Confronting Future Models with Future Satellite Observations of Clouds and Aerosols

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Aerosol, Clouds, Convection and Precipitation (ACCP) Modeling and Assimilation Virtual Workshop

WHAT: More than 150 attendees met to discuss the future of modeling aerosols, clouds and precipitation, and how it can be informed by measurements from a future observing system
WHERE: WebEx (Virtual)
WHEN: 10 & 12th November 2020

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1. Introduction

The NASA Aerosol, Clouds, Convection and Precipitation (ACCP) Study (https://vac.gsfc.nasa.gov/accp/) convened a workshop in November 2020 to understand the future of modeling aerosols, clouds, convection and precipitation, and how satellite data can contribute to that future. ACCP is a project to define a satellite mission to be launched late in the 2020's to advance cloud and aerosol science, following the recommendations of the latest NASA Decadal Survey(https://doi.org/10.17226/24938).

The ACCP modeling workshop goal was to answer the following questions:

1. What will be the critical science questions for clouds and aerosols in 10 years?
2. Where will simulations of clouds and aerosols across scales of space (process models to global) and time (nowcasting to climate prediction) be in 10 years?
3. What data will be available from space? What data would provide the most benefit?
4. What are the state of the art methods for confronting models with cloud and aerosol observations, including assimilation and climatological analysis techniques?

The virtual workshop was anchored by a series of pre-recorded talks. (Talks are available for viewing at https://www.cgd.ucar.edu/events/2020/ACCP/.) Two days of synchronous sessions focused on discussion of the talks, along with small group breakout exercises. After an introduction to the ACCP concept came a panel discussing the future of modeling clouds and aerosols across scales. Participants were then asked to contribute their ideas. On the second day, there were two panel discussions. First came a discussion of the future of satellite observing systems. Second was a discussion of model-data synthesis methods. Finally, participants were asked to develop their own model-data synthesis proposal.

The meeting began with an overview of the ACCP mission concept by Graeme Stephens (NASA-JPL). ACCP is a satellite mission for clouds and aerosols, likely anchored by advanced active lidar and radar systems in space, designed to observe detailed aerosol profile and type information, as well as cloud microphysics and dynamics. ACCP will integrate across sensors and observational types to get multi-spectral views of the same scenes, with better resolution than is available today. Launch is scheduled for 2027 or 2029. ACCP is being thought of as a comprehensive mission that may comprise more than one platform and more than one orbit plane (i.e., inclined and polar), with multiple combinations of sensors.

2. Future Models

The rest of the first day of the meeting focused on the future of weather, climate, and air quality models (with a time horizon of 10 years) and the observations needed to inform and constrain them. The discussion of these topics was seeded by a series of pre-recorded lectures that participants were requested to review prior to the meeting. Curtis Alexander (NOAA) discussed weather/assimilation models from a NWP perspective; Steve Klein (LLNL) and Andrew Gettelman (NCAR) addressed future directions of climate and weather models; Vincent-Henri Peuch (ECMWF) outlined expected advances in air quality and atmospheric composition modeling; and Adam Varble (PNNL) presented views on the next generation of convection and process models. The attendees were asked to discuss what future observations have the best potential to inform and/or constrain models, and to identify science questions related to aerosols, clouds, convection and precipitation.

Common themes emerged from the discussions. Models used in research and weather and climate ‘operational’ prediction will continue to evolve towards higher resolution. Research models will continue to push the limits of computational capabilities, as exemplified by the current experiments with 1 km global ‘cloud permitting’ weather models. Global forecast NWP and air quality models will have extended ranges of 10 days or longer, and will operate at 3-5 km resolution. Climate model resolution will be on the order of 25 km for century long integrations. Regional models for short range weather prediction (or even regional climate and air quality) will move towards resolving clouds at sub-1km horizontal resolution.

Another common theme was that models will continue to grow in complexity. There will be accelerated efforts to advance Earth System Models (ESMs) with more and more components treated together, and targeted to applications. This approach facilitates the inclusion of more processes and feedbacks, and enables the capability to provide seamless predictions across time scales from Nowcast (<6 hours) to Forecast (6 hrs - 10 days) to the Sub-seasonal to Seasonal (S2S: 10-180 days) to Decadal (1-10 years) and Climate (>10 years). ESMs also enable the provision of unified weather, environmental (air quality) and climate predictions, with expected benefits in prediction skill due to better descriptions of processes, and consistency across scales. For example, there will be more consistency of cloud microphysics between weather and climate models. In addition, weather models at all scales will include more interactive aerosol types represented by varying complexity. Models will also include key feedbacks between aerosols, clouds, and radiation to address air quality. Why? There is mounting evidence that adding aerosol to models improves weather prediction skills at forecast and S2S time scales.

Workshop participants also believe that there will be continued development of different modeling approaches. One approach is global frameworks using higher spatial resolutions over targeted regions. Another approach is to run components (e.g. air quality and land surface) on separate grids from atmospheric dynamics with the interactive exchange of key information between the grids. Machine Learning (ML) will become more widely used to parameterize detailed physical processes (discussed further below), and to capture a small subset of outputs of a full dynamical model in terms of a set of inputs (emulation). One can envision emulators becoming more widely used as efficient representations of parts of a model. Areas of increased focus for further model development and applications over the next decade include fires, urban environments, and hydrology. In general, models will evolve with increasing resolution and targeted complexity to increase their fidelity, opening the door to opportunities for new research and applications.

Improvements in prediction skill will also be achieved through advances in process modeling, inclusion of stochastic process treatment, and advances in data assimilation and modes of operations. For example, NWP models are evolving towards more frequent assimilation update cycles, and advances in Large Eddy Simulation (LES) models are trending towards high resolution ensemble predictions. Data assimilation will continue to play a key role in improving prediction skill. Assimilation and observation simulation were identified as key areas of research and development, especially for new parts of the Earth system and new data sources (clouds, land, ocean). There was consensus that lines between the prediction/analysis models and the retrieval models will continue to blur.

Participants identified the importance of critical observations to support these model developments. These observations include cloud vertical motion and vertical profiles of aerosol, cloud, and precipitation properties. Measurements of dynamics (both in terms of temporally evolving systems, and updrafts) are critical for understanding cloud and aerosol processes. These observations can be made by Doppler radar or measurements made at multiple short time intervals. In addition, coincident measurements (same scene at the same time) of cloud microphysics and dynamics, aerosol, and radiation are critical. Better observations of chemical composition, extinction profiles and absorption, and moisture were identified as key to advancing aerosol science.

Key science questions identified for future models included many questions at the ‘interfaces’ of ACCP science. Participants noted that the end goal is improved prediction, and elucidating the key cloud and aerosol processes that affect prediction is important. What observations can improve prediction on different scales? One key observation is the distribution of vertical motions in convection and the organization of convection. Another is how microphysical processes are affected by convective and cloud dynamics. In addition, it is critical to understand how microphysical processes modify the evolution of storms. Other key questions include how aerosols modify convection and cloud microphysical properties, and in turn how convection modifies aerosols. All of these factors may affect the radiative effects of clouds, which in the end affect climate.

3. Future Observing Systems

Day 2 began with a session focused on current and future observing systems and their application to ACCP science. Matt Lebsock (JPL) focused on the future of cloud remote sensing and how such measurements may inform models. Rob Levy (NASA/GSFC) discussed the current state of existing and planned observations of aerosols made by existing and planned observations of aerosols over the next decade. Finally, Arlindo Da Silva (NASA GSFC) and Derek Posselt (JPL) presented insights into data assimilation techniques and the use of assimilation and observation simulation experiments.

There was discussion on the role of Machine Learning (ML) techniques (such as neural networks) in the processing and interpretation of ACCP observations. ML techniques could be very useful for several tasks. One is mining the existing observational record to identify patterns and relationships within the data. This is effective for interpolation, but not extrapolation, and can thus fail with extreme events in a changing climate. Second, existing ML methods have simply provided more complex ways to generate empirical parameterizations from data, but new techniques offer the potential to better understand sensitivity of the results to the input observations, and to better quantify uncertainties. Third, ML may be useful for developing retrieval algorithms for satellite observations, using large and evolving datasets for training, either as a retrieval replacement, or as a way to use data from different regimes to bias-correct retrievals. Finally, there was discussion of using ML for targeted observations: many of our cloud satellites spend a lot of their time observing clear air, and the prospects of developing selectable satellite sampling or retrievals (i.e., only save and download cloudy data) were discussed. ML might be a good approach to guiding the selection of sections or objects on which to focus.

The focus of the discussion then turned to the role of suborbital (aircraft, balloons and ground based) assets in the ACCP satellite mission. Suborbital activities are significantly more important than just for Calibration / Validation of satellite sensors and retrievals. Suborbital measurements allow scientists to answer many of the science questions that simply cannot be answered from space. Suborbital (including ground based) observations extend our capabilities beyond those of space-based observations of aerosol and cloud processes. An example is the measurement of aerosol properties below cloud base. A number of key microphysical properties are needed to enhance the assumptions in and interpretation of remote-sensing optics and algorithms from above clouds. These include aspects such as particle hygroscopicity, mass extinction efficiency, spectral light absorption, and CCN particles smaller than ~0.1 microns. Such aerosol properties and characteristics cannot be measured adequately, if at all, by remote sensing approaches alone.

4. Model-Data Synthesis

Finally, discussion pointed to the need for a more thoughtful coupling of models and observations. Alan Geer (ECMWF) discussed the challenges in the nascent assimilation of clouds, or at least ‘all sky’ properties. Tristan L’Ecuyer (U. Wisconsin) discussed the value of multiple, as opposed to single, observations of geophysical variables from space. Paquita Zuidema (U. Miami) highlighted the insights that can be gained from sub-orbital measurements.

Different modes of ‘data in support of modeling’ were identified: (i) model evaluation; (ii) data assimilation (forecasting); (iii) synthesis of models + data to provide the best assessment of the state of the atmosphere (hindcasting); and (iv) data assimilation as a means of assessing optimal model parameters. Several speakers highlighted the need to evaluate model uncertainties via a number of means, including stochastic representation of processes, optimal physics parameters and their connection to the choice of parameterizations, the use of emulators to assess parametric uncertainties, identification of structural uncertainties, and the challenge of “equifinality” (i.e., there are many combinations of inputs that can yield a given output). Interestingly, assimilation of clouds is still very much in its infancy and needs much further development, for which ACCP measurements will be valuable.

Coincident observations of geophysical variables shed light on processes and can be used to compare to models in new ways. Single variable observations identify model biases but not their provenance. The more co-incident variables are used for evaluation, the greater the possibility of identifying model weaknesses through relationships between quantities. Time evolving data provides even more insights into processes/causality, as can be demonstrated by geostationary satellite-based observations. In the context of ACCP, one can envision temporally evolving, less accurate measurements from geostationary satellites combined with polar orbiting retrievals 2x per day.

The discussion highlighted that ACCP is not just a single satellite program, but the scientific nexus of a suite of observations potentially on multiple platforms. More use needs to be made of integration of existing and planned observations with current models. Tools can be developed to maximize the mutual benefit of geostationary and polar orbiters for model improvement and enhancement.

Several different methods will enable this future. First, better integration of models and data through assimilation of data on the one hand, and the generation of synthetic observations with simulators from models for direct evaluation (e.g., simulated radar reflectivity) on the other hand. Second, better matching of scales of models and observations with the use of scalable and integrated model systems that can refine global models to high resolution over a region of targeted aircraft or ground based observations. Finally, relationships between observables that give insight into key processes (e.g. optical depth and radar reflectivity, or albedo and cloud fraction), viewed as state-space diagrams, can link processes to emergent relationships.

The value of sustained sub-orbital observations was also highlighted. Sub-orbital platforms (either large ground stations or aircraft) contain many coincident measurements, many of which are simply not readily achievable from space in a direct or even indirect way, and provide more process level data to be able to design and test models across scales. Sustained or regular sub-orbital measurements have tremendous potential and value for both satellite validation and uncertainty characterization, as well as model evaluation.

Participants expressed the view that in the future the practice will shift from ‘confronting’ models with observations, as is common today, to more of an integration/fusion of the two, e.g., through Bayesian approaches and data assimilation.

5. Summary

The workshop ended with a few key messages. Models of the future will be higher resolution, often refined resolution over a region of interest, and coupled with applications from air quality and human health to hydrology and runoff. These models will be integrated across scales in space and time (from regional to global, from weather to climate) and also across applications (including NWP and air quality forecasting). They will inevitably include more coupled processes for clouds and aerosols.

Future observations will be refined and expanded. ACCP satellite observations will provide targeted observations with higher quality, higher spatial resolution and more, coincident variables. But there will also be significant additional observations of different variables from a myriad of sensor networks such as geostationary satellites, swarms of small satellites, and suborbital platforms. All these observations will need to be integrated (with models) into observing and modeling systems.

This future requires comprehensive model-data synthesis capabilities. The boundary between observations, retrieval, model and observation simulators will blur. Data will be used across space and time to 'correct' forecasts and 'train' models. These methods will be used to advance both models and observations for better predictability. Models constrained by data (with assimilation if necessary) will be used for operational predictions and generate expanded 'hindcasts'. These hindcasts use the geophysical laws contained in a model and guided by data to take the limited variables and locations available from observations and expand them into a consistent and multivariate representation of the state of the earth system: a 'data cube'. This new paradigm will accelerate the blurring of disciplinary boundaries and create a new generation of interdisciplinary scientists using a fusion of data and models.