The ACE Lidar-Polarimeter Concept to Reduce Uncertainties in Direct Aerosol Radiative Forcing With Applications to Air Quality & Atmospheric Dynamics

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We describe the NASA ACE measurement concepts that: 1) enable the reduction of uncertainties in aerosol radiative forcing, 2) directly address air-quality and human health, and 3) help quantify the impact of absorbing aerosols on atmospheric dynamics and thermodynamics and the effects on monsoonal circulations and the global hydrological cycle.

Introduction

The 2007 NRC Decadal Survey report recommended NASA pursue the Aerosol, Clouds, Ecosystem (ACE) mission as an essential Tier 2 mission to address several global and crosscutting science objectives (NRC, 2007). These objectives address four of the *Earth System Science Themes* identified in the second 2017 Decadal Survey Request for Information (RFI#2): 1) Global Hydrological Cycles and Water Resources, 2) Weather and Air Quality, 3) Marine Ecosystems and Natural Resource Management, and 4) Climate Variability and Change.

In response to the first 2017 DS-RFI (RFI#1), the *Key Challenges and Questions for Earth System Science* addressed by the NASA ACE mission were described in an overview paper (da Silva et al., 2015) as well as in individual papers discussing aerosols (Ferrare et al., 2015), aerosol-cloud interactions (Mace et al., 2015), ocean ecosystem (Behrenfeld et al., 2015), and clouds and precipitation (Skofronic-Jackson et al., 2015). In our response to RFI#1 entitled "*Characterizing Aerosol Processes and Properties for Reducing Uncertainties in Aerosol Radiative Forcing*" (Ferrare et al., 2015), we stressed the need for new aerosol measurement capabilities to reduce uncertainties in direct aerosol radiative forcing (DARF) and described how the ACE mission targets this objective. We describe herein the specific ACE measurement concepts that enable the reduction of uncertainties in aerosol radiative forcing and so directly address the *Climate Variability and Change* Earth System Science theme. Moreover, these measurements also directly address air-quality and human health and can help quantify the impact of absorbing aerosols on atmospheric dynamics and thermodynamics, and effects on monsoonal circulations and the global hydrological cycle, thereby addressing the *Weather and Air Quality* Earth System Science theme.

Science and Application Targets

The immediate science and application targets for the Direct Aerosol Radiative Forcing (DARF) component of the ACE mission are shown below and in Table 2:

Focused Question 1. *What is the direct aerosol radiative forcing (DARF) at the top-of atmosphere, within atmosphere, and at the surface?*

Focused Question 2. *What is the aerosol radiative heating of the atmosphere due to absorbing aerosols, and how will this heating affect cloud development and precipitation processes?*

The primary ACE DARF mission objectives are:

1. Provide firmer measurement-based estimates of global and regional DARF at the top of the atmosphere and its uncertainties. As discussed in Samset et al. (2014), observationally based estimates of DARF uncertainties are larger than stated model-based estimated uncertainties. ACE measurements and data assimilation will help resolve the differences between these methods.
2. Provide the first ever measurement-based estimate of the global DARF at the bottom of the atmosphere with sensitivity up to about ±1 W/m^2, depending on retrieval conditions. This is equivalent to estimating the global evaporation rate at the surface of up to ±1 mm/month.
3. Provide vertically resolved, measurement-based estimates of the aerosol radiative heating of the atmosphere at an accuracy of ±0.25 ^{o}K/day for 1.5 km layers to help observe cloud fraction change due to enhanced aerosol heating.

These objectives are described in more detail in the recent ACE 5 Year Report (ACE Study Team, 2016). ACE seeks to combine satellite measurements with suborbital constraints and integrate these into high-resolution earth-system models by means of data assimilation (Starr et al., 2010). The constrained models provide the basis for calculations of DARF and are key to identifying the portion of DARF that results from anthropogenic aerosols.

Importance

Uncertainties associated with aerosol radiative forcing (ARF) estimates are among the leading causes of discrepancies in climate simulations and the large uncertainties in the total anthropogenic effective radiative forcing (ERF, see IPCC, 2013). The latest IPCC model-based ARF estimate of radiative forcing due to aerosol–radiation interactions is –0.35 (–0.85 to +0.15) W/m^2. However, with the lack of observational constraints, this DARF uncertainty estimate relies primarily on model diversity, which at best represents a lower bound on actual uncertainty (NASA Workshop, 2014). Consequently, there remains considerable observational (Loeb and Su, 2010; Bellouin et al. 2013) and modeling evidence that the *actual uncertainty is a factor of two to four larger* (Fig. 1) (Samset et al, 2014). Simply doubling this estimated uncertainty range would have a large impact on the uncertainty in climate sensitivity and future predictions of surface temperature associated with climate change (Andreae et al., 2005; Myhre et al., 2013; Schwartz et al., 2010). Furthermore, this top-of-atmosphere (TOA)

forcing value alone is insufficient to determine aerosol forcing at the surface and within the atmosphere because vertical variations in aerosol forcing affect the thermodynamical structure of the atmosphere and impact regional and general circulation processes such as evaporation, cloud cover, and precipitation (Ramanathan and Carmichael, 2008; Kim et al., 2016, Lau, 2016).

Current satellite sensors have begun providing quantitative distributions of aerosol optical thickness in the horizontal (e.g. MODIS, MISR, VIIRS), aerosol backscattering in the vertical (e.g., CALIPSO, CATS-ISS), aerosol absorption (OMI), and some information on aerosol size (MODIS, MISR) and shape (MISR, CALIPSO). However, the accuracy of these measurements is insufficient for reducing DARF uncertainties to a level comparable with those of greenhouse gas forcing. Even in the best cases, current satellite sensors measure aerosol optical depth (AOD) to within about ±0.05 (at ~500 nm), which is inadequate to reduce uncertainties in estimates of aerosol direct radiative forcing and to constrain advanced aerosol transport models. CALIPSO daytime profiles of aerosol backscattering and extinction are noisy and inadequate to detect all radiatively significant aerosol (Rogers et al., 2014; Thorsen and Fu, 2015). Vertically resolved aerosol absorption, a key parameter controlling radiative forcing within the atmosphere, is particularly difficult to measure from space. Consequently, atmospheric models rely primarily on ground based AERONET retrievals of absorption, which are column-effective values limited to certain land sites, and are restricted to relatively high (AOD>0.4 at 440 nm) AOD cases. Other sources of global aerosol absorption constraints, such as satellite retrievals in the UV (e.g., TOMS, OMI) or multi-angle, multi-spectral (MISR) plus polarimetric (POLDER) retrievals, tend to be coarse resolution (TOMS, OMI) or qualitative (MISR). Direct, *in situ* sampling that provides detailed absorption information has extremely poor global coverage, and has never yet been deployed systematically sample the major global aerosol air mass types statistically.

The ACE strategy is to produce a comprehensive data set of vertically resolved aerosol optical (e.g. scattering, absorption) properties and estimates of microphysical (e.g. size, shape, some indication of composition via refractive index) parameters as a function of time and location to better characterize global ARF estimates. ACE will provide firmer global and regional DARF estimates and uncertainties by confronting issues not adequately addressed by previous observations, along with the first ever vertically resolved measurement-based estimate of the global direct aerosol radiative forcing at the bottom of the atmosphere with sensitivity up to about ± 1 W/m^2, depending on retrieval conditions. This is equivalent to estimating the global surface evaporation rate of ± 1 mm/month (~ 1% of global rates, see Table 2.). The goal of the satellite component of ACE is to characterize the aerosol direct radiative effect (DRE), which is the instantaneous radiative perturbation due to all aerosol particles and, more specifically, to estimate the anthropogenic component based on the ability to assign speciation to the aerosol components in the column. Model estimates of DRE are more easily tested against satellite observations and offer a more complete picture of aerosols in the climate system (Heald et al., 2014).

Utility of Geophysical Parameters

The geophysical parameters required to meet these objectives are listed in Table 2 and are based on those parameters needed to quantify DARF, DRE, and to estimate their anthropogenic components (Hansen et al., 1995; Schwartz, 2004, Kahn, 2012). These parameters include spectral aerosol optical thickness, effective radius and its variance, real part of the refractive index, the imaginary part of the refractive index or single scattering albedo, and shape. Instantaneous, mid-visible AOD measurement accuracy of 0.02 (ACE goal) is typically required under cloud-free conditions to constrain DARF to about 1 W/m^2 (Mishchenko et al., 2004; McComiskey et al. 2008; CCSP, 2009).

Beyond AOD, aerosol absorption and speciation are the two top aerosol measurement needs identified by the NASA Workshop (2014) and are key parameters required for reducing uncertainties in DARF and the anthropogenic contributions to DRE. Since aerosol absorption is particularly important for accurately deriving DARF at the surface and within the atmosphere, the ACE goal for uncertainty in aerosol single scattering albedo is ±0.02-0.05 depending on aerosol loading. Current satellite sensors provide very limited information regarding these parameters. Moreover, climate models are practically unconstrained regarding aerosol speciation, which is of particular importance when attempting to determine and evaluate the anthropogenic contribution to DRE (NASA Workshop 2014).

Vertically resolved aerosol information is critical for discriminating natural and anthropogenic species and especially for assessing the impact of aerosol radiative forcing on the thermodynamical structure of the atmosphere. Although differential aerosol warming/cooling effects may cancel when vertically integrated, their vertical distribution can have a profound impact on the stability of the atmosphere, convection, and atmospheric

circulation. As current models are also only loosely constrained regarding aerosol vertical distribution, both aerosol speciation and the vertical distribution are current "tall poles" regarding aerosol constraints (NASA Workshop 2014). Therefore, the aerosol parameters shown in Table 2 must be derived above clouds and for the total column for FQ1. Vertical profiles with vertical resolutions of about 1 to 1.5 km in free troposphere and 0.5 km in boundary layer are required for FQ2. The retrieval accuracy requirements (Starr et al., 2010, ACE white paper, Appendix A, 2010) are based on sensitivity studies carried out as part of ACE formulation plan activities and/or peer reviewed literature (see list in Starr et al., 2010, ACE white paper).

Cross-Cutting Issues

The measurements described here will benefit other science topics related to **Theme IV: Climate Variability and Change** as well as applications and other Earth science targets. As discussed in another ACE related RFI#2 paper (Mace et al. 2016), marine boundary layer (MBL) cloud feedback uncertainty is a leading source of uncertainty in current climate prediction. In order to reduce this uncertainty, there must be increased understanding of the processes that cause MBL clouds to change as the climate warms. Understanding the specific role of aerosols in modulating the properties of MBL clouds calls for resolving aerosol properties vertically, which requires lidar profiles of aerosol backscatter, extinction, and depolarization. Multi-wavelength, multi-angle polarimeter measurements as described above would allow mapping of aerosol air mass types globally, based on aerosol size, shape, and absorption constraints, complementing and extending the vertically resolved data. The polarimeter can also characterize occurrence of ice phase at cloud top. Further, the multi-angle stereo imagery can be used to map near-source aerosol plume height, which, combined with downwind layer height obtained from lidar, would provide strong constraints on aerosol vertical distribution which is critical for atmospheric structure and aerosol-cloud-interaction modeling.

The polarimeter and High Spectral Resolution Lidar (HSRL) measurements proposed here will also address **Theme III: Marine Ecosystems and Natural Resource Management** by providing better constraints on aerosol type needed for atmospheric correction (Kahn et al., 2016a), and more accurate ocean property retrieval than currently available. The lidar could also provide vertically resolved plankton distributions as described in the ACE related "Global Ocean Target" RFI#2 paper (Behrenfeld et al. 2016a). The lidar-polarimeter measurement concept also would address key ACE objectives associated with "Ocean Ecosystems and Ocean-Aerosol Interactions" as described in the RFI#2 paper (Behrenfeld et al., 2016b).

Combined polarimeter and lidar measurements are desired to also address the ACE air quality objectives related to **Theme II: Weather and Air Quality: Minutes to Sub-seasonal**, in particular its contribution to air-quality forecasting. Elevated values of $PM_{2.5}$ lead to adverse health effects (*Fig. 2*) prompting increased efforts to monitor air quality from space. Key air quality objectives addressed by a polarimeter and lidar were described in a response to RFI#1 (Kalashnikova et al., 2015). Passive multi-angle radiometry with high accuracy polarimetry will provide column integrated aerosol optical, microphysical, and macrophysical properties with wide areal global coverage. Simultaneous multi-wavelength HSRL backscatter and extinction profiles and retrieval of aerosol concentrations can be used to more accurately derive near-surface PM. The determination of vertically resolved aerosol radiative forcing has direct implications for the thermodynamical structure of the atmosphere and consequent effects on monsoonal circulations and the global hydrological cycle, thus having relevance to **Theme I: Global Hydrological Cycles and Water Resources** as illustrated in *Fig. 3*.

Measurements to Achieve Science Objectives

The ACE Aerosol Working Group identified a multi-angle, multi-spectral imaging polarimeter and a high spectral resolution lidar (HSRL) as the two key instruments/measurement techniques required for pursuing the science objectives described above.

Polarimeter

The Ocean Color Imager (OCI) planned for the Pre-Aerosol, Cloud and ocean Ecosystem (PACE) mission will provide aerosol information similar to the combination of MODIS (or VIIRS) and OMI instruments on the A-train, but with consistently higher-resolution UV measurements. Both the ACE aerosol working group and the PACE science team carefully reviewed the capabilities of the planned OCI instrument and concluded that it alone would be insufficient to answer the ACE aerosol science questions. They concluded that constraining direct aerosol radiative forcing requires an advanced, highly accurate satellite polarimeter for adequate AOD measurements (~ ±0.02 mid-visible) and tighter aerosol type constraints, globally. Multi-wavelength, multi-angle polarization measurements can reduce uncertainties in AOD retrievals as well as enable column retrievals of

particle size, shape, index of refraction and SSA under a broader range of observing conditions than current space-based instruments (PACE Science Definition Report and references within).

An advanced polarimeter may be flown as part of the PACE mission and could provide aerosol retrievals that would improve the atmospheric correction as well as addressing DARF. The Multi-Angle Imager for Aerosols (MAIA) sensor recently selected by the NASA EVI-3 program contains spectropolarimetric cameras mounted on a two-axis gimbal for multi-angle, multi-wavelength polarization measurements (Diner, personal communication, 2016). However, MAIA is designed to sample only a limited number of selected major metropolitan centers and will not have global coverage necessary to address the ACE objectives.

Lidar

CALIOP has enabled studies of global aerosol radiative effects through retrievals of clouds and aerosol properties that have fewer cloud-induced biases than from passive sensors (e.g. Yang et al., 2012). However, CALIOP aerosol extinction profiles can have significant errors due to uncertainties in the values of aerosol extinction/backscatter ratio (the so-called "lidar ratio") used to relate aerosol backscatter to extinction (Rogers et al., 2014). The requirement for accurate profiles of aerosol extinction, day or night, above cloud and near cloud, requires an instrument that can retrieve aerosol extinction *independently* from aerosol backscatter. This will enable the lidar to distinguish radiatively important aerosols more accurately than CALIPSO (Thorsen et al., 2015). In a response to RFI#2, Thorsen et al. (2016) describe in detail the DRE implications of the limited detection sensitivity of CALIPSO and how an advanced lidar will improve upon this.

The combination of backscatter and depolarization measurements at 532 and 1064 and extinction via HSRL at 532 nm provides four aerosol intensive parameters rather than the one (depolarization) currently used in the CALIOP operational algorithm [Omar et al., 2009]. Consequently, airborne HSRL measurements have been used to qualitatively distinguish eight separate aerosol types and apportion aerosol extinction and AOD into those types (Burton et al., 2012, 2013, 2014). With the addition of backscatter and extinction measurements at 355 nm, this suite of lidar measurements (i.e., 355, 532, and 1064 nm) allows for vertically resolved retrievals of aerosol size, refractive index, scattering and absorption, and concentration under diverse retrieval conditions (Kolgotin and Müller 2008, Müller et al., 2014).

Modeling and Data Assimilation

The capability of assimilating observations into comprehensive models is increasingly recognized as an essential part of global and regional observational programs. Assimilating lidar and polarimeter data into high-resolution earth-system models is important for extracting the maximum information from Earth-system observations and for driving quantitative model development. Data assimilation can: 1) organize the observations from diverse sources into a regularly gridded, time-continuous product, 2) complement the observations by propagating information from observed to unobserved regions; this capability can be used to assess the aerosol effect on clouds and climate by deriving the aerosol concentration in regions not observable from satellites and for extending measurements from a single lidar curtain to wider areas; 3) supplement observations by producing estimates of unobserved quantities, using model parameterizations constrained by the observations; 4) maximize the physical and, ultimately, chemical consistency between the observations through the comprehensive model parameterizations. Aerosol forecasting is currently operational at ECMWF, NASA, NRL, NOAA, and JMA (Sessions et al. 2015) and aerosols have recently been introduced for the first time in major atmospheric reanalysis (MERRA-2, Bosilovich et al. 2015). This integrated approach provides concurrent aerosol/meteorological analyses that are key for studying aerosol impacts on the atmospheric circulation and the hydrological cycle (*Fig 3.*) and for enabling improved air-quality forecasting (*Fig. 4*).

Additional Measurements

Additional measurements that would significantly assist in meeting the ACE objectives are listed in column 5 of Table 2. These include ground-based, airborne, and satellite measurements needed to validate and interpret the ACE polarimeter and lidar measurements and for providing observations with accuracy and coverage not possible from space. Characterizing surface albedo will be important for calculating DARF. Shortwave and longwave radiative fluxes, such as those provided by CERES, thermal IR imagery for cloud statistics, collocated measurements of atmospheric temperature and humidity profiles such as provided by AIRS will also be desirable. Systematic, routine *in situ* measurements capable of characterizing aerosol optical, chemical, and microphysical properties would contribute to satellite retrieval algorithms by improving the assumptions made in these algorithms and by relating the retrieved particle optical properties to aerosol mass, which is the fundamental quantity tracked in air quality and climate models (RFI#2, Kahn et al. 2016b).

Success Probability

The ACE mission in its pre-formulation phase has made significant progress regarding mission requirements and instrument technical readiness. ACE has and continues to leverage the advances in technical development and readiness of both instrument concepts (with NASA's Earth Science Technology Office [ESTO] support) and their related algorithm development (with ACE Decadal Survey Study support). The lidar and polarimeter technology that comprises ACE's core measurement suite is expected to continue advancing to a technological readiness level that will permit this ACE component to go in full formulation phase by the time the 2017 Decadal Survey Report is published (ACE Science Study Team, 2016.)

Instrument Readiness

The ACE program continues to advance the development of three polarimeter concepts and two lidar concepts. The polarimeter concept instruments have flown in several recent field missions and provided retrievals of both aerosol and cloud properties. The MSPI concept is similar to that employed by the AirMSPI airborne sensor (TRL 5 increasing to 6 in 2016) and also to that to be employed by the MAIA space-based sensor that was recently selected as a NASA EVI-3 mission. The RSP concept (TRL 8 to 9) has flown on numerous airborne field missions and is a functioning prototype of the Aerosol Polarimetry Sensor that flew on the NASA Glory mission but failed to achieve orbit. The PACS concept (TRL 6) is intended for space application/demonstration on the HARP Cubesat Spacecraft funded under the NASA ESTO InVest program, and an airborne version is expected to fly on the ER-2 in the summer of 2016. Additional information regarding these instrument concepts, readiness, and demonstrations can be found at ACE Five Year Report (ACE Study Team, 2016).

Considerable effort has been put into designing next-generation spaceborne lidars by NASA engineering teams over the last several years. These designs benefit from knowledge gained on CALIOP and other spaceborne instruments including CATS-ISS, ICESat-1, ICESat-2, ATLID on EarthCARE, and ALADIN on ADM-Aeolus and from technology developments through various NASA technology programs, and from many years of experience with airborne prototype instruments. Airborne HSRL measurements (together with a polarimeter in several cases) have been acquired during numerous field missions since 2006; advanced multi-wavelength airborne HSRL measurements have been acquired during the NASA DISCOVER-AQ campaigns in California, Houston, and Denver as well over the ocean during the DoE TCAP mission (Müller et al., 2014; Sawamura et al., 2016). The TRL of this NASA LaRC instrument concept based on the airborne HSRL-2 currently is between 4 and 5; HSRL-2 has also recently been demonstrated operations from the NASA ER-2 and will be deployed from this aircraft during the NASA ORACLES mission in 2016. Additional details are provided by Hostetler et al. (2016). The GSFC Airborne Cloud-Aerosol Transport System (ACATS) lidar (TRL 4 to 5) implements both the HSRL technique and standard backscatter technique at 532 nm. The ACATS telescope rotates to four different look angles and is set at an off-nadir view angle of 45 degrees. It has flown two missions on the ER-2 aircraft and has demonstrated measurements of cirrus clouds and smoke layers.

Algorithm Readiness

ACE and other NASA programs have supported risk reduction activities for the polarimeter and HSRL aerosol retrievals via algorithm development and data collection. The lidars and polarimeters have acquired science data on several field missions over the last several years and have been using these data to develop, demonstrate, and evaluate advanced retrieval algorithms (e.g. Veselovskii et al., 2013; Müller et al., 2014). For example, polarimeter retrievals of particle size and absorption and automated, multi-wavelength lidar retrievals of aerosol particle size and concentration profiles have been demonstrated and evaluated using data collected during recent NASA missions (e.g. Sawamura et al., 2016). ACE continues to support algorithm development and evaluation for combining polarimeter and HSRL data to retrieve profiles of refractive index and absorption to meet the ACE objectives.

Affordability

Years of technology development, airborne instrument development, and algorithm development have put the lidar and polarimeter intended for ACE on paths to affordable implementation within a reasonable schedule. Teams of engineers and instruments scientists associated with ACE have developed detailed instrument concepts and cost estimates using both parametric and bottoms-up approaches (e.g. Hostetler et al., 2016). Those cost estimates and the information on which they are based can be supplied to the NRC Decadal Survey Panel upon request.

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Table 1. List of Acronyms

ACATS = Airborne Cloud-Aerosol Transport System

ACE = Aerosol, Clouds, and ocean Ecosystem

AERONET = Aerosol Robotic Network

AirMSPI = Airborne Multiangle Spectro-Polarimetric Imager

AIRS = Atmospheric Infrared Sounder

AOD = Aerosol Optical Depth

APS = Aerosol Polarimetry Sensor

ARF= Aerosol Radiative Forcing

CALIOP = Cloud-Aerosol Lidar with Orthogonal Polarization

CALIPSO = Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation

CATS = Cloud-Aerosol Transport System

CERES = Clouds and the Earth's Radiant Energy System

DARF = Direct Aerosol Radiative Forcing

DISCOVER-AQ = Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality

DRE = Direct Radiative Effect

DS = Decadal Study

ECMWF = European Center for Medium-Range Weather Forecasts

ERF = Effective Radiative Forcing

ESTO = Earth Science Technology Office

EVI = Earth Venture Instrument

GSFC = Goddard Space Flight Center

HARP = Hyper-Angular Rainbow Polarimeter

HSRL = High Spectral Resolution Lidar

IPCC = Intergovernmental Panel on Climate Change

JMA = Japan Meteorological Agency

LaRC = Langley Research Center

MAIA = Multi-Angle Imager for Aerosols

MBL = Marine Boundary Layer

MERRA = Modern Era Retrospective analysis for Research and Applications

MISR = Multi-angle Imaging SpectroRadiometer

MODIS = Moderate Resolution Imaging Spectroradiometer

MSPI = Multiangle Spectro-Polarimetric Imager

NASA = National Aeronautics and Space Administration

NOAA = National Oceanic and Atmospheric Administration

NPOESS = National Polar-orbiting Operational Environmental **Satellite** System

NRC = National Research Council

NRL = Naval Research Laboratory

OCI = Ocean Color Imager

OMI = Ozone Monitoring Instrument

ORACLES = ObseRvations of Aerosols above CLouds and their intEractionS

PACE = Pre-Aerosol, Cloud, and ocean Ecosystems

PM = Particulate Matter

$PM_{2.5}$ = Particulate Matter with diameters less than 2.5 micrometers

POLDER = POLarization and Directionality of the Earth's Reflectances

RFI = Request for Information

RSP = Research Scanning Polarimeter

SSA = Single Scattering Albedo

TCAP = Two-Column Aerosol Project

TOMS = Total Ozone Mapping Spectrometer

TRL = Technology Readiness Level

VIIRS = Visible Infrared Imaging Radiometer Suite

Table 2: ACE Aerosol Radiative Forcing Science Traceability Matrix.

ACE Aerosol Radiative Forcing Science Traceability Matrix

Themes	Focused Science Questions	Geophysical Parameters	Measurement Requirements	Mission Requirements
Direct Aerosol Radiative Forcing (DARF)	FQ1. What is the direct aerosol radiative forcing (DARF) at the top-of-atmosphere, within atmosphere, and at the surface? FQ2. What is the aerosol radiative heating of the atmosphere due to absorbing aerosols, and how will this heating affect cloud development and precipitation processes?	Column: • $\tau_a(\lambda)$ (AOD) • $\tau_{a,abs}(\lambda)$ (absorption AOD) • $m_a(\lambda)$ (complex refractive index) • r_{eff} (effective radius) • ν_{eff} (dispersion of size distribution) • Morphology (e.g. particle shape - nonsphericity) Vertically Resolved: • Extinction, scattering, absorption coefficients (λ) • $m_a(\lambda)$ (complex refractive index) • r_{eff} (effective radius) • ν_{eff} (dispersion of size distribution) • Morphology(e.g. particle shape - nonsphericity)	High Spectral Resolution Lidar (HSRL) • Backscatter (355, 532, 1064 nm) • Extinction (355, 532 nm) • Depolarization (two wavelengths of 355, 532, 1064 nm) Imaging Polarimeter • Minimum 8 wavelengths spanning UV to either 1630 nm or 2250 nm (additional wavelengths chosen as goals include oxygen A band and bands for water vapor retrievals, fire detection, and separation of tropospheric and stratospheric aerosols) • Multiangle TBD, range ±65 - 70° • Polarization accuracy 0.5% • Combination polarized and nonpolarized channels • Resolution: 250 m in at least one channel	Integrated satellite, *in situ* measurement, modeling, and data assimilation is required to meet science objectives. Expand high-resolution global and regional modeling capabilities to assimilate cloud and aerosol microphysical parameters such as number concentration and optical properties. Required ancillary data: • Land surface albedo map • Ground network $\tau_a(\lambda)$, shortwave and longwave F_d and F_{net} • Ground and airborne: column and vertically resolved $\tau_a(\lambda)$, $\tau_{a,abs}(\lambda)$, $m_a(\lambda)$ (2 modes), morphology, $P_{a,pol}(\theta)$ • Space measurements: Top of atmosphere shortwave and longwave F_u, collocated T(z), q(z)

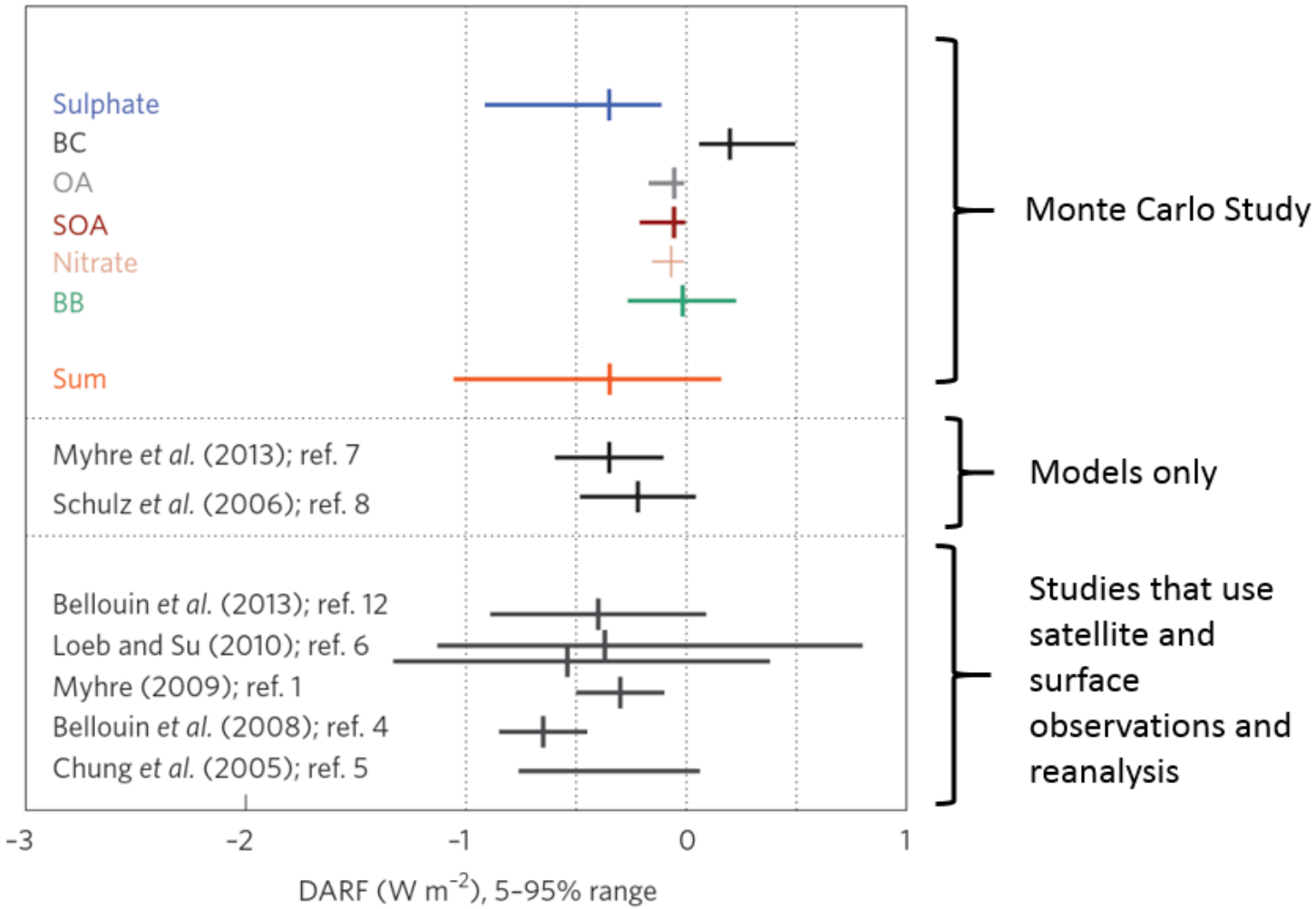

Figure 1. DARF mean and 5-95% confidence ranges for aerosol species as calculated by a Monte Carlo method, which accounts for the variance in relevant input parameters (top), and studies based on a range of models (middle), and observations and reanalysis (bottom) (from Samset et al., 2014).

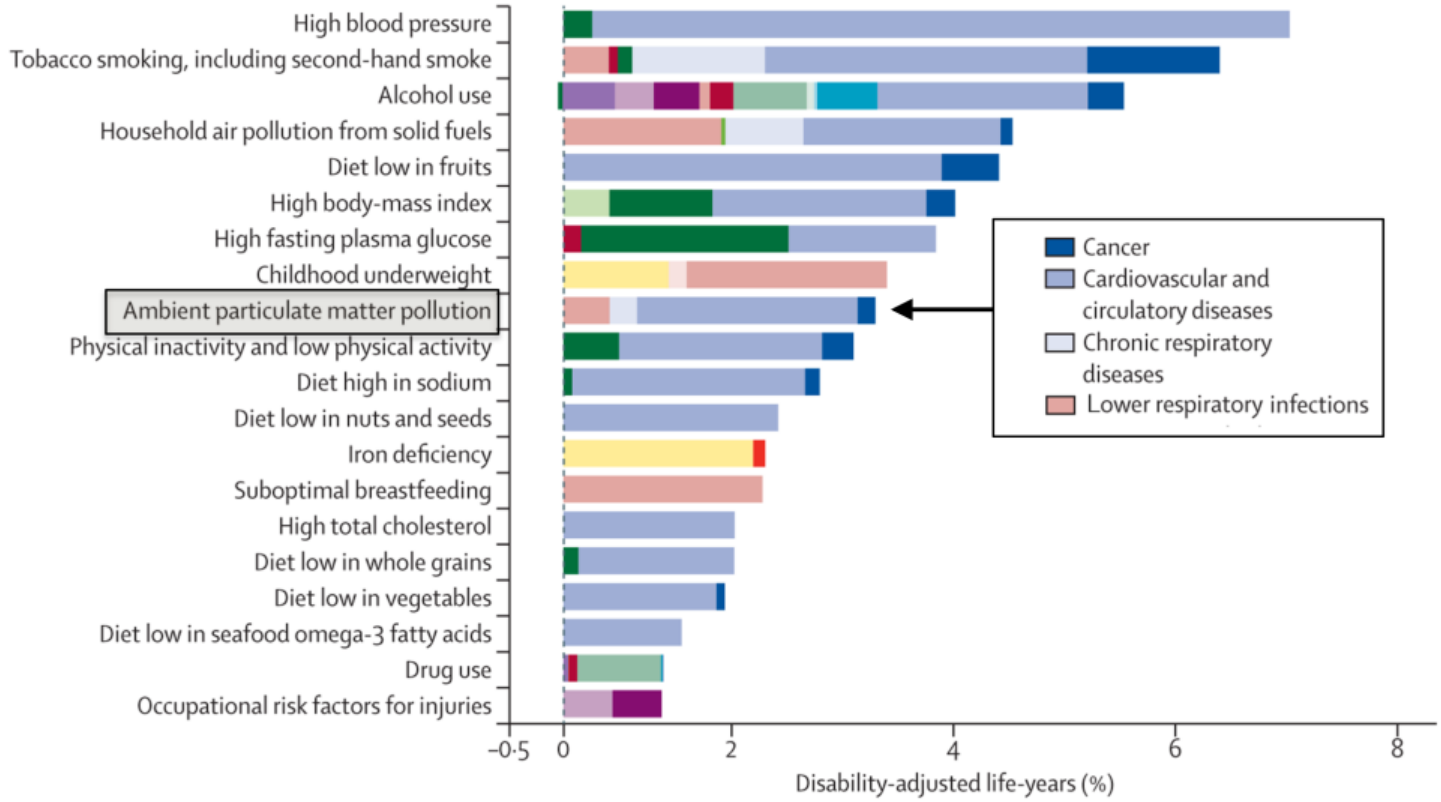

Figure 2. Global burden of disease in 2010 for the 20 leading risk factors, expressed as a percentage of global disability-adjusted life-years (DALY). DALY measures the number of years lost due to ill-health, disability or early death. Adapted from the 2010 Global Burden of Disease Study (Lim et al., 2012). Estimates of PM2.5 abundances were derived using MODIS and MISR data by van Donkelaar et al. (2010) and Brauer et al. (2012). This figure shows several of the primary adverse health impacts of PM2.5.

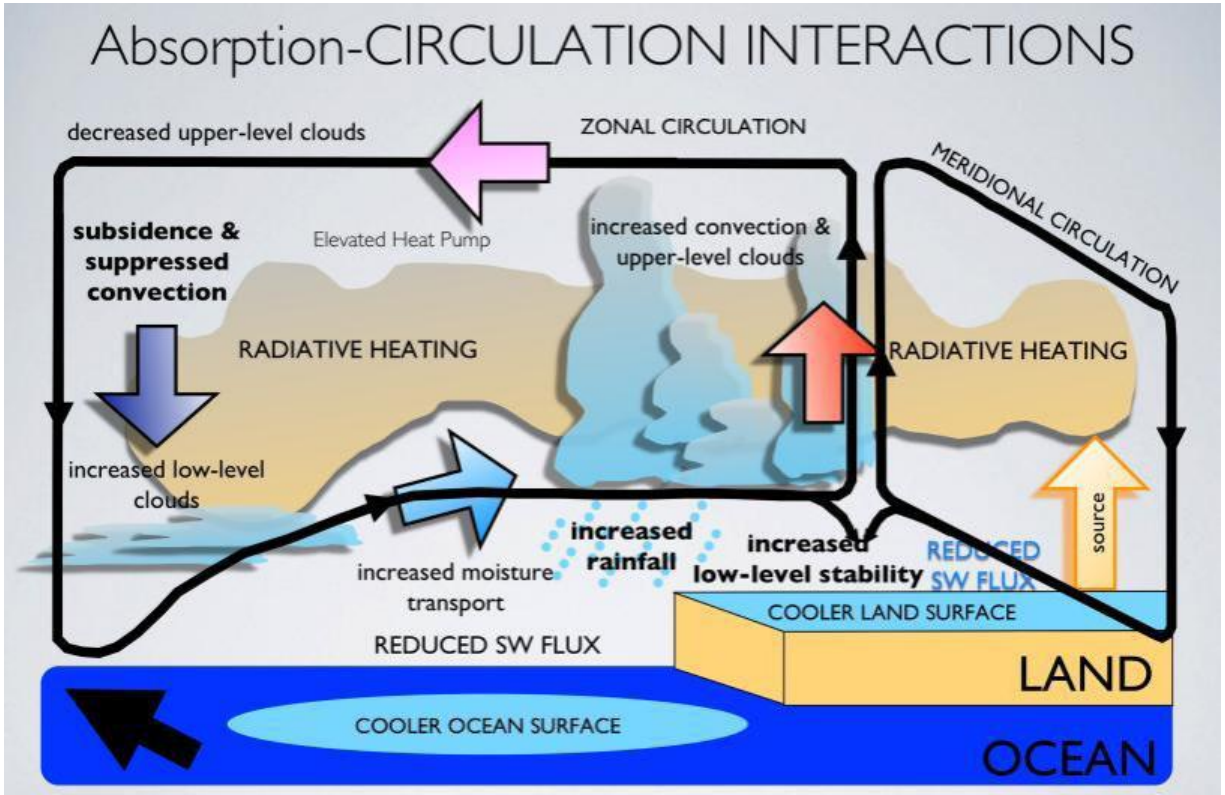

Figure 3. Illustration of the radiative/dynamical processes involved in the interaction between absorbing aerosols and the atmospheric circulation (adapted from Lau et al. 2009). Widespread aerosol layers can impact large-scale circulation and precipitation patterns like the Indian Monsoon (Ramanathan and Carmichael 2008).

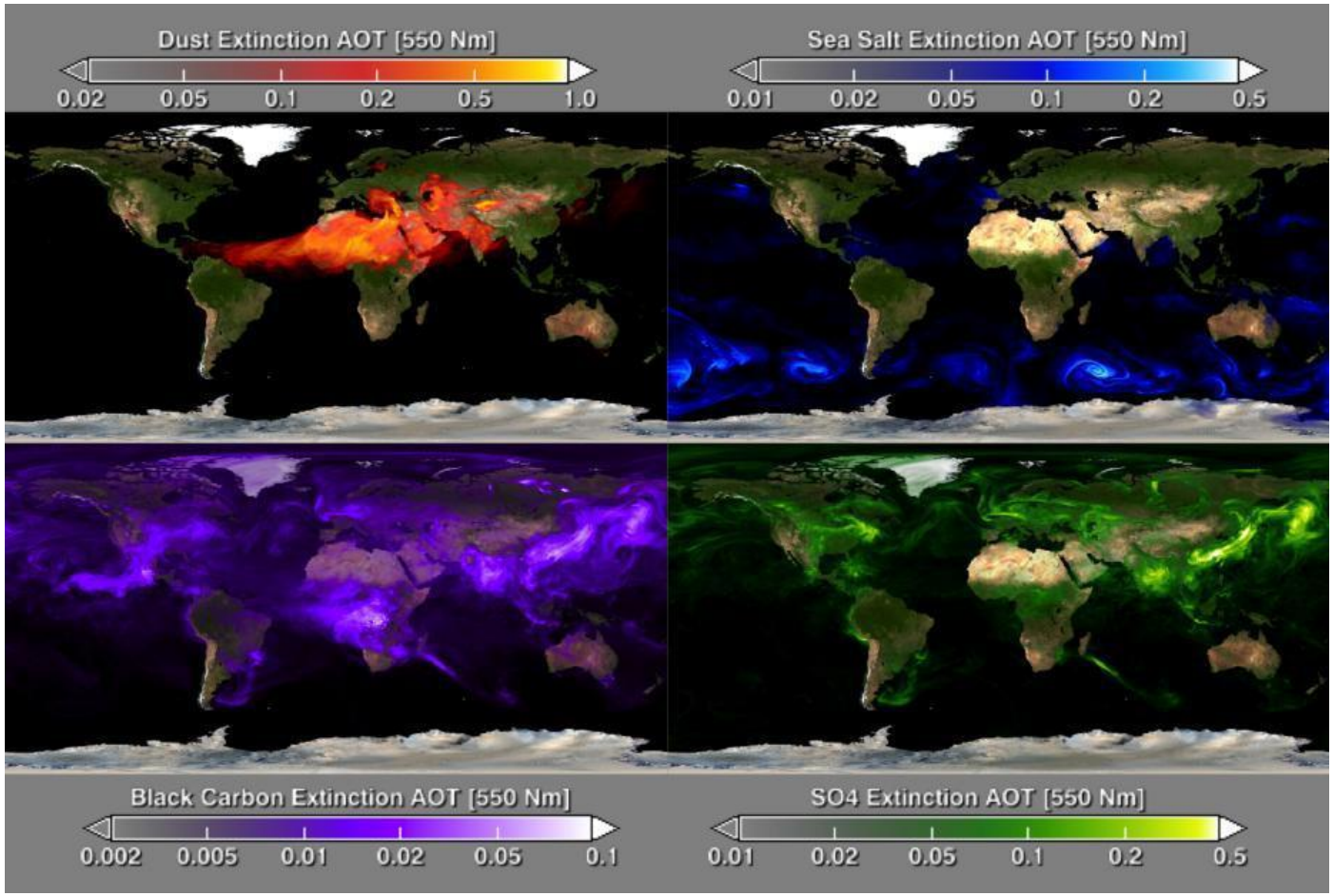

Figure 4. Near-real time GEOS-5 aerosol optical depth analysis valid 12 UTC on May 29, 2013 for dust, sea salt, back carbon and sulfate aerosols (from Davies et al. 2015). The availability of measurements from a multi-angle polarimeter and a HSRL lidar will in much contribute to improve the accuracy of the initial conditions for aerosol forecasting. By means of advanced algorithms such hybrid ensemble-variation 4D data assimilation, these measurements will provide information content to adjust individual species concentrations in the model, as well as provide constraints on size distribution and optical properties.