**CLoud-Aerosol-Radiation Interactions and Forcing: Year 2016 (CLARIFY-2016)**

**CASE FOR SUPPORT PART1: Previous Track Records (see CVs for publications)**

**EXETER (UoE):** Exeter Climate Systems Research Centre (XCS) is an interdisciplinary centre of excellence based within the Mathematics Research Institute (MRI) within the College of Engineering, Mathematics and Physical Sciences. Since its creation in 2007, it has grown rapidly and XCS currently consists of 15 academic staff, 16 postdoctoral fellows, and 22 PhD students. XCS provides an excellent research environment with MRI having 60% of the research rated as world-leading or internationally excellent in the 2008 RAE. XCS has recently made several strategic appointments to strengthen the links between XCS, the Met Office and Hadley Centre and has been selected as one of four universities in the Met Office Academic Partnership.

*Prof Jim Haywood* (Project PI): is Professor of Atmospheric Science with over 20-years experience in aerosol measurements and modelling their impacts upon radiative budget, weather, air-quality, visibility and climate. He has a proven delivery record for aircraft targeted campaigns being PI for SAFARI-2000, SHADE, DABEX, GERBILS, Eyjafjallajokull, and SAMBBA and has co-ordinated several Special Issues integrating the results of measurement campaigns with modelling studies. His pioneering research during SAFARI-2000 highlighted the impacts of stratification of absorbing aerosol and cloud in SE Atlantic on both the radiative forcing of biomass burning aerosols and the impact on satellite retrievals of clouds. He has published over 100 peer-reviewed articles (h-index 38) including articles in Nature, Nature Climate Change, Science, and Reviews of Geophysics, has been lead author of three Intergovernmental Panel on Climate Change (IPCC) Reports. He holds 5 research grants for over £750K and is an international PI of the current SAMBBA NERC consortium project. He collaborates extensively with the Met Office, being employed 50:50 at University of Exeter and as a Research Fellow in the Hadley Centre. He supervises 3 Met Office post-doctoral senior scientists and 2 postdoctoral scientists and a Phd student at the University of Exeter who work on aspects of aerosol-radiation/aerosol-cloud interaction.

*Prof Matthew Collins* (UoE Co-I): is Joint Met Office Chair in Climate Change in the College of Engineering, Mathematics and Physical Sciences at the University of Exeter. His research interests are in climate modelling, quantifying uncertainty and probabilistic climate prediction, seasonal to decadal climate predictability and in understanding climate variability. He currently leads the NERC-MoES funded SAPRISE project which has a component looking at the role of aerosols in the Indian Monsoon. He has over 80 peer-reviewed publications (h-index 31, an average of 56 citations per publication) and has obtained £1.4 million in research funding in the last three years while at Exeter.  He was an expert advisor to the Royal Commission on Environmental Pollution Adaptation report, the UK Climate Change Committee and the Stern Review of the Economics of Climate Change. He has been a contributing author on the two of the most recent IPCC reports. He was recently appointed to the International CLIVAR Pacific Implementation Panel and is serving as a Coordinating Lead Author on the IPCC AR5.

**LEEDS (UoL):** The Institute for Climate and Atmospheric Science (ICAS) in the School of Earth and Environment is a world-class research community of 20 academic staff and ~60 PDRAs and PhD students. ICAS has a long track record of research in clouds and aerosols, and in developing a unique range of models, including the GLOMAP global aerosol model, the UKCA modal global aerosol model in the UK Unified Model and cloud models. ICAS has extensive collaborations with the Met Office, the Met Office Hadley Centre and scientists in the National Centre for Atmospheric Science. ICAS is home to several scientists in NCAS Weather and Composition.

*Prof Ken Carslaw* (UoL PI): is Professor of Atmospheric Science, holds a Royal Society Wolfson Merit Award and has published 120 peer-reviewed papers (h-index 39). He has 20 years’ experience in atmospheric aerosol science. Ken is PI of the GLOMAP global aerosol model project and has a group of 4 PhD students and 8 postdocs working on tropospheric aerosol and cloud problems. His group developed the HadGEM-UKCA aerosol model and is pioneering the use of model emulators and uncertainty analysis of the global indirect effect. His group has a long track record of model evaluation, including black carbon and CCN. He is now leading the ambitious Global Aerosol Synthesis and Science Project (GASSP) to reduce model uncertainty. He collaborates extensively with the Met Office and is a member of the PEGASIS EU Project Steering Group.

*Prof Alan Blyth* (UoL co-I): is the Director of NCAS Weather and Professor of Atmospheric Science. He has over 30 years experience in cloud physics observations and modelling having led UK RICO, ICEPIC, CSIP (consortia), COPS (consortia) and the recent COPE field campaigns, all in collaboration with the Met Office. His research has focussed on the microphysics of clouds, the physical properties of clouds including the influence of aerosols and the interactions between dynamics and cloud microphysics in clouds. His group has developed and used high-resolution cloud models.

*Prof Paul Field* (UoL co-I): has 16 years experience in cloud physics observations and modelling. He manages a group of 3 scientists at the Met Office, responsible for improving cloud microphysical representations in the Unified Model, a PDRA and PhD students at UoL and UoM. He has extensive experience with data analysis of aircraft observations and comparing those with modelling output in novel ways. He has been appointed to the UoL at 30% FTE in 2013 to develop a group exploring aerosol-cloud interactions and is an Affiliate Scientist at NCAR.

**MANCHESTER (UoM):** The Centre for Atmospheric Sciences (CAS) in the School of Earth, Atmospheric and Environmental Sciences comprises 12 members of academic staff, 30 PDRAs and 23 PG students. CAS currently holds over £9M in NERC grants (2006-present). CAS hosts 7 members of National Centre for Atmospheric Sciences (NCAS) staff providing strategic input into UK aerosol and cloud science together with extensive state of the art equipment for airborne measurements of aerosol size and composition along with cloud physics.

*Prof Hugh Coe* (UoM PI): is Professor of Atmospheric Composition with over 20 years experience in measuring the physical and chemical characterisation of aerosol particles. He has published 107 peer reviewed publications (h-index 38) and currently holds 11 research grants, including 9 as lead Manchester PI, totalling over £3M. He is currently the NCAS member of the FAAM Aircraft Operations Committee and was chair until 2008. He is the PI of the VOCALS-UK Consortium and is currently a member of the VOCALS international Scientific Steering group. He is NCAS Co-Director for airborne measurements and the Project PI for the NERC SAMBBA consortium project.

*Prof Martin Gallagher* (UoM co-I): Professor of Atmospheric Physics, Martin is FGAM line manager for national capability in cloud instrumentation, Member NCAS Utilisation Committee, he is manager of non-core FGAM cloud instrumentation and installations on FAAM Bae 146. He has a strong track record in multi-disciplinary research with more than 110 peer reviewed publications.

*Prof Tom Choularton* (UoM co-I): Professor Choularton has over 30 years experience in cloud microphysics and cloud aerosol interactions, having been PI of APPRAISE clouds, CWVC and CLACE. He is an author of over 200 peer-reviewed papers, and was awarded the Mason Gold Medal for research in cloud physics and cloud aerosol interactions by the Royal Meteorological Society in 2007.

*Dr James Allan* (UoM co-I): is a research fellow and NCAS scientist in the composition directorate, who specialises in atmospheric aerosol measurements. He has been involved in the development of the Aerodyne Aerosol Mass Spectrometer and has been central to many of the innovations that have occurred since. He has published 41 peer-reviewed publications, 6 as first author (h-index 23). He is currently an investigator on 5 NERC grants totalling £1.7M, including 1 as PI for ACMME and MC4 grants.

*Dr Paul Connolly (*UoM co-I): SeniorLecturer in Atmospheric Science, with interests in aerosol cloud interactions, convective cloud processes and ice microphysics. He has worked extensively developing the Met Office large eddy simulation model and assessing whether aerosol-cloud interactions should be included in NWP models. He developed the explicit microphysics model ACPIM and has performed laboratory and filed studies of ice nucleation on a range of dust and organic aerosol. He has 25 peer reviewed publications and 5 in press.

*Dr. James Dorsey (UoM co-I):* is an NCAS instrument scientist specialising in preparation, deployment, and operation of cloud spectrometers. He is also working on a single particle depolarisation probe to distinguish between different particle types (drops, ice crystals, ash,and dust) and performing model simulations of scattering and depolarisation of light by particles.

**OXFORD (UoO):** is consistently ranked amongst the top-ten research universities in the world. With substantial recent and ongoing investment in physical climate science research, faculty and infrastructure, the University now employs more than 120 staff directly working within climate science research groups. The University has existing formal links to the European Center for Medium Range Weather Forecasting, and NERC’s National Centre for Atmospheric Science and is one of the partners in the Met Office’s Academic Partnership scheme.

*Dr Philip Stier* (UoO PI): is a University Lecturer in Atmospheric Physics in the Department of Physics where he leads the Climate Processes Group and a Fellow in Physics at Oriel College. Dr Stier is co-chair of the international AeroCom aerosol intercomparison project-working group on direct radiative forcing and on the steering committees of the HadGEM-UKCA and ECHAM-ESM models. He has published widely on aerosol and cloud effects on radiation and climate (over 50 publications with on average over 50 citations, h-index of 24) and a track record of utilising aircraft and remote sensing observations for the assessment of the process representation and effects of black carbon in global aerosol-climate models. To improve the intercomparison and uptake of observational data in modelling studies, he has initiated the development of the STFC/NERC supported Community Intercomparison Suite which will be used for data synthesis and distribution in CLARIFY. He is PI on three NERC and one EC-FP7 projects and is an ERC grant holder. The Climate Processes Group currently consists of 4 postdoctoral researchers and 4 PhD students.

*Prof Richard Washington* (UoO co-I): Richard Washington is Professor of Climate Science at the School of Geography and the Environment and Fellow of [Keble College](http://www.keble.ox.ac.uk/). He runs the Climate Research Lab in the Oxford University Centre for the Environment and specializes in African climate science. Richard is Co-Chair World Climate Research Program African Climate Variability Panel (CLIVAR-VACS) and has published widely on aerosols (in particular mineral dust) production, transport and deposition. He is the PI of the NERC funded FENNEC and DO4MODELS projects (£3.7m, and £1.1m respectively) using aircraft and surface based observations to constrain aerosol models. He oversees 5 postdoctoral positions and supervises 6 PhD students.

**READING (UoR):** The Department of Meteorology has received the highest grading in all the Research Assessment Exercises of research in UK Universities. Housing around 50 academics and senior research fellows, 90 research staff and 85 PhD students, research there includes a wide range of dynamical and physical meteorology, including computer modelling, laboratory measurements and field campaigns. The University recently provided around 20 posts in environment and climate related fields as part of its Academic Investment programme. The Department houses the Directorates for the climate section of the NERC collaborative centres National Centre for Atmospheric Science (NCAS) and National Centre for Earth Observation (NCEO), as well as around 30 MetOffice @ Reading scientists. There is extensive use of and expertise concerning the UM within the Department.

*Dr Nicolas Bellouin* (UoR PI): Dr Nicolas Bellouin has over 10-years of expertise, acquired while working at the Met Office Hadley Centre, in the role of aerosols in the climate system and uses satellite observations and large-scale modelling. His knowledge of the aerosol schemes in the Hadley Centre climate model is of particular relevance to this proposal. He has published 40 papers in peer-reviewed journals and has an h-index of 21. Because of his strong scientific reputation, Dr Bellouin was invited to apply to the Department of Meteorology of the University of Reading as part of its Academic Investment Project, aimed at recruiting excellent researchers working in areas of critical global importance such as climate change. Dr Bellouin joined the Department of Meteorology in November 2012, where he now supervises a PhD student.

*Prof Eleanor Highwood* (UoR co-I): is Professor of Climate Physics with 15 years of experience in the field of aerosol-climate interaction including the use of GCMs to examine the semi-direct effect of aerosols, and the use of airborne observations of aerosol optical properties in modelling studies She has provided scientific leadership for several aircraft campaigns with the FAAM BAe-146 (as PI for ADRIEX and DODO and co-I for FENNEC and ADIENT). Prof Highwood has published over 50 peer-reviewed papers, and has earned more than £3M in research funding in the past 15 years. She currently supervises 4 postdoctoral researchers on 4 separate projects and co-supervises 3 PhD students. She is an NCAS-Climate PI, leading collaborative work on the impact of aerosols, the hydrological cycle and near-term climate predictions. She is also serving as Head of Department of Meteorology (one of 4) and Vice President of the Royal Meteorological Society.

**CLoud-Aerosol-Radiation Interactions and Forcing: Year 2016 (CLARIFY-2016)**

**CASE FOR SUPPORT PART 2: The Science Case**

1. **EXECUTIVE SUMMARY:**

The representation of clouds, aerosols and cloud-aerosol-radiation impacts remain the largest uncertainties in climate change, limiting our ability to accurately reconstruct and predict future climate change. The SE Atlantic is a region where high atmospheric aerosol loadings and semi-permanent stratocumulus cloud are co-located providing a natural laboratory for studying the full range of aerosol-radiation and aerosol-cloud interactions and their perturbations of the Earth’s radiation budget. These perturbations have a significant impact, not just locally but also via global teleconnections on wider changes in climate. There have never been detailed measurements of the combined cloud-aerosol-radiation system over the SE Atlantic although such measurements are crucial in constraining the current generation of large eddy simulation, numerical weather prediction and climate models. CLARIFY-2016 will deliver a wide range of airborne, surface-based and satellite measurements of clouds, aerosols, and their radiative impacts to 1) improve representation and reduce uncertainty in model estimates of the direct, semi-direct and indirect radiative effect of absorbing biomass burning aerosols; 2) improve our knowledge and representation of the processes determining stratocumulus cloud microphysical and radiative properties; 3) challenge, validate and improve satellite retrievals of cloud and aerosol and their radiative impacts; 4) improve numerical models of cloud and aerosol and their impacts on radiation, weather and climate. CLARIFY is a major consortium programme consisting of 5 principal UK universities with project partners from the UK Met Office, European universities and research institutes and the US NSF ONFIRE (ObservatioNs of Fires Impact on the southeast atlantic Region; 5 NASA research centres and 8 USA universities) and US NASA ORACLES (ObseRvations of Aerosols above CLouds and their interactions; 22 USA universities and research labs) consortia making CLARIFY a truly international, synergistic project.

1. **SCIENTIFIC RATIONALE**

The interaction of clouds, aerosols and radiation are highlighted as key climate uncertainties in the recent Intergovernmental Panel on Climate Change (IPCC) assessment report (Boucher et al., 2013). Aerosol-radiation interactions stem from direct scattering and absorption of solar and terrestrial radiation by aerosols, thereby changing the planetary albedo. Aerosol-cloud interactions, also termed indirect effects, arise from aerosols acting as cloud condensation (CCN) in warm clouds. An increase in the number of CCN translates into larger concentrations of smaller cloud droplets, increasing cloud albedo (Twomey, 1974). Both aerosol-radiation and aerosol-cloud interactions trigger fast adjustments to the profiles of temperature, moisture, and cloud water content, which ultimately affect cloud formation and precipitation rates (e.g. Albrecht, 1989; Pincus and Baker, 1994; Johnson et al., 2004). The quantification of interactions in the cloud-aerosol-radiation system remains elusive. The recent IPCC report (Boucher et al., 2013) stresses that aerosol climate impacts remain the largest uncertainty in driving climate change, with a global mean effective forcing of -0.50±0.40Wm-2 for the aerosol-radiation-interaction and in the range 0 to ‑0.9Wm-2 for the aerosol-cloud-interaction thereby counter-balancing a significant, but poorly constrained, fraction of greenhouse gas-induced global warming which is estimated as +2.8±0.3Wm-2 (Myhre et al., 2013a). This uncertainty impacts our ability to attribute climate change, to quantify climate sensitivity, and therefore to improve the accuracy of future climate change projections. In regions with strong anthropogenic influences, aerosol radiative forcings are an order of magnitude larger than their global mean values, limiting our ability to provide reliable regional climate projections.

Biomass burning smoke aerosol (BBA) consists of complex organic carbon compounds mixed with black carbon and inorganic species such as nitrate and sulphate. Black carbon is a strong absorber of sunlight (e.g. Shindell et al., 2012; Bond et al., 2013) and certain organic compounds (so-called ‘brown carbon’) also absorb sunlight, particularly at shorter UV wavelengths (e.g. Andreae and Gelencsér, 2006). BBA is an important component of anthropogenic aerosol being produced from fires from deforestation, savannah burning, agricultural waste, and domestic biofuels with global emissions estimated to have increased by 25% since pre-industrial times (Lamarque et al., 2010). The African continent is the largest global source of BBA currently contributing around 25Tg[C]year-1 or 50% of global emissions (van der Werf et al., 2010). The meteorological transport of BBA over southern Africa during the dry season is dominated by an anticyclonic circulation with westward transport on the northern periphery and eastward transport on the southern periphery (Swap et al., 2002; Garstang et al., 1996). Over the continent, vertical mixing is inhibited by stable layers at the top of the continental boundary layer (around 3km ASL) and by the main subsidence inversion (around 5km ASL) (Harrison, 1993; Garstang et al., 1996).

philip_figure.tifOver the SE Atlantic the BBA in the residual continental boundary layer over-rides the marine boundary layer where low sea-surface temperatures give rise to persistent stratocumulus cloud (Fig 1). A large temperature inversion (e.g. Haywood et al, 2003; Osborne et al., 2004) may inhibit mixing between the BBA in the elevated residual continental boundary layer and the marine boundary layer which, in turn, may limit the interaction with the clouds. However, the degree of aerosol-cloud interaction is highly uncertain, highlighting the need for detailed measurements.

aerocom.tifBBA is estimated to exert a neutral global direct radiative forcing of -0.1 to +0.1Wm-2 (Boucher et al., 2013). Even the sign of the global mean direct radiative forcing is in doubt because the single scattering albedo (SSA) of BBAs is close to the balance point between net reflection and net absorption of sunlight (e.g. Haywood and Shine, 1995). However, regionally BBA plays a far more important role: nowhere is the uncertainty in the direct radiative effect and forcing more apparent than over the SE Atlantic during the August-September dry season (Fig 2).

Fig 2 shows the ‘direct’ radiative forcing derived from models participating in AEROCOM (Myhre et al., 2013b) indicating a regional hotspot for BBA forcing over the SE Atlantic but with significant uncertainty because BBA can exist above the stratocumulus decreasing the planetary albedo. To accurately model the aerosol direct effect, models need to represent all of the following: the magnitude and geographic distribution of the aerosol optical depth (AOD), the wavelength dependent SSA, the BBA vertical profile, the geographic distribution of the cloud, the cloud fraction, the cloud liquid water content, the cloud droplet effective radii, and the cloud vertical profile (Keil and Haywood, 2003; Samset et al., 2012).

Another implication of BBA overlying cloud is that satellite retrievals of cloud that rely on visible wavelengths are generally biased low in cloud optical depth and effective radius (e.g. Hsu et al., 2003; Haywood et al., 2004, Wilcox et al., 2009) with implications for remotely sensed correlative studies of aerosol-cloud interactions (Quaas et al., 2008). Recently de Graaf (2012) used high spectral resolution satellite data to show that the instantaneous direct radiative effect of BBA over clouds in the SE Atlantic region could be stronger than +130 Wm-2 instantaneously and +23 Wm-2 in the monthly mean. These values are far stronger than those diagnosed in climate models which reach only +50Wm-2 instantaneously, suggesting that models misrepresent at least one key parameter noted above.

A further aerosol-radiation interaction occurs as a fast adjustment to the direct effect and is called the semi-direct effect, whereby the heating of the absorbing BBA layer and the reduction in surface temperature modify the atmospheric stability, clouds and hence radiation. Satellite data over the Amazon has suggested a decrease in cloud fraction when BBA is situated above cloud (Koren, 2004). Satellite observations over southern Atlantic stratocumulus have shown a thickening of cloud underlying BBA (Wilcox, 2012, Constantino and Breon, 2013). Wilcox (2012) estimated that this produced a negative radiative effect that compensated for 60% of the above cloud positive direct effect. Model studies of the semi-direct effect take two main approaches: large eddy model (LEM) simulations and global modelling. Each approach has limitations that we will overcome in CLARIFY. LEMs have been used to explore the detailed mechanisms of the semi-direct effect (e.g. Johnson et al, 2004, Feingold et al., 2005, Hill and Dobbie, 2008) although they typically have relatively small domain sizes and therefore cannot account for the impact of aerosol in modifying synoptic scale circulations. Global modelling studies are able to represent impacts on synoptic and regional scale dynamics and circulation patterns (e.g. Allen and Sherwood, 2010; Randles and Ramaswamy, 2010) but are unable to represent the detailed process level mechanisms captured by LEMs. Studies in LEMs and global climate models have emphasised the importance of the vertical profile of aerosol and the degree of absorption (Johnson, 2004, Randles and Ramaswamy, 2010, Samset et al., 2012). Randles and Ramaswamy (2010) and Allen and Sherwood (2010) document the response to the semi-direct effect via atmospheric impacts on stabilisation, reduced surface fluxes and subsequent evolution of the modelled dynamical impacts. Climate models need to parameterise many of the mechanisms by which the semi-direct effect operates and the climate response is likely to be sensitive to the details of the parameterisation. Johnson (2004) found the semi-direct effect to be 5 times smaller in global scale models compared to LEMs although these results are challenged by Allen and Sherwood (2010). In addition, internal variability masks local semi-direct effects, severely decreasing the statistical significance in previous studies of modelled semi-direct effects (e.g. Ghan et al., 2012) and our ability to assess their fidelity.

Aerosol-cloud interactions, or ‘indirect effects’, remain one of the most elusive but key parameters in climate prediction(Stevens and Feingold, 2009; Boucher et al., 2013). For stratocumulus, the effect of increased CCN leading to cloud brightening can be modulated by changes in precipitation and subsequent changes to cloud water amounts through entrainment processes (e.g. Ackerman et al. 2004). Satellite studies of aerosol-cloud interactions in the region emphasise the critical role of the vertical profile of aerosol and cloud (Constantino and Breon, 2013). While global bulk aerosol models and empirical representations of aerosol indirect effects are being replaced with new microphysical aerosol models such as GLOMAP/UKCA-mode (e.g. Mann et al., 2010; Bellouin et al., 2013) and more explicit representation of cloud and precipitation processes (Wilson et al., 2008), such schemes require extensive evaluation. The spatial resolution of global models (~100 km) is widely recognised as inadequate for investigating essential aerosol-cloud interaction processes at the cloud scale (~10’s m). Thus relationships between sub-grid-scale variables such as cloud updraft velocity and entrainment from LEMs and their link to large scale boundary layer variables are being sought, but, while promising, are far from well established (e.g. Golaz et al., 2011; Malavelle et al., 2013). Simulations with HadGEM2-CLASSIC suggest that, while BBA interaction with cloud may be limited by vertical stratification, it does enter the marine boundary layer and interact with cloud producing a strong indirect effect in the region (Fig 3).

classic_1st_indirect_effect.tifAn assessment of parametric uncertainty in the GLOMAP global model driven by ECMWF meteorology and observed low-level clouds (Lee et al., 2013) showed that BBA particles are one of the largest sources of uncertainty in CCN at cloud base. However, the contribution of BBA to uncertainty in indirect forcing was small (Carslaw et al., 2013) because strong particle sources essentially saturated cloud drop concentrations in the affected clouds. However, Lee et al. (2013) and Carslaw et al. (2013) did not assess the effect of uncertainties in the physical model, which control the extent to which BBA and clouds mix.

There are important open questions about such global model assessments of BBA indirect effects that cannot be resolved without additional measurements. For example, the susceptibility of the clouds in background conditions; aerosol activation processes; uncertainty about where and when BBA aerosol is entrained into the MBL and the impact of such entrainment on the microphysical and radiative properties of the cloud.

The stratocumulus decks of the SE Atlantic have been linked via global-teleconnections to precipitation anomalies in Brazilian rainfall, SE Atlantic stratocumulus that is too bright can lead to precipitation deficits in the Norde-Est and Amazonian regions (Milton and Earnshaw, 2007; Jones et al., 2009). Similarly Atlantic sea-surface temperature gradients and the hemispherical asymmetry in the energy balance are strongly impacted by SE Atlantic stratocumulus (Jones and Haywood, 2012) influencing the position of the ITCZ, and hence the African and Asian monsoon.

The last major international measurement campaign investigating biomass burning in Southern Africa was the Southern AFricAn Regional science Initiative in 2000 (SAFARI-2000). The SAFARI-2000 dry-season intensive campaign focussed on the emissions, transport and transformation of BBA plumes and the validation of satellite remote sensing retrievals of aerosol and cloud from the Terra satellite (Swap et al., 2002). The majority of investigations over the SE Atlantic were basic aerosol microphysics and cloud-free radiative impact studies (Haywood et al., 2003, Keil and Haywood, 2003, Osborne et al., 2004). Since SAFARI-2000, significant advances in airborne measurement of BC (e.g. Schwarz et al., 2008; McMeeking et al., 2011); organic and inorganic aerosol compounds (Morgan et al., 2010) and aerosol physical properties have occurred. In addition, improvements in the accuracy and sensitivity of measurements of aerosol optical properties, notably absorption (e,g. Sedlacek and Lee, 2007) have been made. Airborne lidar instrumentation and retrievals allow concurrent mapping of vertical distributions of aerosols above clouds (e.g. Marenco et al., 2011). An extensive set of measurements of stratocumulus clouds has been performed during VOCALS off the Pacific coast of S. America (Wood et al., 2011) with one of the foci being aerosol-cloud interaction (e.g. Yang et al., 2011; Painemal and Zuidema, 2013). However, the aerosol composition, sources and interaction with the clouds in the VOCALS region are very different to those over the SE Atlantic. Model capabilities have also improved: in 2000 aerosol modelling was in its infancy with only two global chemical transport models estimating the direct radiative forcing and cloud-albedo indirect forcing of BBA in the IPCC report (Ramaswamy et al, 2001). Since 2000, the focus for aerosol-radiation interactions has shifted to areas where model results diverge (e.g. SE Atlantic, Fig 1). Global aerosol microphysics models have also been developed and are coupled to climate models and are being coupled to cloud models at high resolution. Aerosol-cloud interactions are now studied at scales ranging from LEMs with resolutions of a few meters, through cloud resolving models, and limited area numerical weather prediction models to global models with resolutions of ~100km. New approaches to understand sources of aerosol uncertainty have also been developed (Lee et al., 2013). However, high quality validation data in the SE Atlantic with which to challenge the global and cloud resolving models is almost entirely lacking.

1. ***THE CLARIFY-2016 APPROACH AND THE NEED FOR A LARGE GRANT***

Quantifying aerosol, cloud and radiation interactions, the role of each forcing mechanism and the associated dynamical and climatic feedbacks are some of the biggest challenges facing the atmospheric science community. Tackling such major problems across scales from the micro-scale to global scale requires the collaborative effort of the UK scientists with collective expertise in aerosol and cloud measurement, microphysical modelling, numerical weather prediction, climate modelling and remote sensing. Such a large collaborative project can only be achieved with a large grant. The UK is at the international forefront of these areas, with comprehensive cloud, aerosol and remote sensing instrumentation having been developed for the FAAM aircraft and the GLOMAP-mode state-of-the-science aerosol model (Mann et al., 2010) which is being incorporated in fine-resolution and coarse resolution versions of the Met Office Unified Model (Bellouin et al., 2013). The Met Office will be involved as a project partner, providing high resolution NWP models for optimal positioning of the aircraft, case study modelling of aerosol-cloud interactions using the newly developed 4A microphysics, the HadGEM3 climate model for assessing the global impacts of aerosol-radiation and aerosol-cloud interactions and significant contributions to the flying hours and superstructure costs (see Pathways to Impacts). Strong links have been developed with both the ORACLES (5 NASA centres and 8 US universities) and ONFIRE (22 US universities and research institutes) who propose complementary concurrent measurements with their ER2, P3-B, and C-130 aircraft (see letters of support). The NSF C-130 deployment is planned for Sao Tome with the P3-B and ER-2 deployed to Walvis Bay over a three year time period allowing co-ordinated dual-aircraft sorties with the FAAM aircraft, placing CLARIFY data in context with respect to inter-annual variability, and effective data sharing between all groups which has proved extremely valuable in past campaigns (e.g. VOCALS; Wood et al., 2011; see International Synergy). The FAAM aircraft is capable of achieving the science objectives documented here by operating either independently or operating in conjunction with other aircraft.

1. **AIMS AND OBJECTIVES**

**CLARIFY-2016 will use the natural laboratory of the SE Atlantic to improve the representation of BBAs and clouds in models of a range of scales, increase the fidelity of aerosol-radiation and aerosol-cloud interaction processes and cloud representation, and their impacts on local, regional and global weather and climate.**

Key objectives of CLARIFY-2016 are:

KO1: Measure and understand the physical, chemical, optical and radiative properties of BBAs in the key SE Atlantic region (WP2).

KO2: Understand, evaluate and improve the physical properties of the SE Atlantic stratocumulus clouds and their environment in a range of models (WP2, 4, 5).

KO3: Evaluate and improve the representation of BBA‑radiation interactions over the SE Atlantic when clouds are absent/present at a range of model scales and resolutions (WP2, 3,,5).

KO4: Evaluate and improve the representation of BBA-cloud interactions over the SE Atlantic at a range of model scales and resolutions (WP2, 4, 5)

These objectives will be achieved by conducting an intensive airborne field campaign with supporting surface and satellite measurements. The measurements will be used to challenge, and develop improved models at different spatial scales from the cloud scale to the global scale that couple aerosols, clouds and radiation. Enabling objectives are:-

EO1: To use forecast and observations to optimise scheduling of the flight plans, balancing our operations to ensure data provision for all our enabling objectives (WP1)

EO2: To characterise chemical, microphysical, optical and radiative properties of BBA over the SE Atlantic region, focussing on black carbon, absorption and single scattering albedo (WP2, WP4).

EO3: To investigate the geographic and vertical profile of BBA over the region (WP2, WP3, WP4).

EO4: To characterise the vertical thermodynamic structure of the MBL, residual continental polluted layer, and free troposphere and diurnal and synoptic scale variations (WP2, WP4).

EO5: To characterise broad-band and spectral reflectance of the ocean surface and stratocumulus clouds when overlying BBA is present/absent from the atmospheric column (WP2, WP3).

EO6: To characterise key cloud processes and parameters such as entrainment, cloud dynamics, cloud-base updraft velocities, cloud condensation nuclei (CCN), cloud droplet number concentrations (CDNC), cloud droplet effective radius, cloud liquid water path and optical depth (WP2, WP4).

EO7: To use CLARIFY campaign data with representative statistical sampling as well as high-resolution models to establish robust relationships between sub-grid scale variables and large-scale model parameters suitable for constraining aerosol-cloud interactions (WP4, 5).

EO8: To use synergistic observations/model simulations to investigate impacts on NWP and climate model performance, feedback mechanisms, regional and global climate impacts and teleconnections (WP2, WP3, WP4, WP5).

1. **INTERNATIONAL SYNERGY**

Aerosol, cloud and radiation interactions are a major international concern. The UK-led CLARIFY‑2016 has stimulated a great deal of international interest. Specifically:-

• An agreement is in place that superstructure costs of the FAAM aircraft detachment and flying hours will be matched by the UK Met Office halving deployment costs (see letter of support).

• NASA propose deploying the ER-2 high altitude platform and the P3-B in-situ sampling aircraft as part of their ORACLES program to Walvis Bay (PI, Redemann, see letter of support).

• USA universities/national labs propose deploying the NSF funded C-130 aircraft as part of their ONFIRE program to Sao Tome Island (PI, Zuidema, see letter of support).

• NWU proposes deployment of their instrumented Aerocommander 690A and a surface site at Gobabeb to provide additional measurements of aerosol and cloud microphysical properties.

• The unique in-situ and remote sensing capabilities of the FAAM aircraft ensures capability both as a stand-alone platform or in conjunction with other platforms minimising deployment risk.

• A data sharing agreement will be put in place so that participants from CLARIFY-2016, ORACLES and ONFIRE will freely exchange data.

• While capable of operating alone, other participating aircraft will extend the geographical and temporal sampling, enable concurrent in-situ and remote sensing measurements, and more comprehensive assessment of the diurnal cycle of BBA, cloud and MBL structure.

• Activities are linked and supported by AEROCOM (http://aerocom.met.no) (see letter of support) allowing comprehensive dissemination and uptake of CLARIFY data.

1. **EXPERIMENTAL AND MODELLING STRATEGIES**

**EXPERIMENTAL:** CLARIFY-2016 will include a major field experiment based primarily around airborne measurements with supporting ground-based and satellite-based measurements designed to target key aspects of the aerosol-radiation and cloud-aerosol interactions.

***6.1: Airborne Measurements:*** The main experimental platform will be the FAAM BAe146 aircraft, which is jointly funded by NERC and the Met Office. The aircraft will be based in Walvis Bay on the coast of Namibia which provides an optimum secure operating base for the study of BBA and stratocumulus cloud (Fig 1). The FAAM aircraft will be equipped to maximise scientific aerosol-cloud-interaction and aerosol-radiation-interaction measurement capability, while maintaining a high duration of over 5hours flight time giving a range of around 2000-3000km depending on altitude. CLARIFY has requested a total of 125hours flying time of which 80hours are in theatre science hours. A summary of the instrumentation is provided in Table 1.

Instrument_Table_3.tiff

Our flight plans are based on PI experience including investigations of BBA and cloud during SAFARI2000, AMMA, VOCALS and FENNEC. Flights will be performed in close co-ordination with satellite overpasses carrying passive and active sensors. The flights detailed below are broadly aligned with the Enabling Objectives and assume that the BAe146 aircraft will be operating alone (except for inter-comparison flights), but flight patterns will be modified to co-ordinate with other participating NASA and NOAA aircraft including wing-tip to wing-tip inter-comparisons. The following flights patterns will be performed (indicative flight hours are in brackets although blends of missions are likely):-

*i) Survey Flights for aerosol, cloud and radiation characterisation (27 hours):* Will consist of long-leg duration flights over large areas performed in conjunction with geostationary (e.g. SEVIRI) and polar-orbiting satellite overpasses (e.g. CALIPSO, MODIS, MISR) to map out the spatial distribution and variability in BBA, cloud and the thermodynamic structure associated with each. High altitude (~25,000ft) straight and level runs (SLRs) will use the lidar to map variations in the BBA structure and stratocumulus cloud-top, spectral and broadband radiometers (SWS, SHIMS) will determine the magnitude and the spectral distribution of the aerosol direct radiative effect (Haywood et al., 2003; 2011), and drop-sondes will be used to characterise the thermodynamic structure of the free-troposphere, BBA rich residual continental layer, and marine boundary layer. These SLRs will identify regions where further detailed investigation is warranted. Aerosol characterisation will be targeted using mid-level (~8,000 to 20,000ft) SLRs and profiles to characterise BBA intrinsic properties (chemical, microphysical, radiative, AODs, fine/coarse mode fractions and CCN properties) and extrinsic properties (geographic distribution and vertical profile). SLRs in the MBL will determine the relative contribution of both BBA and aerosols of other origin (e.g. marine, mineral dust). Cloud characterisation will target key microphysical and dynamics variables of vertical profiles of vertical wind speed, cloud droplet number concentration (CDNC) and size distribution (PSD) from cloud base to cloud top along with derived liquid water content (LWC), integrated liquid water path (LWP), effective radius (reff) with height in cloud and the cloud optical depth () which will be determined as a function of environmental conditions. SLRs near cloud base, within the heart of the stratocumulus cloud and near the cloud tops will also be used to characterise the macro-physical attributes of the cloud such as its depth and a transition to more cumulus-like open cell clouds. One/two baseline radiation flights will be performed in the absence of significant BBA in cloud-free and cloudy conditions (likely in south of operating region, Fig 1) to provide baseline measurements of broad-band and spectral dependence of surface reflectance and clouds. The cloud retrievals of LWP, cloud-top reff, and  from solar and microwave instrumentation will be validated by in-situ measurements with the suite of OPCs.

*ii) Aerosol-Radiation Interaction Flights (27 hours):* Will focus on detailed measurements over a limited area when BBA is present and cloud is absent/present (Fig 4).

direct effect schematic.tifWhen cloud is absent radiometric measurements above and below the BBA will characterise broad-band and spectral irradiances and radiances, provide aerosol vertical distribution from lidar and enable sea-surface reflectance characterisation. SLRs for microphysical characterisation of BBA will be performed. Orbits characterise the radiances as a function of scattering angle will be performed to allow retrievals of aerosol size distribution and the AOD in a manner analogous to AERONET almucantar scans (Osborne et al, 2008, 2011). Profiles through the BBA will characterise the extinction coefficient from the CRD spectrometer the aerosol optical depth. When BBA overlies cloud, SLRs above and below BBA will additionally provide remotely sensed estimates of cloud-top reff and LWP from solar and microwave instrumentation contaminated by the presence of BBA. Saw-tooth through cloud will provide detailed characterisation of cloud microphysical parameters within cloud and at cloud-top from in-situ measurements (reff, LWP, LWC, ). SLRs above cloud will provide spectral and broad-band radiances and irradiances, cloud-top reff and LWP from solar and microwave instrumentation un‑contaminated by the presence BBA. Profiles through the BBA will characterise BBA vertical profile and AOD.

*iii) Aerosol-cloud interactions (27hours):* Key variables include cloud droplet size distributions (and hence CDNC and reff), drizzle and raindrop size distribution and precipitation rates, bulk condensed water, total water specific humidity, LWP, vertical wind speed, SW and LW broadband radiative fluxes, updraft turbulence variation, temperature, liquid water static energy temperature, and humidity, and microphysical and chemical properties of cloud residuals.

clarify_flightplan_schematic_indirect.tifA typical flight pattern is shown in Fig 5. SLRs just below cloud base and just above cloud base will be used to investigate CCN budgets (D4.1), closure and aerosol loss due to scavenging (D4.2). SLRs below-cloud, in-cloud and above-cloud will measure CCN, cloud droplet size distributions and of drizzle size distribution below cloud base using the CIP probes including those from a new high speed cloud spectrometer (SPEC Inc. FCDP) to provide information on the entrainment process, the influence of entrainment on cloud microphysics and constraints on BBA entrainment rates into cloud top. This will include capturing fine scale cloud and turbulence structure and evolution of the entrainment interfacial layer across the transition (Caughey et al. (1982), Kurowski et al (2009) and Malinowski et al. (2013)) using flight strategies developed from past airborne stratocumulus projects. Vertical profile/saw-tooth/stepped profile measurements will also be made of the size distribution of cloud droplets over the size range 1-200 µm using FCDP and 2D-S probes at high frequency capturing cloud droplets and precipitation. The inboard AMS/SP2/OPCs will be switched between the CVI inlet to measure droplet residuals and the total inlet to determine the size and composition of the nucleation scavenged and interstitial aerosol as a function of position and height in the cloud. Measurements higher in the cloud together with turbulence measurements will examine the evolution of the cloud microphysics as condensation growth and coalescence occur. Precipitation susceptibility (dlnP~dlnNccn) will be determined from measurements of precipitation rate, cloud water contents, cloud thickness and CCN concentrations. Compositing of cloudy columns with a given thickness (or LWP) allow derivation of the relation between changes in precipitation and aerosol perturbations (e.g. modifying the method of Terai et al., 2012) (D4.3).

* 1. ***Ground Based measurements:*** A limited surface-based deployment will consist of a GRWS100 Campbell automatic weather station (1.5m temperature, humidity, wind-speed and direction, solar radiation, precipitation), halo-photonics eye-safe Doppler lidar (3-D windspeed, aerosol and cloud), TSI-Dusttraks II aerosol monitor (PM1, PM2.5 and PM10 sampler), CIMELS 6-channel sun-photometer, and passive deposition traps. Installation at Walvis Bay will ensure synergy with the aircraft profile ascents/descents on take-off and landing. This instrumentation will be augmented by surface based instrumentation from the Observational Based Research Department of the Met Office (project partner). A further surface site including CIMELS and lidar instrumentation at Gobabebb ~50km inland will be provided by NWU and LISA (project partners) where clear-skies predominate.

***6.3. Satellite Measurements:*** Geostationary (Meteosat-10 and 11) will provide standard operational SEVIRI cloud products via the Met Office (project partner). Data are available at 15minute resolution provide essential observations for optimally locating the aircraft. Aerosol retrievals derived from cloud-free regions from SEVIRI, MODIS, MISR and SEVIRI will be used to a) direct the FAAM aircraft to areas of high AOD and b) the FAAM in-situ aerosol properties will be used for validation of assumptions used in the satellite retrievals and estimates of uncertainty in retrievals. The CALIPSO lidar (Winker et al., 2004) will provide an independent observational estimate of the relative vertical profile of aerosol and cloud and identify areas where BBA is in close vertical proximity to underlying cloud. Under-flying the CALIPSO overpass using the FAAM lidar to provide ~100m resolution vertical aerosol profiles and cloud tops will allow intercomparison and validation of the coarser spatial resolution CALIPSO retrieval algorithms. Retrievals of AODs from these instruments have been successfully challenged and validated in previous measurement campaigns such as AMMA-SOP-0 for mixtures of mineral dust and BBA (Christopher et al., 2008; 2011). Next-generation satellite instruments are scheduled for launch in 2015-2016 (ATLID lidar and MSI imager on EarthCARE, polarised imager 3MI aboard Sentinel 5) and will require aircraft data in validation of aerosol and cloud retrievals. Strong links with satellite research groups (see letters of support from de Graaf, Waquet, Kahn, Christopher, Remer and Myhre) will ensure that the FAAM measurements will be assessed through very active collaboration.

**MODELLING TOOLS:** The key science questions of CLARIFY will be addressed using models that represent a wide range of both complexity and spatial scales, particularly for aerosol-cloud interactions. Central to this approach is the use of parcel models, large-eddy simulation models (LEMs), limited area numerical weather prediction (NWP) models, global NWP models, coupled-ocean-atmosphere climate models (HadGEM) and idealised GCMs (Fig 6).

scematic_of_range_of_models_no_IGCM.tifFor aerosol-radiation-interactions, the modelling strategy will employ models ranging from the high resolution LEM (~10m resolution), UM limited area NWP model (~1km resolution), UM global model (~10km resolution) and UM HadGEM (~100km resolution). For-aerosol-cloud-interactions we will use high resolution measurements to challenge, improve and validate the processes in a detailed cloud parcel model (ACPIM) and the LEM. The Unified Model (UM) will be run in two main configurations. Firstly a newly developed nested version of the UM limited area NWP model that couples the GLOMAP-mode aerosol scheme with an aerosol-cloud interacting microphysics (4A model) down to 100 m horizontal grid resolution. These simulations will be used to provide meteorologically relevant forcing data to drive the high resolution LEM. Secondly, the global climate (HadGEM3) model configuration that will be used for the next CMIP6 intercomparison studies and IPCC assessment report.

***6.4. Process models:*** The Met Office LEM is a 3-D large eddy simulation model with a domain of ~10km and resolution of ~10m which has been successfully used to investigate the impact of absorbing aerosol on a variety of clouds, and, with modification, to explore the link between indirect and semi-direct effects (e.g Johnson 2004; Hill and Dobbie, 2008). The LEM will be run with the same 4A microphysics as the NWP high resolution model to provide a seamless microphysical link between the scale of metres to many kilometres. Ensembles of air trajectories will be output from the LEM and used to drive a detailed process-based model developed at UoM: the Aerosol Cloud Particle Interaction Model (ACPIM), which simulates the development of the aerosol and cloud microphysics along air trajectories with a high level of detail. ACPIM includes a detailed microphysics scheme that enables the change in the size of aerosol particles following evaporation of precipitation (rain), which is an important process in the development of aerosols near clouds. ACPIM simulates both internal and external mixtures of aerosols, including organics, whose vapour pressures are parameterised following a detailed aerosol thermodynamic model (Topping et al., 2005). Once evaluated by ACPIM, the LEM will be used to investigate aerosol-cloud effects and up-scale to coarser resolution models (Fig 5).

***6.5. Limited area NWP models:*** Cover domains of ~1000km with resolutions of up to around 1km. As a result of successfully implemented NERC measurement campaigns investigating mineral dust and BBA (e.g. AMMA, Lebel et al., 2009 ; DABEX, Haywood et al., 2008), these species and their impacts on radiation and cloud have been included in developmental versions of the Met Office NWP model. Thus, the NWP model will be initialised with near-real-time BBA emissions (e.g. Wooster et al., 2011) to support the CLARIFY detachment by forecasting BBA plumes and stratocumulus clouds, and areas where the aerosol and cloud are likely to interact. Thus a considerable synergy exists between the modelling and the measurements: (1) the NWP model will be used to optimally position the FAAM aircraft, (2) the aircraft measurements will be used to characterise BBA, cloud and aerosol-radiation and aerosol-cloud interaction, (3) the measurements will be used to improve the representation of BBA, aerosol-cloud and aerosol-radiation interactions in the hierarchy of models. High resolution NWP models with BBA modelling capability will make use of the cloud­-aerosol interacting microphysics (4A) to probe the importance of feedbacks between cloud-scale adjustments and cloud field evolution. There will be two way comparison with models of both higher complexity/resolution (LEM/ACPIM) and lower resolution GCMs thus bridging the gap to the low (~100km) resolution climate models that show such variability in estimates of the direct effect (Fig 2). Recently, Malavelle et al. (2013) used the Met Office LEM and nested NWP limited area UM to develop robust boundary-layer-dependent parameterisations of unresolved cloud-base updraft velocities as a function of model resolution. This approach shows considerable potential to bridge the gap between LEM and global scale models to improve the representation of sub-grid scale processes (e.g. West et al., 2013) which is a major hurdle in better constraining aerosol-cloud interactions (e.g. Tonttila et al., 2011; Seifert et al., 2012).

***6.6. Global Climate models:*** The HadGEM3 climate model resolution will be around 100km. The current HadGEM model (HadGEM2-ES) includes the Coupled Large-scale Aerosol Simulator for Studies in Climate (CLASSIC) aerosol scheme where BBA is treated as a separate externally mixed species partitioned into three modes (Bellouin et al., 2011). The fixed aerosol modes in this scheme do not allow physical processes such as condensation nor do they accurately represent changes in number and mass of cloud condensation nuclei (CCN). Bellouin et al (2013) have shown that the GLOMAP-mode aerosol scheme implemented in HadGEM3 overcomes many of the limitations of the CLASSIC scheme as it models aerosols as internal mixtures with dynamically evolving size distributions (Mann et al., 2010). In HadGEM3, GLOMAP-mode aerosol is fully coupled to radiation via the Edwards-Slingo radiation scheme, and cloud via the PC2 cloud scheme (Wilson et al., 2008) using an explicit Köhler theory based activation approach (Abdul-Razzak & Ghan, 2000; West et al., 2013). HadGEM3 will be nudged to observed meteorology allowing more direct comparisons against observations from in-situ measurements using an aircraft flight track simulator (Kipling et al., 2013) and against satellite retrievals using the Community Intercomparison Suite (CIS, 2013; see Data Management Plan). Some free-running (atmosphere only and coupled atmosphere-ocean) transient HadGEM simulations will also be performed to examine the fast and slow climate responses to BBA and link the nudged simulations to the wider context. Strong links with the international aerosol and cloud modelling communities (see letters of support from Schulz, Stevens, Myhre) will ensure an efficient knowledge transfer to the international climate modelling community,

**schematic of WPs.tif7.** **DETAILED DESCRIPTION OF WORK PACKAGES AND DELIVERABLES**

The objectives will be addressed using five inter-related work-packages (WPs). The interaction between the WPs is shown in Fig 7.

**WP1: Deployment and delivery (lead: Coe UoM)**

***Central to delivering the main scientific aims of CLARIFY is the delivery of a high quality robust dataset of aerosols, clouds and radiation from across the SE Atlantic region, supported by satellite and surface observations and a range of bespoke forecast products.***

The FAAM aircraft will operate over the SE Atlantic from Walvis Bay during August/September 2016. A range of forecast and observational tools will be developed to optimally deploy the aircraft.

***WP1.1 Pre-campaign planning. UoM, UoE, Met Office, FAAM:*** Will ensure that the ground support logistics are in place, the instrumentation has been tested and installed on the aircraft and the flight plans have been fully developed in consultation with all WPs and FAAM, and in joint partnership with the Met Office. NCAS and Met Office staff resources are already being employed in the planning of this experiment and this will continue to ensure the organization will be completed well ahead of the campaign.

***D1.1:*** *Delivery of secure operating airport and facilities including aircraft GPU and ACU, laboratory facilities, surface site, accommodation and transport as per FAAM operating protocol.*

***WP1.2 Field campaign support. UoE, UoO, UoL, UoM, Met Office, project partners.*** UoE will use the UM limited area NWP model initialised with near-real-time BBA emissions (e.g. Wooster et al., 2011) to develop and provide forecast maps and cross sections of BBA concentration, cloud fraction, cloud reflectance, precipitation, wind-fields, boundary layer height, areas of interaction of BBA with the marine boundary layer. UoO and UoE will gather near real-time satellite products from project partners (e.g. SEVIRI, CALIOP, MISR, MODIS, VIIRS) and supporting measurements from the Walvis Bay surface site and links to the ORACLES and ONFIRE products for optimal deployment of the aircraft. All will provide mission scientists. Further model and remote sensing products will be provided by ECMWF, ORACLES and ONFIRE consortia (project partners).

***D1.2:*** *Delivery of a website hosting these products and links to forecast products from other operational models (e.g. NOAA and ECMWF models from project partners) for optimal deployment of the aircraft (links to D5.1) .*

***WP1.3 Quality Assured Database. UoM, UoE, UoO, Met Office, FAAM.*** Core data will be provided by FAAM as part of its data protocol. Data analysis tools and quality assurance (QA) procedures exist for much of the FAAM non-core data. The interim non-core data from FAAM will be stored at UoM. Ground-based data QA will be undertaken by Oxford. Final storage with the core data will be in a CLARIFY archive in JASMIN at BADC.

***D1.3:*** *Delivery of core, non-core, and surface site QA data from Met Office, UoM, UoE, UoO to BADC (links to all WPs).*

***WP2: Aerosol, cloud and radiation characterisation (lead UoL: Blyth)***

***Characterisation of aerosol, cloud and radiation focussing on key properties (e.g. aerosol chemical and optical properties, size distributions, CCN activity, cloud liquid water path, cloud effective radius, aerosol and cloud spatial and vertical distributions, cloud reflectance, and cloud susceptibility). Where appropriate, observations will be composited based on meteorological regime, local solar time and BBA-cloud spatial relationships.***

**WP2.1 Aerosol characterisation (UoM, UoE, UoO, Met Office):** WP2.2 will characterise the intrinsic and extrinsic properties of BBA using the flight patterns described in section 6. UoM will use the ToF-AMS to measure detailed aerosol non-refractory composition and the SP-2 to provide BBA core BC measurements, coating thicknesses and the extent of the internal mixing with other species. The UoE CRD and photo-acoustic spectrometers will provide high accuracy aerosol extinction and absorption measurements allowing accurate assessment of the single scattering albedo and AOD while the nephelometer and PSAP provide more routine back-up measurements. UoM/Met Office will measure CCN activity spectra and total CN together with aerosol number and size distribution (10nm – 20m) from wing-mounted and on-board OPCs. UoM post-campaign SEM/TEM analysis of nucleopore filters will provide additional aerosol chemical composition and morphology information. The UoM Differential Mobility Analyser, DMT Aerosol Spectrometer, and wing-mounted and on-board OPCs will provide the aerosol size distributions as a function of height from aircraft profile measurements together with SLRs, below, within and above the aerosol layers. In addition the UoM AMS and SP-2 will also sample and analyse droplet residuals using a new counterflow virtual impactor inlet (CVI) system (Brechtel Manufacturing Inc.) and the Met Office lidar will provide additional aerosol vertical profiles and AODs. The UoO and NWU (project partner) ground-based lidars, CIMELS and in-situ instrumentation will characterise aerosol vertical profiles and surface concentrations. These will be complemented with the analysis of satellite retrieved AOD from MODIS, MISR and SEVIRI, vertically resolved extinction/backscatter from CALIOP (WP2.4). These measurements will be used to challenge and improve the representation of aerosol processes and physical characteristics in the full range of models.

***D2.1:*** *Publication on the mean and variability of BBA intrinsic microphysical, chemical, and optical properties together with extrinsic mean and variability in vertical profile and geographic distribution.*

**WP2.2 Cloud characterisation (UoL, UoM, Met Office):** WP2.2 will characterise cloud dynamics and microphysical structure to determine the response to the changing thermodynamic and BBA environments using the flight methodology described in section 6. UoL/UoM will integrate the full range of cloud optical and imaging spectrometers on the FAAM aircraft covering particle size ranges from 2 to 6400 μm, with the turbulence and meteorological instruments (Table 1). The main focus will be on the cloud data synthesis in conjunction with ACPIM and LEM to characterise the physical properties of stratocumulus clouds. UoL/UoM will link measurements of cloud properties in this WP to the aerosol measurements (WP2.1) using the ACPIM and LEM (WP 4.1). The aerosol, cloud and meteorological parameters derived from the comprehensive set of aerosol size and chemical composition measurements (WP1, WP2.1) will be used in conjunction with the process models to understand the physical behaviour of the stratocumulus clouds, the dynamics and thermodynamics of their local environment, and the relationship between these and the aerosol.

The measurements will allow us to understand the impacts of above-cloud heating from the absorbing BBA layer and subsidence on cloud dynamics, microphysical and optical properties. High-spatial resolution measurements of vertical velocity (from the turbulence probe) and droplet size distributions (see 6.1iii) will enable us to determine entrainment fluxes and the influence of entrainment on cloud droplet evolution across the entrainment interfacial layer. Cloud-top SLRs will allow UoL/UoM to assess how entrainment of BBA aerosols impacts cloud droplet spectra. Entrainment-influenced stratocumulus cloud-top exhibit broadened drop spectra and lower CDNC and LWC, and analysis of these spectra (Pham and Sarkar, 2010) will be used to determine the efficiency and influence of mixing (Malinowski et al., 2013). UoM/UoL will use these measurements to constrain aerosol and cloud processes in the ACPIM and the LEM and provide the basic information required to statistically test the representation of clouds in the models. These in-situ measurements will be complemented by satellite retrieved CDNC from MODIS (Brenguier et al., 2000) cloud fraction, cloud optical depth and cloud top height from MODIS and SEVIRI (WP2.4).

***D2.2:*** *Measurements required for (a) D4.1 publication on CCN budgets (b) D4.2 publication on CCN-CDNC closure paper, and (c) D4.3 publication on impacts of cloud-scale dynamics on CDNC D3.3, & D4.1 publications.*

**WP2.3 Radiation characterisation (UoE):** UoE will use spectral radiance and broad-band and irradiance measurements from cloud-free and cloudy scenes in the absence of BBA to assess the consistency between measurements and observations. UoE will correct spectrally resolved and broad-band radiation measurements for aircraft pitch and roll from SLRs at high and low altitude with neither BBA nor cloud present (section 6.1i). We will use the high spectral resolution radiance and irradiance version of the Edwards and Slingo (1996; ES96) radiation code together with drop-sonde and in-situ measurements of atmospheric temperature, humidity, and ozone to assess the consistency of measured and modelled spectral and broad-band irradiances in clear-skies. In the absence of BBA, UoE will assess the consistency between remote sensing retrievals of cloud optical properties and in-situ measurements and assess the fidelity of the SEVIRI operational products while KNMI (PP) will extend the analysis of de Graaf et al. (2012) to MODIS and UMBC (PP) will utilise VIIRS.

***D2.3:*** *Report on the estimated uncertainty of broad-band and spectrally resolved irradiances and on the uncertainty of aircraft and SEVIRI remotely sensed retrievals of cloud optical properties when compared against observations. These link to D3.1, D3.2, D3.3.*

**WP2.4 Intercomparisons and model evaluation (UoO):** Before complex aerosol-radiation and aerosol-cloud interactions are assessed, the ability of the models used in WP3-5 to reproduce the observed aerosol, cloud and environmental conditions will be evaluated. UoO will integrate in-situ measurements, remote sensing and model data by using the newly developed Community Intercomparison Suite, which merges measurements and models (see Outline Data Management Plan). Models at scales from LEM, through high resolution NWP to HadGEM climate models will be used to run case studies with particular focus on parameterising the unresolved processes. HadGEM simulations will be nudged to meteorological analysis data, providing boundary conditions for the highest resolution UM regional simulations, which will be used to provide data to drive the process models (e.g. LEM). Model results across scales will be compared at native resolution, collocated to observational data and statistically coarse grained to the observations of aerosol, cloud and radiative properties obtained during the observational phase of CLARIFY.

***D2.4:*** *Consolidated, co-located dataset of in-situ measurement, remote sensing and model simulated aerosol and cloud parameters on central CLARIFY group workspace on JASMIN.*

***D2.5*** *Publication on a synthesised aerosol and cloud characterisation from in-situ measurements, remote sensing and the CLARIFY models.*

**WP3: Aerosol-Radiation Interaction (lead UoE: Haywood)**

***WP3 will use the synergy of the FAAM instrumentation and detailed radiative transfer models to assess the aerosol-radiation interaction (direct-effect and semi-direct effect) in cloud-free skies and cloudy skies. The observations will be used to assess the fidelity of modelled direct effects, satellite retrievals of aerosols and biases in cloud retrievals. The aerosol semi-direct effect will be investigated using observations of BBA, cloud and atmospheric structure to drive models with a range of spatial resolutions and complexities.***

***WP3.1: Assessment of the aerosol direct effect in clear-skies* (UoE):**will use spectral radiance and irradiance data from above-aerosol and below-aerosol SLRs from flights detailed in section 6.1ii (Fig 4). We will compare spectral radiance and irradiance data and broadband irradiances against those from baseline unpolluted cases (D2.3). Using the measured aerosol optical depths and microphysical properties, measured atmospheric temperature, humidity, and ozone profiles derived from in situ FAAM core- and non-core data (D1.3), we will include BBA in ES96 radiative transfer calculations (e.g. Haywood et al., 2011). Spectral radiance data (SWS) as a function of scattering angle will be used to derive aerosol size distributions using AERONET almucantar-style retrievals to assess the consistency between the remotely sensed and in-situ size distributions (e.g. Osborne et al., 2008).

***D3.1:*** *Publication assessing the consistency of ‘radiative closure’ obtained in clear-skies.*

***WP3.2: Assessment of the aerosol direct effect in cloudy-skies* (UoE):** Recent work elucidating the impacts of BBA above clouds using passive retrievals has focussed on using the spectral signatures of aerosols in reflectances (Torres et al., 2012; de Graaf et al., 2012; Jethva et al., 2013) or impacts on polarised reflectances (e.g. Knobelspiesse, 2011; Waquet et al., 2012). Combining passive and active retrievals using the CALIPSO satellite-borne lidar (e.g. Chand et al., 2008; Yu and Zhang, 2013) show considerable promise but are hampered by difficulties in co-locating satellite data with different temporal and spatial characteristics. We will circumvent these problems using both the in-situ and remote sensing measurements on the FAAM aircraft from detailed radiative closure flights. We will use spectral radiance and irradiance measurements from above-aerosol and below-aerosol SLRs when cloud is present (Fig 4). We will compare broad-band and spectral radiance and irradiance measurements/modelling when BBA is present against measurements/modelling of baseline unpolluted cases (D2.3) to determine the spectral signature and absolute magnitude of the aerosol direct radiative effect in cloudy skies. We will use aerosol microphysical properties and profiles of aerosol and cloud from the aircraft (D1.3) to assess the degree of ‘radiative closure’. We will adjust aerosol microphysical properties (e.g. black carbon absorption characteristics) to provide an optimal fit between observation and modelling.

***D3.2:*** *Publication assessing the magnitude of the direct radiative forcing of BBA overlying cloud.*

***WP3.3: Impact of overlying BBA on satellite retrievals of cloud optical properties* (UoE, UoO, Met Office, project partners):** UoE will use FAAM data to assess the bias in cloud retrievals derived from the FAAM solar radiometers caused by BBA overlying cloud (e.g. Haywood et al., 2005) using in-situ measurements and modelling the ES96 radiation code. UoE will compare the results derived from aircraft radiometers against those in unpolluted baseline conditions (D2.3). UoE and Met Office will compare case studies of the cloud properties derived from the geostationary SEVIRI instrument. UoO will utilise the CIS to co-locate additional satellite retrievals.

***D3.3.*** *Publication assessing the impact of overlying BBA on aircraft cloud retrievals, operational SEVIRI cloud retrievals and other satellite retrieval algorithms.*

***WP3.4: Assessment of the relative magnitude of the aerosol semi-direct effect* (UoR)*:*** This work-package investigates the semi-direct effect in the LEM while WP5.3 will use this analysis to evaluate coarser resolution models. Using FAAM data collected from vertical profiles throughout the campaign, UoR will compare vertical profiles of aerosol, cloud, temperature, humidity and radiation between situations with and without significant BBA present. UoR will impose combinations of these atmospheric profiles in the LEM with high horizontal and vertical resolution, calculate the direct effect, examine the evolution of the cloud layer within the model and calculate the magnitude of the semi-direct effect across the range of case studies available.

***D3.4.*** *Publication assessing the impact of the BBA semi-direct effect as captured in the LEM.*

***WP4: Aerosol-Cloud Interactions* (lead UoO: Stier)**

***WP4 will assess aerosol-cloud interactions by combining the in situ and remote sensing measurements with a hierarchy of aerosol-cloud models, from detailed process to global climate models. The observations will be used to evaluate the representation of aerosol and cloud processes in the models and to constrain uncertain model processes, such as vertical velocity variability in large-scale models.***

***WP4.1 Near-cloud CCN budgets* (UoO, UoL, UoM):**will be derived from measured and modelled near-cloud aerosol microphysical and chemical profiles to determine the relative role of BBA and other aerosols as sources of CCN. Measurements of aerosol size distribution, size-resolved aerosol composition from the AMS and SP-2, including CVI residual measurements, together with vertical wind measurements just below cloud base, just above cloud base, in the centre of cloud and just above cloud top will allow UoM to derive fluxes of the aerosol entrained into the cloud. Additional diagnostics of below-cloud and above-cloud aerosol entrainment will be implemented into the high-resolution (UoL) and global models (UoO) to derive measurement-equivalent budgets of in-cloud aerosol sources. Comparison with observations and between the model hierarchy across different resolutions (high and low resolution UM) will allow identification of systematic model biases and limitations in the ability to simulate small scale aerosol cloud interactions.

***D4.1:*** *Publication on impact of biomass burning and other sources on CCN budgets in marine stratocumulus clouds in the SE Atlantic.*

***WP4.2: Aerosol-cloud interactions* (UoL, UoM, UoO):** The aerosol and cloud measurements will be used to evaluate and improve the high-resolution process models. UoM will use ACPIM to establish whether this highly detailed model fully captures the microphysical evolution of the cloud and, in particular the sensitivity of the cloud to changes in the aerosol entering cloud from below and above. This will extend D4.1 to perform a full closure between aerosol, CCN and droplet number. Sensitivity studies using ACPIM will determine those aerosol properties that control the partitioning between interstitial and activated aerosol in each case study to evaluate the high-resolution limited area UM with cloud-­aerosol interacting microphysics (4A) and low-resolution HadGEM setups (D4.2) nudged to meteorological analyses.

The high-resolution 4A model (running at resolutions between 100m and 1 km) will be used by UoL to analyse aerosol-cloud interaction processes, focussing on the small-scale dynamics of aerosol cloud interactions and the subsequent evolution of the cloud field. In particular, the representation of entrainment processes near cloud top (and the model vertical resolution required to capture them) will be explored in close co-operation with WP2.2 (Cloud Characterisation). The sensitivity of the cloud fields to aerosol properties and profiles will be explored by varying the modelled aerosol field around a ‘baseline’ that has been adjusted to match the observations as closely as possible (from D1.3). These high-resolution simulations will be performed on large-scale domains (~1000km), providing sufficient statistics to evaluate the global HadGEM model run by UoO at climate resolutions. Particular emphasis will be placed on evaluating and improving the HadGEM aerosol entrainment into cloudy layers using in situ data and high-resolution modelling, investigating the role of the vertical resolution and the sub-grid scale mixing parameterisations. Statistics on sub-grid scale variability of updraft velocities will be used by UoO to constrain their parameterisation in the global model setup (c.f. West et al., 2013; Malavelle et al., 2013). The simulated cloud properties will be evaluated against CLARIFY campaign data (D1.3) as well as satellite retrieved droplet number concentrations. Evaluation of the simulated cloud droplet spectra in the high-resolution and global simulations will provide constraints on unresolved model processes (e.g. Partridge et al., 2012) that will be explored in WP5.2.

***D4.2:*** *Publication on the closure between aerosol, CCN and droplet number and the assessment of its representation in high-resolution 4A and low-resolution HadGEM models.*

***D4.3:*** *Publication on impact of small-scale dynamics, including entrainment and vertical velocity variability, on simulated droplet numbers in high-resolution 4A and low-resolution HadGEM.*

***D4.4:*** *Publication on deficiencies of low-resolution climate models in capturing aerosol-cloud interaction.*

**WP5: Regional and global scale integration (lead UoR, Bellouin)**

***WP5 will use the Met Office NWP and climate models to assess the impacts of BBA, aerosol-radiation-interaction and aerosol-cloud-interaction on local, regional and global scales for both weather and climate simulations.***

The overarching aim of this work-package is to assess the “before and after” impacts on NWP prediction and climate modelling, develop an optimal, observationally constrained climate model, and to engage the global aerosol climate modelling community via AEROCOM.

***WP5.1. Evaluation of effects in NWP models* (UoE, Met Office):** The brightness of stratocumulus cloud in the SE Atlantic has been shown to be closely coupled to precipitation in the Amazonian region in the forecast and climate models (Milton and Earnshaw, 2007; Jones et al., 2009). UoE will investigate the dominant dynamical mechanisms leading to this global teleconnection in the limited area and global NWP models by explicitly including aerosol-radiation and aerosol-cloud interactions in the models and compare the performance against a fixed BBA climatology that is currently used in the operational version of these models. Aerosol-radiation and aerosol-cloud interactions will be isolated and the direct, semi-direct effect and indirect effects over the region will be quantified to assess the dominant processes that maximise improvements in model performance. These assessments will be performed regionally, using both the limited area and global NWP models, and globally using the global NWP model in order to assess impacts on global teleconnections.

***D5.1.*** *Publication assessing the performance of the regional and global NWP model against observations, the relative benefits of including prognostic BBA on model performance, and investigation of global scale teleconnections*

***WP5.2 Evaluation of impacts in global climate models* (UoR, UoO):** Aerosol-cloud and aerosol-radiation interactions in the HadGEM3 climate model will be addressed together to highlight the importance of integrating all aerosol interactions into a consistent analysis of impacts. Improvements to aerosol-radiation interactions, especially aerosol optical properties, will be derived from estimates of the aerosol direct effect in cloud-free (WP3.1) and cloudy skies (WP3.2). Semi-direct effect will be compared against the LEM, run at lower resolution and over larger domains than in WP3.4. Improvements to aerosol-cloud interactions will derive directly from development activities in WP4.2. HadGEM3 atmosphere-only simulations, nudged to re-analysed winds, will be run to estimate effective radiative effect before and after improvements to BBA and aerosol-radiation-cloud interactions. Then, following the methodology of Dong et al (2009, 2013), ensembles of short-duration HadGEM atmosphere-only and atmosphere-ocean coupled simulations to evaluate the transient response to aerosol-radiation and aerosol-cloud interactions, with focus on the additivity of the response and the role of local radiative changes compared to circulation changes. The benefits of CLARIFY improvements on aerosol-radiation-cloud interactions in other regions and seasons will also be identified, with a focus on stratocumulus regimes worldwide, where aircraft observations of entrainment of free-tropospheric aerosols (Clarke at al., 2013) and satellite estimates of cloud susceptibility (Gryspeerdt and Stier, 2012) provide further constraints.

***D5.2****. Publication on observationally-constrained HadGEM3 best estimates of BBA radiative effects and fast adjustments, contrasted with previous AEROCOM results and compared to satellite-derived estimates of direct effects and cloud susceptibilities.*

***WP5.3 Reduction of uncertainties in climate models* (UoL, UoO):** UoL and UoO will evaluate the climatic impacts and key structural and parametric uncertainties of aerosol-radiation-cloud interactions by combining the detailed budget analysis (WP4.1), which constrains the perturbations underlying aerosol-cloud interactions, with the process understanding derived in the observational and modelling studies of WP3 and WP4.2. *Structural uncertainties* include the background aerosol, which influences the strength of aerosol-radiation-cloud interactions and depends heavily on the representation of sources and sinks in the model. For example, previous simulations of aerosol-cloud interactions for the VOCALS-observed stratocumulus deck revealed that the permanent drizzle in the then state of the art HadGEM configuration caused a low bias in CCN (West et al., 2013), an issue that has been improved in subsequent model revisions. *Parametric uncertainties* are caused by imperfect choices of parameters, and apreliminary analysis by *UoL* with the GLOMAP-mode offline model version highlights biomass burning emission strength and BBA size distribution as dominant source of parametric uncertainty for surface CCN in the CLARIFY region (Lee et al., 2013). UoO will systematically investigate the influence of structural uncertainties focusing on the representation of drizzle formation and its re-evaporation, autoconversion and the uncertainties in the representation of aerosol emissions, such as biomass burning injection heights. UoL will perform a detailed parametric uncertainty analysis, based on statistical emulation of simulations of the SE Atlantic region to assess the major causes of uncertainty prior- and post- measurement campaign to assess the reduction in uncertainty of the aerosol-radiation and aerosol-cloud-interactions. Similar analyses with the online HadGEM-UKCA model with extended CCN metrics are ongoing within the Global Aerosol Synthesis and Science project (2013-2016).

***D5.3:*** *Publication assessing the impact of parametric and structural uncertainties on aerosol-radiation-cloud interactions.*

***WP5.4 Projections of future climate impacts* (UoR, Met Office):**The improved HadGEM3 model will be used in CMIP-style coupled atmosphere-ocean simulations of future climate change based on RCP scenarios, in timeslices at different points of the 21st century including present-day. Those simulations will guide preparations and simulations for the upcoming CMIP6 activities and IPCC assessment reports. The present-day simulation will serve as a baseline for comparison of AEROCOM models to identify and isolate the causes of the extreme spread in modelled estimates over the region in the aerosol direct effect (Fig 2), and as a benchmark for estimates of semi-direct and indirect effects. This simulation will also be a key input to the semi-direct intercomparison activity that has already been proposed by CLARIFY partners (Bellouin, Stier) to the international aerosol modelling community assembled under AEROCOM.

***D5.4*** *Model simulation of direct, semi-direct, and indirect effect delivered to AEROCOM database.*

***D5.5.*** *Publication documenting the multi-model AEROCOM assessment against the LEM and improved HadGEM3.*

***D5.6:*** *Publication assessing effective BBA radiative forcing for present-day and future scenarios.*

**8. CO-FUNDING AND COLLABORATIONS**

The CLARIFY project benefits from several key national and international partnerships and collaborations that bring significant co-funding and broaden the activity. Descriptions are integrated in the ‘International Synergy’ section and Pathways to Impact, but a summary of in-kind costs is:-

1. Met Office: 50% contribution to flying programme = £511K (secured)
2. Met Office: 30months of in-kind effort across work-packages = £200K (secured)
3. ORACLES programme: mission cost estimate = $30.6m (proposed)
4. ONFIRE programme: mission cost estimate = $7.5m (proposed)

**9. WEBSITE AND COMMUNICATION PLAN**

A CLARIFY-2016 website will be hosted at UoE and will be used both to provide information to the consortium, the project partners, and the science to the wider community. It will also be used to advertise meetings, present presentations and disseminate other project information.

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