Smoke and Clouds above the Southeast Atlantic: Upcoming Field Campaigns Probe Absorbing Aerosol's Impact on Climate

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ABSTRACT

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From July through October, smoke from biomass burning fires on the southern African subcontinent are transported westward through the free troposphere over one of the largest stratocumulus cloud decks on our planet (Fig. 1). Biomass burning aerosol (smoke) absorbs shortwave radiation efficiently. This fundamental property implicates smoke within myriad small-scale processes with potential large-scale impacts on climate that are not yet well-understood. A coordinated, international team of scientists from the United States, United Kingdom, France, South Africa and Namibia will provide an unprecedented interrogation of this smoke-and-cloud regime from 2016 to 2018, using multiple aircraft and surface-based instrumentation suites to span much of the breadth of the southeast Atlantic.

The scientific motivations are many. Smoke warms the atmosphere, in contrast to the climate cooling provided by the reflected sunlight from the extensive low clouds residing mostly below the smoke layer. Yet, the low clouds also respond to the presence of the smoke, in counterintuitive ways that can either strengthen or weaken the low cloud deck. Smoke can stabilize the atmospheric temperature profile, by warming the free troposphere, and cooling the surface below. The stabilization strengthens the low cloud deck, so that the net smoke+cloud effect is an enhanced cooling. This effect is thought to dominate the low cloud response, because space-based lidar informs us that much of the BB aerosol resides above the cloud deck (Fig. 1). In contrast, if the smoke mixes directly into the cloud layer, warming provided by the smoke could reduce the relative humidity and help dissipate the cloud. Changes in the amount of aerosol nucleating the clouds also alters the cloud microphysics and the cloud's likelihood of rain. Other effects exist, for example, from the moisture associated with the aerosol layer, while further effects may yet still remain to be discovered. At a larger scale, the change in atmospheric warming from the smoke affects the neighboring precipitation distribution. The smoke's influence on the surface energy budget ultimately affects the equatorial climate and its variability through the trade winds, and changes the energy distribution between the northern and southern hemisphere.

The complexities of the southeast Atlantic climate are not currently well captured by models (Fig. 2). The aerosol spatial and vertical distribution must be modeled well, along with the aerosols' capacity to absorb shortwave radiation - the single-scattering albedo. Equally important to capturing the aerosol's direct radiative effect is the ability to accurately represent the underlying low cloud deck. Smoke overlying a bright cloud will darken the scene when viewed from space, whereas smoke overlying a dark ocean will brighten the scene. Thus, the ability to represent the low cloud albedo, and in turn the distribution of cloud properties, with and without smoke present, is critical to modeling the regional and by extension global climate. Climate change projections for Africa indicate strong future warming and changing precipitation patterns; increases in the variability of the rainfall has strong implications for agriculture in the arid regions.

Basic aspects of the meteorology such as the trade winds and free-tropospheric easterlies reveal a strong coupling between the atmosphere, ocean, and land neighboring the southeast Atlantic. For example, the deep land-based anticyclone over southern African encourages the recirculation of offshore smoke back to the continent, at times from long distances. Many open questions remain, and much of what is hypothesized about this regime comes from satellite studies, surface-based sun photometers at a few widely-separated locations, and modeling simulations. Satellite studies indicate clouds are thicker, and the cloud deck is larger, when smoke is present overhead, consistent with a response to a more stable atmosphere, but the meteorology encouraging the smoke outflows may also be advecting warmer air above the cloud top. The cloud response is highly sensitive to details of the aerosol-cloud vertical structure, but even our most sophisticated satellite tool, a space-based lidar, has difficulty determining whether the typically-diffuse bottom of a smoke layer is touching the cloud top.

Clues about the aerosol absorption have primarily come from the surface-based sun photometers that comprise the international Aerosol Robotic Network (AERONET). Such measurements suggest that the biomass-burning aerosols become less absorbing as the burning season evolves, perhaps because the type of fire fuel and combustion conditions change. A well-maintained sun photometer has been present on Ascension Island (14.5° W, 8°S) since 2000, but nevertheless single-scattering albedo data remain scarce because of strict retrieval criteria (Fig. **??**). The little available data are consistent with a seasonal evolution documented for fire sources on land: smoke particles that absorb less sunlight as the biomass-burning season evolves.

The data in Fig. **??** are intriguing, but too sparse to be much more than anecdotal, and ignore other factors, such as the possible presence of aerosols from South America. Existing sparse datasets highlight the need for in-situ data of important climate variables. This is now poised to occur. The aircraft campaigns and surface-based instrumentation suites currently committed are shown in Fig. **??**. These will also serve to improve satellite retrievals, and initialize and test model simulations at all scales.

The campaigns possess unique foci, detailed below.

- The NASA Earth Venture Suborbital-2 ORACLES (ObseRvations of Aerosols above Clouds and their interactions; http://espo.nasa.gov/oracles) campaign will sample a different month (August to October) from each of 2016, 2017 and 2018, using a P-3 airplane. The high-altitude ER-2 plane will additionally participate in 2016. The multiple-year deployments allow ORACLES to characterize the seasonal evolution in the single-scattering albedo and loading of the offshore BB aerosol, and in aerosol-cloud interactions. Its multi-aircraft deployment in 2016 allows for stacked aircraft flight patterns that optimize careful remote sensing retrieval development and produce datasets for supporting future satellite instrument constellations and designs. Airborne lidar and radar capture the aerosol-cloud vertical structure. One-half of the campaign is devoted to facilitating model comparisons through survey flights occurring along regular latitude-longitude lines. Remaining flights target specific assessments of the direct radiative effect from BB aerosol, and changes in atmospheric stability, circulation and cloud properties from the absorption of solar radiation by smoke. While the 2016 deployment will be based in Walvis Bay, Namibia, efforts will be made to survey the larger Atlantic basin, potentially using auxiliary bases or overnight stops on equatorial Sao Tome (6.5° E), Ascension Island, and even St. Helena Island (15°S, 5°W) throughout the three years. Another separate NASA initiative will add more sun photometers and a new micro pulse lidar to sites in southern Africa and St. Helena.

- The UK CLARIFY (CLouds and Aerosol Radiative Impacts and Forcing: Year 2016) campaign plan to bring the UK FAAM BAe-146 plane to Namibia in August-September 2016, overlapping with ORACLES-2016. In conjunction with the UK Met Office, CLARIFY is also planning to instrument St. Helena island with additional radiosondes, a Doppler lidar, a passive microwave radiometer, optical particle counter. This suite would then be joined by the U of Miami 94 GHz Doppler cloud radar through a DOE-NOAA-UM collaboration. CLARIFY's goal is to improve the representation and reduce uncertainty in UK Meteorological Office model estimates of the direct, semi-direct and indirect radiative effects.

- The DOE LASIC (Layered Atlantic Smoke Interactions with Clouds; http://www.arm.gov/campaigns/amf2016lasic) campaign deploys the ARM Mobile Facility 1 (AMF1) to Ascension Island from June 1, 2016 - October 31, 2017. Ascension Island is located 2000 km offshore of continental Africa in the trade-wind cumulus regime over near-equatorial warm waters (Fig. **??**). Its deepening boundary layer, combined with the subsiding aerosol layer aloft, increases the chances that smoke will be entrained into the cloud layer. LASIC includes a large suite of both aerosol in-situ and remote sensors and cloud remote sensors, including a lidar to fully profile the aerosol vertical structure of the partially-cloudy skies and several cloud radars. Multiple radiosondes per day will provide the first characterization of the diurnal cycle with and without smoke present overhead. The diurnal cycle serves as one test for smoke-cloud interaction hypotheses, and is useful for climate model assessments of low cloud representations. The 17-month time span overlaps with two of the ORACLES deployments, robustly sampling the seasonal cycle in both aerosol and cloud properties. The dual instrumentation of Ascension and St. Helena also allow for an examination of the evolution of the boundary layer flow between the two islands from stratocumulus to shallow cumulus, with and without the presence of BB aerosols overhead.

- The French AEROCLO-sA (AErosol RadiatiOn and CLouds in southern Africa) is a long-term collaboration with South Africa and Namibia taking aerosol column and *in-situ* measurements at the Henties Bay Aerosol Observatory, approximately 100 km north of Walvis Bay, since 2012. AEROCLO-sA will augment its observational capabilities during August-September 2016 with sophisticated measurements of the aerosol chemical, physical, optical and hygroscopic properties using a mobile surface station that includes two lidars. Dust is the most dominant aerosol by mass over much of southern Africa, typically residing in the boundary layer. The lidars will determine the relative vertical structure of both the dust and smoke, to distinguish their radiative effects and potential interactions with clouds. Measurements from the French F20 aircraft, equipped with a high-resolution lidar and based in Walvis Bay to maximize international synergy, will improve polarimetric satellite retrievals of cloud properties.

- The Sea Earth Atmosphere Linkages Study in southern Africa (SEALS-sA) proposes to use research vessel measurements to better understand the complex coastal land-atmosphere-ocean coupling, in which strong northward along-shore winds upwell cold nutrient-rich waters into one of the most productive fisheries in the world. Inland, additional aerosol measurements are planned to examine aerosol-fog interactions and land-atmosphere interactions, building on a depth of expertise in unique arid land ecosystems. Six new AERONET sun photometer sites are currently becoming established in southern Africa, including two in Angola, and two new lidars in Namibia as part of NASA?s Micro-Pulse Lidar Network (MPLNET). A focus on coastal fog, the dominant source of moisture for life in the arid near-coastal Namib Desert, is naturally complemented by the interest of other partners on low cloud processes. The international scientists can mutually benefit from each other's expertise, through expanded local hands-on research involvement in the Namibian-based aircraft and surface-based campaigns. These scientific exchanges will potentially extend to visits to US and European institutions, including graduate studies, and lay the groundwork for long-lasting scientific collaborations. Further collaborations contemplated include summer schools on climate change modeling, remote sensing and instrumentation. SEALS-sA is envisioned as a longer-term, interdisciplinary initiative within southern Africa continuing well beyond 2018.

These active observational and modeling strategies form COLOCATE: the Clarify-Oracles-Lasic-aerOClo-seAls Team Experiment. International collaboration is already apparent in the combined efforts of UK and US scientists to instrument St. Helena Island. A significant aspect of field experiments is their ability to focus attention on specific scientific problems. Pre-deployment modeling and analysis of existing satellite datasets combined with reanalysis are valuable in their own right and sharpen the driving hypotheses. The representation of absorbing aerosol in climate models was first treated explicitly in the Intergovernmental Panel on Climate Change (IPCC) 2001 assessment, then subsumed in the IPCC 2007 assessment with all other aerosol, but is now explicitly recognized again as an important constraint on climate model behavior. The local direct radiative forcing over the southeast Atlantic is much stronger than the global mean. The focus on southeast Atlantic reflects a larger consensus within the research community that absorbing aerosol's impact on climate must be better understood. Significant progress can now be made in a five-year time frame, and other related initiatives will very likely augment those already planned in the near future. We encourage further initiatives for becoming involved, for example through DOE's guest instrumentation program. The opportunity for complementary science over the remote Atlantic exists until October, 2018, the date for ORACLES' last deployment, and extend much longer within Namibia. The airfield at Sao Tome provides an excellent base from which to access the main continental aerosol outflow plume. Additionally, St. Helena Island will acquire its first-ever airfield in the spring of 2016, providing a potential new aircraft deployment base strategically located in the remote stratocumulus region. We are anxious to hear from others with complementary interests.

Acknowledgments. ORACLES is funded by NASA Earth Venture Suborbital-2 grant NNX15AF98G. The planning for LASIC is funded through DOE grant DE-SC0013720. CLARIFY-2016 is funded by the Natural Environment Research Council project, grant code NE/L013797/1. AEROCLO-sA is funded by the French Agence National de la Recherche (ANR) under contract ANR-15-CE01-0014, the French national programs LEFE/INSU and LEFE/PNTS, and the Centre National des Etudes Spatiales (CNES). We thank Brent Holben and the AERONET team for maintaining the Ascension Island station and for leadership in establishing further sites in southern Africa, and Judd Welton for leadership in establishing the new Namibian MPLNET sites.

We also thank Marcos Henry, Station Manager of the UK Meteorological Office at St. Helena Island from 1992-2015, for inclusion of his photo in Fig. 4.

LIST OF FIGURES

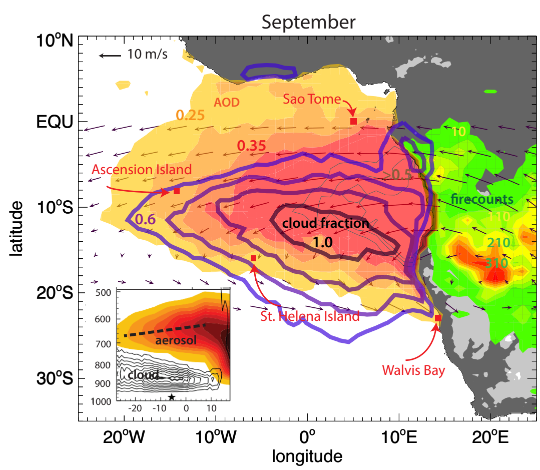

FIG. 1. During September, 600 hPa winds escort the biomass burning aerosol (optical depth in warm colors) emanating from fires in continental Africa (green to red, 50 to 310 firecounts per 1° box) westward over the entire south Atlantic stratocumulus deck (cloud fraction in blue contours). The inset, a 4°E-7°E latitude slice, highlights the subsiding aerosol layer and deepening cloudy boundary layer further offshore, increasing opportunity for direct smoke-cloud interactions. Main figure is based on MODIS 2002-2012 data and the ERA-Interim Reanalysis, inset is based on the space-based Cloud Aerosol Lidar with Orthogonal Polarization (CALIOP) and CloudSat 2006-2010 data. Henties Bay is approximately 100 km north of Walvis Bay, other main deployment sites and Sao Tome are indicated.

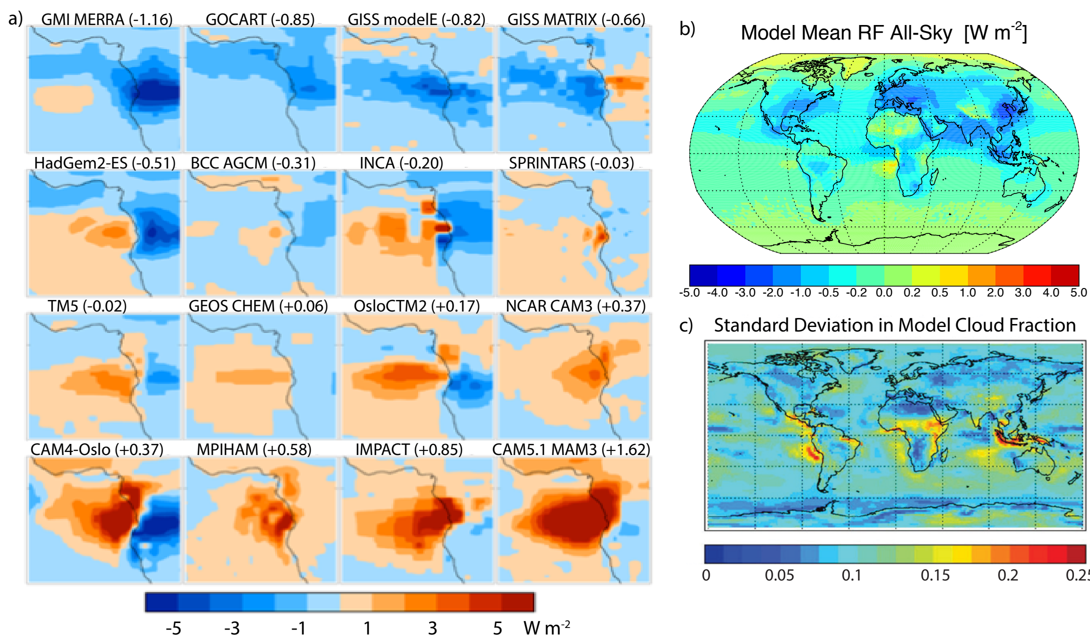

FIG. 2. Modeled August-September direct aerosol radiative forcing in a) individual AeroCom models ordered by their regional- and annual-average difference from the b) ensemble-mean indicating the regional hotspot for biomass-burning aerosol forcing over the southeast Atlantic. c) indicates the large diversity in the models' cloud fraction. The latter also helps determine if the aerosol shortwave absorption influences the climate more than the aerosol scattering. More model details can be found in Myrhe et al., 2013, Atmos. Chem. Phys.

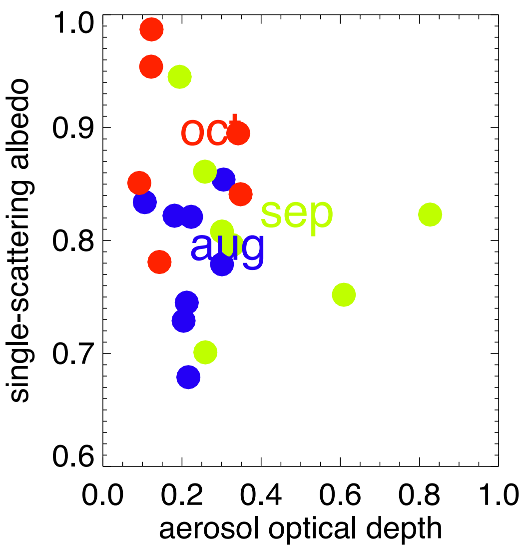

FIG. 3. Single-scattering albedo versus daily-mean aerosol optical depth at 500 nm wavelength at Ascension Island, using all available daily-mean AERONET values from August (blue), September (green) and October (red) spanning 2000 through 2013. Single-scattering albedo values (Level 1.5) are only available for these 21 days out of the 398 days with daily-averaged aerosol optical depths. Month names indicate the monthly-mean values. Please note that these Level 1.5 data only serve an illustrative purpose. AERONET recommends only Level 2.0 data be used for rigorous data analysis.

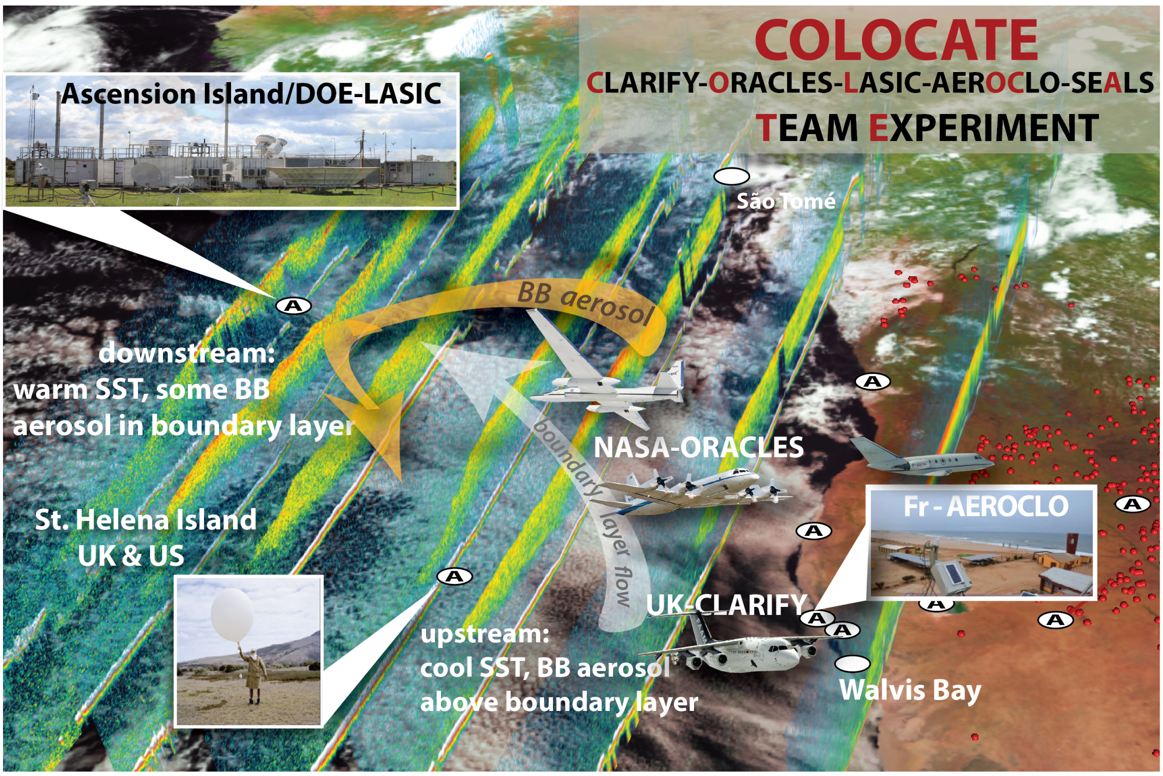

FIG. 4. Space-based CALIOP lidar curtains highlight the prevalence of smoke above the southeast Atlantic stratocumulus deck on a typical September day, with broad arrows indicating the prevailing boundary layer flow (white) and a major recirculation pattern for the BB aerosol (dark yellow). The four aircraft of the ORACLES, CLARIFY and AEROCLO-SA campaigns are shown along with the surface-based deployments at Ascension Island, St. Helena Island, and Henties Bay, Namibia. The UK has long maintained meteorological offices at Ascension and St. Helena, with, as shown, almost-daily radiosondes launched at St. Helena. ”A” on small white circles indicate AERONET sites.