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U.S. DEPARTMENT OF ENERGY | Office of Science

BIOLOGICAL AND ENVIRONMENTAL RESEARCH

# Climate and Environmental Sciences Division

## U.S./EUROPEAN WORKSHOP ON CLIMATE CHANGE CHALLENGES AND OBSERVATIONS



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Prepared by the
Climate and Environmental Sciences Division

within the

U.S. Department of Energy Office of Science
Office of Biological and Environmental Research

U.S. DEPARTMENT OF ENERGY | Office of Science

# Contents

# Executive Summary

The workshop aimed to identify outstanding climate change science questions and the observational strategies for addressing them. The scientific focus was clouds, aerosols, and precipitation, and the required ground- and aerial-based observations. The workshop findings will be useful input for setting priorities within the Department of Energy (DOE) and the participating European centers. This joint workshop was envisioned as the first step in enhancing the collaboration among these climate research activities needed to better serve the science community.

Science questions derived during the first day's breakout sessions provided the structure for the rest of the meeting:

1. What is the distribution of aerosol properties for the Atmospheric Model Intercomparison Project (AMIP) period (i.e., since 1979)?
2. What is the coupling among microphysics, aerosols, and cloud dynamics as a function of scale and regime (e.g., vertical velocity or stability)?
3. How are precipitation, water vapor and cloudiness coupled, and what roles does organization play in this coupling?
4. How do clouds and precipitation couple with surface properties?
5. What is the response of clouds to warming?
6. What is the response of the probability density function (PDF) of precipitation to warming?

Strategies for enhancing collaboration among the Atmospheric Radiation Measurement (ARM) Climate Research Facility and European programs were identified in the later sessions.

Atmospheric observations (in situ and remote sensing) from ARM sites and corresponding European sites can play a key role in addressing these critical scientific questions. However, the value of these individual centers would be enhanced by a coordinated free and open data infrastructure for access to data archives and repositories. The objective for the European Union (EU) programs and ARM is to jointly develop the architecture, standards, and framework for an integrated central portal (flexible and extensible) to relate all relevant data sets necessary to facilitate collaborative science and research. This activity should include consistently processed data products, target classification, and retrieval algorithms from all advanced remote sensing sites.

Aerosol extinction profiles, water vapor (integrated and profiling), liquid water path (LWP), and liquid water content (LWC) are common products that can be used to test the process chain from remotely sensed quantities to geophysical parameters. For that purpose, work on calibration standards, data harmonization, algorithms, uncertainty assessment, value-added products, and synthesis products is necessary. Finally, a common observational data set to be used for the Coupled Model Intercomparison Project Phase 5 (CMIP5) modeling evaluation should be established.

Retrieval development including the assembly of background climatologies and uncertainty assessment offers excellent chances for collaboration between the DOE and the EU. In order to facilitate this collaboration, a workshop between members of the Atmospheric System Research (ASR) program's Quantification of Uncertainties in Cloud Retrievals (QUICR) focus group and corresponding EU experts from the European Ground-Based Observations of Essential Variables for Climate and Operational Meteorology (EG-Climet) should be planned for 2013.

Ground-based remote sensing instruments including lidar, radiometer, and radar (and their spectra) are excellent sources for making measurements of critical parameters: for example, vertical velocities and vertical profiles of atmospheric state parameters. However, the use of large-eddy simulations (LES) to bridge the gap from spatially limited observations to the temporal development of the full volume (4D) is desirable. The LES output can then be used as powerful additional "virtual observations" of processes that cannot or only partly be observed. This strategy has been successfully implemented at the Cabauw site in the Netherlands in near-real-time operation. These procedures can be evaluated for transfer to the ARM Southern Great Plains (SGP) site, in particular for data from ARM's airborne Routine AAF Clouds with Low Optical Water Depths (CLOWD) Optical Radiative Observations (RACORO) field campaign dedicated to thin water clouds, and later to other atmospheric observatories. For running the LES, large-scale forcings are needed that can come from short-term numerical weather prediction (NWP) but could eventually be improved by constraining with scanning radars and lidars.

The advent of new scanning remote sensing instrumentation also offers the chance to observe aerosols, clouds, and meteorology in high temporal and spatial resolution. New configurations (scanning strategies) of existing and new instruments are needed to fully explore this path. To more closely align observations and model inputs, a denser network of cheaper instruments (for example, ceilometers and/or microwave radiometers surrounding a single scanning cloud radar) will help gain spatial resolution (20 kilometers) at the LES scale. In this sense the High Definition Clouds and Precipitation for Climate Prediction [HD(CP$^2$)] Observational Prototype Experiment (HOPE) in April–May 2013 in Germany can serve as a testbed for models.

In order to study the influence of the heterogeneous land surface on cloud processes, heat fluxes and surface energy budget components over 10-kilometer x 10-kilometer areas near intensive/comprehensive atmospheric observatories should be characterized, preferably with a combination of measurements and LES. Existing data from RACORO and Transregional Collaborative Research Centre 32 (TR32) can be exploited, and better connections with the hydrology/land-surface and Arctic ocean/sea-ice communities should be established.

Current ARM/EU sites cover many important climate zones, but there are also important observational needs over other regions. To derive appropriate aerosol climatologies for general circulation model (GCM) evaluation and cloud impact studies, key locations for the characterization and observation of aerosol parameters in terms of concentration, optical, and chemical properties (including the vertical profiles) need to be defined and better aligned with cloud observations. Studies on land surface should have an emphasis on drought-sensitive areas (e.g., Mediterranean, Sahel) and areas with large atmosphere-land exchanges of water and carbon (e.g., Amazon). The ARM GOAMAZON campaign in 2014–2015 is an opportunity for collaboration. Thus, in 2013, a workshop should be held in Europe to foster activities in 2015.

Barbados represents a potentially useful site for collaborative experiments in the sub-tropics. The site is particularly interesting because it is at times in a pristine environment and at other times has significant aerosol loading. Together with the new ARM site in the Azores, the setup builds a bridge across the Atlantic that can be strengthened by ship cruises. Further workshops should address collaboration for better defining an international Arctic sea ice study and a Southern Ocean deployment.

For analyzing cloud systems and their organization, observations from ground-based sites must be combined with radar networks and satellite data. A sounding network is also critical, particularly in regions where NWP does not provide good estimates of advective tendencies. It is noted that in well-observed regions, forecast models provide reasonable representations of precipitation. Higher temporal and spatial resolution of observations are needed in order to better capture extreme precipitation events. This requirement can be met through synergistic use of scanning cloud radars and scanning profilers to obtain simultaneous water vapor profiles, and vertical velocity measurements.

There is a need to identify pathways to link forecast models to GCM models. This may include the development of cloud-resolving models that are large enough to represent a cloud life cycle during increased dynamics.

# U.S./European Workshop on Climate Change Challenges and Observations

The U.S. Department of Energy (DOE) and several European centers sponsored this workshop with the objective of identifying outstanding climate change science questions and the observational strategies for addressing them. The scientific focus was clouds, aerosols, and precipitation, and the observational focus was ground- and aerial-based platforms. The third element of the workshop was to explore opportunities for collaboration between European and DOE centers and scientists. The workshop was conducted November 6–8, 2012, at the Renaissance Hotel in Washington, DC.

The meeting's focus on clouds, aerosols, and precipitation was based on scientific assessments that have identified these areas as major sources of uncertainty in earth system models. In large part, this uncertainty is due to a lack in understanding of how water (in all its phases) couples to circulations. Additionally, the close connection and coupling between terrestrial and atmospheric processes for important climatic functions (cloud cover and precipitation) and the need to better represent these processes in earth system models is also a major challenge for the scientific community. Thus, a better understanding of the physical and biological processes involved in these systems is required for reducing uncertainties in climate model simulations. It is understood that a strong collaboration among international activities will greatly enhance scientific advancement in understanding these critical scientific questions.

The meeting opened with four talks to provide the context for the meeting, but the majority of time was concentrated in breakout groups focusing on developing strategies for better understanding these processes. Relevant program descriptions were given for:

- EUCLIPSE: European Union Cloud Intercomparison, Process Study & Evaluation Project (Pier Siebesma)
- $HD(CP)^2$: High Definition Clouds and Precipitation for Climate Prediction (Björn Stevens)
- ACTRIS: Aerosols, Clouds, and Trace Gases Research Infrastructure Network (Gelsomina Pappalardo)
- Major DOE programs (Gerald Geernaert)

On the first day, participants were asked to identify the key climate change scientific challenges, which were the basis of discussion for the following two days. On the second day, participants were asked to provide insights on the observations and data products required for addressing these questions. The third day focused on identifying collaborative efforts between the U.S. and European centers that would facilitate addressing these issues. The workshop findings will be useful input for setting priorities within DOE and the participating European centers. This joint workshop is envisioned to be the first step in enhancing the collaboration among these climate research activities needed to better serve the science community.

# Day 1 Breakout Sessions

The goal of the Day 1 breakout sessions was to brainstorm and catalog science drivers and technical approaches to improve the scientific understanding of aerosol-cloud-precipitation processes. The discussion guidelines were to address the critical scientific uncertainties that could be addressed by collaborations between the European and U.S. climate observational and modeling programs. Opportunities for other programs and agencies were also to be considered (e.g., remote sensing, specialized instrumentation, additional measurements). Breakout groups were instructed to balance "blue-sky" discussions with pragmatic consideration of European and U.S. research foci and practical limitations.

### *Science Questions Derived from Day 1 Breakout Sessions*

1. What is the distribution of aerosol properties for the Atmospheric Model Intercomparison Project (AMIP) period (i.e., since 1979)?
2. What is the coupling among microphysics, aerosols, and cloud dynamics as a function of scale and regime (e.g., vertical velocity or stability)?
3. How are precipitation water vapor and cloudiness coupled, and what roles does organization play in this coupling?
4. How do clouds and precipitation couple with surface properties?
5. What is the response of clouds to warming?
6. What is the response of the probability density function (PDF) of precipitation to warming?

# Day 2 Breakout Sessions

The goal of the Day 2 breakout sessions was to identify and discuss observation strategies to address each of the identified science questions. The discussion guidelines were to address the geophysical variables needed, with what accuracy and what resolution (vertical, spatial, temporal). The breakout groups were also asked to address the type of correlated data sets (synergy) needed to address the scientific questions. The participants were to discuss the best mix of laboratory, campaign mode, and long-term data sets.

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## ***Question 1:*** *What is the distribution of aerosol properties for the Atmospheric Model Intercomparison Project (AMIP) period (i.e., since 1979)?*

### *Interpretation*

The evaluation and improvement of GCMs requires an accurate description of the spatial and temporal variability of aerosols in the atmosphere. In addition to the aerosol radiative properties [aerosol optical depth ($\tau$a), single-scattering albedo ($\omega_o$), and asymmetry parameter (g)] that determine aerosol radiative forcing in clear-sky conditions, cloud condensation nuclei (CCN) and ice nuclei (IN) concentrations are of particular importance to the formation and regulation of clouds. Although a climatology of AOD has been developed for the AMIP period, climatologies of $\omega_o$, g, and CCN and IN concentrations are not available. Such climatologies would be particularly useful for constraining (adjusting uncertain parameters to improve agreement with the data) global aerosol models and (when used directly as input) for understanding different estimates of direct and indirect aerosol radiative forcing by GCMs.

### *Discussion*

Given the large spatial variability of aerosols, it is not feasible to measure the global distribution of properties other than AOD and extinction (which can be retrieved from satellite instruments). Development of a climatology of the other aerosol properties requires an aerosol data assimilation system that uses a global aerosol life cycle model, emissions estimates, available observational data, assimilation techniques, and physical constraints to estimate the global distribution of aerosols (and especially CCN and IN) and the anthropogenic contributions to the aerosol. In order to minimize the dependence of the climatology of CCN, IN, and optical properties on the particular aerosol life cycle model used for assimilation, it is necessary to have spatially distributed measurements of precursor gases, aerosol particle size distribution (PSD) and composition as well as CCN, IN, and optical properties. Existing aerosol data assimilation systems already ingest AOD data; further development would be needed to ingest other aerosol data.

### *Observables*

Detailed aerosol observations have been made at the ARM Facility, the Baseline Surface Radiation Network, the Micropulse Lidar Network (MPLNET), and the Aerosol Robotic Network (AERONET) sites for over a decade, and the above measurement strategy should build on these. An immediate need is to develop a monthly climatology of CCN and IN in various regions around the Earth. Marine and ship-based measurements would be an important complement to land-based measurements to extend the geographic coverage. In lieu of CCN measurements, measurements of the aerosol PSD and hygroscopicity are a useful substitute; however, filter-based measurements are needed if direct IN measurements are not available. These measurements would be useful for aerosol model evaluation even if a global distribution is not produced.

The above measurements only address the need for developing a climatology of aerosol properties. To distinguish natural and anthropogenic aerosol, it is essential that we understand what processes affect the variability of these properties, and thus a full range of additional measurements (e.g., precursor gases, primary particle concentrations and composition, etc.) at key locations (e.g., in source regions) in different climatic regimes is needed.

### *Analysis*

There are many of very diverse aerosol measurements available [e.g., from ACTRIS, the ARM Facility, AERONET, MPLNET, satellite retrievals, ceilometer networks, air quality observations, etc.]. A new data product should be developed that merges these different efforts to provide an aerosol climatology for model evaluation and forcing. The development of this climatology will likely identify regions (e.g., near dust basins, anthropogenic sources, or biogenic sources) where additional in situ or remote sensing measurements of $\tau a$, $\omega_o$, and g are needed to establish a reference measurement background.

Measurements using multiple wavelength, co-polarized Raman lidars together with sun photometers can be used to determine aerosol composition, size distributions, and refractive index through direct physical measurement or retrievals. Lidar observations help to link surface in situ observations to the atmospheric profile.

### *Outcome*

- Define key locations for the characterization and observation of aerosol parameters in terms of concentration, optical, and chemical properties (including the vertical profiles) to derive appropriate climatologies for GCM evaluation and cloud impact studies. Cooperation between different communities as it is done in Europe within ACTRIS might be necessary.
- Investigate the possibility of using fixed, mobile, and/or shipboard measurements for the characterization of different source or type regions. At these locations collect or establish the measurement records necessary to address the spatial and temporal requirements of modeling studies.
- Extend aerosol assimilation systems to ingest past measurements and retrievals of CCN, IN, composition, aerosol absorption optical depth, and extinction, as well as AOD.

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## **Question 2:** *What is the coupling among microphysics, aerosols, and cloud dynamics as a function of scale and regime?*

### *Interpretation*

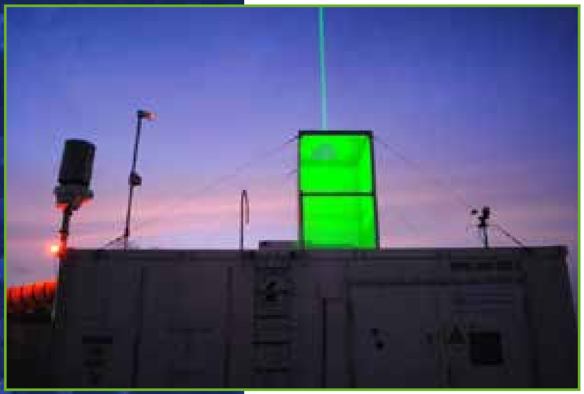
The question concerns the response of cloud microphysics to aerosol perturbations given the dynamical environment of the cloud or cloud system. While these responses are not universal, there is coherence within cloud type (e.g., warm phase, super-cooled, convective) and regime (e.g., vertical velocity or stability.) The coupling of cloud microphysics with aerosol and cloud dynamics is also variable through space and time and will manifest differently at the cloud scale and the cloud system scale. Responses should be characterized as a function of these conditions. Warm-phase clouds at the cloud system scale constitute the largest uncertainties in global climate models; therefore, understanding these interactions for this system is a priority.

Cloud microphysical responses are best resolved by a process-based approach on the cloud scale. Coupling surface-based remote sensing instrumentation and cloud-scale models is required to understand this cloud scale question.

### Discussion

Clearly, a large amount of data is needed to develop the correlations and statistical interpretations to understand the interactions of aerosol and meteorological effects on cloud microphysics. In addition, a high-level strategy to understand these effects needs to be developed for different cloud types. The group discussed whether satellite observations could be used to address this issue and concluded that even the best attempts fall short of the appropriately resolved spatial and temporal scales of critical parameters (turbulence, precipitation, etc.). Surface-based observations coupled with LES or other cloud-scale models currently provide the best opportunity to understand the cloud/aerosol/dynamic interactions. However, the group expressed the need for more sites in different climatic regimes to develop a diversity of forcing algorithms for LES models.

The cloud/aerosol issue requires multiple information sources that cannot be uniquely resolved by one single instrument. This is a smaller problem for water clouds (spherical drops) than it is for ice and mixed-phase clouds in which a large variety of different ice crystals can occur. Retrieval algorithms that use observations from different instruments in a synergistic way to provide improved estimates of geophysical values (e.g., cloud ice water content) are needed but must have well-characterized uncertainty estimates.



### Observables

Ground-based remote sensing instruments such as lidar, radiometer, and radar (and their spectra) are excellent ways to provide measurements of critical parameters such as vertical velocities as well as the usual vertical profiles of state parameters. The following measurements should be included, should cover scales of 1 to 100 kilometers and time scales of seconds to minutes, and should always be stored at highest resolution.

- Water vapor profile
- Temperature profile
- LWP and LWP in precipitating conditions
- Vertical velocity
- Aerosol profiles and characteristics (size, shape, concentration, etc.)
- CCN (ideally CCN as a function of supersaturation) and IN
- Hydrometeor profile identification (i.e., cloud droplets, drizzle, rain, ice, snow, and ideally size distribution, phase, shape per hydrometeor type but minimum water content/path and effective radius)

- Ice fall speed
- Large-scale advective tendencies (for driving the models)

In general, there is a high priority for well-calibrated standardized data and enhanced data such as covariances between geophysical parameters (w'q', etc.) and PDFs. Because processes (e.g., entrainment, evaporation of hydrometers, precipitation efficiency) cannot be directly observed, a better coupling to models is needed. However, even LES models do not have sufficiently accurate microphysical parameterizations in their current form.

To more closely align observations and model inputs, a denser network of cheaper instruments (e.g., ceilometers and/or microwave radiometers surrounding a single scanning cloud radar, etc.) will help gain spatial resolution (20 kilometers) at the LES scale, which works for low clouds. Different sets of instruments for other cloud types may be necessary.

Scanning Doppler lidar and cloud and precipitation radars are certainly a very powerful combination; however, the question remains as to whether these instruments are currently sensitive enough to "see" clouds and cloud processes, and can the impacts of signal attenuation of the active remote sensors be overcome? Thin water clouds can be a challenge and require infrared detection. A sounding array or other methods (e.g., using output from a numerical weather prediction model) to determine the advective tendencies and large-scale vertical motion is required to drive the LES model.

New measurements and observations strategies were discussed. For example, ice nuclei counters could be placed on commercial jets to obtain global sampling of IN to better characterize aerosol background information. Cloud tomography may be useful to resolve cloud microphysical components. In addition, water vapor isotope measurements may be useful. There needs to be a closer coupling between the modelers and observationalists working hand in hand; modelers need to more clearly define what is needed, so observationalists can develop methods to make the appropriate observation, if possible.

### *Data Analysis*

The best approach for studying cloud/aerosol interactions is using observations from surface-based remote sensing systems and developing forcing algorithms for cloud-scale model studies. This is best done by coupling LES and other cloud-resolving models with surface-based observations. It would be extremely useful to run these cloud-scale models in near-real-time at operational sites. Accurate vertical profiles of many geophysical parameters and the location and density of measurements are important considerations to address the spatial resolution that is needed to best utilize cloud-scale models. For that purpose, microphysical retrieval algorithms must be improved. In particular, a sufficiently large a priori cloud database of condensed mass, area, and hydrometeor distribution as a function of size, phase, and habit distribution is needed. This prior data set is a critical component for ground-based remote sensing algorithms and requires aircraft measurements (piloted and unpiloted).

One approach is to describe the atmosphere at LES scales using unique arrays of multiple-sensors to vertically and spatially (i.e., 3D) resolve cloud properties and processes for specific cloud types and at different climatic regimes. This requires development of new scanning configurations of existing instruments. This should be tested in field experiments like ARM's Midlatitude Continental Convective Clouds Experiment (MC3E) or HOPE.

### Outcome

- There is a need for consistently processed data products, target classification, and retrieval algorithms from all advanced remote sensing sites, such as ARM and EU sites. This includes the assembly of background climatologies to get robust a priori information for the retrieval algorithms.
- There is a need to develop new configurations (scanning strategies) of existing (and new) instruments to observe aerosol, clouds, and meteorology in high temporal and spatial (3D) resolution.
- There is a need to use LES to bridge the gap from spatially limited observations to the temporal development of the full volume (4D). Near-real-time operation at operational sites is desirable. Explicit microphysical parameterizations in LES models should be implemented. Data assimilation into LES needs to be explored.
- Current ARM and EU sites cover many important climate zones, but there are also important observational needs over the sub-tropical, southern, and Arctic oceans.

## **Question 3:** *How are precipitation, water vapor, and cloudiness coupled, and is organization important?*

### Interpretation

Precipitation, water vapor, and cloud macrophysical characteristics (e.g., cloud amount, optical depth, overlap) are part of a highly coupled system that depends on meteorology/dynamics at larger scales. Within the large-scale circulation regime, the question is how precipitation, water vapor, and cloudiness interact, considering the radiative feedbacks on the system. Does the large-scale synoptic and/or mesoscale dynamical environment regulate the clouds? This is a large-scale circulation/parameterization question rather than a cloud process question.

### Discussion

The coupling of water vapor, clouds, and precipitation has important implications for weather (e.g., via intense storms) and climate (e.g., via cloud patterns and radiative feedbacks). Intrinsic in this discussion is how cloud systems organize, examples of which include the large stratocumulus decks off the west coasts of South America and Africa, tropical cyclones, and the large anomalous convecting regions of the Madden-Julian Oscillation that propagate through the Indian Ocean and West Pacific. Because these phenomena are inextricably linked to mesoscale and larger circulations, focus needs to be placed on observations of entire cloud systems and the large-scale environment in which they are embedded. This includes measurements of spatial distribution of precipitation along with clouds, vertical and horizontal wind fields, thermodynamic environment, and heating rates.

### *Observations*

The scale of this problem requires a multi-platform approach. Due to the low repetition time, cloud lifetime cannot be observed by low-Earth-orbiting satellites. Geostationary satellite data with a high repeat cycle have coarser resolution but still would be useful for validation of model output. Ground systems provide the highest resolution of the cloud systems and their environment both in time and space, but their spatial range is often limited to 150 kilometers or less (much less in the case of attenuating radars), and the least noisy measurements often come from vertically pointing sensors.

In an ideal scenario, ground sites would have a diversity of radar capabilities (scanning and vertically pointing, cm- and mm-wavelengths, polarimetric, and Doppler) with high temporal sampling of the environment by soundings and profiling ground instrumentation like wind profilers and microwave radiometers. Radar observations need to be combined with disdrometers and rain gauges to achieve good precipitation estimate. The observational period should be as long as possible to robustly sample the phenomena of interest, since the analysis will likely be statistics-driven, especially as the results relate to model parameterization.

Organized cloud systems are postulated to feedback on the environment via their heat, moisture, and momentum budgets. As such, focus should be placed on observations that will inform parameterizations ranging from the boundary layer to deep convection to radiation and the interactions between these parameterizations as they relate to water in the environment. These observations (of boundary layer moisture and temperature at high resolution, in-cloud vertical velocity, entrainment, ice microphysical properties of anvil and cirrus, etc.) are often difficult to obtain, but their retrievals have a greater potential payoff than more standard variables.

### *Analysis*

Before the observational platforms are combined, it is important to define cloud lifetime and organization since that will impact the nature of the analysis. For example, how do you define the lifetime of a stratocumulus deck (e.g., from cloud spacing from geostationary satellite images or the time series of LWP from a vertically pointing instrument) and the organization of a mesoscale convective system (e.g., using the spatial scale of the precipitation or the vertical motions embedded in the storm)?

The observational strategy will depend upon cloud types. A potential first step may be to take the core cloud processes and basic measurements (especially LWP and precipitation) from Question 2 and apply them to the climate model grid scale. It is critical to identify the appropriate parameters for GCMs to use to realistically drive clouds at the climate model grid scale. One approach is to combine field campaign mode (golden days) and long-term data sets (statistics) to drive parameterizations, including the environment. A complementary approach is to conduct rather large-scale type field campaigns (Tropical Warm Pool-

International Cloud Experiment [TWP-ICE], Dynamics of the Madden-Julian Oscillation [DYNAMO], ARM MJO Investigation Experiment [AMIE], etc.) covering larger domains. Field campaigns that are high priority for Europe and U.S./ARM should be identified for a collaborative effort (See Section "Day 3 Breakout Sessions").

### Outcome

- Identify observable quantities that GCMs use to drive cloud dynamics at the climate model grid scale.
- Use the same basic measurements outlined in Question 2 at the climate model grid scale, with the addition of large-scale weather radar and sounding networks and satellite data.
- Produce model forcing data sets that encompass the scale of the cloud system.
- Prioritize locations/field campaigns that showcase the most climate-relevant coupling of water vapor, cloud, and precipitation (e.g., West Africa compared to the Amazon for large-scale convective organization over tropical land, AMIE/DYNAMO in the Indian Ocean and tropical western Pacific for convective organization over the tropical ocean, and the routine *Polarstern* route between Germany and the southern tip of South America for low-level marine clouds).

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## **Question 4:** *How do clouds and precipitation couple with surface properties?*

### Interpretation

The group discussed using a combination of measurements and LES modeling to explore the interaction of the surface and atmosphere with an emphasis on capturing the effects of surface heterogeneity on fluxes of water and energy as well as carbon, and effects of clouds and precipitation on properties and surface heterogeneity. The issue of sea-ice retreat was also discussed in the context of interaction of the complex broken sea-ice surface with the atmosphere via surface energy budgets. The not-yet-understood 2007 Arctic sea-ice minimum in conjunction with an observed cloud cover minimum is of special importance. This issue should be considered via the interactions of the complex broken sea-ice surface with the atmosphere via surface energy budgets. An important question is what roles clouds play in the retreat and variability of sea ice. Additionally, the importance of surface moisture availability for land/atmosphere interactions including the associated cloud processes was considered.

### Discussion

Over the Arctic Ocean, heat flux gradients associated with water/ice boundaries are critical for cloud, atmosphere, and sea-ice processes; however, measurements of heat fluxes, or the overlying atmospheric boundary layer, are very difficult in that region, so there are very few measurements available. Over land, surface heterogeneity is also very important and impacts clouds largely by gradients in moisture availability. While the measurements over land are simpler than over the ocean or sea ice, the highly variable spatial inhomogeneities involved still make this a difficult problem. Progress in science is currently hampered by insufficient data sets of combined surface moisture availability and the associated surface energy fluxes on a scale appropriate to study the impact and response to the overlying atmospheric cloud field.

### *Observations*

In the discussions, it was agreed that the regions in most need of understanding surface-atmosphere interactions, and particularly the role of spatial heterogeneity, are those over land or ice. Atmosphere-surface interactions over oceanic regions are somewhat better understood, in part due to relative spatial homogeneity.

The most important locations to characterize the interaction of the surface with the atmosphere over land are expected to be regions that are prone to droughts, including the southern Mediterranean and the Sahel, and regions with large exchanges of water and carbon between the atmosphere and surface. Measurements in these dry land regions and over sea ice should be made over an annual cycle. For the atmosphere, measurements of clouds, precipitation, and thermodynamic profiles are required.

Current ARM and EU atmospheric observatories generally measure these components. These observatories, however, typically place less emphasis on the measurement of surface properties, including surface moisture availability and important elements of the surface energy budget. One key parameter required for the surface is moisture availability; however, it is very difficult to measure this parameter with sufficient resolution to constrain LES simulations. Ultimately, gradients in moisture availability result in gradients in turbulent heat fluxes that provide the actual coupling between the surface and the atmosphere. Thus, it is critical to characterize these heat fluxes over representative spatial areas.

It is proposed that in representative 10-kilometer x 10-kilometer areas near atmospheric observatories, a few point measurements of surface moisture availability and turbulent heat flux be made and that the information from these point measurements be extended spatially using remote sensing measurements. Specifically, a combination of scintillometers and Doppler lidars could be used to provide measurements of heat fluxes and boundary-layer structure over a spatial domain spanning the required 10-kilometer range. Accompanying these spatial measurements of surface heat fluxes would need to be a complete atmospheric instrument suite including measurements of the cloud, thermodynamic, and precipitation fields from scanning radar, lidar, and passive sensors and surface measurements of radiation, meteorological state, and aerosol properties. The time scale of these measurements should fall in the range of approximately 1–10 minutes. To further understand the requirements for characterizing the surface moisture, it would be valuable to engage the hydrology community that has long focused on this issue.

In the Arctic sea-ice environment, similar measurements are needed. In this environment specifically, it is critical to understand all components of the surface energy budget, the different factors and processes that influence these components, and the variability of these processes over the full annual cycle. To obtain such measurements over the central Arctic, it will likely be necessary to stage comprehensive instrument suites (as described above) on and near ships embedded within the ice pack as was done during the Surface Heat Budget of the Arctic Ocean (SHEBA) field campaign.

Surface energy budget measurements will be more difficult in this environment but should be designed to represent the spatial heterogeneity associated with variability in sea-ice age and thickness, ice-ocean fraction, and atmospheric processes. Doppler lidar measurements will provide very useful information over the ocean/ice surface, specifically with regard to characterizing the boundary-layer structure, which is a critical link between the sea ice and free atmosphere but is relatively understudied in this environment. To understand the energy budget in the sea-ice environment, it is also critical to understand the oceanic influences. For the measurements of the ocean properties, it will be important to engage the sea-ice and oceanographic communities. In addition, there are a variety of international observation programs that should be engaged and data sets that should be used to augment the proposed measurements.

Next to the surface energy budget, the question of what maintains an Arctic cloud is closely related to the microphysical properties and the aerosol environment. LES runs simulating the complex interaction between surface and cloud microphysics crucially depend on a realistic representation of IN and ice particle habits. Next to enhanced cloud property retrievals from atmospheric observatories in the crucial environments, this demands significant advances in measurement techniques for IN, as well as in situ measurements of cloud and thermodynamic properties from airborne (especially unmanned aerial vehicle) platforms.

### *Analysis*

The surface/atmosphere interaction problem has several relevant spatial scales. These range from the local scale (several hundred meters to several kilometers, corresponding to the depth of the boundary layer in the vertical dimension and approximately 10 kilometers in the horizontal dimension) to the mesoscale. A general strategy for exploring surface/atmosphere interactions at the local scale should involve a combination of LES modeling and spatial, ground-based measurements that are designed to represent heterogeneity on 10-kilometer scales. Enhanced satellite observations of soil moisture availability from polar orbiters in conjunction with cloud property retrievals from space are also critical for this study. The mesoscale aspects of this problem can be explored using several separate LES/observation domains distributed throughout a local region, nested mesoscale models that are coupled to high resolution inner domains, or regional climate models run at high resolution.

### Outcome

- Emphasize drought-sensitive areas (e.g., Mediterranean, Sahel) and areas with large atmosphere-land exchanges of water and carbon (e.g., Amazon).
- Emphasize understanding the interactions and feedbacks between Arctic sea-ice loss, surface energy budgets, and atmospheric processes. Similarly, sea/lake ice heat fluxes should be studied.
- Characterize heat fluxes and surface energy budget components over 10-kilometer x 10-kilometer areas near intensive/comprehensive atmospheric observatories, preferably with a combination of measurements and LES. Existing data such as RACORO and TR32 can be exploited and better connections with the hydrology/land-surface and Arctic ocean/sea-ice communities should be established.
- Use existing Arctic data sets including data associated with the 2007/2012 sea-ice minimum.

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## **Question 5:** What is the response of clouds to warming?

### Interpretation

The groups discussing this question came to the conclusion that because of the complex nature of clouds and the relatively limited historical record of detailed cloud observations, it will be difficult to discern a change in cloud properties that can be readily attributed to climate change on time scales on the order of a decade. Therefore, the preferred approach for understanding the response of clouds to warming is through better understanding of cloud processes and improvement of LES models by using more detailed and statistically significant ground-based observations.

### Discussion

Because of the challenges in observing trends in cloud properties, it is necessary to use models to study the response of clouds to a warming environment. The strategy that has been developed over the past two decades is to use high resolution LES and cloud-resolving models (CRM) along with ground-based observations to study physical processes as a function of varying environmental conditions (i.e., temperature profile). This process-level understanding is then represented in specific parametric relationships that can be applied to develop parameterizations for global-scale models. The combined data set could be used to test ideas such as the Fixed Anvil Temperature (FAT) hypothesis and others. In these applications, LES and CRM models are forced using reanalysis data or, for focused field campaigns, with analyses from radiosonde arrays.

### Observables

For evaluation of cloud processes in LES models, it is particularly important to obtain macroscale cloud properties including optical depth and cloud layer boundaries. For warm clouds, droplet effective radius and LWP are also critical. It was noted that particular attention needs to be given to improving measurements of LWP, particularly under precipitating conditions. Such measurements are best possible when combining passive microwave radiometer with cloud radar and lidar measurements. The latest developments show the need to analyze cloud radar Doppler spectra in order to discriminate between cloud

and precipitation in a sophisticated manner. For cold clouds, with the added complexity of ice crystals, there is more of a need to retrieve details of the PSD using radar and other remote sensors. It is also important to obtain diabatic heating profiles and condensate outflow from tropical convection. These can be obtained using remote sensors (especially scanning cloud radars).

Efforts in using polarimetric and multi-frequency wavelength approaches seem most promising. In order to characterize tropical convection in the best possible way, it is necessary to obtain diabatic heating profiles in conjunction with the outflow of convection into the upper troposphere. This implies not only measuring the vertical profile of the PSD within the tropical cloud, but also radiative fluxes at top of troposphere, turbulent fluxes within anvil, and water vapor in the upper troposphere. Only dedicated campaigns with simultaneous ground-based remote sensing (especially scanning cloud radar and water vapor lidar), airborne, and satellite measurements can deliver such detailed information.

High temporal resolution (~10 minutes) profiles of the thermodynamic state and vertical motion are important for evaluating LES simulations. Currently there are many instruments being applied to obtain information about the water vapor profile (e.g., radiosondes, Raman lidar, and microwave radiometer), but measurements from these instruments will have to be combined and integrated, and likely new techniques will need to be developed to obtain water vapor profiles at such high temporal resolution. Similarly, there are a variety of instruments including radar and Doppler lidar that are being used to provide information about vertical velocity. With this combination of parameters, it will be of particular interest to understand the spatial and vertical variability of supersaturation conditions and how these relate to spatial variability in vertical turbulent air motions. In addition, these parameters are critical for understanding cloud evolution in relation to the environment.

### *Analysis*

There are several ways that observational data have been used to evaluate output from global-scale models. Single-column versions of GCMs can be run over a site by forcing the model in the same way just described for high resolution models. In the EU, operational retrieval data from Cloudnet are routinely compared with NWP output, while in the U.S., the Cloud-Associated Parameterizations Testbed (CAPT) project runs a climate model in NWP mode, validating the model over an ARM site.

To further advance the strategy of using LES models as an interface between ground-based observations and GCMs, it would be valuable to run LES models over atmospheric observatories on a more continuous basis. This would require providing a continuous forcing data set, likely from NWP reanalysis for middle latitude locations. This is already being done over the ARM SGP site and could be done at other locations. LES parameters can be compared directly with observed and retrieved atmosphere and cloud variables. An important complementary method is to also implement instrument simulators in the model to create output that is comparable to parameters that are measured more directly by instruments. This technique still involves many of the same assumptions needed in the retrieval process, but the alternate perspective has been found to be very useful for some applications.

While the ARM SGP site is perhaps in the best position to implement this strategy, there are other locations that would greatly benefit from this detailed analysis. These include the sub-tropics and the Southern Ocean. Barbados represents a potentially useful site in the sub-tropics. The site is particularly interesting because it is at times in a pristine environment and at other times has significant aerosol loading. There are already some instruments there, but some key instruments, including a microwave radiometer, are missing.

### *Outcome*

- Standardized retrieval products are needed with clear definitions (e.g., for frequency of occurrence, cloud top height); additionally, the assumptions for microphysical retrievals need to be specified in detail.
- Retrieval accuracies need to be specified as a function of cloud and precipitation type
- Observations and LES model output integrations need better and continuous communication between providers and users concerning the error sources and their magnitude.
- Observations from the tropical east Pacific and southern extra-tropical (Macquarie Island) areas are most required from a GCM perspective.

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## **Question 6:** *What is the response of the probability density function distribution (PDF) of precipitation to warming?*

### *Interpretation*

A general presumption is that a warmer climate will feature a generalized increase in relative humidity in some regions and decrease in other regions. Depending on the region and timing as well as aerosol characteristics, it is anticipated that there will be changes in the probability density function of precipitation in terms of both intensities and frequency. As warming extremes are expected to be more frequently observed in polar and mid-continental regions, it is generally expected that the large-scale patterns of precipitation will also change. Varying precipitation patterns can result from dynamical responses to changes in the global temperature distribution, redistribution of latent heat in the atmosphere, or from modified microphysical and thermodynamic phase properties of clouds.

The intent of this question assumes that a warming regime will occur. The evaluation of the question did not include the long-term monitoring of warming. Focus should be placed on improved process understanding and modeling of precipitation, especially on heavy precipitation (flash flood and heavy snow). Drought potential (precipitation suppression) received limited consideration in the discussions.

### Discussion

Global models generally under-predict the occurrence of extreme precipitation events. Understanding changes in precipitation PDF requires improved observations and model representation of precipitation processes. Observational biases that are associated with a dearth of precipitation gauges and difficulties at characterizing solid-phase precipitation need to be recognized and addressed. Future changes in precipitation patterns can result from changes in dynamic responses to large-scale circulation or a shift in microphysical properties. The net resulting precipitation is influenced by rain rate and redistribution of latent heat in the atmosphere.

### Observables

Important measurements with potentially changing patterns include precipitation efficiency, rain rates, and impacts of aerosol scavenging efficiency. Water isotope ratio measurements have the potential to identify the origin of the water vapor that ultimately forms precipitation and are a factor to consider during the evaluation of changes to precipitation. Observing changes in the precipitation PDF requires more comprehensive measurement of precipitation amounts and processes (i.e., scanning precipitation radars that are carefully calibrated with rain gauges and disdrometers). These measurements need to represent a significant spatial region in order to best characterize the spatial-temporal distribution of precipitation events, and extreme events in particular. They must also be over long continuous time periods in order to statistically identify changes to the PDF.

Better parameterizations are needed for droplet evaporation and droplet autoconversion (aggregation of drops into larger hydrometeors that fall as rain). Both of these processes determine the efficiency and susceptibility of precipitation, both of which can also be influenced by the aerosol properties. New extremes in aerosol properties might impact on precipitation patterns that could vary spatially, temporally, diurnally, and seasonally.

The group emphasized the critical importance of having observations from balloon sounding networks to obtain large-scale forcing data for models.

### Analysis

Analytical frameworks considered variations in model microphysics based on detailed measurements during the ARM MC3E campaign (guest radars and lidars). Radar observations were also intensified by the implementation of new ARM radars and disdrometers and the repositioning of existing ARM profilers.

### Outcome

- There is need for a higher temporal and spatial resolution of observations to better capture extreme precipitation events. This can be accomplished through synergistic use of scanning cloud radars and scanning profilers to obtain simultaneous water vapor profiles, and vertical velocity measurements. This may require the addition of more radars and profilers as well as the development of enhanced operational techniques to derive vertical velocities. Efforts need to be made to acquire high-resolution precipitation data from "operational radars" (weather forecast, airport operations, etc.).

- Cloud systems need to be examined to find cases of longer periods of precipitation suppression or persistence. Attributes that explain variations in precipitation need to be examined when the LWP is constant. This analytical framework and others may need partitioning into precipitation efficiency regimes so that secondary process changes can be observed.
- Forecast models provide reasonable representations of precipitation. There is a need to identify pathways to link forecast models to GCM models. This may include the development of CRM that are large enough to represent a cloud life cycle during conditions where large-scale organization occurs.

## Day 3 Breakout Sessions

The goal of Day 3 was to identify and discuss the appropriate strategies for coordination among the ARM and European programs. Opportunities for collaboration between EU and DOE centers and scientists were explored. The discussions were based on the science questions and associated strategies that were raised during the first two days of the workshop. These discussions centered on four topics:

- Retrieval algorithms and uncertainty
  - Calibration
  - Joint data products and shared algorithms
  - Unified uncertainty analysis
- Field experiments/cruises
  - Collaboration in upcoming experiments (e.g., HOPE, GOAMAZON)
  - Planning of joint experiments
- Merging data and models
  - Role of LES
  - From aerosol precursors to aerosol characteristics
  - Validation of GCM and NWP parameterizations schemes
- Standardization and organization
  - Coordination of access to archives
  - Joint baseline requirements for atmospheric observatories

In addition, graduate education and academic exchange were discussed as means to foster collaboration. First steps could be taken within the EU project Initial Training Network for Atmospheric Remote Sensing (ITARS; www.itars.net).

## Collaboration Topic 1: Retrieval Algorithms and Uncertainty

*Dave Turner (Lead), Maria Caddedu, Domenico Cimini, Ewan O'Connor, Ulrich Löhnert, Gerald Mace, Giovanni Martucci, Ulla Wandinger, and Shaocheng Xie*

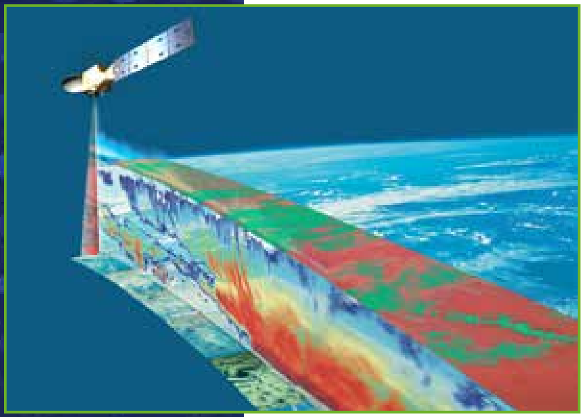
ARM and EU observing stations operate very similar instrumentation suites and have similar scientific goals. There is a strong interest in merging these data, thereby providing a greater integrated data set for the combined scientific community. As a precursor to merging data, it will be important for the DOE and EU observation communities to develop common methods for calibrating instruments and characterizing uncertainties.

### Calibration

The first requirement is to develop a common framework for calibration. One objective is to define metrics for instrument calibration that include quantifying the covariance of the instrument calibration (e.g., the covariance between the microwave channels) but also monitoring calibration against standards such as radiative transfer operators. In this sense, the necessary quantification of bias errors is also possible. Fully characterizing instrument error is a demanding but essential task. It requires dedicated field campaigns as well as laboratory measurements. Of foremost importance in the realm of calibration is the calibration of the growing array of millimeter-wavelength cloud radars. These instruments are the cornerstone of cloud measurements, but their utility is greatly diminished if accurate, consistent calibrations are not maintained. Finally, calibration techniques should be peer-reviewed. In this way, the community can be clear about the details of the quality of data.

### Retrieval

It is also important to develop a common approach for evaluating uncertainties in retrievals. Several strategies were discussed during the breakout session including use of synthetic data, sharing and expanding a priori data, and sharing remote sensing data.



A very useful technique for evaluating uncertainties in retrievals is to use a set of synthetic data as input. While the data are not meaningful in a real atmosphere sense, they provide a very controlled test of a retrieval that can lead to a greater understanding of particular sources of uncertainties within the retrieval algorithm. Dave Donovan has already developed an extensive set of synthetic data applicable to many instruments for the Earth Clouds, Aerosols and Radiation Explorer (EarthCARE) mission, including ground-based instruments. They have proven to be very useful in earlier cloud-retrieval comparison studies.

Typically, retrievals are based on some a priori information, such as direct measurements of the retrieved quantity, in order to provide constraints in the often ill-defined retrieval problem. In the case of cloud properties, these direct measurements are nearly always obtained from cloud model output or in situ aircraft probes in campaigns such as the ARM

Small Particles in Cirrus (SPARTICUS) field campaign. Because of the large expense of obtaining such detailed model output and measurements, it would be a great service to the community to share such data and to work across international boundaries to make the most of airborne field campaigns.

Finally, sharing real data sets for retrievals would advance understanding across the community by providing access to more data for particular conditions and across a broader range of conditions.

Radiative closure checks using surface and top-of-atmosphere (TOA) fluxes are often used to assess the quality of cloud retrievals. This approach can be applied to long time series over ARM and Cloudnet sites to produce a statistical estimate of retrieval accuracy (from a radiative point-of-view) in different meteorological situations, but the approach itself does not allow for a vertically resolved check of the cloud-retrieval accuracy. The DOE ARM Facility and ASR program have developed the Broadband Heating Rate Profile (BBHRP) testbed for testing various cloud retrievals against surface and TOA radiative flux observations. The Radiatively Important Parameters Best Estimate (RIPBE) value-added product (VAP) and the ARM Cloud Retrieval Ensemble Data Set (ACRED) have been also recently created in ARM to facilitate the use of BBHRP in evaluating and inter-comparing cloud-retrieval products.

An illustration of the problem faced in characterizing uncertainties in retrievals is through the QUICR project. QUICR, under the leadership of Shaocheng Xie, is a multifaceted project designed to assess cloud-retrieval uncertainties. In one QUICR activity, ACRED brings together multiple cloud retrievals into a common framework. ACRED comparisons show retrievals disagreeing outside the expected uncertainties. Possible contributors to this situation could be poorly characterized inputs or application of retrievals to periods when retrieval assumptions are not valid (e.g., a retrieval may require non-precipitating conditions). This experience illustrates the need to carefully characterize all aspects of a retrieval including the inputs. Similar problems have been addressed within the European Cooperation in Science and Technology (COST) action EG-CLIMET (expiration date November 2012), where a group of scientists under the lead of Ulrich Löhnert is dedicated to comparing four different liquid water cloud retrievals by means of a synthetic measurement environment. The performance of the different methods under different cloud conditions is analyzed in detail, and recommendations for an optimal method retrieval method will be acquired.

### *Outcome*

Considering the calibration and retrieval uncertainty landscape, there are many areas in which collaboration would be fruitful. A simple way to begin this work to ensure progress would be to work together on the retrieval of several relatively simple parameters, such as LWP and effective radius or aerosol extinction and aerosol number concentration. With such a pair of retrievals, one could work through the various methodologies described here on a specific case and, by working with two related parameters, could also examine the interaction of uncertainties in a simple system.

The workshop proposed to set the stage for the following three points through a dedicated workshop session on U.S./EU collaboration concerning atmospheric parameter retrieval in spring 2013 in Germany:

- Organize a short-term exchange for the operators of the HD(CP)$^2$ and other European atmospheric observatories and experts from the ARM cloud radar group to initiate common, traceable methods for cloud radar calibration.

- Enhance the collaboration between the operations of ARM microwave radiometers and MWRnet for a common procedure on the data flow of operational microwave radiometer measurements through participation of European experts in ASR science team meetings.
- Organize an U.S./EU workshop on the retrieval of the cloudy, thermodynamic atmospheric state through ground-based remote sensing by bringing together the retrieval experts of ARM (QUICR), Cloudnet, EG-CLIMET, and the HD(CP)$^2$ initiative.

The three prior points should strongly engage early-stage U.S. & EU researchers working within the topic of ground-based atmospheric remote sensing (i.e., in the European Marie-Curie ITARS. Finding and applying for common funding possibilities for the exchange of early stage researchers should be of high priority. Quick progress in instrument and retrieval performance as well as international collaboration is expected in this case.

## Collaboration Topic 2: Field Experiments and Cruises

*Matthew Shupe (Lead), Greg McFarquhar, Courtney Schumacher, Bjorn Stevens, Jian Wang, Sebastian Biraud, Clemens Simmer, and Andreas Macke*

In addition to upcoming experiments, new geographic regions with climate regimes not covered so far were discussed for future collaboration.

**Planned Experiments with Possibilities for Coordination**

- HOPE (April–May 2013; PI: Andreas Macke). This program is designed to address boundary-layer clouds and atmospheric structures. It makes use of the existing, long-term supersite Jülich Observatory for Cloud Evolution (JOYCE) in Western Germany and will attempt to comprehensively observe a cube (10-kilometer x 10-kilometer to top of troposphere) with 100-meter spatial resolution. Input data of surface properties for LES, multiple scanning remote sensors, aircraft (helicopter), and dense surface network make it well suited as testbed for LES models. This is a very heterogeneous site with embedded pollution sources (power plants). While the observational aspects of HOPE are already established since the field component is near at hand, there are opportunities for U.S. coordination and contributions in the area of LES modeling.
- GOAMAZON–Observations and Modeling of the Green Ocean Amazon (2014–2015; PI: Scot Martin). This project is designed to investigate aerosol/cloud/biogenic-land aerosol interactions in Brazil. The ARM Mobile Facility (AMF) will be located downwind of the

city of Manaus, Brazil. Other PIs are bringing instrumentation to add to the AMF suite. Some of these include: ARM Aerial Facility (G-1) aircraft in 2014 and European aircraft (UK, Germany). The German High Altitude and Long Range Research (HALO) aircraft will also be used to conduct the contemporaneous Aerosol, Cloud, Precipitation, and Radiation Interactions and Dynamics of Convective Cloud Systems (ACRIDICON) campaign. While Germany has some contributions to GOAMAZON, these could be better coordinated. In addition, there is the possibility to draw in additional European participants. The French were especially mentioned. There is the need to be sensitive to existing agreements with Brazil. A workshop was proposed wherein GOAMAZON could reach out to additional European participants.

**U.S./European Themes for Bridging the Atlantic Ocean**

The influence of aerosols on cloud processes can be studied by looking at different air masses (pristine, Sahara mineral dust, biomass burning).

- Over several years, annual transects with the German research vessel *Polarstern* have been carried out from Germany to the southern tip of South America and South Africa using AMF2-type instrumentation (PI Andreas Macke) to study cloud/aerosol interactions.
- The German research vessel *Meteor* also travels transects between the Cape Verde Atmospheric Observatory (CVAO), Leibniz Institute for Tropospheric Research (TROPOS), and Barbados (Max Planck Institute for Meteorology Hamburg) sites.
- There were discussions of enhancing the observational capabilities on Cape Verde, perhaps with an AMF, in order to better capture and characterize an east-west transect across the tropical Atlantic Ocean region.

**Arctic Sea Ice Study**

Understanding the changing Arctic sea ice within the context of atmospheric and oceanic systems is of high importance. An international experiment with focus on atmospheric and oceanic boundary-layer processes that interact with the sea ice is currently in an initial planning stage (MOSAiC, the Multidisciplinary Drifting Observatory for the Study of Arctic Climate). The initial conception is that a central facility will be deployed in and near an icebreaker ship that will be embedded within the Arctic sea ice and left to drift for at least one year. A network of buoys and other distributed measurements will provide spatial context and variability for the intensive central observatory. The deployment of the AMF2 on the icebreaker ship (potentially German or Canadian) for this Arctic experiment should be explored. U.S.-EU coordination is critical for leading this international effort. In particular, from the EU side, the German National Science Foundation could be involved.

**Southern Oceans**

There were broad discussions about the need for cloud observations in the Southern Ocean. Specific discussions targeted the possible deployment of AMF2 to a variety of potential locations in Southern Oceans to study marine clouds in pristine areas where information is strongly missing (See "Science Questions Derived from Day 1 Breakout Sessions"). Possibilities included islands like the Falkland, Tasmania, or others. It was agreed that this is a priority direction, but that there is still much to be done in terms of planning and coordination of ideas.

### *Outcome*

- Use HOPE campaign in April–May 2013 as testbed for models.
- Set up a workshop in spring 2013 for GOAMAZON collaboration for 2015 participation, perhaps in Europe, to explore European (German/French/UK) collaborations.
- Set up a workshop on collaboration for Atlantic observations and involvement of the AMF2, possibly in conjunction with the ASR Science Team Meeting in spring 2013 or European Workshop.
- Set up a workshop for better defining an international Arctic sea-ice study.
- Set up a workshop for possible Southern Ocean deployment.

## *Collaboration Topic 3: Improving the Link Between Models and Observations*

*Pier Siebesma (lead), Anthony Illingworth, Tony Del Genio, Jim Hack, Steve Ghan, Minghua Zhang, Graham Feingold, Sonia Kreidenweis, and Catherine Rio*

Most of the discussion focused on how LES models could be implemented or operated in new locations where data are available for merging with model results. LES models were selected because they provide details comparable to many observations and recent graphical processing unit (GPU) implementation of LES models allow for larger collections of simulations (seasonal or annual).

**Operational Use of Large-Eddy Simulations**

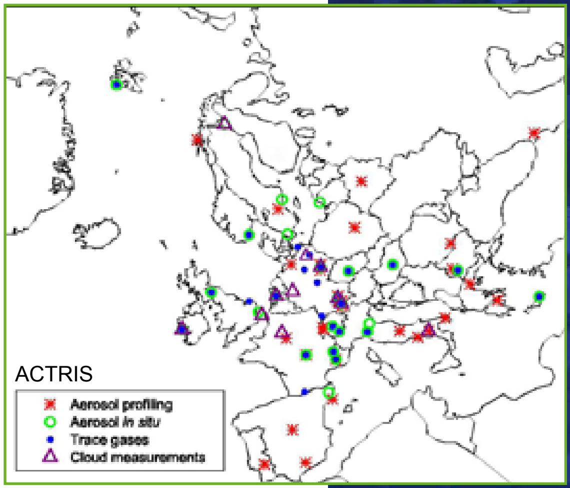
If the mean state (i.e., profiles) and large-scale forcings are available at supersites and during field experiments, these can be used to drive high-resolution LES on a daily routine basis on a domain centered around an observational site. The LES output can then be used as powerful additional "virtual observations" of processes that cannot or only partly observed. Some examples include:

- 3D cloud morphology (overlap)
- joint PDFs of temperature, humidity, vertical velocity, variances, and turbulent fluxes
- effect of heterogeneous terrain
- indirect aerosol effects.

This strategy has been successfully implemented at the Cabauw site in the Netherlands. The first obvious next candidate would be the ARM SGP site, since realistic estimates of the mean state and the large-scale forcings are available at this site on a continuous basis. It also would be an ideal site to study heterogeneous terrain influences with land flux data products (derivative of surface maps) and point measurement of flux (heat, water, and carbon) available. The RACORO campaign with intense observations for 6–8 months, aircraft data for many days, SCM model results, and constrained forcings data set includes a variety of seasonal and transition states and might be a good period to start with. The objective of this study is the evaluation of the timing and height of the simulated cloud fractions.

**Common Observational Data Set to be Used for Modeling Evaluation**

Both in Europe (EUCLIPSE) and the U.S. ([Fast-Physics System Testbed and Research] [FASTER]), there are ad-hoc activities to produce comprehensive data sets of clouds, radiation, and atmospheric profiles such as those observed at the various supersites that can be easily used for direct evaluation of (CMIP5) climate model runs and NWP forecasts with different parameterization schemes. However, there is a strong need to have these activities coordinated in a better way so that European and American data sets have a common retrieval method, data format, naming, etc. Cloudnet data products are available at several sites but not all and not for all periods, but this should soon be rectified under the ACTRIS project. Potential data products should include joint PDFs for a limited range of conditions and microphysical properties for comparison between simulations. The LES output can also be used to characterize shadow clouds, low-cloud feedback, cloud timing, and life span.




Instrument simulators should be developed and used to exploit the full potential of the ground-based remote sensing measurements (lidar, cloud radar, radiometer). This is especially important for those variables for which the outcome depends strongly on the retrieval method. If these simulators are used in climate and weather models, this will greatly facilitate a proper comparison between models and observations. Several NWP centers are already developing lidar and radar simulators. This route has been proven especially successful for satellite-based remote sensing products. Further development of integrating profiling techniques through combining different measurements in a physically consistent way (e.g., integrated profiling techniques [IPT], Löhnert et al. 2009) should lead to best estimates of atmospheric profiles and their uncertainty.

The role of aerosols in models was briefly discussed. CCN is mostly included as a "state value." The response to CCN could be evaluated by "extreme CCN" values and looking at the simulation differences. A significant need exists for improved aerosol input data for global models. Currently only global aerosol optical depth (AOD) derived from satellites is available. A breakdown into first-level "species" would be helpful (e.g., dust, black carbon, biogenic, secondary organics). Scavenging CCN factors and other aerosol processes should be added to LES as resources allow.

### Outcome

- Establish the operational use of LES at supersites and during field experiments. Experiences from the Cabauw site can serve as a prototype, and the procedures should be transferred to the SGP site (RACORO campaign) and later to others.
- Improve forcings by constraining with scanning radars and lidars.
- Establish a common observational data set to be used for (CMIP5) modeling evaluation.
- Use and development of simulators and IPT in models of ground-based remote sensing measurements. (See also "Collaboration Topic 1: Retrieval Algorithms and Uncertainty.")

## Collaboration Topic 4: Standardization and Organization

*Gelsomina Pappalardo (Lead), Herman Russchenberg, Tom Ackerman, Felix Ament, Nico Cimini, Martial Haeffelin, and Susanne Crewell*

The goal is to provide an understanding and approach for the sharing of data products and associated information between the atmospheric science and climate research activities of the U.S. and Europe. A baseline name for the overall effort will be proposed and the collaboration between activities is reviewed.

**Archive and Data Products**

To address the science questions there is a strong need to provide a coordinated free and open data infrastructure for access to data archives and repositories shared between the EU and U.S. collaborators. For the EU, no single archive or data-clearing house currently exists. At the moment the ACTRIS data center provides access to the largest atmospheric data set in the EU, including in situ aerosol and gas-phase measurements, remote column aerosol observations, vertical aerosol profile information, and cloud observations. ACTRIS is also already linked to the World Data Center for Aerosols. Work is necessary to better link ACTRIS to other data centers from other EU and national projects.

In the U.S. and the EU, several other data repositories from different organizations (National Oceanic and Atmospheric Administration and other weather service surface reference sites, AeroNet, World Data Centers, etc.) provide important complementary information. In general all facilities providing profiles of atmospheric water compounds should be included. An objective is to create an integrated central portal (flexible and extensible) to relate all relevant data sets necessary to facilitate collaborative science and research. To that end, the rules and policy for data sharing and registration need to be established. The record of users is important so proper registration using a single sign-on (SSO) service is a requirement. Product tracking and user metrics are also required. For standards, NetCDF and HDF file standards, WMO and ISO methodologies, and the Climate and Forecast (CF) metadata convention will be adopted. Data product version control and reprocessing need to be incorporated in the processing architecture.

### *Baseline Requirements*

Baseline requirements for atmospheric observatories were discussed and identified to include lidar, cloud radar, microwave radiometer, and surface radiation observations, thus providing information on the atmospheric profile. Because science questions address the atmospheric water cycle from the evaporation at the surface via cloud formation and precipitation generation, the water cycle should be reflected in a "brand name" for such profiling stations. "Profiling Atmospheric Water Cycle Sites" (PAWs) is proposed as the descriptor for this overall collaboration.

### *Collaboration*

The collaboration between EU and U.S. networks and activities are ongoing and performing well. Other programmatic areas will continue to be discussed as the structure and communication pathways are defined.

### *Outcome*

- Develop the architecture, standards, and framework for an integrated portal and document the metadata, products, and related information. Focus on products toward scientific utility. Identify tasks and form working groups as necessary to define scope. ACTRIS and ARM data portal coupling is a logical place to start.
- Identify a common product that can be used to test the process—geophysical parameters, data harmonization, algorithms, uncertainty, value-added, and synthesis products—for specific cases. Suggestions are: aerosol extinction profiling, water vapor (integrated and profiling), LWP, and LWC.
- Identify specific data sets focused towards GCM and LES initialization (scale and temporal), evaluation, and parametrization improvement, and harmonize products.
  - GCM
  - LES
  - ARM, ACTRIS, Norsk Institutt for Luftforskning (NILU)/EU: Work together on data sharing across product holdings.

# Acronyms

| | |
|---|---|
| ACRED | ARM Cloud Retrieval Ensemble Data |
| ACTRIS | Aerosols, Clouds, and Trace Gases Research Infrastructure Network |
| AMF | ARM Mobile Facility |
| AMIP | Atmospheric Model Intercomparison Project |
| AOD | aerosol optical depth |
| ARM | Atmospheric Radiation Measurement (Climate Research Facility) |
| ASR | Atmospheric System Research |
| BBHRP | Broadband Heating Rate Profile |
| CAPT | Cloud-Associated Parameterizations Testbed |
| CCN | cloud condensation nuclei |
| CF | Climate and Forecast |
| CRM | cloud-resolving models |
| DOE | Department of Energy |
| EU | European Union |
| EUCLIPSE | European Union Cloud Intercomparison, Process Study & Evaluation Project |
| FAT | Fixed Anvil Temperature |
| GCM | general circulation models |
| GPU | graphical processing unit |
| HALO | High Altitude and Long Range Research |
| HDF | hierarchical data format |
| IN | ice nuclei |
| IPT | integrated profiling techniques |
| ITARS | Initial Training Network for Atmospheric Remote Sensing |
| JOYCE | Jülich Observatory for Cloud Evolution |
| LES | large-eddy simulations |
| LWC | liquid water content |

| | |
|---|---|
| LWP | liquid water path |
| MPLNET | Micropulse Lidar Network |
| NILU | Norsk Institutt for Luftforskning |
| NWP | numerical weather prediction |
| PAW | Profiling Atmospheric Water Cycle Sites |
| PDF | probability density function |
| PI | principal investigator |
| PSD | particle size distribution |
| QUICR | Quantification of Uncertainties in Cloud Retrievals |
| RACORO | Routine AAF Clouds with Low Optical Water Depths (CLOWD) Optical Radiative Observations |
| RIPBE | Radiatively Important Parameters Best Estimate |
| SGP | Southern Great Plains |
| SHEBA | Surface Heat Budget of the Arctic Ocean |
| SSO | single sign-on |
| TOA | top-of-atmosphere |
| UAV | unmanned aerial vehicle |
| VAP | value-added product |

# Appendix 1: Meeting Agenda

## *U.S./European Workshop*
## *Washington D.C. Renaissance, 999 9th St. NW*
## *November 6–8, 2012*

**Tuesday, November 6**

| | |
|---|---|
| 8:30 a.m. | Welcome (Sharlene Weatherwax, Associate Director of Science for Biological and Environmental Research [BER]) |
| 8:50 a.m. | Workshop Objectives, Agenda, and Output (Wanda Ferrell, BER, and Susanne Crewell, University of Cologne) |
| 9:10 a.m. | Introduction to the Current Major EU Programs<br>• EUCLIPSE (Pier Siebesma, Royal Netherlands Meteorological Institute)<br>• HDCP$^2$ (Bjorn Stevens, Max-Planck-Institut für Meteorologie)<br>• ACTRIS (Gelsomina Pappalardo, Italian National Research Council - Institute of Methodologies for Environmental Research) |
| 10:00 a.m. | Break |
| 10:30 a.m. | Introduction to Major U.S. DOE Programs (Gerald Geernaert, Division Director, Climate and Environmental Sciences, BER) |
| 11:00 a.m. | Guidance to Breakout Groups (Ashley Williamson, BER) |
| 11:30 am | **Breakout Session #1**: Open discussion to identify important aerosol-cloud-precipitation questions |
| 12:30 p.m. | Working Lunch provided |
| 1:30 p.m. | Breakouts reconvene |
| 3:30 p.m. | Break |
| 4:00 p.m. | Plenary—Report out from Tuesday breakouts by group Discussion Leads (Chair: Pier Siebesma) |
| 5:00 p.m. | Convene Moderators and Rapporteurs to summarize workshop discussions |

**Wednesday, November 7**

| | |
|---|---|
| 8:30 a.m. | Consolidated summary of Day 1 breakouts and instructions for Day 2 (Chair: Wanda Ferrell) |
| 9:00 a.m. | **Breakout session #2**: Open group discussion to identify and discuss observation strategy and address gaps in the understanding. What are the geophysical variables we need, with what accuracy and what resolution |

(vertical, spatial, temporal)? What types of correlated data sets (synergy) are needed to address the scientific questions? To answer these questions, what is the best mix of lab, campaign mode, and long-term data sets? Where do we need to have these data?

| | |
|---|---|
| 10:30 a.m. | Break |
| 11:00 a.m. | Breakouts continue |
| 12:00 p.m. | Working Lunch provided |
| 1:00 p.m. | Guidance for Breakout Session # 3 (Ashley Williamson) |
| 1:15 p.m. | **Breakout session #3**: How do we derive/measure the above geophysical variables? What observational strategies are needed to address each of the identified scientific questions? What locations? What are possible joint experiments? |
| 3:30 p.m. | Break |
| 4:00 p.m. | Plenary—Report out from Wednesday breakouts by group Discussion Leads (Chair: Susanne Crewell) |
| 5:00 p.m. | Convene moderators and rapporteurs to summarize workshop discussions |

**Thursday, November 8**

| | |
|---|---|
| 8:30 a.m. | Consolidated summary of Day 1 and Day 2 breakouts and instructions for Day 3 (Chair: Susanne Crewell) |
| Plenary discussion | What are the appropriate strategies for coordination among the ARM and European programs (Chairs: Susanne Crewell, Wanda Ferrell, and Ashley Williamson)<br><br>Topics include:<br>• Coordinated access to archives<br>• Joint data products and shared algorithms<br>• Unified uncertainty analysis (or strategies for this)<br>• Joint experiments |
| Noon | Summary of workshop (Chairs: Susanne Crewell, Wanda Ferrell, and Ashley Williamson) |
| 1:00 p.m. | Adjourn |
| 2:00 – 5:00 p.m. | Moderators and rapporteurs remain and draft summary |

# Appendix 2: Breakout Sessions

The goal of the Breakout Sessions is to brainstorm and catalog science drivers and technical approaches to address aerosol-cloud-precipitation processes. Leveraging opportunities will focus on the critical scientific uncertainties that should be addressed by the European and U.S. climate observational and modeling programs. Opportunities for other program and agencies may also be considered (e.g., remote sensing, specialized instrumentation, additional measurements). Breakout discussions need to balance "blue-sky" discussions with pragmatic consideration of European and U.S. research foci and practical limitations.

Moderators will lead the discussion. Discussion leaders, in conjunction with the rapporteurs, will summarize each day's breakout sessions. Discussion leaders will present summaries in plenary.

**Breakout Assignments:**

**Day 1:** Four groups of nine people, with the moderator listed in bold

Group #1: **Bjorn Stevens**, Jian Wang, Matt Shupe, Herman Russchenberg, Thomas Ackerman, Catherine Rio, Sebastian Biraud, Domenico Cimini, Greg McFarquhar

Group #2: **Allison McComiskey**, Ulla Wandinger, Jay Mace, Ewan O'Connor, Tony Del Genio, Pier Siebesma, Sonia Kreidenweiss, Andreas Macke, Susanne Crewell

Group #3: **Anthony Illingworth**, ,Steve Ghan, Martucci, Giovanni Martucci, Courtney Schumacher, Ulrich Löhnert, James Hack, Clemens Simmer, Maria Cadeddu, Shaocheng Xie,

Group #4: **Minghua Zhang**, Graham Feingold, Gelsomina Pappalardo, Dave Turner, Martial Haeffelin, Felix Ament, Christine Chiu, Marjolaine Chiriaco, Sandra Yuter

**Day 2:** Four new groups of nine people, with the moderator listed in bold

Group #5: **Matt Shupe**, Clemens Simmer, Gelsomina Pappalardo, Maria Cadeddu, Anthony Illingworth, Allison McComiskey, Pier Siebesma, Marjolaine Chiriaco, Andreas Macke

Group #6: **Ulrich Löhnert**, Greg McFarquhar, , Thomas Ackerman, Ulla Wandinger, Sandra Yuter, Graham Feingold, Felix Ament, Tony DelGenio, Sebastian Biraud

Group #7: **Herman Russchenberg**, Giovanni Martucci, Jay Mace, Courtney Schumacher, Susanne Crewell, Jian Wang, James Hack, Catherine Rio, Shaocheng Xie

Group #8: **Dave Turner**, Sonia Kreidenweiss, Martial Haeffelin, Domenico Cimini, Ewan O'Connor, Steve Ghan, Minghua Zhang, Bjorn Stevens, Christine Chiu

# Appendix 3: Attendees

| **Name** | **Organization** |
|---|---|
| Tom Ackerman | University of Washington |
| Felix Ament | Universität Hamburg |
| Sebastien Biraud | Lawrence Berkeley National Laboratory |
| Maria Cadeddu | Argonne National Laboratory |
| Marjolaine Chiriaco | Université Pierre et Marie CURIE |
| Christine Chiu | University of Reading |
| DomeNico Cimini | Institute of Methodologies for Environmental Research - Italian National Research Council |
| Susanne Crewell | University of Cologne |
| Tony Del Genio | NASA Goddard Institute for Space Studies |
| Graham Feingold | National Oceanic and Atmospheric Administration |
| Steve Ghan | Pacific Northwest National Laboratory |
| Jim Hack | Oak Ridge National Laboratory |
| Martial Haefflin | École Polytechnique |
| Anthony Illingworth | University of Reading |
| Sonia Kreidenweis | Colorado State University |
| Ulrich Löhnert | University of Cologne |
| Jay Mace | University of Utah |
| Andreas Macke | Leibniz Institute for Tropospheric Research |
| Gianni Martucci | National University of Ireland, Galway |
| Allison McComiskey | University of Colorado |
| Greg McFarquhar | University of Illinois |
| Ewan O'Connor | Finnish Meteorological Institute |
| Gelsomina Pappalardo | Institute of Methodologies for Environmental Research - Italian National Research Council |
| Catherine Rio | Université Pierre et Marie CURIE |
| Herman Russchenberg | Delft University of Technology |
| Courtney Schumacher | Texas A & M University |
| Matthew Shupe | University of Colorado |
| Pier Siebesma | Royal Netherlands Meteorological Institute |
| Clemens Simmer | University Bonn |
| Björn Stevens | Max-Planck-Institut für Meteorologie |
| Dave Turner | National Severe Storms Laboratory |
| Ulla Wandinger | Leibniz Institute for Tropospheric Research |
| Jian Wang | Brookhaven National Laboratory |
| Shaocheng Xie | Lawrence Livermore National Laboratory |
| Minghua Zhang | Stony Brook University |

## *Rapporteurs*

| **Name** | **Organization** |
|---|---|
| James Mather | Pacific Northwest National Laboratory |
| Raymond McCord | Oak Ridge National Laboratory |
| Doug Sisterson | Argonne National Laboratory |
| Jimmy Voyles | Pacific Northwest National Laboratory |