ASSIMILATING SATELLITE OBSERVATIONS OF CLOUDS AND PRECIPITATION INTO NWP MODELS

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Satellite observations in the visible, infrared, and microwave spectrum provide a great deal of information on clouds and precipitation as well as the atmosphere in which the clouds are embedded. A major issue is how to use this information to initialize cloudy and precipitating atmospheric regions in NWP models. Most cloud- and/or rain-affected observations are discarded in current data assimilation systems. The major problems are the discontinuous nature, in time and space, of clouds and precipitation, the complex nonlinear and not-well-modeled processes involved in their formation/prediction, and the need for current data assimilation systems to use linearized versions of these nonlinear processes. As a result, cloud/rain-affected radiances are much more difficult to assimilate than clear-sky radiances, which are sensitive to the smoother fields of temperature and water vapor that are controlled by more linear, well-modeled processes. Since clouds and precipitation often occur in sensitive regions in terms of forecast impact, improvements in their assimilation are likely necessary for continuing significant gains in weather forecasting and, in particular, the prediction of two key weather elements affecting human activities: precipitation and cloudiness (which impacts another key weather factor, surface temperature).

In 2005, the National Aeronautics and Space Administration (NASA)–National Oceanic and Atmospheric Administration (NOAA)–Department of Defense (DoD) Joint Center for Satellite Data Assimilation (JCSDA) sponsored an international workshop on assimilating observations in cloudy/precipitating regions. Papers from that workshop were published in a special section of the November 2007 issue of the *Journal of the Atmospheric Sciences*

THE ECMWF–JCSDA WORKSHOP ON ASSIMILATING SATELLITE OBSERVATIONS OF CLOUDS AND PRECIPITATION INTO NWP MODELS

WHAT: Sixty-five experts in numerical weather prediction (NWP) and remote sensing were invited to document progress in cloud and precipitation data assimilation and to recommend pathways for future research and development.
WHEN: 15–17 June 2010
WHERE: Reading, United Kingdom

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(available online at http://journals.ametsoc.org/toc/atsc/64/11). In spring 2010, the European Centre for Medium-Range Weather Forecasts (ECMWF) hosted a joint ECMWF–JCSDA workshop to document the developments since the 2005 workshop and to produce recommendations to ECMWF, JCSDA, and other NWP centers and scientific communities for future research developments and collaboration. About 65 participants attended the workshop, representing most major NWP centers around the world as well as research institutes and universities.

The workshop sessions covered the current status of cloud/precipitation assimilation at NWP centers, special issues related to cloud- and precipitation-affected observations, radiative transfer modeling, cloud and precipitation representation in numerical models, and problems of integrating such data in operational data assimilation systems. Working group summaries and recommendations were discussed in a final plenary session and were integrated into a set of recommendations to ECMWF and JCSDA, and other NWP centers, to advance the assimilation of cloud/precipitation observations. More details on the workshop and all presentations can be accessed online (see www.ecmwf.int/newsevents/meetings/workshops/2010/Satellite_observations/index.html). A number of papers from the Workshop will be published as a Special Section of the Quarterly Journal of the Royal Meteorological Society.

CURRENT ASSIMILATIONS OF SATELLITE OBSERVATIONS OF CLOUDY/PRECIPITATING AREAS. Since 2005, most operational NWP centers have begun to assimilate hyperspectral IR radiance observations, from the Atmospheric Infrared Sounder (AIRS) and/or Atmospheric Sounding Interferometer (IASI) instruments, in cloudy regions. Assimilation of these cloudy IR radiances provides critical sounding data in active regions of the atmosphere. Currently, cloudy radiances are assimilated only over the oceans, and the cloud information extracted from the observations is not assimilated.

Satellite observations of bulk cloud water and precipitation from microwave (MW) imagers [e.g., Special Sensor Microwave Imager (SSM/I), Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), and Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E)] have been assimilated at the operational centers for some time now. The ECMWF has recently implemented a system to assimilate the radiances for such instruments for all sky conditions. An all-sky system is easier to develop for MW observations than for IR observations because of the more continuous and linear sensitivity of MW brightness temperature to the transition from clear to cloudy conditions and as a function of cloud and precipitation state.

MAJOR ISSUES. Major issues that were identified by the workshop's working groups included modeling, data assimilation, verification, and observations.

Modeling. Parameterization of cloud and precipitation forming processes in NWP models is still rather crude, and model biases in cloud/precipitation prediction are significant. A prominent problem is the quick loss of observational information gained in the analysis during the early time steps of the model forecast. The rapid falloff of impact with time may not only be a modeling problem: poor balance in the analysis itself and/or a real lack of predictability of convective scales may also contribute. A basic question is how much medium-range impact can be gained from constraining clouds and precipitation (vs. temperature and moisture in clouds) in the analysis.

With increasing complexity of the moist physics model, a divergence may occur between the nonlinear processes used to predict the model clouds/precipitation and the linear representation of these processes required for the assimilation stage.

Additionally, development of fast, accurate radiative transfer models for clouds and precipitation remains a critical issue.

Data assimilation. The link between the accurate characterization of the initial conditions and the sensitivity of forecast skill to this characterization is still uncertain. In addition, model errors in clouds and precipitation are not well known and need explicit definition in weak constraint systems.

The nonlinearity of physical parameterizations and radiative transfer models and the need to linearize these models for assimilating the observations, as well as the non-Gaussian error characteristics of the models, can be limiting factors for data assimilation. The difficult match between spatial representativeness of satellite observations and model grid points and the frequent mislocation of clouds in model forecasts are additional barriers.

Verification. While satellite data have a large potential for verifying cloud and microphysics parameterizations, the apparent scale mismatch and mislocation of clouds in model forecasts produce statistics that are noisy and may not be a true measure of forecast accuracy. General forecast skill score evaluation with model analyses often shows neutral impact and strongly depends on the verifying analysis. The 500-hPa field may not be the best way to examine the impact on forecasts of assimilating observations of cloudy/precipitating regions.

Observations. Most recent improvements in cloud and precipitation forecasting have resulted mainly from improved models and data assimilation systems, likely leaving current observational capabilities underexploited. NWP centers prefer to assimilate radiance observations rather than derived products.

SUMMARY OF RECOMMENDATIONS. The reports of the working groups, after review and discussion at the final plenary session, were integrated into the following set of recommendations.

Modeling. Improve cloud and precipitation physical parameterizations (in particular, the representation of subgrid-scale processes such as convection) and their linearized versions to reduce current biases. Focus on the short-impact bias problem and characterize the rate of dissipation of the analysis increments into the forecast. Increase the vertical resolution of models to generate more realistic cloud features.

- Improve the characterization of systematic and random errors of moist physics variables in models by, for example, facilitating interactions between the data assimilation and modeling communities.
- Foster increased collaboration between the global modeling and cloud-resolving model communities to develop improved parameterizations of moist physics processes in global models and to investigate linearity validity, optimal four-dimensional variational data assimilation (4D-Var) window length, data assimilation prognostic variable choice, microphysics, background error covariances, and observation types and frequency.
- Compare model cloud with associated observation statistics [probability distribution functions (PDFs)] in radiance/reflectivity and model parameter space (e.g., cloud optical depth, cloud water, melting level heights, timing of convection) to improve models. Continue to develop fast, accurate radiative transfer models for clouds and precipitation and foster the comparison of models constructed by different groups.

Assimilation. Identify and quantify critical analysis errors governing the sensitivity of forecast skill to accuracy of initial conditions.

- Improve applicability of the linear assumption in variational and ensemble Kalman filter assimilation by smoothing the observations or the nonlinear trajectory.
- Entrain the research community to investigate alternative methods [e.g., particle filters or hybrid approaches (nudging, variational and ensemble, also with outer loop updates, multiple steps)] to avoid the linearity constraint for moist physics. Explore more statistical assimilation of observations rather than point by point.
- Determine optimal schemes for handling scale mismatch between observations and models by, for example, encouraging cooperation between mesoscale and global data assimilation groups and investigating optimal observation smoothing.
- Improve the specification of model error covariances through, for example, better flow dependence, anisotropy, and diabatic balance; use of variable transforms that yield control variables with Gaussian statistics; and/or propagation of covariances in 4D-Var using ensemble and (possibly) adaptive ensemble covariance localization because ensemble covariances respect error saturation bounds associated with fast, small-scale moist processes whereas tangent linear models and adjoints do not.
- Treat IR and MW observations in a similar (all-sky like) framework.

Verification. In addition to the standard (e.g., 500-hPa anomaly correlation statistics), use additional verification approaches:

- Examine the impact of cloud/precipitation assimilation on forecasts of high impact weather events.
- Investigate statistical spatial verification and smoothing techniques for comparing cloud/precipitation observations with models.
- Evaluate wavelet or scale-dependent verification to eliminate the effect of weather system misplacements on traditional statistics.
- Expand verification activities to include cloud- and precipitation-related variables, with efforts focused on creating verification datasets from cloud/precipitation profile information from surface and spaceborne radar and lidar observations; radiances and cloud/precipitation products from visible, IR, and MW observations from low Earth orbit and geosynchronous satellites; and surface rain gauge data.

- Compare PDFs of variables between models and observations (e.g. cloud fraction PDF vs vertical velocity, or rain PDF vs cloud type PDF).

Observations.

- Make use of higher temporal resolution data to resolve cloud evolution.
- Better exploit information on clouds and precipitation from hyperspectral IR and MW observations, both in polar and geostationary orbits.
- Enhance complementary usage of active and passive observations from space and ground stations.
- Investigate the value of vertical velocity observations as a complement to cloud parameter observations.

An overarching recommendation of the workshop is to continue improvements in cloud/precipitation assimilation within the framework of current data assimilation systems, while recognizing that the nonlinearity of processes and non-Gaussian error characteristics are ultimately limiting factors for these systems. In particular, the reduction of model biases and the more specific definition of background error statistics as well as weak-constraint and smoothing approaches promise immediate impact. In the longer term, nonlinear and non-Gaussian data assimilation systems and hybrids between linear and nonlinear systems need to be considered. These developments should be undertaken across the modeling, data assimilation, and verification communities through joint projects between operational NWP centers and external research institutions.