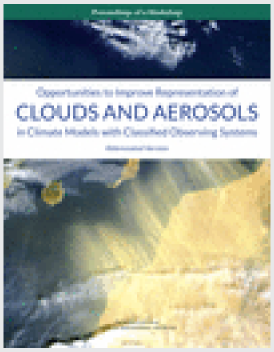

Opportunities to Improve Representation of Clouds and Aerosols in Climate Models with Classified Observing Systems: Proceedings of a Workshop: Abbreviated Version

DETAILS

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Opportunities to Improve Representation of

CLOUDS AND AEROSOLS

in Climate Models with Classified Observing Systems

Proceedings of a Workshop

Abbreviated Version

Katie Thomas, *Rapporteur*

Committee on Opportunities to Improve the Representation of Clouds and Aerosols in Climate Models with National Collection Systems: A Workshop

Board on Atmospheric Sciences and Climate

Division on Earth and Life Studies

The National Academies of
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This document is an abbreviated version of a classified Proceedings of a Workshop. The classified Proceedings of a Workshop was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published Proceedings of a Workshop as sound as possible and to ensure that the proceedings meet institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. The committee wishes to thank the following individuals for their review of these proceedings:

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DOMINICK VINCENT, U.S. Navy
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Although the reviewers listed above have provided constructive comments and suggestions, they did see the final draft of the Proceedings of a Workshop before its release. The review of these proceedings was overseen by Rita Colwell, University of Maryland, who was responsible for making certain that an independent examination of classified Proceedings of a Workshop was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this Proceedings of a Workshop rests entirely with the rapporteur and the institution.

Contents

Opportunities to Improve the Representation of Clouds and Aerosols in Climate Models with Classified Observing Systems: Proceedings of a Workshop

OVERVIEW

One of the most significant and uncertain aspects of climate change projections is the impact of aerosols on the climate system. Aerosols influence the climate indirectly by interacting with nearby clouds leading to small changes in cloud cover, thickness, and altitude, which significantly affect Earth's radiative balance. Advancements have been made in recent years on understanding the complex processes and atmospheric interactions involved when aerosols interact with surrounding clouds, but further progress has been hindered by limited observations.

The Intelligence Community (IC) asked the National Academies of Sciences, Engineering, and Medicine to plan a workshop to discuss the usefulness of the classified observing systems in advancing understanding of cloud and aerosol interactions (see Appendix A for the full Statement of Task). Because these systems were not developed with weather and climate modeling as a primary mission objective, many participants said it is necessary for scientists to find creative ways to utilize the data. The data from these systems have the potential to be useful in advancing understanding of cloud and aerosol interactions.

Workshop participants were briefed on several classes of classified observing systems and then suggested several strategies for leveraging the data:

- Working with data that have already been collected and archived, but that have not yet been studied because they are outside of IC interest;
- employing tasking and engineering study requests;
- gathering information from atmospheric corrections used in retrieving data related to surface conditions;
- co-collecting the classified data with data from: field campaigns, civilian satellites, civilian ground and in situ measurements, commercial satellites, and other IC sensors; and
- identifying particular locations (e.g., data sparse) and associated phenomena that would be useful for studying.

However, workshop discussions highlighted several technical, scientific and policy challenges in utilizing the classified data. The most significant challenge, according to several participants, is the difficulty in accessing the data due to their classification, which is problematic because civilian science is grounded in transparency for reproducibility. Even if derivative products could be unclassified, some participants said that the data would not be nearly as useful or viable without the metadata. Another major limitation is calibration accuracy, which is critical for data usability for environmental applications. Other limitations include collection constraints, self-emission issues, lack of vertical information, and data processing (i.e., models will likely need to be modified to use some of the data).

Many workshop participants said that the best path forward is to test the potential utility of the classified data by bringing small groups of civilian scientists with the appropriate clearances together with scientists from the IC to conduct pilot projects. Individual participants identified four pilot projects that could probably be pursued now and would likely provide valuable outputs.

A co-benefit of these pilot projects is the opportunity they provide for collaboration between the IC and cleared civil scientists (especially as more gain security clearances). Such collaborations have been infrequent and ad hoc. Many workshop participants said collaboration would be beneficial to both groups, particularly if conducted in a more consistent, organized manner to integrate the classified data and leverage the opportunities for advancing understanding of clouds and aerosol interactions.

INTRODUCTION AND MOTIVATION FOR THE WORKSHOP

One of the most significant and uncertain aspects of climate change projections is the impact of aerosols on the climate system. Observed global warming from the increase in greenhouse gases may have been and continue to be reduced by aerosol effects. Aerosols influence the climate most directly by increasing the amount of sunlight that is reflected back to space and indirectly through their interactions with clouds. Small changes in cloud cover, thickness, altitude, and cloud particle size and type (liquid versus ice) affect the Earth's radiative balance significantly, but these complex processes are incompletely captured in climate models (Rosenfeld et al., 2014). Aerosol effects are the largest uncertainty in the human (anthropogenic) radiative forcing of the climate system. Thus there remain significant uncertainties in estimating radiative forcing caused by human activities, leading to a large range in projections of future global warming (Figure 1).

Advancements have been made in recent years in understanding the complex processes and atmospheric interactions involved when aerosols interact with surrounding clouds, but further progress has been hindered by limited observations and coarse resolution climate models. There are a vast range of scales of cloud and aerosol properties and they are significantly smaller than those resolved in climate models (IPCC, 2013).

In light of this, the IC asked the National Academies of Sciences, Engineering, and Medicine to appoint a committee to plan a workshop to determine the usefulness of data from classified observing systems to advance understanding of cloud and aerosol interactions. Such an improved understanding could lead to a more accurate representation of cloud and aerosols in climate models, reducing the uncertainty of climate projections.

In her opening remarks, committee chair Pamela Emch, Northrop Grumman Aerospace Systems, noted that the committee was tasked to plan a workshop to address the following questions:

- How could the data from classified observing systems be utilized to advance understanding of aerosol-cloud-precipitation interactions?
- What are the potential contributions to climate modeling?
- What follow-on scientific research could render such improvements using classified observing system data?

The committee[1] planned and organized two workshops (one unclassified and one classified), selected and invited speakers and discussants, and moderated the discussions.

The unclassified workshop was held June 24-25, 2015, in Irvine, California, immediately following the Sackler Colloquium on Improving Our Fundamental Understanding of the Role of Aerosol-Cloud Interactions in the Climate System to leverage participation from scientists who did not hold the appropriate clearances (Seinfeld et al., 2016; see Appendix B). The primary goal of this workshop was to inform the committee's planning of the classified workshop. Participants discussed current and planned, non-proprietary and unclassified satellite observations of aerosols, clouds and precipitation. They identified gaps that exist in the knowledge as well as observations or data that may be useful in understanding cloud and aerosol interactions. A full recap of the discussions at this workshop is included in Appendix C.

The classified workshop was held September 28-30, 2015, in Washington, DC. Its main goal was to foster interactions with scientists from both the civil and intelligence communities and determine the

[1] Some members of the planning committee already held the required clearances to participate in the classified workshop, some obtained a clearance after being appointed to the committee, and others did not receive a clearance and participated in only the unclassified meetings.

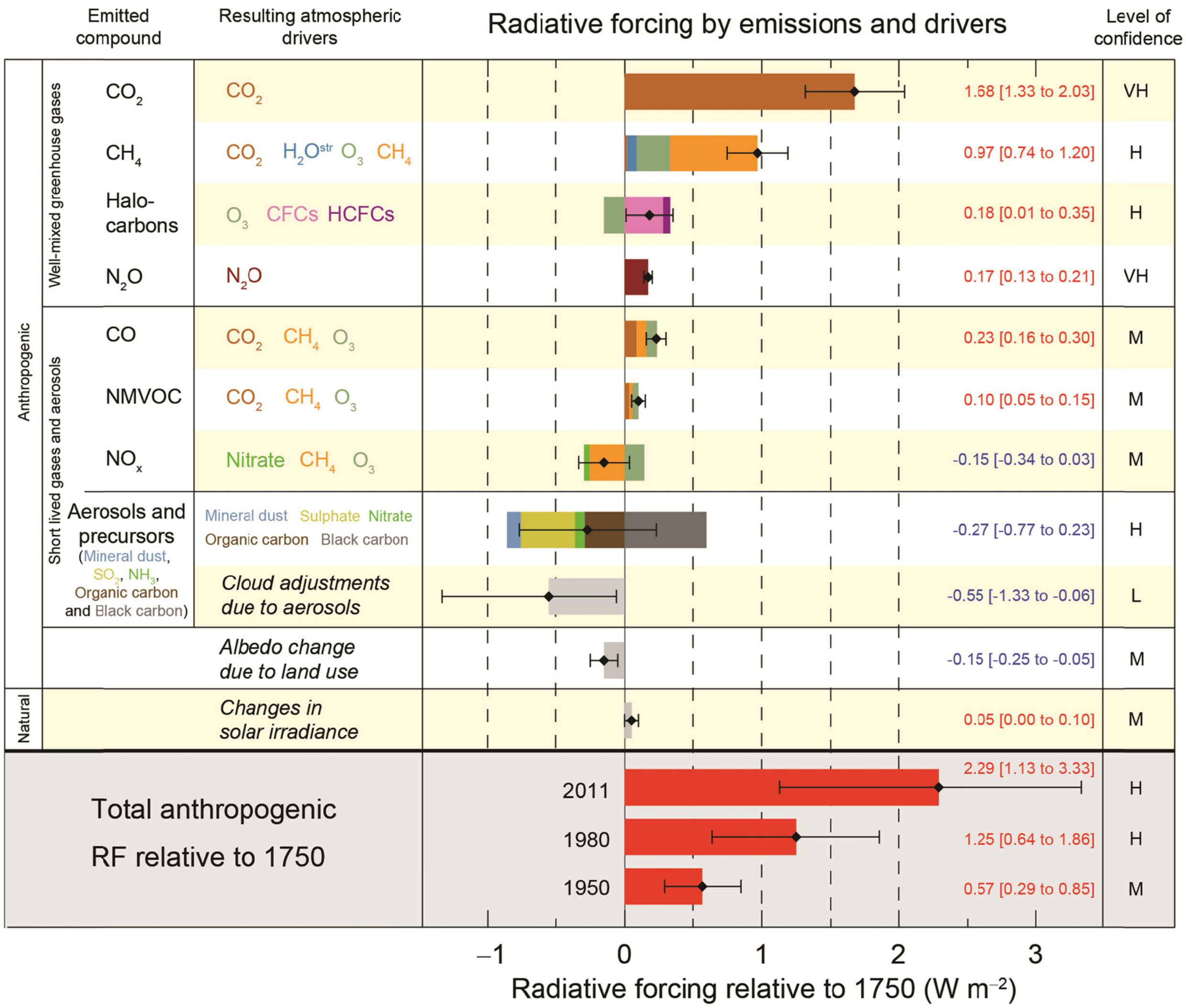

FIGURE 1 Radiative forcing estimates in 2011 compared to 1750 and uncertainties for the main drivers of climate change. The uncertainty associated with estimated radiative forcing resulting from cloud and aerosol interactions is the largest of any of the global radiative forcing uncertainties. The best estimates of the net radiative forcing are shown as black diamonds with corresponding uncertainty intervals; the numerical values are provided on the right of the figure, together with the confidence level in the net forcing (VH-very high, H-high, M-medium, L-low, VL-very low).
SOURCE: IPCC, 2013.

usefulness of classified observing systems to advance understanding of cloud and aerosol interactions. The workshop agenda is included in Appendix D.[2]

The presentations and discussions that took place at the classified workshop are described in these proceedings.[3] This abbreviated version of a classified report does not step through the classified workshop agenda topics in chronological order; rather it summarizes the workshop topics thematically. First, the scientific context for the workshop (including civilian observing gaps and challenges) is discussed. Next, the proceedings discuss cloud and aerosol processes and parameters that could be potentially estimated with the IC sensors. Finally, the proceedings provide strategies for and limitations in leveraging the classified data.

[2] A participant list for this workshop is not available.

[3] These proceedings have been prepared by the workshop rapporteur as a factual summary of what occurred at the classified workshop. The planning committee's role was limited to planning and convening the workshop. The views contained in the report are those of individual workshop participants and do not necessarily represent the views of all workshop participants, the planning committee, or the National Academies of Sciences, Engineering, and Medicine.

The primary audience of the classified report is IC scientists who are looking to work with leading experts in the civil science community to identify the most promising applications of classified assets to improve representation of clouds and aerosols in climate models. A secondary audience (of this abbreviated version of the classified report) is the civilian scientific community who could consider how potential algorithm improvements might be incorporated into climate models.

PERSPECTIVES FROM THE SPONSOR AND OFFICE OF SCIENCE AND TECHNOLOGY POLICY (OSTP)

The primary goal of this activity is to consider the usefulness of the IC data as is or in some modified way. Although there are several limitations to utilizing the data, the workshop is a first step review of what is possible. Some potential options for utilizing the data if they are not declassified include collecting data and then processing them into a form that is declassified, bringing scientists into a classified setting to use classified data, or a combination of these. Such programs are also a good opportunity to facilitate exchange of information between different agencies.

A related effort that utilized classified data was the Measurements of Earth Data for Environmental Analysis (MEDEA) program. It was initiated in 1994 to create a team of cleared civilian scientists outside of government, who were extensively briefed on classified observing systems, and then were called upon to advise the IC and the White House on environmental issues. MEDEA scientists utilized classified data to advance science on the civilian side. For example, this program was instrumental in the release of physical oceanographic data collected by the Navy as well as older imagery from fiducial sites[4] in the Arctic.

Matthew Heavner, OSTP, noted that the timing of the workshop is excellent because of President Obama's increased visibility and interest in climate-related activities. For example, the President released a Joint Presidential Statement on Climate Change with China (2014); highlighted the implications of climate change on national security in his commencement speech to the Coast Guard (2015); addressed the 2015 Conference on Global Leadership in the Arctic: Cooperation, Innovation, Engagement, and Resilience (GLACIER); and will be participating in the 2015 United Nations Climate Change Conference (COP21) meetings. Dr. Heavner also pointed out that from a national security point of view, the impact of clouds and aerosols on the hydrologic cycle could result in regional instability.

SCIENTIFIC CONTEXT FOR THE WORKSHOP

Processes and Parameters to Advance Understanding

Committee member Michael Prather, University of California, Irvine, gave an overview of specific processes and relationships related to cloud and aerosol interactions. He emphasized the challenge of studying clouds and aerosols from space due to the vast range in size and forms of the particles and droplets (Figure 2). For example, clouds consist of water vapor, liquid droplets, ice particles, graupel (mixed) and range in size from 8-12 μm radius (liquid clouds), 50 μm radius (some cirrus, drizzle), and up to 1 mm (rain). Furthermore, aerosols come in many sizes and composition (e.g., sea salt, dust, sulfate, nitrate, organic, bacteria, fungal spores, and pollen), and range in size from 3-5 μm to more than 10 μm).

Dr. Prather noted that the processes involved are dynamic, not static (Figure 3). For example, the effective radius of droplets affects the albedo of liquid water clouds, whereas the size and shape of ice

[4] Under MEDEA auspices, the global "fiducials" program was established whereby participating scientists could request collection of classified images at environmentally sensitive locations around the globe. The term "fiducials" refers to the fact that the classified images were to be kept "in trust" in classified archives, with the eventual goal of declassification and release to the broader scientific community for research purposes.

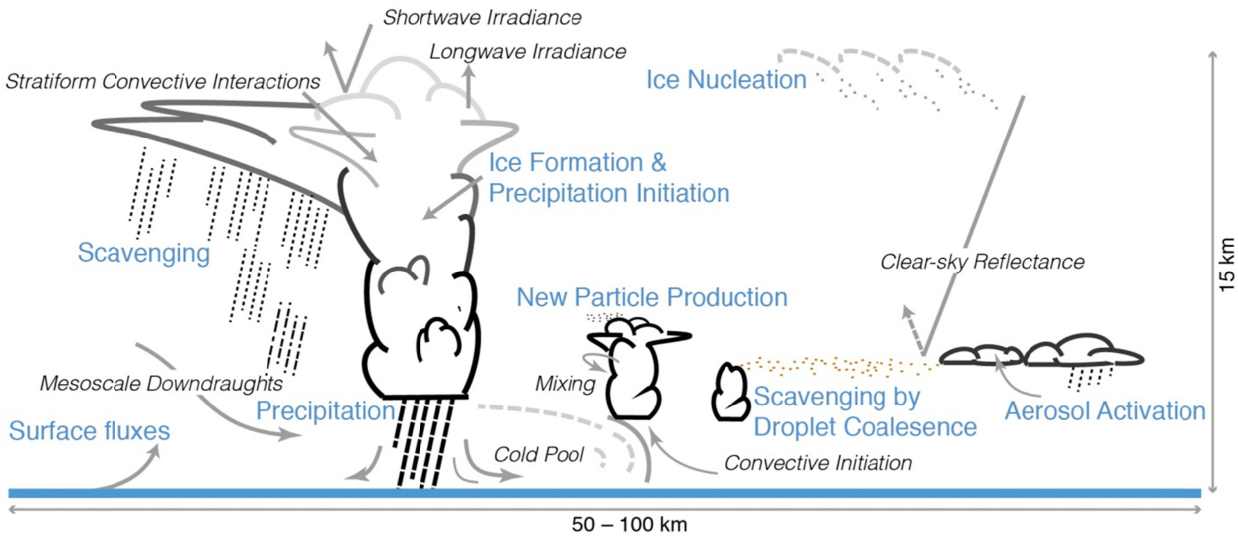

FIGURE 2 There are numerous cloud-aerosol-precipitation related processes that can occur in a typical general circulation model grid box. Such processes encompass a large range of spatiotemporal scales. SOURCE: Boucher et al., 2013.

affects the albedo of ice water clouds. Furthermore, given that cloud liquid droplets and ice cloud particles vary greatly in size, it is crucial to know the effective radius and column amount. Ice shape and asymmetry factor are also important properties. Aerosols vary in size (and shape for some) and have different chemical composition and radiative properties. In addition to effective radius and column amount, it is also important to know if there are different mode distributions. Other aerosol characteristics that are useful to know include:

- Is the aerosol absorbing?
- Is the aerosol hydrophilic or hydrophobic?
- Does the aerosol form cloud drops?
- Is the aerosol an ice nucleus?
- Was the aerosol caused by human pollution?

In her presentation, committee member Sonia Kreidenweis, Colorado State University, noted that there is a mismatch between necessary measurements to understand processes, and measurement capabilities from the existing civil platforms. For example, for aerosol properties, the following parameters need to be measured to test understanding: cloud condensation nuclei (CCN) number concentrations, ice nucleating particle (INP) number concentrations, aerosol composition, and particle size distribution. However, current capabilities are limited to aerosol optical depth (AOD), extinction profile, whether a particle is fine or course, and composition proxies. Dr. Kreidenweis noted that AOD is often used to estimate but does not always provide an accurate estimate of number concentration. To get at the microphysics, scientists need to know droplet and/or aerosol number concentration, not total-column values.

Necessary measurements and current capabilities are also mismatched for warm and cold cloud properties, said Dr. Kreidenweis. For warm cloud properties, the following parameters need to be retrieved: droplet number concentrations, droplet size distributions, vertically resolved liquid water content (LWC), drizzle, rain drop size distribution (DSD), and precipitation and evaporation rates. However, only the following properties can currently be derived with civilian satellites: cloud reflectivity, cloud optical depth, cloud top height, precipitation retrievals (heavy/light), and cloud fraction. A similar mismatch also occurs for cold cloud properties. Estimates of ice crystal number concentrations, ice particle size distributions (by type),

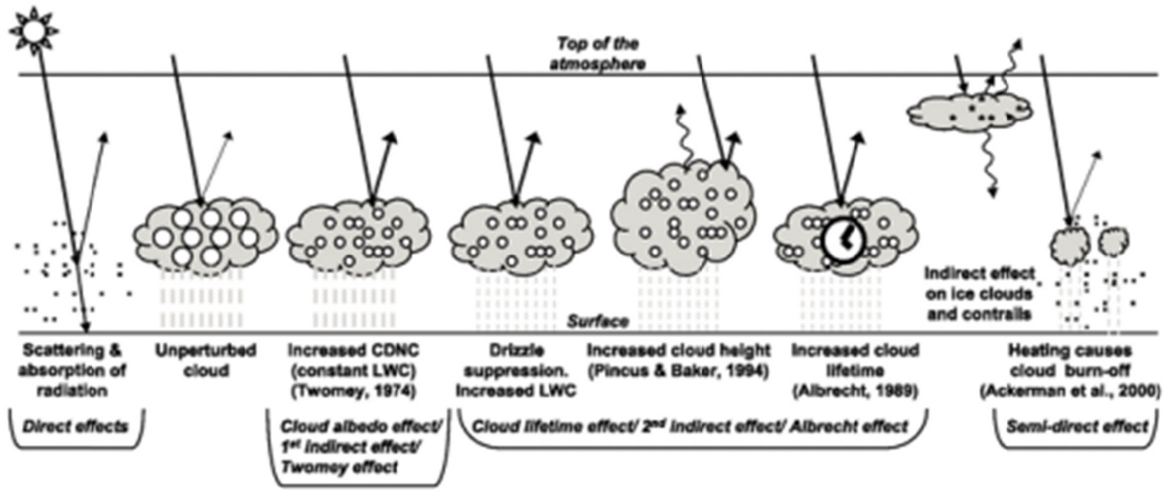

FIGURE 3 Schematic diagram showing the various impacts of aerosols on clouds. The small black dots represent aerosols; the larger open circles cloud droplets. Straight lines represent the incident and reflected solar radiation, and wavy lines represent terrestrial radiation. The filled white circles indicate cloud droplet number concentration. The vertical gray dashes represent rainfall.
SOURCE: Foster et al., 2007; modified from Haywood and Boucher, 2000.

vertically resolved (ice water content [IWC]; by type), and precipitation/evaporation rate would all advance understanding. Currently, properties that can be derived from satellites are limited to cloud reflectivity, cloud optical depth, cloud top height, some microphysics retrievals, and some phase discrimination.

There are several additional observational needs for improving understanding, said Dr. Kreidenweis. Increased spatial resolution for AOD would allow for cloud removal, possibly resulting in improved correction for relative humidity. Increased resolution would also allow for retrievals closer to clouds, which is relevant for studying their interactions with aerosols. Satellite instrumentation with additional wavelengths would enable more properties to be derived (e.g., particle size) and potentially allow scientists to estimate shapes of particles (e.g., spherical versus irregular). Satellites in a geostationary orbit (GEO), due to the capability to view a particular location over a long period of time, could observe the evolution of aerosol and cloud formation. Vertically resolved observations place particles in the correct layers, which would allow for more understanding of their impact on cloud development and aerosol transport. Absorption measurements from satellites would help identify particle type and direct effects. Concurrent relative humidity measurements would allow for correction to dry AOD.

Dr. Kreidenweis also discussed several hypothesized impacts of aerosols on clouds and noted that such hypotheses are difficult to test using civil observations. For example, it is hypothesized that aerosols impact cloud reflectivity, but scientists are limited to calculating statistical changes, correlated to aerosols in the context of an inferred environment to test this impact. It is also hypothesized that aerosols modify cloud lifetime, but this is only possible to test using a geostationary satellite and current civil geostationary satellite observations do not have sufficient spatial resolution to detect these sorts of processes. Testing the hypothesis that aerosols inhibit drizzle is challenging because changes in clouds can be due to other environmental factors in addition to aerosols. However, advanced radar could be used to show that aerosols lead to changes in phase/hydrometeor development. Anvil properties and extent changes may also be due to interactions with aerosols, but scientists are only able to estimate size changes because such properties are challenging to retrieve with satellites. Dr. Kreidenweis also noted improved aerosol fields are required to test all of these hypothesized impacts on clouds. Box 1 lists key processes and properties that were suggested by various participants as necessary to advance understanding of cloud and aerosol interactions.

BOX 1
KEY PROCESSES AND PROPERTIES TO ADVANCE UNDERSTANDING

Aerosols:
- aerosol cloud condensation nuclei concentration
- droplet number concentration or size
- Ice nucleating particle number concentrations
- aerosol composition
- particle size distribution
- concurrent relative humidity
- mode distributions

Clouds:
- liquid water path
- cloud base height
- cloud top height
- cloud top temperature
- cloud optical depth
- cloud top temperature
- effective radius and column amount
- droplet number concentrations
- droplet size distributions
- vertically resolved liquid water content
- rain drop size distribution and liquid water content
- precipitation and evaporation rates
- ice crystal number concentrations
- ice particle size distributions (by type)
- ice shape and asymmetry factor
- vertically resolved (ice water content; by type)
- vertical motion
- precipitation/evaporation rate

Current Capabilities of the Civilian Satellite System: Gaps and Challenges

Committee member Michael Prather, University of California, Irvine, provided an overview of civilian satellite capabilities for deriving cloud and aerosol data (see Appendix E for more detailed satellite specifications). Dr. Prather discussed civilian satellites that have been utilized to study clouds and aerosols:

- AVHRR (The Advanced Very High Resolution Radiometer)[5] has a 1.9 km spatial resolution and some spectral resolution (4-6 channels). It measures intensity (radiance) and can retrieve AOD and some size information.
- MODIS (MODerate resolution Imaging Spectroradiometer)[6] data can be used to retrieve many more cloud and aerosol parameters than AVHRR data, in part because of the broadband spectral limitations of AVHRR as compared to MODIS (36 channels), and the placement of spectral channels with retrieval objectives in mind. Its spatial resolution is 250 m (day) and 1,000 m (night) and it has a 2,330 km swath. It also measures intensity and retrieves aerosol loading[7] and some

[5] http://noaasis.noaa.gov/NOAASIS/ml/avhrr.html
[6] http://modis.gscf.nasa.gov
[7] Atmospheric aerosol loading is suspensions of solids and/or liquid particles in the air and is usually measured by the mass concentration of aerosol particles or by an optical measure, AOD.

absorption information. MISR (Multi-angle Imaging Spectroradiometer)[8] measures intensity with angular signature (9 angled cameras) and some spectral resolution (4 bands). It has a spatial resolution between 275 m and 1 km. It can retrieve loading, shape, size, and some absorption and height information.
- CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation)[9] includes an active Lidar instrument with passive infrared (IR) and visible imagers. It can retrieve range-resolved AOD, cirrus optical depth, and extinction and backscatter coefficients upward from the lower troposphere.
- CloudSat[10] is a 94-GHz (mm) nadir-looking radar sensitive to typical water clouds (10 μm), but more sensitive to cirrus or drizzle (50 μm). It can retrieve ice water path and cloud fraction. It has a vertical resolution of 500 m, a cross-track resolution of 1.4 km and an along-track resolution of 2.5 km.
- POLarization and Directionality of the Earth's Reflectances (POLDER)[11] measures intensity and polarization with angular spectral signature, limited by accuracy and pixel spatial resolution. It can retrieve loading and an array of particle properties. It has a 2,400 km swath and a spatial resolution of 6.5 km.
- ADM-Aeolus (Atmospheric Dynamics Mission-Aeolus)[12] is a European Space Agency (ESA) satellite expected to launch in 2017. It will have a sun synchronous orbit at an altitude of 400 km with a Doppler wind lidar to probe the lowermost 30 km of the atmosphere to measure the winds. It also will have a 355 nm Lidar with a high-spectral resolution receiver and separate detection of molecular and particle backscatter.
- Landsat[13] 8 has been used to improve aerosol retrieval algorithms. It has a 16-day repeat and a spatial resolution of 15-30 m.
- Commercial satellites such as Quickbird, WorldView, and IKONOS have all been used to study aerosols.
- SEVIRI (Spinning Enhanced Visible and InfraRed Imager),[14] a second generation geostationary orbit (GEO) satellite from the European Union Meteosat, has been used to retrieve AOD.

Dr. Prather also discussed the algorithm, PMAp (Polar Multi-sensor Aerosol Properties), which utilizes data from two platforms and three sensors—GOME2, AVHRR, and IASI—to retrieve aerosol and volcanic ash (from IR channels) properties.

Dr. Prather presented two slides courtesy of Ralph Kahn, National Aeronautics and Space Administration (NASA). The first slide summarized satellite capabilities for studying aerosol cloud interactions:

- Polar orbiting imagers provide infrequent[15] global coverage
- Geostationary platforms offer high temporal resolution
- Multi-angle imagers offer aerosol plume height and cloud-top mapping
- Passive instruments can retrieve total-column aerosol amount (i.e., AOD)
- Active instruments determine aerosol and some cloud vertical structure
- Ultraviolet (UV) imagers and active sensors can detect aerosols above clouds
- Multi-angle, spectral, polarized imagers obtain some aerosol type information
- Active sensors can obtain some aerosol type information, day and night
- Satellite trace-gas retrievals offer clues about aerosol type

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8 http://www-misr.jpl.nasa.gov
9 http://www-calipso.larc.nasa.gov
10 http://www.nasa.gov/mission_pages/cloudsat/main/index.html
11 https://polder-mission.cnes.fr
12 http://www.esa.int/Our_Activities/Observing_the_Earth/The_Living_Planet_Programme/Earth_Explorers/ADM-Aeolus/ESA_s_wind_mission
13 http://landsat.usgs.gov
14 http://eumesat.int/website/home/Satellites/CurrentSatellites/Meteosat/MeteosatDesign/index.html
15 Polar imagers typically view each point on the earth twice per day.

- Vis-IR imagers can retrieve cloud phase, LWP, and some other cloud properties

The second slide summarized satellite limitations:

- Polar orbiters provide snapshots only
- Difficult to probe cloud base
- Typically hundreds of meters or poorer horizontal resolution
- Passive instruments (imagers) offer little vertical information
- Active instruments (e.g., lidar) offer little spatial coverage
- Little information about aerosol particle microphysical properties
- Bigger issues retrieving aerosols in the presence of clouds
- Cloud property retrievals can be aliased by the presence of aerosols

Dr. Prather discussed additional satellite limitations. In many satellite images, clouds appear to be brightening and "bluing" and aerosols appear brighter and larger near clouds. The closer aerosols are to a cloud, the larger the increases of AOD, which is due to undetected cloud contamination, three-dimensional radiative effects, and humidification on aerosol size. Additionally, for ice water clouds, MODIS-like retrievals of optical thickness and effective radius are biased because of an unknown asymmetry parameter.

Climate Modeling Considerations

Committee member Steven Ghan, Pacific Northwest National Laboratory (PNNL), presented research on constraining effective radiative forcing by cloud-aerosol interactions in climate models. He said that in order to be confident that the net result is correct for the right reasons, all of the relevant cloud-aerosol interactions in the models should be constrained.

Dr. Ghan noted that a "chain of relationships" drives aerosol effects on cloud radiative forcing. These relationships are not always a single process (Figure 4). In many cases, existing modeling frameworks reflect only a partial set of known cloud-aerosol interaction processes. In some sense, the models only produce partial results by illustrating a result of a particular process, with all other processes being held constant.

$$\Delta R = R\left(\frac{d\ln C}{d\ln N_d} + \frac{d\ln R_c}{d\ln \tau}\boxed{\frac{d\ln \tau}{d\ln N_d}}\right)\frac{d\ln N_d}{d\ln CCN}\frac{d\ln CCN}{d\ln E}\Delta\ln E$$

$$\boxed{\frac{d\ln \tau_c}{d\ln N_d}} = \frac{\partial\ln \tau_c}{\partial\ln r_e}\frac{d\ln r_e}{d\ln N_d} + \frac{\partial\ln \tau_c}{\partial\ln L}\frac{d\ln L}{d\ln N_d}$$

FIGURE 4 The relationship between clouds and aerosols is not always straightforward and does not always indicate the same magnitude or sign of relationship. These two equations are an example of the "chain of relationships" that drives aerosol effects on cloud radiative forcing. One factor in the top equation (in the blue box) actually represents several processes (bottom equation). ΔR: the effective forcing of cloud and aerosol interactions; R: "clean-sky" shortwave cloud forcing; C: cloud fraction; τ_c: cloud optical depth; N_d: cloud droplet number; E: anthropogenic emission; L: liquid water path; r_e: droplet effective radius; R_c: in-cloud cloud radiative forcing.
SOURCE: Ghan, 2015.

In order to make progress on quantifying aerosol-cloud interactions for climate assessments, Dr. Ghan believes it is important to:

- develop metrics that relate anthropogenic change to present day observables,
- use measurements where and when aerosol has changed, and
- apply measurements to cloud regimes.

For example, aerosols measurements taken from locations where aerosols have increased (e.g., China) or decreased (e.g., Europe) would allow scientists to study how the change in aerosol load impacted cloud regimes.

Dr. Ghan noted that diversity in estimated effective radiative forcing through aerosol effects on clouds is driven by diversity in several factors. Constraints on anthropogenic aerosol effects are needed for each factor. Constraining sensitivities using data from present day variability is often insufficient to constrain anthropogenic aerosol effects. He concluded that new present day metrics are needed. Regional trends for selected periods could be helpful. Global satellite data availability limits trend analysis of factors to 2002 and later.

OVERVIEW OF CLASSIFIED OBSERVING SYSTEMS

During the workshop, representatives from the IC briefed the cleared civil scientists on several classified observing systems.

POTENTIAL APPLICATIONS OF CLASSIFIED OBSERVING SYSTEMS FOR CLOUDS AND AEROSOLS

Workshop participants discussed several processes and properties related to cloud and aerosols that could be estimated utilizing some of the unique characteristics of the classified sensors (Box 2).

BOX 2
POTENTIAL CLOUDS AND AEROSOLS-RELATED CAPABILITIES FROM CLASSIFIED OBSERVING SYSTEMS

- Vertical velocity
- Cirrus optical thickness or aerosols at night
- Cloud top height
- Cloud optical thickness
- Characterization and statistics of clouds (including polar clouds)
- Cloud formation, dissipation, and movement
- Side view cloud phase
- Global mapping of ice crystals
- Glaciation process at polar clouds
- Thunderstorm evolution in aerosol laden and clean areas
- Formation and transition of cloud cells and column water vapor
- Overshooting convection
- Cold pool formation at night
- Automated cloud masks
- Near cloud radiance fields
- Boolean cloud mask between sensors, or stereoscopic if two are available
- Nighttime cloud top velocities
- Diurnal cycle of cloud tops and deep convection

BOX 3
STRATEGIES FOR LEVERAGING THE IC DATA

- Working with data that have already been collected and archived, but that have not yet been studied because they are outside of IC interest;
- Employing tasking and engineering study requests;
- Gathering information from atmospheric correction used in retrieving data related to surface conditions;
- Co-collecting the classified data with data from field campaigns, civilian satellites, civilian ground and in situ measurements, commercial satellites, and other IC sensors; and
- Identifying particular locations (e.g., data sparse) and associated phenomena that would be useful for studying.

STRATEGIES FOR LEVERAGING IC SENSOR DATA

During the workshop, several possible strategies and opportunities for leveraging the IC data were suggested (Box 3). Some strategies use data already available in IC archives. In other cases, the civil science community would want to work with the IC to guide new data collection that could address science questions related to clouds and aerosols.

One strategy for utilizing the data is co-location of IC sensors with other assets. Co-collects may help scientists determine the statistical nature of smaller scale processes that can be observed by instruments that resolve different variables at the same time. Such an approach is particularly valuable if there is covariance among the variables that would then allow scientists to infer unobserved parameters from more readily available observations of other variables.

Data from the IC sensors could be coordinated with co-collects with data from field campaigns (e.g., Southern Ocean Field Campaign) or civilian ground-based remote sensing (e.g., AERONET[16]) and in situ instruments (e.g., the Department of Energy's Atmospheric Radiation Measurement Program [DOE's ARM] sites), said some participants. Field campaigns, and some in situ observing stations, are designed to study environmental processes and sometimes to assist with satellite calibration and validation, which would benefit both the civil and IC communities. However, some participants cautioned that it would be a significant challenge to have classified communication in the field.

Another opportunity is to co-collect with space-based civilian sensors (e.g., VIIRS, MODIS, MISR, CERES). Some participants also said it would be useful to co-collect data from classified satellites with other classified satellites.

Another strategy discussed by many participants is to identify particular locations and associated phenomena that would be useful for detailed analysis. Such locations might be selected because they either have interesting phenomena or are data sparse in the civilian community.

Specific priority locations suggested by some participants include:

- Indian monsoon (Ganges River valley) because it occurs in a high aerosol environment.
- Straits of Malacca because it has both high aerosol loading and strong storms.
- Locations in the Eastern Hemisphere because there is greater opportunity for co-collects.
- Darwin, Australia, where a thundercloud (named "Hector") forms there regularly each afternoon from September to March.
- Venezuela's Lake Maracaibo, which also has regular thundercloud formation each day.
- ARM sites such as Barrow, Alaska, and the Azores.

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[16] The AERONET (Aerosol Robotic Network) program is a federation of ground-based remote sensing aerosols networks established by NASA and PHOTONS (PHOtometrie pour le Traitement Operationnel de Normalisation Satellitaire). It provides a long-term, continuous, and readily accessible public domain database of aerosol optical, microphysical, and radiative properties for aerosol research and characterization, validation of satellite retrievals, and synergism with other databases.

Follow-on research ideas to improve utilization of the classified data were discussed briefly by some participants. One idea is to study implications of high resolution retrievals to gain a better understanding of what is really "seen." For example, smaller grid boxes would result in more boxes that are completely clear and others that are completely cloud covered. This impacts how much of the cloud is reacting with the rest of the atmosphere in the retrievals. Another idea is to explore how an individual cloud is identified (e.g., optically or thermodynamically).

Pilot Projects

Based on the workshop discussions, four potential pilot projects were identified by various participants to test the usefulness of the IC data in advancing understanding of cloud and aerosol interactions. Scientists could be cleared to work on these projects on the classified side to test the utility on a small scale. Some government scientists (e.g., Naval Research Laboratory [NRL]) have the capacity to work with classified data already, and even if their research were not declassified it would still benefit the IC and the scientists involved, said some participants. This would facilitate pilot projects, and improve their chance of success. If the pilot proves promising, then the case could be made to declassify or downgrade the data for release. It was noted by several participants that even projects that fall short of their scientific goals could provide useful lessons for the IC to improve data collection and processing.

Workshop participants divided into small groups to discuss the pilot projects in more detail. For each project, groups discussed the relevant IC sensors, scientific value, IC/Department of Defense (DoD) value, civil applications, barriers and limitations (scientific, technical, and policy), opportunities to coordinate with other assets (IC, civilian, and commercial), and future scientific research to advance utility.

Civilian and IC Collaboration

Many participants said that there are potential co-benefits from the partnership of civilian scientists and the IC community. One benefit is the co-development of algorithms. New algorithms and models (e.g., physics-based retrievals of plumes) developed on the civilian side could be shared with the IC for their classified systems. This also would potentially lead to shared observing system simulation experiments (OSSEs) and the development of retrieval assimilations and validation.

Some participants raised the idea of a potential IC/NRL collaboration to improve climate and weather models. Full assimilation of meteorological and aerosols data into the models would be ideal (e.g., fluxes, what is going into clouds, where they are flowing, all at high resolution), said participants. This product could be released and used by civilians, without releasing classified information about the satellite that did the collection. Committee member Dr. Jeffrey Reid, NRL, said that FNMOC (Fleet Numerical Meteorology and Oceanography Center)[17] and NRL already have these types of capabilities for their models.

Calibration techniques honed for civilian sensors could be applied to IC sensors, many participants said. An example is the research and development partnership between the IC and NASA Goddard Space Flight Center (GSFC). One of the goals of this partnership is to utilize data from unclassified sensors (remote and in situ) and apply techniques from NASA to improve calibration of the IC sensors. Another example discussed by some participants is utilizing coincident observations with MODIS and VIIRS to help the IC community with calibration. Such coincident observations could also benefit the civilian community by advancing understanding of clouds and aerosols.

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[17] FNMOC utilizes high performance computing at all levels of classification to provide worldwide meteorology and oceanography support to the U.S. Navy.

SCIENTIFIC AND TECHNICAL LIMITATIONS

Although there are many potential benefits in utilizing the IC data, participants highlighted several technical and scientific limitations in leveraging the IC data. One major limitation is calibration accuracy, which is critical for data usability for environmental applications. Other limitations include collection constraints, self-emission issues, lack of vertical information, and data processing (i.e., models will likely need to be modified to use some of the data). Additionally, there are limitations due to the mismatch between mission targets for the classified observing systems (e.g., missile launches, nighttime activity, etc.) and retrievals needed for advancing understanding of clouds and aerosols.

POLICY-RELATED LIMITATIONS

In addition to the scientific and technical challenges, there are several policy-related limitations in leveraging IC data. The biggest limitation, said many participants, is data access. Most civilian scientists will not have access to classified data, and the few that do will have difficulty in finding, navigating, and citing the data. They would likely find it difficult to publish study results that utilize the classified data because the results would not meet the requirement for reproducibility. Methods need to be developed to enable easy identification and access, said many participants. Merging and integrating data from classified and civilian systems could provide significant value, but would be a major challenge that requires significant financial and human resources.

One possible solution suggested by some workshop participants, would be to have civilian cloud and aerosol experts potentially influence future classified systems to consider environmental applications in their design and factor in a pathway to provide data from these future classified systems into the unclassified realm.

Metadata

Another policy-related limitation discussed at the workshop is the lack of metadata available about the IC data. Dr. Reid gave a presentation on metadata in the context of utilizing the IC data to study clouds and aerosols. Metadata describes the nature and context of a dataset such that the dataset can be used for a specific application. He said that scientists who will utilize the IC data will need metadata on the sensor, on how the data were processed to produce downstream products, and the environment as a whole. He said the following types of metadata are needed:

- Sensor: Characteristics of the sensor and onboard processing, including field of view, wavelength bands and spectral response function, saturation, sampling, gain, coregistration, point spread function, and calibration cycle.
- Ephemeris: What, when, where, and geometries of how the data were collected.
- Environmental state: State vector of the atmosphere and surface; this information can be derived from the sensor or taken from elsewhere.
- Atmospheric correction: How the correction was done, including whether it corrected for molecular contributions.
- Downstream products: What process was used to create the products, including the assumptions, uncertainties, and intermediate products.

Dr. Reid noted that declassifying metadata is a significant challenge because some of the required information is highly classified. Also, in some cases, even if the metadata were to remain classified, some of these details could be determined from analysis of the data, making it difficult to declassify the data themselves. He noted that some common metadata for civilian applications can be bypassed; however, civilian science is grounded in transparency for reproducibility, and scientists would likely have a difficult time using data that lacks appropriate metadata in their peer-reviewed research.

Dr. Reid also noted that there are several types of biases that need to be described in the metadata:

- Method Bias: Biases related to shortcomings in the method itself.
- Calibration Bias: Drift in the instrument response characteristics that cannot be explained.
- Sampling and Contextual Bias: Biases related to where the retrieval is performed or contextually related uncertainty in a scene. This leads to a skewed data population relative to what is thought to have been collected.
- Aggregation and Data Reduction Bias: Loss of required information during conversion to higher level products or during analysis.
- Cognitive Bias: The investigators misinterpret, withhold, or frame data or results without consideration of the full nature of the data.
- Other considerations for multi-sensor work:
    - Correlated error: “Independent” products that share similar biases.
    - Tautology: Circular reasoning or treating non-independent data as independent during data reduction.

Dr. Reid offered some considerations for utilizing the IC data. Given that it is possible to determine the orbit, location, and a time from an image, he said it would be beneficial to IC data users, if the IC could clearly identify the type of information that must remain classified.

CONCLUSION

Although several limitations and challenges were identified in utilizing the classified data, some participants were optimistic that the IC and civilian scientists could come together to find creative ways to leverage the data for advancing understanding in cloud and aerosol interactions. Many participants said that the four pilot projects would be an excellent first step forward to test the utility of the data, and any pilots that prove promising could potentially provide rationale for declassifying or downgrading the data for release allowing for wider use.

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Appendix A
Statement of Task

An ad hoc committee will organize a classified workshop to discuss the usefulness of national collection systems to advance understanding of aerosol-cloud-precipitation interactions. Such an improved understanding could lead to a more accurate representation of clouds, precipitation, and aerosols in climate models, reducing the uncertainty of climate projections. The workshop will bring together leading climate experts with scientists from the Intelligence Community who have expertise in the relevant collection systems.

Workshop attendees will be asked to discuss the following questions:

- How could the national collection systems be utilized to advance understanding of aerosol-cloud-precipitation interactions?
- What are the potential contributions to climate modeling?
- What follow-on scientific research could render such improvements using national collection systems?

The committee will plan and organize the workshop, select and invite speakers and discussants, and moderate the discussions. An individually authored classified summary and an individually authored public summary of the presentations and discussions at the workshop will be prepared by a designated rapporteur in accordance with institutional guidelines.

Appendix B
June 24-25, 2015, Workshop Agenda

Wednesday, June 24, 2015

7:30 AM **Shuttle from Hotel Irvine to Beckman Center**

8:00 AM Sackler Colloquium

3:00 PM Sackler Adjourns

Workshop on Opportunities to Improve the Representation of Clouds and Aerosols in Climate Models with National Collection Systems

The impact of aerosols on the atmosphere is widely acknowledged as one of the most significant and uncertain aspects of climate change projections. Although scientists know much about the general nature of the interactions between aerosols and clouds, the simulation of clouds and how they will respond to aerosol changes is a central challenge in climate modeling. At the request of the Intelligence Community, the National Academies is organizing a series of two workshops on this topic:

Unclassified workshop: June 24-25, 2015, to engage with Sackler and other uncleared participants to identify gaps in our capabilities, significant barriers and challenges, and potential opportunities for improvements.

Classified workshop: September 28-30, 2015, to discuss the usefulness of classified observing systems in advancing understanding of aerosol-cloud-precipitation interactions.

Such an improved understanding could lead to a more accurate representation of cloud and aerosols in climate models, reducing the uncertainty of climate projections. Unclassified and classified summaries of the workshops will be prepared by a designated rapporteur.

Premise: The current satellite systems and their available data streams do not provide adequate observations of aerosols, clouds, and precipitation to constrain our modeling of the relative impact of aerosols and their precursors on the climate and hydrologic systems on a global or regional scale.

- Review current and planned, non-proprietary and unclassified, satellite observations capable of measuring the relationships between aerosols, clouds and precipitation.
- Hear from invited experts on specific instrument-related topics, including
    - attributes, measurements, tolerances and calibration
    - current observing system capabilities (multiple instruments), and gaps in that system
    - next-generation instruments and systems
- Identify opportunities available in the current and planned Global Earth Observing System of Systems (GEOSS), including the civilian space sector, for building a coherent system to address aerosol-cloud interactions and related questions. Identify also the limitations.

Remote Observations of Aerosol-Cloud-Precipitation Properties: The Current Systems

Chair: Pamela Emch

3:30 PM Welcome, Introductions, and Purpose of Workshop — Pamela Emch, Northrop Grumman

4:15 PM Gaps in Active Remote Sensing — Graeme Stephens, JPL(Jet Propulsion Laboratory)

4:45 PM Breakout group discussion: Initial brainstorming — Pamela Emch

1. What properties and processes related to aerosol-cloud-precipitation interactions could/would we like to observe from orbit?
2. What specific satellite instrument attributes, measurements, and tolerances are needed to constrain aerosol-cloud-climate models?
3. Can the gaps and barriers regarding aerosol-cloud interactions in the current observing system be addressed by calibration, coincidence, resolution, orbits?
4. What are the biggest challenges, given anticipated capability from orbit, to using satellite observations to improve cloud-aerosol-precipitation modeling?

5:30 PM Breakout group rapporteurs report back

6:00 PM Adjourn

6:05 PM Working dinner with participants (Executive Dining Room)

7:45 PM **Shuttle from Beckman Center to Hotel Irvine**

Thursday, June 25, 2015

7:30 AM **Shuttle from Hotel Irvine to Beckman Center**

8:00 AM Breakfast available in meeting room

8:30 AM Review and summarize Post-Sackler discussion — Pamela Emch
Goals for today's meeting

8:40 AM Motivations of the NRC Activity

Challenges and Opportunities in Future Remote Observations of Aerosol/Cloud/Precipitation Properties: Next Generation Systems

9:00 AM What are future opportunities and challenges related to moving to very high resolution Electro-optical/Infrared (EO/IR) instruments?
[Hi res MODIS, MASTER, ASTER, EO-1]
Chair: Jeffrey Reid, Naval Research Laboratory
Speaker: Michael King, University of Colorado

9:20 AM Brief perspective from Chair and general discussion

9:45 AM What are future opportunities and challenges related to better utilizing multi-angle views and obtaining better time coverage for EO/IR instruments?
[Hi res MISR; Air MSPI]
Chair: Sonia Kreidenweis, Colorado State University
Speaker: Michael Garay, JPL

10:05 AM Brief perspective from Chair and general discussion

10:30 AM Break

10:45 AM	What are future opportunities and challenges related to innovative use of the electromagnetic spectrum for EO/IR instruments? [RSP (Research Scanning Polarimeter), hyperspectral and polarization] Chair: Michael Prather, University of California, Irvine Speaker: Jacek Chowdhary, NASA GISS (Goddard Institute for Space Studies)	
11:05 AM	Brief perspective from Chair and general discussion	
11:30 AM	What are future directions for improving 3D Radiative Transfer? Chair: Everett Joseph, State University of New York at Albany Speaker: Howard Barker, Environment Canada	
11:50 AM	Brief perspective from Chair and general discussion	
12:15 PM	Working lunch	
1:15 PM	What are future opportunities to use radar and passive microwave to observe precipitation and clouds? [Global Precipitation Mission] Chair: Rob Wood, University of Washington Speaker: Jay Mace, University of Utah	
1:35 PM	Brief perspective from Chair and general discussion	
2:00 PM	What are future opportunities to use lidar and polarimetry? Chair: Steven Ghan, Pacific Northwest National Laboratory Speaker: Rich Ferrare, NASA Langley	
2:20 PM	Brief perspective from Chair and general discussion	
2:45 PM	Break	
3:00 PM	Panel discussion focusing on derived products/separating constituents Chair: Steve Ghan • Aerosol Composition: Ralph Kahn, NASA GISS • Cloud Properties: Zhien Wang, University of Wyoming • Cloud-Aerosol Relationships/Interactions: Joyce Penner, University of Michigan	
4:00 PM	General Discussion	
4:30 PM	Breakout group discussions: Optimizing the current satellite systems, defining the future systems • What are characteristics of an optimal, but realistic satellite observing system that would make a breakthrough in understanding cloud/aerosol relationships? • What key needs, gaps, and barriers should the committee should consider going into the September classified meeting?	Pamela Emch

5:15 PM	Breakout group rapporteurs report back	
5:50 PM	Wrap up: What did we learn and where do we go from here?	Pamela Emch
6:00 PM	Adjourn	

Participant List

June 24-25, 2015

- Howard Barker / Environment Canada
- Jacek Chowdhary / National Aeronautics and Space Administration (NASA)
- Adarsh Deepak / Science and Technology Corporation
- Pamela Emch / Northrop Grumman Corporation
- Graham Feingold / National Oceanic and Atmospheric Administration (NOAA)
- Richard Ferrare / NASA Langley
- Michael Garay / NASA Jet Propulsion Laboratory (JPL)
- Andrew Gettelman / National Center for Atmospheric Research (NCAR)
- Steven Ghan / Pacific Northwest National Laboratory (PNNL)
- Mike Griffin / Massachusetts Institute of Technology Lincoln Library
- Jeffrey D. Hawkins / Naval Research Laboratory
- Darrell Herd / United States Geographical Survey (USGS)
- Everette Joseph / State University of New York
- Ralph Kahn / NASA
- Michael King / University of Colorado Boulder
- Ian Kraucunas / PNNL
- Sonia Kreidenweis / Colorado State University
- Jay Mace / University of Utah
- Jerry Miller / National Academy of Sciences
- Daniel Murphy / NOAA
- David Noone / Oregon State University
- Joyce Penner / University of Michigan
- Michael Prather / University of California, Irvine
- Phil Rasch / PNNL
- Jeffrey Reid / Naval Research Laboratory
- Lorraine Remer / University of Maryland, Baltimore County
- Daniel Rosenfeld / The Hebrew University of Jerusalem, Israel
- Graeme Stephens / NASA JPL
- Susan Van Den Heever / Colorado State University
- Wenshan Wang / University of California, Irvine
- Zhien Wang / University of Wyoming

Appendix C
June 24-25, 2015, Workshop Recap

National Academies Beckman Center
Irvine, CA

Disclaimer: This meeting recap was prepared by the Academies staff as an informal record of issues that were discussed during the public Academies workshop: Opportunities to Improve the Representation of Clouds and Aerosols in Climate Models with National Collection System held on June 24-25, 2015. This document was prepared for information purposes only. It has not been reviewed and should not be cited or quoted, as the views expressed do not necessarily reflect the views of the Academies or the Committee on Opportunities to Improve the Representation of Clouds and Aerosols in Climate Models with National Collection Systems.

Committee Members Present: Pamela Emch, Everette Joseph, Sonia Kreidenweis, Michael Prather, Jeffrey Reid, Robert Wood

Committee Members Absent: Steven Ghan

Academies Staff Present: Rita Gaskins, Michael Hudson, Kristina Pistone, Amanda Staudt, Katie Thomas

This recap is not a comprehensive summary of all the issues discussed at the workshop. Rather it summarizes the specific workshop discussions on challenges and gaps related to observing clouds and aerosols in the context of the classified assets potentially addressing those gaps. The purpose of this recap is to help inform the sponsor about which types of data to present at the follow-on classified workshop (September 28-30, 2015) and inform the committee in the planning of the workshop. Presentation slides are available upon request.

An often asked question during the workshop was whether the data, if identified as useful, will be declassified. Some participants asked if it would be possible for scientists to be "declassified" to speak to people without security clearances about the data or metadata. Other participants noted that even if the data are not published, perhaps they could inform (either positively or negatively) the directions and specifications for future missions.

Several participants said it is critical to know the specifications (e.g., wavelengths, tolerances, uncertainties, precision, viewing geometry, pushbroom versus whiskbroom) and calibration/validation details in order to use the data for scientific research. For example, information on wavelength spectral band location and width is important in cloud identification.

Furthermore, many participants said that, for any data that is declassified, it will be critical to also declassify the metadata associated with the observations. Others were more optimistic and noted that the current state of knowledge of some science questions (e.g., ice crystals, ice clouds) is in its infancy, and therefore any increase in statistics, even without spatial and temporal metadata, would advance the science. For other questions (e.g., process studies in warm clouds), spatial and temporal location needs to be known precisely so that scientists could geolocate the data with other observations.

Many participants said that the value of the classified data lies in its potential integration with other unclassified data and measurements. For example, it would be helpful to know coincidence (or offset) from other platforms, wavelengths, and time shifts.

Finally, numerous participants raised concerns related to human resources. Some noted that extracting data from A-train or A-train-like sensors (e.g., using CloudSat as a passive sensor to better understand precipitation processes) requires deeper analysis. Many participants highlighted the additional challenges of data calibration, intercalibration, storage, and quality control. Georectification of data from multiple platforms (with different instruments, view volumes, times, etc.) may also be intensive and difficult, and require significant staff time.

To inform the sponsor about specific types of data to present at the September workshop, individual workshop participants discussed a number of ways that understanding of clouds, aerosols, and their interactions could be advanced with additional data from classified assets. These concepts and issues should not be seen as conclusions of the workshop or as consensus statements of the workshop participants or organizing committee.

- Improve understanding of aerosol-cloud interactions.
    - These interactions could be elucidated with better observations of changes in cloud brightness (sometimes), droplet size, cloud height, and cloud fraction.
    - A significant challenge is that the greatest microphysical effects are in the cleanest environments, while the greatest radiative effects are in environments with the heaviest aerosol loading.
    - Aerosol-cloud interactions span many scales.
        - The spatial scales range 13 orders of magnitude from the different classes of aerosols and droplets (fine mode [100 nm]/coarse mode/cloud drop/drizzle drop/rain drop, with a factor of 10 between each); to the macroscales of turbulence (10 m) updrafts, cumulus, thunderstorms, convective systems (also factor of 10 between each). In some cases the spatial resolution of the instrument will determine the values calculated for the fields, especially in the case of cloud fraction.
        - The timescale ranges from seconds to days.
    - Some participants said periodic snapshots are sufficient, even though observations of how processes evolve over time provide more information. Some participants said available satellite observations provide enough constraints to retrieve process rates, while others said vertically-resolved measurements would be needed.
- Improve understanding of cloud physical processes and their representation in models.
    - Important variables to measure include:
        - Liquid cloud: water content or liquid water path (LWP), optical depth, particle size, and number concentration.
        - Ice variables: water content, particle size, extinction or optical depth, number concentration and crystal shape.
- Improve discrimination between liquid and ice phases.
    - Important variables to measure include:
        - A combination of particle size and backscatter (lidar and radar).
- Improve understanding of long-term processes.
    - Targeted observations of processes that are stable year-to-year might advance understanding.
- Improve observations of aerosols located over snow or ice.

- Aerosol retrievals from satellites located over snow and ice are difficult because their surface optical properties are uncertain.

Throughout the workshop, individual workshop participants identified numerous types of data and instruments that would potentially be useful to advance understanding of cloud, aerosols, and their interactions. These concepts and issues should not be seen as conclusions of the workshop or as consensus statements of the workshop participants or the organizing committee.

- Measurements (e.g., air quality or meteorological monitoring) from under-observed areas (e.g., embassies or military bases) to estimate emissions.
- Aerosol sources (e.g., injection site, frequency of emissions, plume height, etc.) would be useful to initialize models.
- Aerosol type (e.g., chemical composition of aerosols, measurements of local visibility) to validate remote sensing retrievals.
- Vertical velocity measurements (e.g., vertical profiles of temperature, humidity) as many cloud and aerosol processes have strong dependencies on the meteorology.
- Observations from a radiative forcing perspective over the "pristine" Southern Hemisphere ocean.
- Measurements of microphysical properties rather than bulk or column properties (aerosol optical depth, cloud condensation nuclei, aerosol index).

    - Aerosol optical depth, for example, is taken to be a proxy for number of particles, which limits process-level understanding. Cloud effective radius does not represent droplet size distribution, which varies throughout the cloud. These measurements are important for comparing model outputs, which give different parameters.

- High-resolution ground- or aircraft-based radar or lidar data (e.g., radar with more or different wavelengths or high sensitivity, even if in one location, to either co-locate or get a general climatology).

    - HSRL (High Spectral Resolution Lidar) can measure aerosol optical properties and derive measures of size, composition, aerosol backscatter, extinction, and optical depth. HSRL can also measure cloud properties including: fraction, optical depth, extinction, and cloud droplet number concentration, particularly in difficult retrieval conditions (high latitudes, nighttime, above clouds).
    - HSRL measurements of aerosol extensive and intensive parameters provide additional constraints for developing and assessing models. The aerosol profiles are used to assess and improve aerosol data assimilation systems.

- Hyperspectral infrared (IR) provides good horizontal measurements to tell us something about cloud height and depth. IR can also be utilized over ice and snow.
- High-resolution (~1 km) microwave observations.
- Computed tomography to leverage full information content of various sensors.
- Observations from satellites with unique orbits (e.g., highly elliptical) that could "dwell" on specific areas. One example is the proposed Canadian PCW (Polar Communications and Weather) system focused on Arctic.
- Very high spatial resolution (e.g., Landsat) combined with time information. A system that could stare and be pointed (versus the typical nadir-view of satellites), as it moves over the variable of interest. It could look at the variable from different angles: multi-angle, stereo, visible and infrared (IR)/thermal IR.
- In situ data sources and observations (e.g., in situ atmospheric ice crystals, buoys that make atmospheric measurements above the ocean).
- A sensor similar to VIIRS (Visible/Infrared Imager/Radiometer Suite) that could be used for nighttime aerosol retrievals.

- Instruments which employ the A-Train model: multiple simultaneous measurements from active and passive sensors.
- Observations that have overlap with existing observation systems to improve utility and to avoid to the extent possible difficult geo-rectification efforts. Ideally, the observations would be completely coincident or slightly offset in time to observe the development of systems (e.g., between the A-train satellites or Terra MISR/Landsat offset).
- Pre-A-Train observations, in similar orbit, to help extend the record.
- Miniaturization of current technologies to place on commercial or military aircraft, ships, satellites to improve coverage.
- Multi-angle, stereoscopic observations and high capability geosynchronous observations.
- Observations from broadband radiometers such as CERES (Clouds and the Earth's Radiant Energy System) to better constrain the global radiation budget.
- Polarimeter and polarized data could offer insights on droplet size distributions, for example, and in understanding the full 3D character of the atmosphere.

    - Retrievals of fine and coarse mode aerosol: optical depth, size distribution, complex refractive indices for each mode, cloud phase, droplet size distribution, shape, roughness, and asymmetry parameter retrievals for ice clouds, aerosols retrievals under cirrus. These instruments are not sensitive to absorption.

        - Ideally has wide spectral range from blue to NIR; perhaps also UV. Wide angular range to capture a wide range of scattering angles. High accuracy: 0.5% or smaller, 0.1-0.2% would be ideal. Dense angular sampling to resolve structures in rainbow peak to calculate droplet size distribution while not being sensitive to 3D cloud effects or cloud shadows. This allows for aerosol retrievals over oceans, over land, and under (thin) clouds.

    - Retrievals of water and ice clouds: dense angular sampling (~50 viewing angles; aerosol could be done with ~5-6 viewing angles).

- Observing systems that could track the evolution of cloud systems to compare with cloud models.

    - This could be achieved by a few satellites flying in unison in low orbit, providing views of a cloud system with temporal resolution on the order of 5 minutes and recording at least 15-30 minutes of evolution.
    - It would be difficult to record a cloud system from birth to senescence except via geo-orbit. The definition of a single cloud becomes vague as cloud systems evolve. However, a series of snapshots of the system over a brief period of time (e.g., on the order of 30 minutes) would catch a range of systems at different stages of their evolution and thus it would be useful to test the dynamics of aerosol-cloud models if the swath of observations covered a range of aerosol-cloud systems.
    - To the extent that some of these cloud systems exhibit self-similar properties, much could be deduced about system evolution from composites of a series of snapshots.
    - Commercial satellite imagery such as the Quickbird or Digital Globe systems would provide a zoomed in view of cloud structure for detailed process inference. These instruments have a resolution of 0.6 m panchromatic, and 2.4 m in 4 bands (RGB [red, green, blue] + NIR) over a 16 km footprint. With 30-sec retargeting, it would be possible to get multi-angle views (-45°, -30°, nadir, +30°, +45°) but this only covers 2 minutes.

- Suborbital sampling (even if scientists do not know the location) to provide verification, albeit at poorer spatial sampling.

    - Examples include ER-2 and Global Hawk.

- The Google Loon balloon project is designed to hover over an area to provide Wi-Fi connectivity in remote areas. Balloons currently have small payload (10 kg) but can stay aloft for up to 6 months at approximately 18 km altitude. Such technology might be very useful over heavily instrumented surface sites such as DOE/ARM (Department of Energy's Atmospheric Radiation Measurement Program) sites.
- Other sub-orbital assets, such as military flights, could be tasked with providing regular in situ sampling.

Appendix D
September 28-30, 2015, Classified Workshop Agenda

National Academy of Sciences (NAS) Building
2101 Constitution Ave., NW
Washington, DC
Room: NAS SCIF

Goals for Activity

1) Discuss the usefulness of national collection systems to advance understanding of aerosol-cloud-precipitation interactions.
2) Specifically address the following questions:
    - How could the national collection systems be utilized to advance understanding of aerosol-cloud-precipitation interactions?
    - What are the potential contributions to climate modeling?
    - What follow-on scientific research could render such improvements using national collection systems?
3) Consider the following sponsor interest areas:
    - Gaps, barriers, what modelers want, information for future planning

Monday, September 28, 2015

8:00 AM	Breakfast	
8:30 AM	Welcome and Brief Introductions	Pamela Emch, Northrop Grumman
8:40 AM	General Security Orientation	Detra Bodrick, NAS
9:20 AM	In-brief	
10:00 AM	Break	
10:30 AM	Welcome, Introductions, and Purpose of the Workshop	Pamela Emch, Northrop Grumman
11:00 AM	Perspective from the Sponsor	
11:15 AM	Perspective from Office of Science and Technology Policy (OSTP)	Matt Heavner, OSTP
11:30 AM	Scientific context for project: What variables need to be measured and where? What variables can we currently measure with civilian systems, and what are the limitations?	Michael Prather, University of California, Irvine
12:00 PM	Lunch	

1:00 PM Sponsor briefing #1 (Radar capabilities) + technical questions

2:00 PM Sponsor briefing #2 (Electro-optical capabilities) + technical questions

3:00 PM Break

3:30 PM Sponsor briefing #3 (OPIR capabilities) + technical questions

4:30 PM Review and Discussion Session for Briefings 1, 2, 3
Andrew Gettelman, National Center for Atmospheric Research

- How could the data advance understanding of cloud/aerosol interactions?
- What processes can be investigated using these data?
- What are the potential contributions to climate modeling?
- What are potential scientific barriers in utilizing these data?
- What are barriers to getting the data cleared for public use?
- What other metadata are needed?

5:30 PM Adjourn

6:00 PM Dinner for all participants (Members Room)

Tuesday, September 29, 2015

8:00 AM Breakfast available in meeting room

8:30 AM Sponsor briefing #4 (Capabilities and limitations of radiometric calibration) + technical questions

9:30 AM Sponsor briefing #5 (In situ data) + technical questions

10:30 AM Break

11:00 AM Sponsor briefing #6 (Environmental Applications at the National Air and Space Intelligence Center) + technical questions

12:00 PM Lunch

1:00 PM Review and Discussion Session for Briefings 4, 5, 6
Jeffrey Hawkins, Naval Research Laboratory

- How could the data advance understanding of cloud/aerosol interactions?
- What processes can be investigated using these data?
- What are the potential contributions to climate modeling?
- What are potential scientific barriers in utilizing these data?
- What are barriers to getting the data cleared for public use?
- What other metadata are needed?

2:00 PM Sponsor briefing (OPIR Environmental Intelligence) #7 + technical questions

3:00 PM Break

3:30 PM Sponsor briefing (GPS/BDYE Earth Background Scan Data: Potential Applications for Atmospheric Research) #8 + technical questions

4:30 PM Review and Discussion Session for Briefings 7 and 8
Anthony Davis, NASA Jet Propulsion Laboratory

- How could the data advance understanding of cloud/aerosol interactions?
- What processes can be investigated using these data?
- What are the potential contributions to climate modeling?
- What are potential scientific barriers in utilizing these data?
- What are barriers to getting the data cleared for public use?
- What other metadata are needed?

5:30 PM Adjourn

Wednesday, September 30, 2015

8:00 AM Breakfast available in meeting room

SESSION ON LEVERAGING THE DATA

8:30 AM Observing challenges with respect to cloud and aerosol interactions — Michael Prather, University of California, Irvine

9:30 AM Ancillary data needs and metadata — Jeff Reid, NRL

10:30 AM Break

11:00 AM Specific processes and relationships related to clouds and aerosols interactions — Sonia Kreidenweis, Colorado State University

12:00 PM Lunch

1:00 PM Constraining models with observations — Steve Ghan, Pacific Northwest National Laboratory

2:00 PM What are the opportunities to merge the national collection system data with civilian data? — Pamela Emch, Northrop Grumman

3:00 PM Plan for report; what more needed from this workshop?
What key points should be included in the report?
What is a possible outline for the report? — Pamela Emch, Northrop Grumman

4:00 PM Adjourn

Appendix E
Civilian Satellite Specifications

TABLE E.1 Specifications of Civilian Satellites for Deriving Cloud and Aerosol Data

Instrument Name Short	Instrument Name Full	Instrument Agencies	Instrument Status	Instrument Type	Measurements and Applications	Waveband Categories	Spatial Resolution	Swath Width	Orbit
MODIS	MODerate-Resolution Imaging Spectroradiometer	NASA	Operational	Imaging multi-spectral radiometers (vis/IR) and ocean color instruments	Data on biological and physical processes on the surface of the Earth and in the lower atmosphere, and on global dynamics. Surface temperatures of land and ocean, chlorophyll fluorescence, land cover measurements, cloud cover (day and night).	VIS, NIR, SWIR, MWIR, TIR	Cloud cover: 250 m (day) and 1,000 m (night), Surface temperature: 1,000 m	2,330 km	LEO – sun-sync
MISR	Multi-angle Imaging SpectroRadiometer	NASA	Operational	Multiple direction/polarization radiometers	Measurements of global surface albedo, aerosol, and vegetation properties. Also provides multi-angle bidirectional data (1% angle-to-angle accuracy) for cloud cover and reflectances at the surface and aerosol opacities. Global and local modes.	UV, VIS, NIR	275 m, 550 m, or 1.1 km, Summation modes available on selected cameras/bands: 1 x 1, 2 x 2, 4 x 4, 1 x 4. 1 pixel = 275 x 275 m	380 km common overlap of all 9 cameras	LEO – sun-sync
CPR (CloudSat)	Cloud Profiling Radar	NASA	Operational	Cloud profile and rain radars	Primary goal to provide data needed to evaluate and improve the way clouds are represented in global climate models. Measures vertical profile of clouds.	MW, W-Band	Vertical: 500 m, Cross-track: 1.4 km, Along-track: 2.5 km	Instantaneous Footprint < 2 km	LEO – sun-sync
AVHRR/3	Advanced Very High Resolution Radiometer/3	NOAA	Operational	Imaging multi-spectral radiometers (vis/IR)	Measurements of land and sea surface temperature, cloud cover, snow and ice cover, soil moisture and vegetation indices. Data also used for volcanic eruption monitoring.	VIS, NIR, SWIR, MWIR, TIR, FIR	1.1 km	3,000 km approx, Ensures full global coverage twice daily	LEO – sun-sync
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization	NASA	Operational	Lidars	Two-wavelength, polarization lidar capable of providing aerosol and cloud profiles and properties.	VIS, NIR	Vertical sampling: 30 m, 0-40 km	333 m along-track	LEO – sun-sync

SEVIRI	Spinning Enhanced Visible and Infra-Red Imager	EUMETSAT (ESA)	Operational	Imaging multi-spectral radiometers (vis/IR)	Measurements of cloud cover, cloud top height, precipitation, cloud motion, vegetation, radiation fluxes, convection, air mass analysis, cirrus cloud discrimination, tropopause monitoring, stability monitoring, total ozone and sea surface temperature.	VIS, NIR, SWIR, MWIR, TIR	HRV = 1 km, All other channels = 3 km (spatial sampling distance at SSP)	9 km swath scanning E-W, moving up S-N a swath width at the end of each swath. Full Disc Coverage (FDC) or Local Area Coverage (LAC) possible.	GEO
ALADIN	Atmospheric Laser Doppler Instrument	ESA	Being developed	Lidars	Global wind profiles (single line-of-sight) for an improved weather prediction.	UV	One wind profile every 200 km along track, averaged over 50 km	Along line 285 km parallel to satellite ground track	LEO – sun-sync
GOME-2	Global Ozone Monitoring Experiment - 2	EUMETSAT (ESA)	Operational	Atmospheric chemistry	Measurement of total column amounts and stratospheric and tropospheric profiles of ozone. Also amounts of H_20, NO_2, OClO, BrO, SO_2, and HCHO.	UV, VIS, NIR	Horizontal: 40 x 80 km (1,920 km swath) to 40 x 10 km (for polarization monitoring)	120-1,920 km	LEO – sun-sync
IASI	Infrared Atmospheric Sounding Interferometer	CNES (EUMETSAT)	Operational	Atmospheric temperature and humidity sounders and atmospheric chemistry	Measures tropospheric moisture and temperature, column integrated contents of ozone, carbon monoxide, methane, dinitrogen oxide, and other minor gases that affect tropospheric chemistry. Also measures sea surface and land temperature.	MWIR, TIR	Vertical: 1-30 km, Horizontal: 25 km	2,052 km	LEO – sun-sync
OLI	Operational Land Imager	USGS (NASA)	Operational	Imaging multi-spectral radiometers (vis/IR)	Measures surface radiance, land cover state and change (e.g., vegetation type). Used as multi-purpose imagery for land applications.	VIS, NIR, SWIR	Pan: 15 m, VIS - SWIR: 30 m	185 km	LEO – sun-sync
TIRS	Thermal Infrared Sensor	USGS (NASA)	Operational	Imaging multi-spectral radiometers (vis/IR)	Measures surface emittance, lands cover state and change). Used as multipurpose imagery for land applications.	TIR	100 m	185 km	LEO – sun-sync

Instrument Name Short	Instrument Name Full	Instrument Agencies	Instrument Status	Instrument Type	Measurements and Applications	Waveband Categories	Spatial Resolution	Swath Width	Orbit
TIRS-2	Thermal Infrared Sensor - 2	USGS (NASA)	Approved	Imaging multi-spectral radiometers (vis/IR)	Measures surface radiance and emittance, lands cover state and change (e.g., vegetation type). Used as multipurpose imagery for land applications. TIRS-2 will adhere to the Landsat 8 TIRS instrument performance specifications, but will be built to NASA Class-B instrument standards (including a 5-year design life).	TIR	100 m	185 km	LEO – sun-sync
POLDER	Polarization and Directionality of the Earth's Reflectances	CNES (EUMETSAT)	Operational	passive optical imaging radiometer and polarimeter	Designed to observe solar radiation reflected by Earth's atmosphere, including studies of tropospheric aerosols, sea surface reflectance, bidirectional reflectance distribution function of land surfaces, and the Earth Radiation Budget.	15 spectral bands which range from 443 nm to 910 nm.	6.5 km	2400 km	LEO – sun-sync

NOTE: Table created using data from Prather (2015), https://polder-mission.cnes.fr/fr, and http://database.eohandbook.com/.

Appendix F

Acronyms

ADM-Aeolus	Atmospheric Dynamics Mission-Aeolus
AERONET	Aerosol Robotic Network
AMS	American Meteorological Society
AOD	aerosol optical depth
ARM	Atmospheric Radiation Measurement (program)
AVHRR	Advanced Very High Resolution Radiometer
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CCN	cloud condensation nuclei
CERES	Clouds and the Earth's Radiative Energy System
COP21	United Nations Climate Change Conference
DoD	Department of Defense
DOE	Department of Energy
DSD	drop size distribution
EO	Earth orbit; electro-optical
ESA	European Space Agency
FNMOC	Fleet Numerical Meteorology and Oceanography Center
GEO	geostationary orbit
GEOSS	Global Earth Observing System of Systems
GISS	Goddard Institute for Space Studies
GLACIER	Global Leadership in the Arctic: Cooperation, Innovation, Engagement, and Resilience
GOES	Geostationary Operational Environmental Satellite
GSFC	Goddard Space Flight Center
HSRL	High Spectral Resolution Lidar
IASI	Infrared Atmospheric Sounding Interferometer
IC	Intelligence Community
INP	ice nucleating particle
IR	infrared
IWC	ice water content
JPL	Jet Propulsion Laboratory
LWC	liquid water content
LWP	liquid water path
MEDEA	Measurements of Earth Data for Environmental Analysis (program)
MISR	Multi-angle Imaging Spectroradiometer
MODIS	MODerate resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NIR	near infrared
NOAA	National Oceanic and Atmospheric Administration
NRL	Naval Research Laboratory
OPIR	Overhead Persistent Infrared

OSSE	Observing System Simulation Experiment
OSTP	Office of Science and Technology Policy
PCW	Polar Communications and Weather
PHOTONS	PHOtometrie pour le Traitement Operationnel de Normalisation Satellitaire
PMAp	Polar Multi-sensor Aerosol Properties
POLDER	POLarization and Directionality of the Earth's Reflectances
PNNL	Pacific Northwest National Laboratory
RGB	red, green, blue
SEVIRI	Spinning Enhanced Visible and InfraRed Imager
USGS	United States Geographical Survey
UV	ultraviolet
VIIRS	Visible/Infrared Imager/Radiometer Suite
VIS	visible radiation

Appendix G
Biographical Sketches of Planning Committee Members

Dr. Pamela G. Emch, Chair
Northrop Grumman Aerospace Systems

Dr. Pamela G. Emch is a senior staff engineer/scientist with Northrop Grumman Aerospace Systems in Redondo Beach, California. She works in Northrop's Space Systems business area on weather, climate, and environmental remote sensing and information technology activities supporting the National Oceanic and Atmospheric Administration, the National Aeronautics and Space Administration (NASA), the Department of Defense, and international customers. From 2005 to 2007 she was system engineering, integration, and test lead on Northrop's Geostationary Operational Environmental Satellite (GOES)-R Program Definition and Design Risk Reduction (PDRR) Program. Before working on GOES-R, Dr. Emch spent eight years on Northrop's National Polar-orbiting Operational Environmental Satellite System (NPOESS) Program, the last two years of which she relocated to Washington, DC, to serve as Northrop's system engineering and science interface to the NPOESS government program office in Silver Spring, Maryland. Prior to that Dr. Emch managed development of end-to-end physics/instrument/satellite remote sensing simulations, oversaw the archives for environmental multimedia data, and led environmental data-collection and application activities for hyperspectral airborne instruments. Dr. Emch holds an M.S. in aerospace engineering from the University of Southern California and a B.A. in mathematics and a Ph.D. in civil and environmental engineering from the University of California, Los Angeles, specializing in water resources with a minor in atmospheric sciences. She is a past chair of the American Meteorological Society (AMS) Board on Enterprise Economic Development, a member of the Executive Committee of the AMS Commission on the Weather and Climate Enterprise, and a co-chair of the Weather Coalition. She was a member of National Research Council's Committee on the Assessment on the National Weather Service's Modernization Program. Dr. Pamela Emch is a member of the National Academies of Sciences, Engineering, and Medicine's Board on Atmospheric Sciences and Climate.

Dr. Steven Ghan
Pacific Northwest National Laboratory

Dr. Steven Ghan is a climate scientist in the Atmospheric Sciences and Global Change Division at the Pacific Northwest National Laboratory. His research is to understand the atmospheric processes that drive regional and global earth systems, with a primary focus on climate, aerosol, and cloud physics; global and regional scale modeling; integrated assessment; and complex regional meteorology and chemistry. Dr. Ghan's work involves a combination of development, evaluation, and application of parameterizations for climate models. For the past 15 years, he has also focused his research on the representation of the subgrid influence or orography on atmospheric and land surface processes. He is a member of the American Geophysical Union and an editor (2007 to present) and editor-in-chief (2012 to present) for the *Journal of Geophysical Research-Atmospheres*. Dr. Ghan earned his B.S. in atmospheric science at the University of Washington and his M.S. and Ph.D. in meteorology at the Massachusetts Institute of Technology. From 2009 to the present he is a member of the Science and Infrastructure Steering Committee, Department of Energy (DOE) Atmospheric Systems Research Program and Co-chair of the Atmospheric System Research (ASR) Cloud-Aerosol-Precipitation Interactions Working Group (2009 to the present). Dr. Ghan was a member of the ARM Climate Research Facility Science Board (2010-2012). From 2012 to the present, he is Co-chair, Climate and Chemistry Working Group for the Community Earth System Model and on the External

Advisory Panel for the National Science Foundation's Center for Multiscale Modeling of Atmospheric Processes.

Dr. Everette Joseph
State University of New York at Albany

Dr. Everette Joseph is Director of the Atmospheric Sciences Research Center at the State University of New York at Albany. Prior to that, he was on the faculty at the Howard University Program in Atmospheric Sciences (HUPAS),which he directed from 2008-2013. Joseph has conducted extensive research observing the role of aerosols and certain gases on climate and weather from field observations in the Mid-Atlantic to marine expeditions across the Atlantic Ocean. HUPAS, through the work of Joseph and his colleagues, significantly increased the number of minority Ph.D. graduates in the atmospheric sciences nationally over the past 10 years. At Howard, he led the Climate and Radiation Group, a core research component in the Department of Physics and Astronomy. There he also led the development of a major field observation program with university, government, and industry partners designed to improve the ability of satellites to monitor the atmosphere from space and the skill of atmospheric models to better forecast weather, climate and air quality. Joseph has participated on a variety of advisory boards, including the DOE Atmospheric Radiation Measurement Climate Research Facility Science Board, the American Meteorological Society Board on Higher Education, and the NASA Science Mission Directorate Research and Analysis Management Operations Working Group. He presently serves on the Board of Trustees of the University Corporation for Atmospheric Research, which manages the National Center for Atmospheric Research, a federally funded research and development center supported by the National Science Foundation. He earned his Ph.D. from the State University of New York at Albany's Department of Physics in 1997, and spent one year in the Atmospheric Sciences Research Center (ASRC) as a postdoctoral research associate. Dr. Joseph is a member of the National Academies of Sciences, Engineering, and Medicine's Board on Atmospheric Sciences and Climate.

Dr. Sonia M. Kreidenweis
Colorado State University

Dr. Sonia Kreidenweis is a professor of atmospheric science at Colorado State University. She spent three years as an assistant professor in the Department of Chemical Engineering at San Jose State University, where she received the Meritorious performance and Professional Promise Award for two consecutive years for her accomplishments in research and teaching. Dr. Kreidenweis also served as a consultant in aerosol and chemical interactions in the atmosphere at the Lawrence Livermore National Laboratory. In 1993 she was named an Office of Naval Rsearch Young Investigator. Her research focuses on characterization of the physical, chemical, and optical properties of atmospheric particulate matter, and the effects of the atmospheric aerosol on visibility and climate. She has conducted field studies in several U.S. national parks to establish the sources and characteristics of particulate matter responsible for visibility degradation, with a recent focus on the impacts of prescribed and wild fires. Ongoing laboratory and field studies have investigated the role of particles and of individual compounds found in particulate matter in the nucleation of cloud droplets and ice crystals. Dr. Kreidenweis is a past president of the American Association for Aerosol Research. She received her B.E. in chemical engineering from Manhattan College and her M.S. and Ph.D. in chemical engineering from the California Institute of Technology.

Dr. Michael J. Prather
University of California, Irvine

Dr. Michael J. Prather is Professor of Earth System Science at the University of California, Irvine. His research focuses on the simulation of the physical, chemical, and biological processes that determine atmospheric composition; development of detailed numerical models of photochemistry and atmospheric radiation; and global chemical transport models that describe ozone and other trace gases. Post-Ph.D., Dr. Prather was a research fellow at Harvard University and then a scientist at the Goddard Institute for Space Studies, including also managing NASA headquarters programs on upper atmosphere and aviation impacts. A fellow of the American Geophysical Union and a member of the Norwegian Academy of Science and Letters, he served from 1997 through 2001 as Editor-in-Chief of *Geophysical Research Letters*. He received a B.A. in mathematics from Yale University, a B.A. in physics from the University of Oxford, and a Ph.D. in astronomy and astrophysics from Yale University. Prather currently participates in key United Nations' environmental efforts, including the international ozone assessments (1985, 1988, 1989, 1991, 1994, 2010, 2014) and climate assessments (Intergovernmental Panel on Climate Change: 1992, 1995, 1995, 1999, 2001, 2007, 2013, 2014). Dr. Prather has served on numerous NRC committees, most recently as a member of the Assessment of NASA's Earth Science Programs. He also previously served on the Committee on Methods for Estimating Greenhouse Gas Emissions, the Panel on Climate Variability and Change of the 2007 decadal survey on Earth science and applications from space, and the Committee for Review of the U.S. Climate Change Science Program Strategic Plan. Dr. Prather is a member of the National Research Council's Committee on a Framework for Analyzing the Needs for Continuity of NASA-Sustained Remote Sensing Observations of the Earth from Space. Dr. Prather is also a member of the Measurements of Earth Data for Environmental Analysis program.

Dr. Jeffrey S. Reid
Naval Research Laboratory

Dr. Jeffrey Reid is a meteorologist and aerosol scientist in the Marine Meteorology Division at the Naval Research Laboratory in Monterey, California. His research is in the area of aerosol observability, with an emphasis on regional aerosol environments and aerosol data assimilation. Dr. Reid works to improve electro-optical systems and retrieval algorithms for environmental monitoring. A veteran of numerous field campaigns, Dr. Reid is currently the Mission Scientist for the 7 Southeast Asian studies (7SEAS), a grass roots effort to link western and Asian researchers, and to understand the Southeast Asian aerosol environment and its potential impacts on the earth system. From 1998 to 2002, he was a project scientist at the Space and Naval Warfare Systems Center, San Diego, where he led several field missions directed towards aerosol parameterization development and model verification. Dr. Reid earned his B.S. in applied physics (quantum optics) at the University of California, Davis, in 1991. His undergraduate work was in experimental aerosol science with an emphasis on nuclear techniques for aerosol analysis. In 1993 he earned his M.S. in atmospheric science at the University of California, Davis, where he studied issues related to dust production and transport. At the University of Washington, Seattle, in 1998, Dr. Reid earned his Ph.D. in atmospheric science; he studied chemical evolution and optical properties of biomass burning smoke. Dr. Reid also devotes a great deal of time to international collaboration, development and outreach and he was a founding organizer of several cooperative workshops on biomass burning and aerosol prediction.

Dr. Robert Wood
University of Washington

Dr. Robert Wood is Associate Professor of Atmospheric Sciences at the University of Washington. He is responsible for the development of a program of research centered on the understanding of cloud physical processes; he also teaches the undergraduate and graduate programs in atmospheric sciences. From 2004 to 2010, Dr. Wood was research assistant professor and then assistant professor. As a research associate, he studied boundary layer cloud structure, variability, and microphysical processes. At the Meteorological Research Flight Office in the United Kingdom from 1997 to 2001, he was a scientist who did research on boundary layer cloud microphysical processes and structural properties; he was also responsible for planning and executing aircraft-based field programs. Dr. Wood is the editor of the *Journal of Climate* since 2009. In 2011 he received the Henry G. Houghton Award from the American Meteorological Society for advancing understanding of the interactions between cloud droplets, aerosols, radiation, and precipitation in marine stratocumulus. He received the Editors' Citation for Excellence in Refereeing for the *Journal of Geophysical Research-Atmospheres* in 2007. From the Royal Meteorological Society in 2001, Dr. Wood received the L.F. Richardson Prize which is awarded annually for a meritorious paper that was published in a society journal during the preceding four years, and was contributed by a member of the society who is in their early career in meteorology. Dr. Wood is a co-author of more than 60 journal articles on atmospheric sciences. He holds a B.A in natural sciences (physics and theoretical physics) from the University of Cambridge and a Ph.D. in atmospheric physics from the University of Manchester Institute of Science and Technology, United Kingdom.