Cross-cutting Applications of Vertically Resolved Optical Properties to Reduce Uncertainties in Atmosphere and Ocean Earth System Processes

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The launch of CALIPSO into the A-train started a new era in remote sensing by providing the first global vertically resolved measurements of cloud and aerosol optical properties and composition. These data have been used in over 1600 publications documenting science advances in our understanding of the Earth's radiation budget, including stratospheric radiative forcing, cloud-climate feedbacks and aerosol-cloud interactions; the hydrological cycle including the partitioning of cloud water and cloud thermodynamic phase; processes and transport including strat-trop exchange and long range transport of aerosols; air quality; and ocean ecosystems. These advances were made possible by virtue of the profiling capability of the lidar. This instrument has significantly advanced our understanding, yet there remain pressing science questions that can only be addressed using vertically resolved measurements in the atmosphere and in the ocean.

These science questions cover a huge scope over four of the Earth System Science Themes: I. Global Hydrological Cycles and Water Resources; II. Weather and Air Quality; III. Marine and Terrestrial Ecosystems and Natural Resource Management; and IV. Climate Variability and Change: Seasonal to Centennial Forcings and Feedbacks of the Ocean, Atmosphere, Land, and Cryosphere within the Coupled Climate System. A random sample of focused science questions requiring vertically resolved measurements demonstrates the breadth of lidar applications: What is the direct aerosol radiative forcing at the top of the atmosphere, within the atmosphere, and at the surface? How large are the feedbacks between Arctic low clouds and other changes in the Arctic system? What are the annual cycles of plankton ecosystems in the climate-sensitive polar oceans? How will marine boundary layer cloud coverage change as the climate warms? What are the health impacts of global and regional changes in anthropogenic and natural processes in a warming climate?

These questions were selected from at least a dozen responses to RFI#1 and RFI#2 that stipulate vertically resolved measurements from lidar. Given the cross-cutting applicability of lidar measurements, it is worthwhile to consider these diverse science focus areas together. The commonality of similar requirements for a far-reaching set of objectives suggests that a single lidar instrument can be an affordable means to make a huge scientific impact. This paper identifies measurement requirements common to several RFI submissions and explains the range of lidar capabilities required for the cross-cutting applications described therein.

Science Objectives/Targets

A selection of the white papers that call for vertically resolved measurements from lidar are referenced in Table 1, which shows the full title, science focus, and science theme area. For example, Winker et al. discusses the need for continued cloud observations from space lidar to constrain uncertainties in climate sensitivity and to advance abilities to predict consequences of climate change at regional scales. With high vertical resolution, only lidar can accurately characterize shallow clouds at the heart of feedback uncertainties. Additionally, cloud vertical profiles from combined lidar and W-band radar are required to characterize cloud heating profiles and to constrain estimates of the surface radiation budget.

A recurring theme in many of these papers is the urgent need to reduce uncertainties in estimates of global radiative forcing. Focusing on aerosol-radiation interactions, Ferrare et al. and Thorsen et al. set goals for reducing uncertainties in the aerosol direct radiative effect and aerosol direct radiative forcing. Current model diversity in aerosol radiative effects is partly driven by a lack of constraint on the vertical distribution of aerosols, so High Spectral Resolution Lidar (HSRL), with its unique capability to measure vertically resolved aerosol extinction and backscatter at high accuracy, is critical for this task.

Similarly, aerosol-cloud interactions is a key focus of at least six other white papers (Mace et al., Meskhidze et al., Taylor et al. in Table 1; see also Chin et al., Garay et al., and Davis et al.). Mace et al., and Meskhidze et al. focus specifically on marine low clouds, highlighting that the marine boundary layer cloud feedback is currently the leading source of uncertainty in global climate models. Taylor et al. focus on Arctic low clouds, recognizing the key role of Arctic feedbacks in global climate and the timeliness of understanding Arctic feedbacks now during a pivotal transition state. Modeling to improve process level understanding of aerosol-cloud interactions critically depends on adequate measurement constraints of aerosol-cloud systems. Again, active remote sensing via lidar has important advantages over passive measurements in this domain. First, its unique vertical profiling capability allows for the determination of aerosols at cloud heights rather than integrated through the entire vertical column. Additionally, lidar can provide aerosol profiling above clouds, below thin clouds, and in broken-cloud situations that are very difficult or impossible to probe accurately with passive systems, providing the necessary capability of observing aerosols and clouds in the same volume. HSRL, with its direct measurement of aerosol extinction, provides more accurate aerosol measurements and more accurate constraints formodels than is possible with an elastic backscatter lidar, which loses calibration at lower altitudes due to attenuation from overlying layers. Lidar also provides essential coverage at night and in regions of high albedo, including snow and ice covered polar regions and marine regions with persistent cloud cover, which are fundamental to these scientific goals, but which have dramatically lower sampling yield from passive sensors.

Beyond providing layer heights and vertically resolved abundances, multi-wavelength HSRL lidar provides unique information for determining vertically-resolved aerosol size, concentration, and composition. At a minimum, aerosol type (Figure 2) is required for distinguishing natural from anthropogenic aerosol and therefore constraining estimates of aerosol forcings [Ferrare et al., Meskhidze et al.]. Information on particle size and abundance from advanced lidar retrievals provides better estimates of cloud-condensation-nuclei (CCN), which are required for determining aerosol-cloud interactions. Aerosol microphysics retrievals – possible from advanced lidar especially in combination with a polarimeter – also provide information on absorption, necessary for determining aerosol direct radiative forcing.

Several of the RFI responses have scientific goals that go beyond reducing uncertainties in climate forcing and focus on the effects of climate change on systems. For example, Kalashnikova et al. have the goal of improving understanding of the effect of aerosol on human health in a changing climate. Vertically resolved aerosol measurements are again central to this air-quality focus, since it is vital to understand aerosol abundance close to the surface where interactions with human health occur. Kalashnikova et al. also discuss the need for aerosol composition data to better distinguish differential effects on health; as in the aerosol direct radiative forcing focus, this vertically resolved aerosol composition information will require combined retrievals from a polarimeter and an advanced lidar.

Continuing with the focus on effects of climate change, Taylor et al. highlight the sensitivity of Arctic systems to a changing climate, pointing out the effects on natural and human systems in the Arctic of rapid and unprecedented climate change. Behrenfeld et al. takes the discussion all the way to biospheric responses, outlining a plan of study that will provide unprecedented understanding of the effects of climate on ocean ecosystems. Both Taylor et al. and Behrenfeld et al. again highlight lidar as having a key advantage over passive instruments in the ability to make measurements in polar regions; for Taylor et al., this requires aerosol and cloud measurements, and for Behrenfeld et al., this includes measurements below the ocean surface. An optimized lidar can penetrate below the ocean surface and provide vertically resolved profiles of phytoplankton abundance and and light attenuation, providing key global measurements of ocean ecosystem properties.

Utility

The white papers referenced above describe a broad range of science and application targets, all of which are aided by vertically resolved lidar measurements of particulate backscatter, extinction and depolarization in the atmosphere and/or ocean. For some of these application targets, the lidar variables are the primary requirement for addressing the science target, while for others, the authors envision a combination of lidar and other instruments which synergistically address the targets. Table 2 summarizes the utility of the vertically resolved lidar particulate measurements for addressing these targets, with respect to the other instruments involved in each RFI response.

Quality

The extensive series of cross-cutting applications have common requirements for global, vertically resolved measurements of particulate properties in the atmosphere and/or ocean. While details about the required accuracies and coverage can be found in the individual responses, the primary driver in the tradeoff between quality of the lidar products and complexity of the instrument is the number of lidar channels. A basic lidar similar to the CALIOP lidar on the CALIPSO satellite would provide very limited utility for achieving the range of cross-cutting goals. Such a lidar measures attenuated backscatter and depolarization (an indicator of particle shape) from both air molecules and particulates (i.e., aerosol and cloud targets and particulates in the ocean), but the measurement accuracy at a given altitude is limited by the attenuation and by the lack of ability to separate the molecular and particulate scattering. That is, aerosol extinction must be derived using an inferred lidar ratio which may be in error by as much as 30-50% [Winker et al., 2007; Omar et al., 2009], and errors in both particulate backscatter and particulate extinction accumulate as the profile is built from the top of the atmosphere down to lower altitudes (See Figure 1). This uncertainty in lidar ratio can lead to large (> 40-50%) uncertainties in aerosol extinction (Omar et al., 2009). The HSRL technique, by adding an additional optically filtered channel, separates the particulate and molecular signals in the atmosphere and in the ocean, and therefore enables direct, independent and calibrated measurements of particulate backscatter and extinction at all vertical levels. This, in turn, improves the retrieval of particulate depolarization as well. An instrument using the HSRL technique at one channel (532 nm or 355 nm) would represent a substantial increase in the quality of the vertically resolved measurements for most applications. By including the HSRL technique at both channels (532 nm and 355 nm), information can be obtained about particulate microphysical properties in both the atmosphere and ocean, allowing for the differentiation of particle sizes ranges and a more accurate retrieval of aerosol number concentration. The HSRL technology provides the increased accuracy required to evaluate increasingly sophisticated regional and global aerosol models [Fast et al., 2014, Saide et al. 2015, Buchard et al., 2016] and to help resolve the differences between CALIOP and AEROCOM [Koffi et al., 2012] that may arise due to uncertainties in lidar ratio estimates and concomitant errors in the attenuation correction. HSRL is also critically important to characterizing the aerosol concentrations and composition (NASA SMD, 2014). Moreover, including both the 355 and 532 nm HSRL channels provides continuity with the measurements from CALIOP on CALIPSO and ATLID on EarthCARE. This multi-wavelength HSRL instrument is also required for combined retrievals with polarimeters to provide vertically resolved absorption data necessary for some applications. Table 2 provides the traceability of science value to lidar capability for each of the selected RFI responses.

Success Probability

Instrument Readiness

The fact that the CALIOP instrument continues to operate after 10 years on orbit has proven that lidar is a robust and reliable technique. Considerable effort has been put into the design of the next-generation space-borne lidar by NASA engineering teams over the last several years. That design benefits from knowledge gained on CALIOP and other space-borne instruments including ICESat-1, ICESat-2, ATLID on EarthCARE, and ALADIN on ADM-Aeolus. It also benefits from technology developments through the NASA Instrument Incubator Program (IIP), Airborne Instrument Technology Transition (AITT) Program, internal NASA Center R&D funding, and ACE pre-formulation funding, and from years of experience with airborne prototype instruments including their development and refinement of them based on years of routine science operations with them (see Hair et al., 2008; Müller et al., 2014; Burton et al. 2015).

The laser for the lidar required for the cross-cutting applications listed in Tables 2 and 3 is a minor variant of the laser flown since 2012 on the NASA LaRC HSRL-2 instrument and which has demonstrated successful automated operations on the NASA ER-2 aircraft. This laser technology is on track to mature to TRL 6 via an Earth Science Technology Office funded project known as the High Efficiency Ultra-Violet Demonstrator (HEUVD), under which a laser generating the required outputs at 355, 532, and 1064 nm has been developed, is under life test, and will complete environmental testing in 2017. Through this and the European Space Agency (ESA) lidar programs, much knowledge has been gained on the source of laser damage for 355 nm operation and the techniques required to mitigate it. The HEUVD laser is injection seeded, and several generations of seed laser subsystems have been developed for the LaRC airborne program. That technology is being matured to TRL 6 in 2017 under a very successful Small Business Innovative Research (SBIR) Program contract. The HSRL technique relies on an optical filter in the receiver that enables the separation of molecular and aerosol backscatter. Interferometric receiver development has also gone through several generations of improvement, with a near-space like version currently flying on the airborne HSRL-2 instrument and a space version under development for environmental testing in fall of 2016. Alternate approaches exist as well: ESA has qualified an interferometeric receiver for ATLID on EarthCARE and researchers at UPMC Université Paris/LATMOS-IPSL have demonstrated an interferometric receiver on an airborne prototype instrument (Bruneau, et al., 2015). Telescopes of the type required have been developed on past programs (CALIOP, ADM-Aeolus) and manufacturing capabilities have been maintained by the vendors. Most other instrument components involve straightforward engineering using components that are space qualified or can easily be screened and tested for qualification.

Algorithm Readiness

Algorithms for a future cloud-aerosol-ocean lidar addressing the cross-cutting applications listed in Tables 1 and 2 are mature. Algorithm development has greatly benefitted from the CALIPSO mission and its algorithm development and validation efforts. Algorithms taking advantage of advanced capabilities enabled via the HSRL technique have been developed and matured over the last decade through deployments of the HSRL-1 and HSRL-2 airborne prototype instruments. These prototypes have been deployed on over 25 science-focused field missions over the past decade, often involving measurements on other platforms that provided corroborative data for retrieval validation. The basic HSRL aerosol extinction and backscatter retrievals were first validated by Rogers et al. (2009). Advanced aerosol microphysical retrievals (e.g., aerosol particle size and concentration profile) using three-wavelength data (HSRL at 355 and 532 nm, standard backscatter at 1064 nm) have been made fully operational and have been demonstrated and evaluated on a series of field missions (e.g., Müller et al., 2014, Sawamura et al., 2016). Furthermore, Behrenfeld et al., (2013) demonstrated that space-borne lidar could achieve the sensitivity to provide important ocean ecosystem properties using comparisons of CALIOP retrievals to those from MODIS. More advanced ocean profiling retrievals taking advantage of the accuracy provided by the HSRL technique have been demonstrated on three field missions (Azores 2012, SABOR 2014, and NAAMES 2015) (see Figure 3), and the operational retrievals from the airborne HSRL have been in excellent agreement with both coincident ocean color and in situ ocean optical measurements. Importantly, the teams that developed the airborne prototypes also developed the algorithms for reducing the data. Years of data analysis from those lidars have guided the refinement of the instruments and generated a wealth of corporate knowledge on which the design of current satellite instrument concepts have been based.

Affordability

The complementarity between the science discussed in the RFI responses summarized in Tables 1-3 and the similarities in measurement requirements indicates that a single instrument approach can accommodate many important but independent science objectives in a cost-effective manner. The critical elements to control costs are (1) development of design by instruments scientists experienced with the hardware and retrievals (ensures that the design will be robust and sources of error or bias are properly managed); (2) having few aspects of the design left open to trade studies (no funding/schedule lost to managing a large trade space); and (3) mature technologies (i.e., no funding and schedule lost to R&D activities required during the implementation phase). Elements (1) and (2) have been addressed by experience gained on CALIOP, the design and years of refinement of the airborne prototype instruments (HSRL-1 and HSRL-2), and efforts by engineering teams to transition the airborne designs to space. Element (3) has been addressed by past and ongoing investments in maturing the component technologies that ensure that the instrument can be developed at an affordable cost with little risk to cost growth. While the successful but extended instrument development phase on programs like ICESat-2, for which requirements and technical approach were significantly changed after selection, and ATLID, which took many years to conquer the difficult problem of UV laser damage, may raise concerns about costs, significant care has been taken to mitigate any risk of similar issues for a lidar of the type called for by the RFI responses listed in Table 1. Years of technology development, airborne instrument development, and algorithm development have put lidars of this type on a path to affordable implementation within a reasonable schedule. A team of engineers and instruments scientists at NASA Langley developed a detailed instrument concept in January 2016. The cost of that instrument has been estimated using a parametric cost estimation tool and a bottoms up approach. 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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Acronyms

Acronym	Definition
ACE	Aerosol-Cloud-Ecosystems
ADM-Aeolus	Atmospheric Dynamics Mission
AITT	Airborne Instrument Technology Transition
ALADIN	Atmospheric LAser Doppler INstrument
AOD	Aerosol Optical Depth
ATLID	ATmospheric LIDar
A-Train	Afternoon Train
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CCN	Cloud Condensation Nuclei
CDOM	Colored Dissolved Oganic Matter
DRE	Direct Radiative Effect
EarthCARE	Earth Clouds, Aerosols and Radiation Explorer
ESA	European Space Agency
HEUVD	High Efficiency Ultra-Violet Demonstrator
HSRL	High Spectral Resolution Lidar
ICESat	Ice, Cloud,and land Elevation Satellite
IIP	Instrument Incubator Program
IPSL	Institut Pierre Simon Laplace
IWC	Ice Water Content
LaRC	Langley Research Center

Laser	Light Amplification by Stimulated Emission of Radiation
LATMOS	LABORATOIRE ATMOSPHÈRES, MILIEUX, OBSERVATIONS SPATIALES
Lidar	Light Detection And Ranging
LWC	Liquid Water Content
NAAMES	North Atlantic Aerosol and Marine Ecosystems Study
NASA	National Aeronautics and Space Administration
NRC	National Research Council
PM2.5	Particulate Matter < 2.5 nm
RFI	Request For Information
SABOR	Ship-Aircraft Bio-Optical Research
SBIR	Small Business Innovative Research
SMD	Science Mission Directorate
Strat	Stratosphere
TRL	Technology Readiness Level
Trop	Troposphere
UPMC	University Pierre and Marie CURIE
UV	Ultra Violet

Table 1. Selected responses to Decadal Survey RFI. These papers all call for lidar measurements to address their respective science objectives. Themes are I. Global Hydrological Cycles and Water Resources, II. Weather and Air Quality, III. Marine and Terrestrial Ecosystems and Natural Resource Management, and IV. Climate Variability and Change.

Science Focus	**Full Title**	**Authors**	**Science Themes**
Aerosol Health Impacts	Space-based Global Assessment of Aerosol Source-Specific Impacts on Human Health in a Changing World	Kalashnikova et al.	II
Ocean Ecosystem Climate Response	A global ocean science target for the coming decade: Response to the 2017 NRC Decadal Survey Request for Information	Behrenfeld et al.	III
ACE Ocean-Aerosol	Response to the 2017 NRC Decadal Survey Request for Information regarding the OCEAN ECOSYSTEM and OCEAN-AEROSOL INTERACTIONS components of the Aerosol, Cloud, and ocean Ecosystem (ACE) Mission	Behrenfeld and Meskhidze	Primarily III, also I,II,IV
ACE Direct Aerosol Radiative Forcing	The ACE Lidar-Polarimeter Concept to Reduce Uncertainties in Direct Aerosol Radiative Forcing With Applications to Air Quality & Atmospheric Dynamics	Ferrare et al.	Primarily IV, also I,II,III
ACE Cloud-Aerosol Interactions	The Link Between Climate Sensitivity Uncertainty and Understanding Cloud-Aerosol Interactions	Mace et al.	Primarily IV, also I
Marine CCN	Response to the 2017 NRC Decadal Survey Request for Information regarding High Spectral Resolution Lidar (HSRL)-based CCN estimates over the ocean as part of the Aerosol, Cloud, and ocean Ecosystem (ACE) Mission	Meskhidze et al.	Primarily IV, also I,II,III
Aerosol Direct Radiative Effects	Quantifying Truly Global Aerosol Direct Radiative Effects	Thorsen et al.	IV
Arctic Low Clouds	Quantifying the Magnitude and Uncertainty in Feedbacks between Arctic Clouds and the Arctic Climate System	Taylor et al.	IV
Cloud climate sensitivity	Reducing current uncertainties in cloud-climate feedbacks with satellite lidar	Winker et al.	IV

Table 2. Utility of lidar-measured geophysical variables (vertically resolved profiles of aerosol backscatter, extinction, and depolarization) for selected responses to Decadal Survey RFI

Science Focus	**Other required measurements**	**Utility of vertically resolved lidar measurements**
Aerosol Health Impacts	Polarimeter	Objectives call for vertically resolved aerosol properties distinguished by aerosol type, requiring combined lidar + polarimeter retrieval.
Ocean Ecosystem Climate Response	Ocean radiometer, profiling float array	Radiometer provides global ocean color. Lidar provides ocean properties to ~3 optical depths, including critical high-latitude coverage. Float array extends the vertical column deeper into the ocean.
ACE Ocean-Aerosol	Ocean radiometer, polarimeter, dual-frequency Doppler radar	Lidar provides vertically resolved aerosol heights & composition, plankton biomass, particulate organic carbon, and ocean subsurface light attenuation.
ACE Direct Aerosol Radiative Forcing	Polarimeter	Objectives require vertically resolved aerosol measurements only possible from lidar and an extensive suite of aerosol microphysics including absorption, best obtained by combined lidar+polarimeter retrieval.
ACE Cloud-Aerosol Interactions	Radar; stereo imager	Lidar provides essential profiles of aerosol properties for inferring CCN.
Marine CCN	Possibly other ACE instruments, including polarimeter	Objectives call for satellite-based CCN concentrations from lidar. Combined lidar+polarimeter retrieval would provide additional accuracy in CCN microphysical retrieval.
Aerosol Direct Radiative Effects	none	Lidar provides vertically resolved aerosol measurements
Arctic Low Clouds	Radar; passive microwave; improved model reanalysis	Lidars provide cloud fraction and vertical distribution requirements; combined with radar provides IWC/LWC. Passive microwave needed for sea ice extent.
Cloud climate sensitivity	Passive albedo and flux measurements; vertical distribution of water vapor	Objectives require stable and accurate measurements of vertical distribution of shallow cloud properties, best addressed by lidar. Also requires passive measurements for cloud albedo and diabatic heating.

Table 3. Traceability of science value to lidar capability.

	Increasing Lidar Capability			
Science Focus	**Attenuated backscatter and depolarization at 532 nm**	**Aerosol backscatter and extinction from HSRL at 532 nm plus depolarization**	**Aerosol backscatter and extinction from HSRL at 532 nm plus attenuated backscatter at 1064 nm; two wavelengths of depolarization**	**HSRL backscatter and extinction at 355 and 532 nm, plus attenuated backscatter at 1064 nm; depolarization at two or three wavelengths**
Aerosol Health Impacts	Vertically resolved attenuated backscatter provides some constraint on model vertical distributions of aerosols.	**Adds** vertically resolved aerosol amount: better proxy for PM2.5 at surface than AOD, better constraint on vertical distributions from models.	**Adds** aerosol typing, helps distinguish aerosol particulate matter relevant to human health.	**Adds** retrieval of some microphysical properties; enables joint retrieval with polarimeter of full suite of vertically resolved microphysical properties.
Ocean Ecosystem Climate Response	Surface-weighted, vertically integrated phytoplankton biomass.	**Adds** profile of vertically resolved phytoplankton biomass and submarine diffuse attenuation coefficient.		**Adds** profile of phytoplankton biomass and diffuse attenuation coefficient at two wavelengths; **Adds** particle size (community composition); **Adds** greater penetration depth. **Adds** discrimination of CDOM vs. phytoplankton absorption.
ACE Ocean-Aerosol	Surface-weighted, vertically integrated phytoplankton biomass.	**Adds** vertically resolved aerosol properties to address uncertainties in atmospheric correction algorithms. **Adds** vertical structure in ocean ecosystem properties.	**Adds** aerosol type information relevant to understanding terrestrial aerosol inputs to ocean ecosystems.	**Adds** discrimination of phytoplankton community composition; **Adds** greater penetration depth. **Adds** discrimination of CDOM vs. phytoplankton absorption; **Adds** retrieval of detailed aerosol properties including CCN.
ACE Direct Aerosol Radiative Forcing	Cloud-aerosol discrimination and layer heights only.	**Adds** vertically resolved aerosol amount allowing for probing DRE at top and bottom of the atmosphere separately.	**Adds** distinction between coarse & fine modes. **Adds** capability to distinguish natural from anthropogenic aerosol.	**Adds** retrieval of microphysical aerosol properties relevant to radiative effects. Enables joint retrieval with polarimeter of absorption microphysical properties.

ACE Cloud-Aerosol Interactions	Cloud-aerosol discrimination and layer heights only.	**Adds** CCN proxy on cloud scales from vertically resolved extinction.	**Adds** capability to distinguish fine and coarse mode.	**Adds** retrieval of microphysical properties including particle size and concentrations for better CCN proxy.
Marine CCN	Cloud-aerosol discrimination and layer heights only.	**Adds** vertically resolved aerosol amount at high resolution and SNR: addresses challenges of high spatiotemporal variability and low concentrations.	**Adds** capability to distinguish sea spray aerosol from transported terrestrial aerosols in marine environment, and capability to distinguish aerosols types most relevant to ice nucleation.	**Adds** retrieval of microphysical properties including particle size and concentrations for better CCN proxy.
Aerosol Direct Radiative Effects	Cloud-aerosol discrimination and layer heights only.	**Adds** accurate AOD. **Adds** estimate of DRE within atmosphere from vertically resolved extinction.	**Adds** aerosol typing: improves estimates of aerosol properties, like index of refraction, relevant to radiative effects.	**Adds** retrieval of microphysical aerosol properties relevant to radiative effects.
Arctic Low Clouds	Cloud-aerosol discrimination and layer heights only	**Adds** CCN proxy on cloud scales from vertically resolved extinction. Particular relevance in the arctic due to extensive tenuous aerosols. Improves distinction between aerosols and optically thin ice prevalent in the Arctic.	**Adds** aerosol typing providing distinction of aerosols that are efficient CCN or IN.	**Adds** retrieval of microphysical properties including particle size and concentrations for better CCN proxy.
Cloud climate sensitivity	Cloud vertical structure, cloud fraction, and cloud phase (especially boundary clouds and thin cirrus) consistent with CALIPSO for multi-decadal continuity.	**Adds** accuracy in cloud optical depth and vertically resolved extinction for cloud radiative heating, better separation of clouds from optically thick aerosols.		

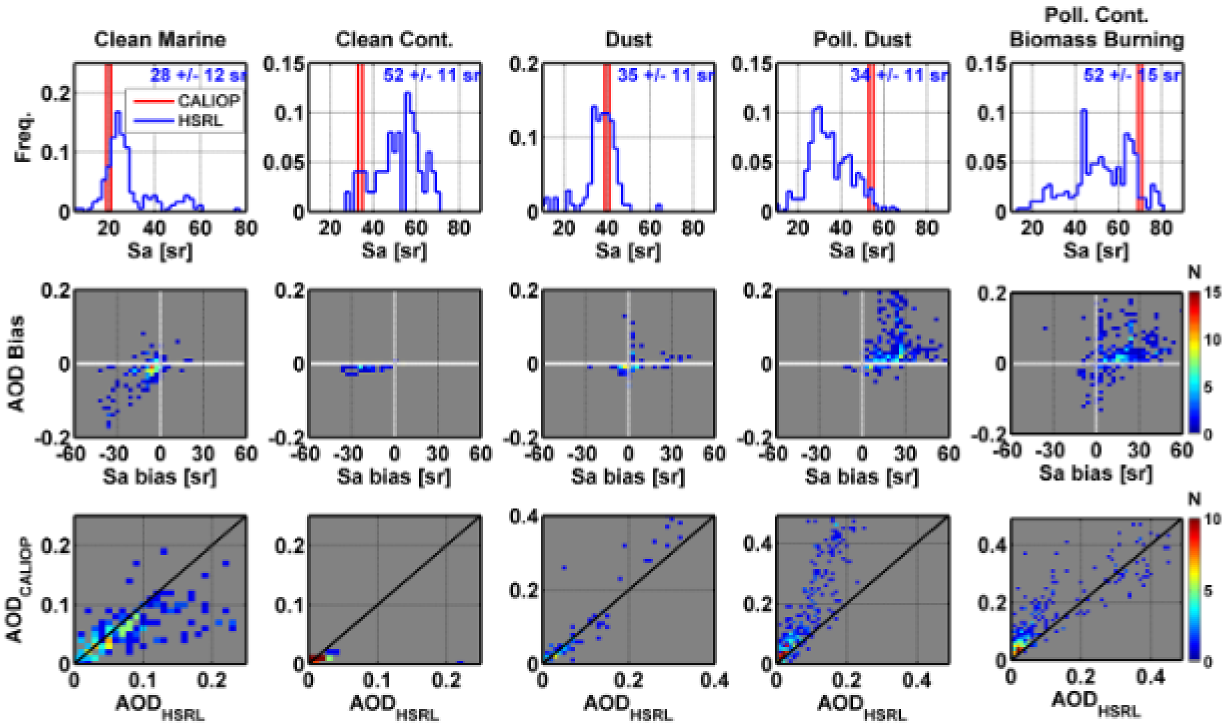

Figure 1. From Rogers et al. [2014]. Comparison of lidar ratio (S_a, the extinction-to-backscatter ratio) and layer aerosol optical depth (AOD) for CALIOP (CALIPSO satellite) and HSRL (airborne) for coincident measurements at night from >900 layers measured during 18 field campaigns. Each column represents an aggregate of those layers identified by CALIOP as having a specific type. The top row shows histograms of HSRL-measured lidar ratio with the CALIOP assigned lidar ratio marked in red. The bottom row shows the comparison of AOD from CALIOP vs HSRL showing significant bias in several of the aerosol types, particularly clean marine, polluted dust and polluted continental/biomass burning. In the middle row, it is demonstrated that the AOD bias is directly related to the error in lidar ratio, since the assigned lidar ratio is used in the CALIOP processing to generate the layer extinction and optical depth. For CALIOP, the lidar ratio is assigned using an inference of the aerosol type, which must be selected from a limited set of types, each of which is assigned a single value. Since many aerosol scenarios are composed of mixtures, a single lidar ratio often is a poor match for a given scene [Burton et al, 2013, 2014]. By making a direct measurement of extinction and lidar ratio, the HSRL technique avoids the need to assign the lidar ratio based on inferred aerosol type.

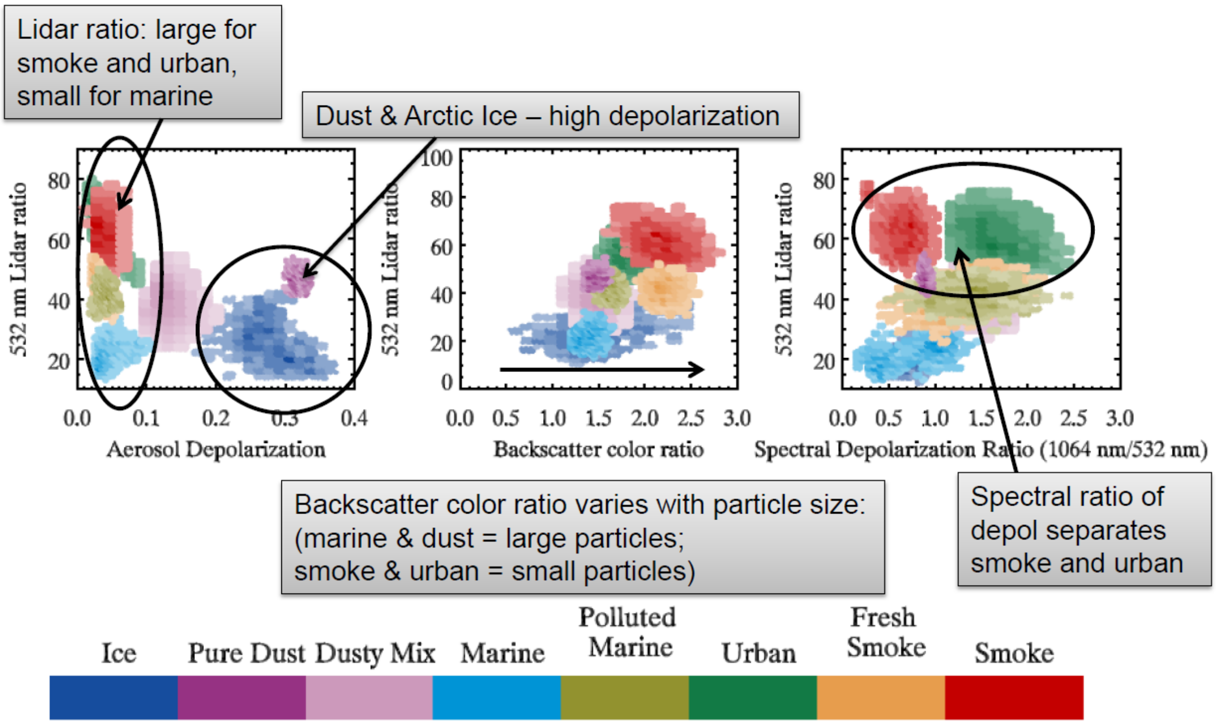

Figure 2. Adapted from Burton et al. [2012]. Aerosol classification from airborne HSRL-1 instrument from 18 field campaigns. The airborne HSRL-1 instrument measures aerosol backscatter and extinction at 532 nm using the HSRL technique, attenuated backscatter at 1064 nm, and aerosol depolarization at two wavelengths. The HSRL-measured extinction and backscatter at 532 nm is used to correct the attenuation in the 1064 nm channel. Ratios of the extinctions and backscatter coefficients make the lidar ratio (extinction to backscatter ratio) and backscatter color ratio. These, along with depolarization and the spectral ratio of depolarization are calibrated, intensive measurements that do not vary with aerosol loading and thereby provide information about intrinsic properties of aerosol. For example, particulate depolarization indicates non-spherical particles. The lidar ratio varies significantly with type and plays a pivotal role in separating the types of spherical particles like marine aerosol from smoke. The intensive parameters can be used for aerosol classification which in turn informs various applications such as identifying types that act as ice nuclei or separating natural from anthropogenic aerosol.

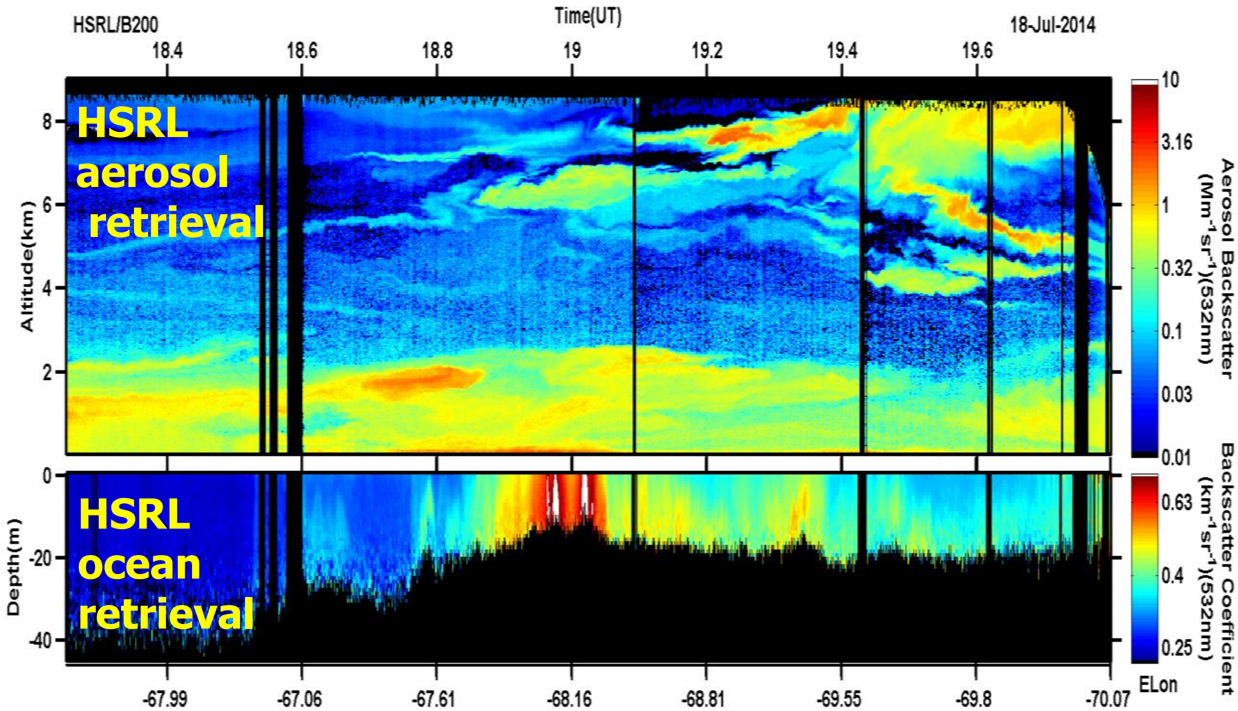

Figure 3. An atmosphere- and ocean-optimized HSRL can provide accurate independent retrievals of particulate backscatter and extinction (or "attenuation" for the ocean). Shown here is a simultaneous curtain of aerosol backscatter and ocean particulate backscatter acquired with the NASA Langley airborne HSLR-1 during the Ship-Aircraft Bio-Optical Research (SABOR) field experiment conducted in July 2014. The curtain starts in the North Atlantic gyre and terminates in the productive waters of the Gulf of Maine. The curtain of ocean diffuse attenuation coefficient for this scene is shown in the Behrenfeld et al., ocean ecosystems climate response paper referred to in Table 2. Unlike passive ocean color retrievals, the lidar retrieval is insensitive to the overlying aerosol layers. In addition to making unique and valuable measurements, an ocean-optimized HSRL flown in formation with PACE or other ocean color instrument would enable assessment and improvement of the aerosol corrections in the passive ocean color algorithms.