equally by the Met Office and NERC, the aircraft is owned by BAe Systems and operated on their behalf by Directflight. It is based at Cranfield University Airfield in Bedfordshire.

The FAAM aircraft is capable of carrying a 4 tonne instrument load, and can operate at altitudes between 50 and 35 000 ft (15–10 600 m) (Gratton, 2012). This aircraft is highly instrumented and makes a wide range of core measurements on

Figure 6. The FAAM research aircraft. Some of the probes which can be seen in this image include cloud physics probes (under the wing), and core thermodynamic probes (below the cockpit window).

all scientific flights; these include measurement of temperature, humidity, wind speed and direction, a selection of trace gases, and cloud droplet number and size. Many of these core measurements use technology designed specifically for airborne atmospheric measurement and the operational principles of some measurements, such as the use of a frost-point hygrometer for the measurement of humidity, were developed by Met Office scientists working in MRF. These core measurements provide the context for more bespoke instrumentation flown by the Met Office and the UK university researchers (McBeath *et al.*, 2012).

The establishment of FAAM as a joint facility has led to an increase in collaboration between researchers in the Met Office and the university community. This collaboration has been vital during some high profile incidents such as the fire at Buncefield oil terminal in 2005 (Met Office, 2012) and the Eyjafjallajökull volcanic eruption in 2010 (Johnson *et al.*, 2012) both of which required collaboration between the Met Office and universities to co-ordinate the measurement and analysis of data from a wide range of specialized airborne instruments.

As with Section 2, the description of the work presented in this section has been divided into subsections (cloud physics, aerosol, atmospheric radiation, and chemistry); however, modern airborne atmospheric research increasingly involves a cross-disciplinary approach, with expertise in different areas of atmospheric measurement required to understand the processes at work fully.

3.1. Cloud physics

The Met Office uses cloud physics measurements from the FAAM aircraft to support the development of parameterisations which represent cloud within the Met Office Unified Model (UM). With the advent of higher resolution numerical weather prediction (NWP) models capable of representing processes on the convective scale ($\sim$1 km), accurate representation of cloud is particularly important, and the need for high quality research observations to support the development of these computer models continues.

The role that clouds play in the climate system was highlighted by the 4th Intergovernmental Panel on Climate Change (Solomon *et al.*, 2007) as one of the largest uncertainties in climate prediction, thereby improving the understanding of clouds is a vital part of improving Earth system modelling capability and thus projections of climate change.

Since coming into service in 2004, many cloud physics studies have been undertaken involving the FAAM aircraft. Some of these have formed part of large international research projects, whereas others have been smaller UK-based campaigns, taking advantage of the range of cloud conditions experienced locally.

During the summer of 2007, the FAAM research aircraft was one of the 10 aircraft which participated in the Convective and Orographically-induced Precipitation Study (COPS). This study examined the formation, growth, and decay of convective clouds over southeast Germany with the aim of improving probabilistic quantitative precipitation forecasts.

The COPS project involved over 300 researchers from 10 countries, including research aircraft from Germany, France and the United Kingdom: the UK involvement in COPS was driven by researchers from the University of Leeds. The FAAM aircraft provided a range of aerosol and cloud physics measurements, and was tasked with making these measurements in and around cloud, whereas other aircraft examined the thermodynamic and aerosol properties upstream of the region where convective clouds were forming.

This work has led to improvements in the understanding of errors in probabilistic quantitative precipitation forecasts, particularly in small high-impact events (Wulfmeyer *et al.*, 2011).

Some of the key results from the COPS experiment include understanding the importance of orographically induced thermodynamic flows on the formation of convergence lines, and how shallow-convection can precondition the lower troposphere for deeper convection through the transport of moisture. The data from COPS has also been used to assess the performance of high-resolution deterministic and probabilistic forecast models in the Met Office and other research centres: this assessment found convection-permitting models to be more skilful than models with convective parameterisations in the representation of these precipitation events (Bauer *et al.*, 2011).

During 2008 the FAAM aircraft participated in the Variability of the American Monsoon Systems (VAMOS) Ocean–Cloud–Atmosphere–Land Study Regional Experiment (VOCALS-REx) field campaign, a multi-platform international field campaign measuring the properties of stratocumulus in the southeast Pacific (Wood *et al.*, 2011). This experiment provided observations from five aircraft, two ships and two surface sites of critical but poorly understood elements of the coupled climate system of the southeast Pacific.

This area is of interest to international research as it experiences strong coastal upwelling and has the lowest sea surface temperatures (SSTs) in the tropical belt. The region also contains the largest stratocumulus deck anywhere in the world, which formed the centre of the first research theme guiding the VOCALS experiment: examining links between aerosols, clouds and precipitation, and their impacts on the radiative properties of marine stratocumulus. The UK involvement in the VOCALS project included research scientists from the Met Office working alongside scientists from the University of Leeds and the University of Manchester.

During this campaign the FAAM aircraft was involved in sorties making *in situ* measurements of the stratocumulus cloud, pollution sampling close to the coast, and profiling through the boundary layer using the aircraft and dropsondes: instruments that measure temperature, humidity, pressure and wind speed while falling to the ground on a parachute. These measurements were often co-ordinated with other research aircraft or vessels involved in the experiment and contributed to the large dataset of observations obtained for the VOCALS experiment. A diagram showing the role that each aircraft played in the *in situ* cloud sampling flights is shown in Figure 7.

The Met Office analysis of data from the VOCALS experiment has led to improvements in the representation of cloud and rain drop size in the Met Office UM (Abel and Boutle, 2012; Boutle and Abel, 2012). Many other areas of research have been pursued with the VOCALS dataset and the aircraft measurements made during this field campaign have provided a valuable contribution to the understanding of stratocumulus cloud (Wood *et al.*, 2011).

3.2. Aerosol research

The role of aerosols in the Earth system has impacts both on NWP and climate timescales, and as such is of great importance to a range of Met Office and university research aims. Recent developments in Earth system modelling include more complete representations of aerosol properties including a range of aerosol types and aerosol–cloud interactions. One

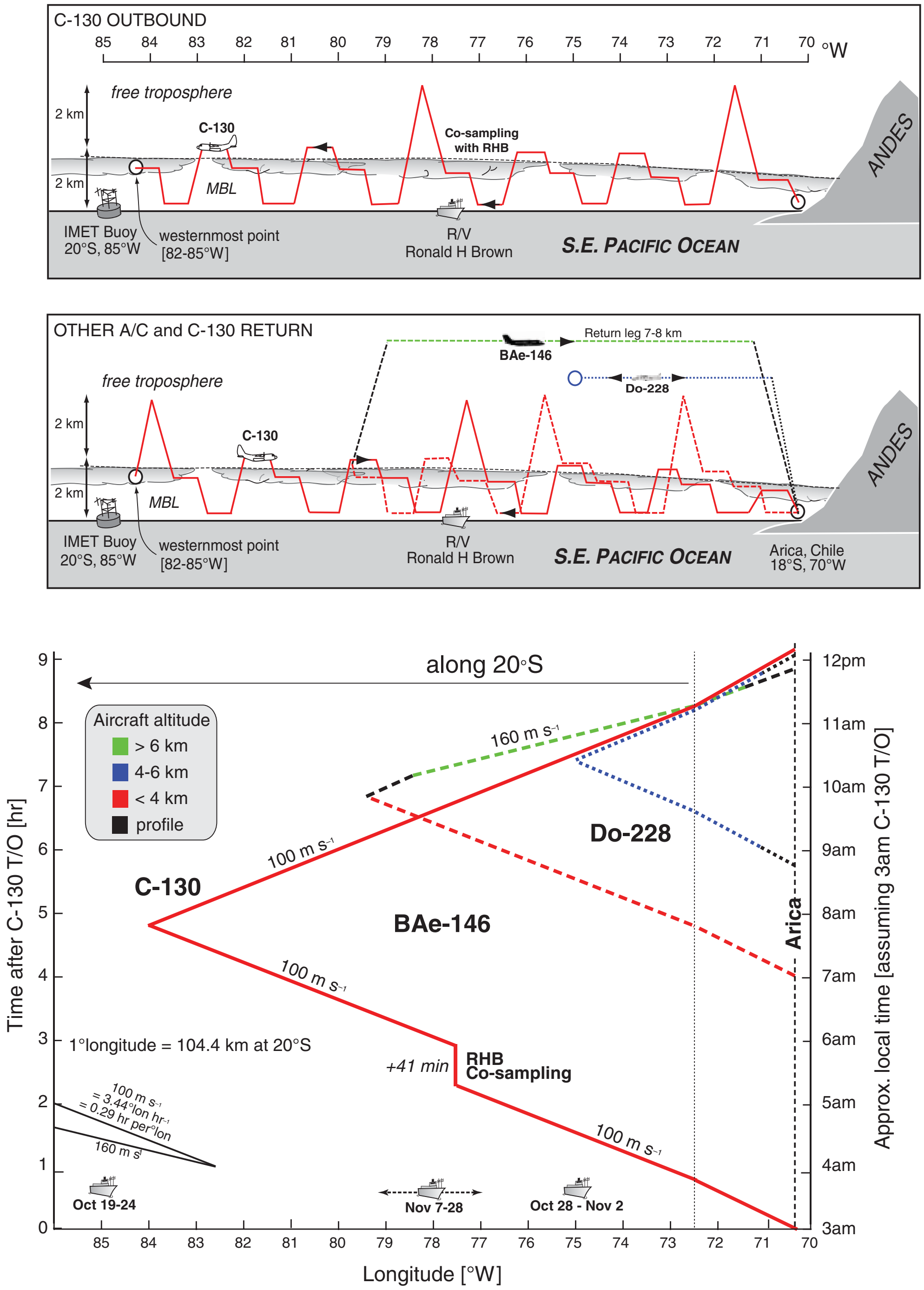

Figure 7. Cross-section mission flight plan from the VOCALS-REx project. The upper two panels show longitude-height diagrams, whereas the lower panel shows a time-longitude plot colour coded with altitude range. The aircraft shown are the NCAR C-130 Hercules; the NERC Dornier-228 (Do-228) and the FAAM BAe-146. Figure reproduced from (Wood *et al.*, 2011).

recent example of this is the improved treatment of aerosols in the HadGEM2-ES model that has led to new developments in the understanding of anthropogenic climate change (Collins *et al.*, 2011).

These developments have been supported by *in situ* measurements made using research aircraft, which have improved massively the understanding of aerosol characteristics and their radiative impacts. Some examples of this work are given in the following paragraphs.

In 2006 the FAAM aircraft was involved in the Dust And Biomass-burning Experiment (DABEX), which formed part of the African Monsoon Multidisciplinary Analysis (AMMA) project. The AMMA campaign was a major international field experiment that aimed to improve the understanding of the West African monsoon; this project included a long-term observing period (LOP), an enhanced observing period (EOP), and four special observing periods (SOP0-3) which took place at different times throughout 2006.

The DABEX study was led by Met Office researchers, and aimed to perform high quality remote sensing and *in situ* measurements of biomass-burning and mineral dust aerosol in West Africa, to determine how these different aerosols interact with each other, and to examine the impacts of these aerosols on a regional and global scale. These aims were well aligned with those of the 1st SOP (SOP0) of AMMA.

In situ measurements were made using a range of sorties to sample fresh biomass-burning, aged biomass-burning, and mineral dust aerosol. The aircraft was equipped with a range of aerosol instruments as well as trace gas and meteorological measurements. Ground-based measurements of aerosol optical properties were also made, which helped to provide radiative closure for the *in situ* measurements.

The mixture of biomass-burning and mineral dust aerosol measured during DABEX was found to produce a local reduction in local solar surface irradiance of over 25, 50% of which was due to biomass-burning smoke. This shows that biomass-burning smoke has a significant impact on local conditions (Johnson *et al.*, 2008).

The measurements made using the aircraft, along with remote sensing measurements, were used to develop improvements in the prediction of dust in NWP models, which have also been implemented in the Met Office Hadley Centre climate models: providing improvements in both short and long term predictions of aerosol production and transport, and it's direct and indirect radiative impacts (Brown *et al.*, 2012).

Data from the FAAM aircraft was used to assess visibility predictions of the Met Office UM by making detailed *in situ* measurements of aerosol properties around the United Kingdom. This was done for four flights during 2007 in a range of different meteorological conditions, in order to sample different aerosol loadings and types. These measurements were in response to an observed bias in UM visibility predictions, with lower visibilities being overpredicted, particularly in clean air mass conditions, when the aerosol loading in the atmosphere would be expected to be low.

A range of instrumentation was flown on the aircraft for these measurements including a nephelometer, wet nephelometer, a passive cavity aerosol spectrometer probe (PCASP-100X), particle soot absorption photometer (PSAP), and a quadrupole aerosol mass spectrometer (Q-AMS): details of these instruments are given in Haywood *et al.* (2008). The aircraft measurements were also complimented by ground-based measurements made at the Meteorological Research Unit (MRU) at Cardington, Bedfordshire which are also detailed in Haywood *et al.* (2008).

The measurements made by the FAAM aircraft found a range of aerosol species including ammonium nitrate, ammonium sulphate, and organic carbon, all of which have different hygroscopic properties, and so respond to variations in water vapour differently.

The *in situ* measurements were compared to model predictions of aerosol concentration and visibility, and quite good agreement (within a factor of two) was found between the model and observations for aerosol concentration (shown in Figure 8). However, the visibility values forecasted by the model were often lower than those observed (shown in Figure 9), this was attributed to the model having only one type of aerosol (sulphate aerosol) which is very hygroscopic, and responds strongly to changes in humidity; this caused the model to overestimate the amount of aerosol wetting in high humidity conditions and led to lower visibility predictions than were observed.

The ability to characterize a range of aerosol types and conditions allowed the aerosol and humidity assumptions used to predict visibility to be examined separately. This found that the problem in the model was not the prediction of either aerosol concentration or humidity but aerosol hygroscopicity. This information has been used to improve the parameterization of aerosol hygroscopicity in the model, which has brought about improvements in the prediction of visibility in the UM (Haywood *et al.*, 2008).

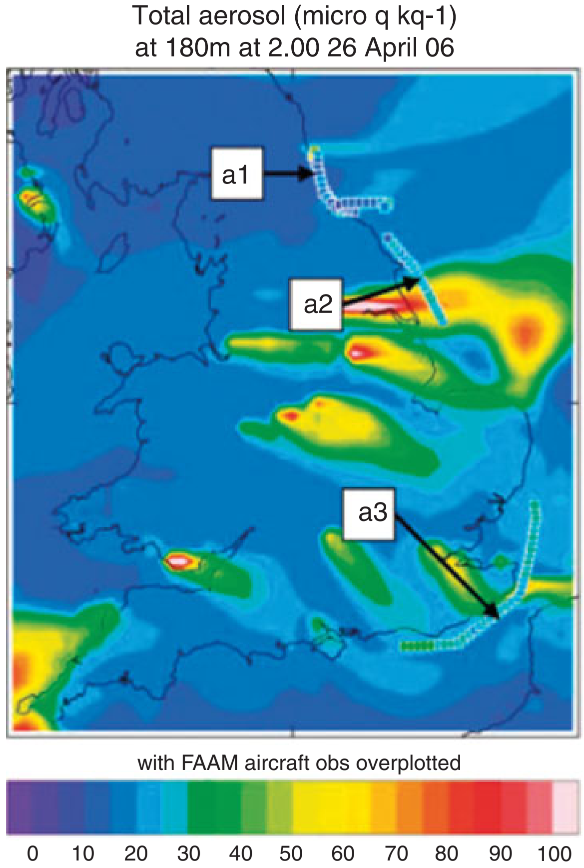

Figure 8. The aerosol mass mixing ratio determined from the model and the aircraft measurements for one of the four flights undertaken to assess visibility prediction in the Met Office UM during 2007. The highlighted sections (a1, a2, and a3) show flight legs which sampled transitions in aerosol loading and for all three the model shows reasonable agreement in the spatial distribution of aerosol: for a1 the model slightly underpredicts the aerosol loading associated with the observed plume, for a2 and a3 the model overpredicts the aerosol loading. Figure reproduced from (Haywood *et al*., 2008).

3.3. Atmospheric radiation measurement

The growing role that satellite data plays in the observation of the atmosphere has been accompanied by the Met Office developing a range of radiometric measurements on board the FAAM aircraft. These provide measurements across the electromagnetic spectrum from the visible through to the microwave wavelength ranges. These instruments have been used to improve the understanding of radiative transfer, in clear and cloudy sky conditions, the measurement of cloud liquid water content, and the retrieval of surface properties for a range of surfaces. The use of research aircraft in the calibration and validation of satellite data is an area which the Met Office has been involved in for many years. This research still forms a significant area of Met Office airborne research and the following paragraphs provide examples of some of the recent work done in this area.

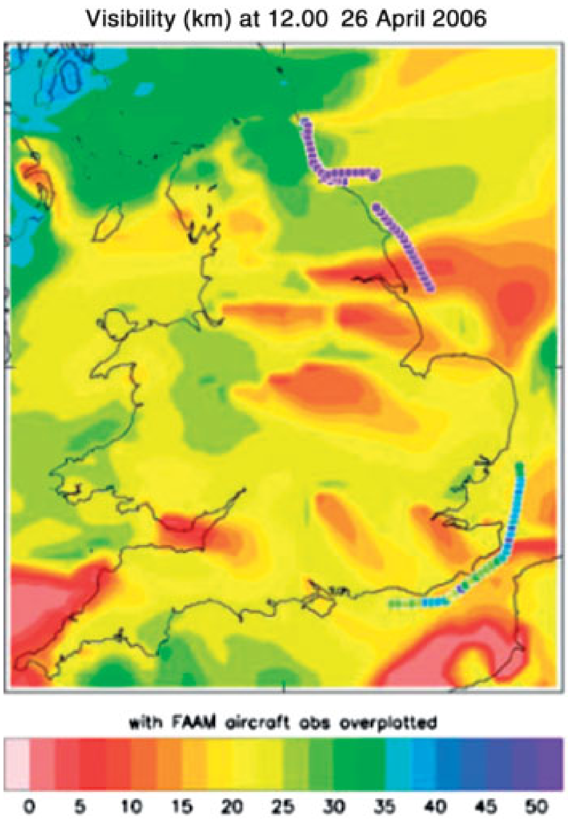

Figure 9. The visibility (km) diagnosed by the model at the altitude of the aircraft and from the nephelometer measurements on the FAAM aircraft, for the same flight as shown in Figure 8. This shows that for the same flight legs highlighted in Figure 8 the model significantly underpredicts visibility. Figure reproduced from (Haywood *et al*., 2008).

In 2004 the FAAM aircraft participated in the European Aqua Thermodynamic Experiment (EAQUATE), which aimed to validate data from the Atmospheric Infrared Sounder (AIRS) instrument on board the Earth Observing System (EOS) Aqua satellite.

The EAQUATE field campaign consisted of two parts; the first took place in Italy and involved the NASA Proteus aircraft, the second was based in the United Kingdom and also involved the FAAM research aircraft.

As the flight ceiling of the Proteus aircraft is significantly higher than that of the FAAM aircraft, the two flew stacked under the satellite footprint: with the FAAM aircraft operating in the troposphere, and the Proteus operating in the stratosphere, as shown in Figure 10.

The Airborne Research Interferometer Evaluation System (ARIES) was operated on board the FAAM aircraft, which provides radiometric measurements similar to those of AIRS. ARIES consists of a commercially available interferometer developed by BOMEN inc. of Canada, which was modified by the Met Office for airborne use during the 1990s. It has a spectral range of 550–3000 cm^{-1} (3.3–18 mm) with a maximum nominal resolution of 1 cm^{-1} and uses a pointing mirror to obtain views at a range of angles between nadir and zenith (Wilson *et al.*, 1999).

The FAAM aircraft was also used to provide *in situ* measurements of parameters such as temperature, humidity, and chemical species such as carbon monoxide, and released dropsondes (these are also shown in Figure 10).

The radiometric measurements from both aircraft were compared to provide a cross-calibration, and the data from the radiometers on board the Proteus aircraft was compared with data from AIRS. These high quality radiance measurements provided a valuable source of comparison for the satellite data, as the comparison could be done on a like-for-like basis.

The temperature and humidity profiles from the FAAM aircraft provided high resolution *in situ* measurements of the atmospheric state which were used to assess the retrievals of temperature and humidity from the AIRS instrument.

The spectral data from the airborne instruments were measured at a higher spatial and temporal resolution than that of the AIRS instrument, which was especially useful when examining data from complex scenes (e.g. cloudy conditions). This campaign showed the importance of having co-ordinated measurements from tropospheric and stratospheric research aircraft, as the high variability of water vapour in the troposphere can lead to uncertainties in the retrieval of atmospheric properties; *in situ* measurements of water vapour allow the retrievals to be better constrained (Taylor *et al.*, 2008). Similar measurement strategies were used to validate data from the Infrared Atmospheric Sounding Interferometer (IASI) satellite instrument during the 2007 Joint Airborne IASI Validation Experiment (JAIVEX) (Newman *et al.*, 2012).

In 2008 the FAAM aircraft was detached to Fairbanks, Alaska, for the second Cold Land Processes Experiment (CLPX-II), to investigate surface emissivity of sea ice and snow-covered surfaces. This work followed on from the 2001 POLar EXperiment-Surface Emissivity in Polar Regions (POLEX-SEPOR) campaign which made use of the C-130 Hercules aircraft (Harlow, 2007, 2011).

An understanding of surface emissivity is required when retrieving temperature profiles from satellite sounding instruments such as the Advanced Microwave Sounding Unit (AMSU-A/AMSU-B). The uncertainties in the surface emissivity of snow and ice-covered surfaces lead to large amounts of satellite data going unused, as temperature data close to the surface cannot be retrieved with enough accuracy. These data are mostly from polar regions: areas with few surface observations, but which are viewed frequently by a range of polar-orbiting satellites. Therefore, understanding the surface emissivity of these regions could lead to a significant increase in the available observational data for NWP.

The CLPX-II project involved ground measurement sites which were manned by a consortium of investigators from the University of Alaska, NOAA, University of Aberystwyth, University of Edinburgh, and University of Newcastle. These provided *in situ* data about the snow surface's physical state including temperature, density, depth and stratigraphy. These ground measurements provided valuable information about the surface, which was used to put the radiometric measurements into context (Harlow and Essery, 2012).

Flights were undertaken by the FAAM aircraft which included low and high level flight legs, deep profiles through the troposphere, and numerous dropsondes. This provided a range of atmospheric measurements which were combined with the ground measurements to evaluate the surface properties. The Microwave Airborne Radiometer Scanning System (MARSS) was flown on board the aircraft; MARSS is an along-track scanning radiometer which measures brightness temperatures at the AMSU-B frequencies (89, 157, 183 ± 1, 183 ± 3 and 183 ± 7 GHz) and observes at a range of viewing angles between zenith and nadir.

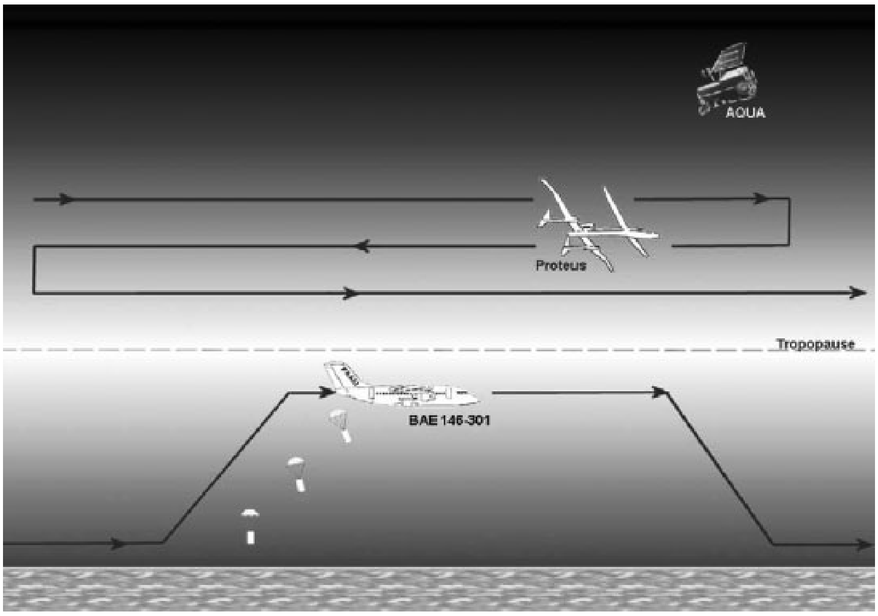

Figure 10. Diagram showing the sortie profiles used by the FAAM and Proteus aircraft during the EAQUATE project. Figure reproduced from (Taylor *et al.*, 2008).

Comparisons of upwelling and downwelling radiation measurements, along with *in situ* surface measurements, allowed the surface emissivity to be modelled using a range of settings. This found that the snow surface emissivity is best described when a Lambertian reflection scheme was used. This development in the understanding is an important step in developing the assimilation of data from microwave satellite sounding instruments.

In future, this knowledge could be coupled with NWP predictions of the snow surface to provide a more accurate representation of the surface and allow lower-tropospheric data from microwave sounders to be exploited over a broader range of surfaces. This could allow data which are currently being discarded to be included in NWP models, which could prove especially valuable in data-sparse polar regions (Harlow, 2011; Harlow and Essery, 2012).

3.4. Atmospheric chemistry research

Since the creation of FAAM in 2001, much of the atmospheric chemistry research undertaken by the aircraft has been led by the UK university community. This section provides an overview of some of the atmospheric chemistry research which the FAAM aircraft has been involved with since coming into service in 2004.

In 2004 the FAAM aircraft participated in the Intercontinental Transport of Ozone and Precursors (ITOP) experiment, which formed part of the International Consortium for Atmospheric Research on Transport and Transformation (ICARRT) co-ordinated experiment. The ICARRT experiment focussed on air quality in the eastern United States, transport of North American emissions over the Atlantic, and the influence of this transport on air quality in Western Europe. This experiment involved researchers from over 100 institutes making *in situ* measurements in the northeastern United States, across the Atlantic and in Europe. The ITOP part of ICARRT examined chemical processing of North American emissions from pollution and biomass-burning, in air masses transported across the Atlantic, and therefore the impact of these emissions on European air quality.

For this project the FAAM aircraft was based in the Azores, approximately halfway between America and Europe: the aircraft measured chemical species to assess how long after emission air masses remained chemically active. Similar measurements were made by the German Aerospace Centre's (Deutsches Zentrum für Luft- und Raumfahrt; DLR) Falcon aircraft, which flew over Western Europe examining the emissions within air masses as they were transported over the continent, and measuring pollution from local sources.

The co-ordination of measurements between the FAAM aircraft and the DLR Falcon, combined with trajectory modelling of the emissions, allowed the chemical transformation of pollutants within air masses to be examined. These were linked to measurements made near the emission source in the United States using aircraft and ground-based instruments, and allowed researchers to gain a complete understanding of the transport and processing of North American emissions (Fehsenfeld *et al.*, 2006).

In 2011 the aircraft was detached to Halifax, Nova Scotia, for the BORTAS (quantifying the impact of BOReal forest fires on Tropospheric oxidants over the Atlantic using Aircraft and Satellites) experiment; this involved researchers from a range of institutions including the universities in the United Kingdom, Italy, Canada, and the United States.

The BORTAS experiment aimed to improve the understanding of the chemical aging of air masses containing emissions from boreal wildfires, and the impact of this on their downwind chemical composition, particularly the production of ozone (O_3) in pyrogenic plumes. This was done using measurements from the FAAM research aircraft, along with instrumented ground stations, ozonesondes, and satellite measurements; these observations have been used alongside computer modelling of atmospheric chemistry and transport to examine the processes involved comprehensively.

The high frequency *in situ* measurements made using the FAAM research aircraft provided a wealth of information about the chemical composition of these plumes, both close to the source and as they aged (over days and weeks). Analysis of data from the aircraft found net ozone production taking place in the plumes as they aged, and that this was controlled by the atmospheric aerosol abundance. This data supports other studies that have shown that biomass-burning can lead to increased tropospheric ozone concentrations, which can have serious impacts on air quality, and should be taken into account when modelling and monitoring air quality (Palmer *et al.*, 2013).

4. International collaboration

Across the world there are many research aircraft in operation, undertaking a range of meteorological studies. Some of the research areas examined by these aircraft are similar to those examined using the FAAM aircraft, and for many field experiments aircraft from different countries have collaborated in order to maximize the breadth and value of the observations. Some examples of such collaboration are given in the following section, as with previous sections this is not an exhaustive list and simply aims to provide a sample of the type of international collaboration which the FAAM aircraft has been involved with.

In 2005, the FAAM aircraft collaborated with two aircraft from the United States as part of the Rain In shallow Cumulus over the Ocean (RICO) campaign: a Lockheed C-130 operated by the National Centre for Atmospheric Research (NCAR) and a King Air 200T owned and operated by the University of Wyoming.

During this experiment the FAAM aircraft and the NCAR C-130 flew sorties to sample fields of shallow cumulus statistically, and characterize sub-cloud turbulence and aerosols, whereas the King Air used its 94 GHz cloud radar to select clouds for repeated sampling. On some occasions the aircraft worked in co-ordination, with two aircraft sampling the same cloud at different heights (Rauber *et al.*, 2007). This range of airborne measurements provided a wealth of knowledge, and the combination of statistical sampling and in-depth process studies helped to understand the representativeness of the clouds measured. These measurements have shed new light on the warm rain processes that take place in shallow cumulus, including the impact that aerosol can have on these processes (Gerber and Frick, 2012; Blyth *et al.*, 2013).

The FAAM aircraft has also collaborated with research aircraft funded by NASA, such as during the 2004 EAQUATE and 2007 JAIVEX projects. Both of these involved stratospheric aircraft deployed by NASA working above the FAAM aircraft, deploying high-altitude radiometric instruments used for satellite calibration and validation (Taylor *et al.*, 2008; Newman *et al.*, 2012).

The French office of aircraft instrumented for environmental research (Service des Avions Francais Instrumentés pour la Recherche en Environnement: SAFIRE) has collaborated with FAAM during numerous campaigns including the 2007 COPS field experiment. During COPS two SAFIRE aircraft were involved: their Falcon-20 aircraft, used to map water vapour heterogeneity and fluxes across the COPS region and their ATR-42 aircraft which made *in situ* measurements of aerosol–cloud-precipitation microphysics along predetermined tracks through the region. These measurements complemented those made by the FAAM aircraft and helped to characterize the processes at work more thoroughly than would have been possible with one aircraft (Wulfmeyer *et al.*, 2011).

During the 2006 AMMA campaign, SAFIRE operated multiple aircraft in co-ordination with the FAAM research aircraft. The SAFIRE aircraft involved were the ATR-42, which has a flight profile similar to the FAAM aircraft and made *in situ* measurements of aerosol properties; the Falcon-20 which operated at high altitude; and an ultralight aircraft which operated in the boundary layer. These observations complemented those of the FAAM aircraft and this broad range of measurements allowed the Saharan boundary layer to be observed more thoroughly (Lebel *et al.*, 2010).

FAAM has also collaborated with the German Aerospace Centre (DLR) which operates numerous research aircraft. The FAAM aircraft worked with the DLR Falcon-20 aircraft during the 2004 ITOP experiment, providing atmospheric chemistry measurements over Europe which were linked with measurements made by the FAAM aircraft over the Azores, and by aircraft in the United States to examine the transport and transformation of emissions from North American sources and their impacts on Europe (Fehsenfeld *et al.*, 2006).

The DLR Falcon-20 aircraft also worked with FAAM during the 2007 COPS field experiment, during which the Falcon-20 worked with the SAFIRE Falcon-20 to map water vapour across the region of interest (Wulfmeyer *et al.*, 2011).

Across Europe, the European Facility for Airborne Research in Environmental and Geo-sciences (EUFAR) works to bring together the leading European institutions involved in airborne atmospheric research, with the aim of ensuring that researchers have access to the most suitable aircraft infrastructure for their needs. Fifteen operators of airborne research facilities are involved in EUFAR, including SAFIRE, DLR, and the United Kingdom's FAAM research aircraft.

This approach brings together expertise from institutions across Europe to share best practice in aircraft measurement techniques, and allows researchers from across Europe to access research aircraft facilities, promoting the important role that such measurements play in atmospheric research.

EUFAR also provides educational access to research aircraft and has organized several summer schools for PhD students across Europe, these have allowed junior researchers to gain a much better understanding of airborne measurement techniques (European Facility for Airborne Research in Environmental and Geo-sciences, 2009).

5. Conclusions

The Met Office has made use of research aircraft for over 70 years, and the measurements made with such platforms have contributed to many developments in the study of the atmosphere. These developments in understanding have been used by the Met Office to improve the Unified Model (UM) which is used for both numerical weather prediction (NWP) and climate studies.

Much of the early work done by scientists within the Meteorological Research Flight (MRF) has proved invaluable, and without developments such as the frost-point hygrometer much of the more recent airborne research would not have been possible.

From the 1990s onwards, the UK university community has had an increased involvement with airborne atmospheric research (McBeath *et al.*, 2012) and since 2001 the Natural Environmental Research Council (NERC) has collaborated with the Met Office in the provision of the UK's primary research aircraft (McBeath *et al.*, 2012). This platform has proved as valuable to university researchers as to the Met Office, and many field campaigns have been led by researchers from the UK universities community. The creation of a joint facility has also increased the extent of collaboration between the Met Office and university researchers, which has been beneficial for both parties. This collaboration has allowed researchers from the Met Office and academia to share knowledge and funding, which helps to maximize the efficient use of the facility ensuring that the data from field experiments is exploited by researchers from a range of research institutions.

The wide ranging measurement capability of the current Facility for Airborne Atmospheric Measurements (FAAM) research aircraft allows it to be used to study a range of atmospheric processes including cloud processes, aerosol properties, radiation transfer studies, satellite calibration, and atmospheric chemistry transport and transformation. The research interest in these various topics comes from the Met Office and also from researchers in the UK university community, and the FAAM aircraft is an important research resource used by researchers from a wide range of institutions.

In the Met Office, data from the FAAM research aircraft have been used to improve the representation of cloud and aerosol within the UM, which has brought about improvements in NWP forecasts and in climate models. Aircraft data have also been used to improve the use of satellite data, and work is continuing to ensure that satellite data are exploited completely, allowing improvement of global observations for both NWP and climate purposes (Hilton *et al.*, 2012).

Access to such a highly instrumented aircraft has allowed UK participation in international campaigns such as the 2006 African Monsoon Multidisciplinary Analysis (AMMA) experiment (Johnson *et al.*, 2008) and the 2008 VAMOS Ocean–Cloud–Atmosphere–Land Study (VOCALS) experiment (Wood *et al.*, 2011). Involvement in these experiments provides the Met Office and the broader UK atmospheric research community with access to data from the full range of platforms involved and encourages cross-border collaboration on large problems such as the impact of aerosol on radiative forcing and the exploitation of satellite platforms for Earth observation. Involvement in international field experiments often leads to collaboration with atmospheric research aircraft elsewhere in the world and encourages collaboration and data sharing with international researchers. The bespoke nature of installing, operating, and analysing data from airborne instrumentation makes collaboration and idea-sharing particularly useful in this field. Many of these experiments also involve measurements from other platforms such as ground sites and research vessels, all of which complement aircraft measurements and help to develop a comprehensive observations set.

The unique measurement capability provided by research aircraft, with the ability to provide detailed, targeted observations in a wide range of conditions, simply cannot be matched by models or other observational platforms, and the expertise involved in the provision of airborne atmospheric research measurements should not be underestimated.

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