

1 **Confronting Future Models with Future Satellite Observations of Clouds**  
2 **and Aerosols**

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

16

17 **WHAT:** More than 150 attendees met to discuss the future of modeling aerosols, clouds and  
18 precipitation, and how it can be informed by measurements from a future observing system

19 **WHERE:** WebEx (Virtual)

20 **WHEN:** 10 & 12<sup>th</sup> November 2020

## 21 **1. Introduction**

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

28

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

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

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

45

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

54

## 55 **2. Future Models**

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

67

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

76

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

91

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

104

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

114

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

124

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

135

### 136 **3. Future Observing Systems**

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

144

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

160

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

173

#### 174 **4. Model-Data Synthesis**

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

181

182 Different modes of ‘data in support of modeling’ were identified: (i) model evaluation;  
183 (ii) data assimilation (forecasting); (iii) synthesis of models + data to provide the best

184 assessment of the state of the atmosphere (hindcasting); and (iv) data assimilation as a means  
185 of assessing optimal model parameters. Several speakers highlighted the need to evaluate  
186 model uncertainties via a number of means, including stochastic representation of processes,  
187 optimal physics parameters and their connection to the choice of parameterizations, the use of  
188 emulators to assess parametric uncertainties, identification of structural uncertainties, and the  
189 challenge of “equifinality” (i.e., there are many combinations of inputs that can yield a given  
190 output). Interestingly, assimilation of clouds is still very much in its infancy and needs much  
191 further development, for which ACCP measurements will be valuable.

192

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

201

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

207

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

217

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

224

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

228

## 229 **5. Summary**

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

237

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

244

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

