CGMS

CGMS-34, NOAA-WP-37
Prepared by M. Goldberg
Agenda Item: II/7
Discussed in WG2

ASSIMILATION OF SATELLITE CLOUD AND PRECIPITATION OBSERVATIONS IN NUMERICAL WEATHER PREDICTION MODELS: REPORT OF AN INTERNATIONAL WORKSHOP

A report from the cloud and precipitation data assimilation workshop for CGMS consideration

ASSIMILATION OF SATELLITE CLOUD AND PRECIPITATION OBSERVATIONS IN NUMERICAL WEATHER PREDICTION MODELS: REPORT OF AN INTERNATIONAL WORKSHOP

Ronald Errico, Goddard Earth Sciences and Technology Center (GEST), Baltimore, MD
George Ohring, NOAA/NESDIS Center for Satellite Applications and Research (STAR) (Consultant), Camp Springs, MD
Peter Bauer, European Center for Medium Range Weather Forecasting (ECMWF), Reading, UK
Brad Ferrier, NOAA/NWS National Centers for Environmental Prediction (NCEP), and Science Applications International Corporation (SAIC), Camp Springs, MD
Jean-Francois Mahfouf, Meteorological Service of Canada, Dorval, Canada
Joe Turk, Naval Research Laboratory, Monterey, CA
Fuzhong Weng & Mitch Goldberg, NOAA/NESDIS Center for Satellite Applications and Research (STAR), Camp Springs, MD

1. Introduction

Every day, millions of observations, obtained using a variety of instruments, are analyzed to estimate the current state of the earth's atmosphere, usually, but not always, to provide the initial conditions for numerical weather prediction (NWP). This information is combined, attempting to account for the error statistics of each data type. A weather forecast model is used to both interpolate and extrapolate information in time and to provide physical relationships and constraints among the diverse fields. Other models are used to relate what is observed (e.g., radiances) to the fields to be analyzed (e.g., temperatures). This is the process of atmospheric data assimilation. Forms of it have been in continuous operation at several centers around the world for decades.

As a result of better NWP models, computers, satellite observations, and data assimilation, the accuracies of forecasts of mid-tropospheric flow patterns have steadily improved over the past few decades. Today's 4-day forecasts of those patterns are as accurate as 3-day predictions were just a decade ago and as 2-day forecasts were two decades ago. Forecasts for the Southern Hemisphere, where satellites provide the bulk of observations, are now as accurate as those for the Northern Hemisphere. However, progress in forecasting some fields, such as quantitative precipitation, remains lagging.

Satellites provide over 90 % of the data ingested by today's weather forecast models. Most of the satellite data (more than 75 %), however, are discarded because they are cloud- or rain-affected or redundant. These excluded observations contain potentially useful information about clouds and precipitation properties that could benefit NWP forecasts.

Forecasts of precipitation and clouds are of particular public interest. Quantitative forecasts of precipitation or cloud properties quickly loose usefulness after 2-3 days. The radiative and diabatic process related to those properties also influence forecasts of other fields, particularly temperature but also wind, and thus act to also reduce their skill to some significant degree.. The sensitive regions where numerical forecasts tend to be most influenced by initial condition error often coincide with the presence of clouds. It is precisely these regions where much of the satellite data currently cannot be used, either because the infra-red (IR) sounders and IR and visible (VIS) imagers cannot penetrate the clouds or because the models cannot adequately assimilate cloud or precipitation information. Advances in the assimilation of satellite observations of clouds and precipitation together with improved observations of these regions hopefully will lead to more accurate predictions of clouds and precipitation and more accurate weather forecasts in general.

In addition to improving weather predictions, several other benefits would be realized from a capability to assimilate cloud and precipitation observations. These include

- Improved moist physics in models
- Enhanced cloud data sets for climate and weather applications
- Better defined hydrological and energy cycles

To accelerate progress in the field, the NOAA-NASA –DoD Joint Center for Satellite Data Assimilation (JCSDA) convened an international workshop on 2-4 May 2005 in Lansdowne, VA. Forty invited scientists, with expertise in either satellite observations of clouds and precipitation, radiative transfer, modeling clouds and precipitation in NWP, or data assimilation, participated. The Workshop format consisted of plenary sessions of invited overview and shorter presentations, and breakout groups focused on the above topics. Workshop goals were to:

- Critically review the current capabilities in:
    - Observations of clouds and precipitation from satellites
    - Modeling of clouds and precipitation for NWP
    - Assimilating satellite observations of clouds and precipitation
- Identify the key impediments to progress in assimilation of cloud and precipitation information
- Develop a list of recommendations to accelerate progress

2. FINDING FROM THE WORKSHOP

2.1 Issues concerning observations

Satellite observations of clouds and precipitation are of two basic types: passive and active. Passive observations measure the visible (VIS), infrared (IR), or microwave radiation reflected or emitted to space by cloud and precipitation particles. They provide cloud-top or path integrated information. From this, “retrievals” of cloud amounts, cloud top temperatures and heights, particle phases and effective radii, optical depths, and rain rates are obtained. Polar orbiters provide global VIS, IR, and microwave images and IR and microwave sounder coverage, while geostationary satellites provide temporally frequent VIS and IR images and IR sounder observations.

The fleet of passive instruments has recently been joined by active instruments, such as radars and lidars, which provide information on the vertical distribution of clouds and precipitation. The Tropical Rainfall Measuring Mission (TRMM) Precipitation

Radar measures the profiles of water and ice precipitation particles with a vertical resolution of about 250 m. The CloudSat carries a cloud radar that measures the vertical profiles of water and ice particles in clouds, and vertical cloud boundaries, with similar resolution. The CALIPSO satellite has a 2-wavelength lidar that measures ice and water extinction profiles, and cloud heights of optically thin clouds, with a vertical resolution of 30 – 60 m.

A major impediment to improving satellite measurements of clouds and precipitation is insufficient ground-based validation observations. Routine cloud observations are conducted at weather stations around the world. These are primarily made by human observers, although in the U.S. automated ceilometers have replaced the observers. Measurements by humans typically vary significantly from observer to observer and ceilometer measurements are restricted to low and middle clouds. Both types of measurements are limited to cloud fraction and cloud base height, and the view of clouds from below may be very different than the view from above, especially if there is more than one cloud layer. More detailed observations of cloud properties are made at the three Atmospheric Radiation Measurement (ARM) program sites of the DoE.

Ground truth for satellite precipitation measurements consists of radar and rain gauge observations. However, the ground observations suffer from poorly calibrated radars and unreliable gauge data. Representativness errors may also be large. There is little or no over-ocean ground truth, although progress is being made in developing acoustic rain gauges. Meanwhile, the TRMM Precipitation Radar measurements are used for global truth over the ocean, but since TRMM is a single satellite, these can only verify long-term averages and consistency between the TRMM radiometer and radar rain rates. Major validation campaigns, involving a variety of ground-based remote sensing instruments and in-situ aircraft observations, are rare.

Satellites provide poor temporal sampling relative to the time scales of precipitation development. The revisit time by polar orbiters is too long (6-hrs worst case in the tropics). Also, such measurements lack sensitivity to drizzle and snowfall. Drizzle and snowfall retrievals are hampered by the poor relationship between cloud top temperatures and rain rates when using geostationary satellite IR measurements, or by sensitivity to the underlying (and highly variable emissivity) land surface, or weak emission signals over ocean in the case of microwave observations.

In addition to the general recommendations described at the end of this report, some specific ones regarding observations include:

- Expand the use of ARM site observations and conduct well planned field campaigns to provide better validation of satellite cloud and precipitation measurements. Design validation programs, e.g., those for the Global Precipitation Measurement (GPM) mission, with data assimilation applications in mind.

- Improve modeling of moist physical processes in cloud resolving models, especially convection (which will inherently be influenced by the dynamics in the model). Such advances would lead to satellite-based precipitation structure retrievals that better represent the underlying cloud state.

- Exploit millimeter-wave sounding channels (e.g., Advanced Microwave Sounding Unit-B, Special Sensor Microwave Imager Sounder (SSMIS)) with improved sensitivity to snow and drizzle to retrieve these variables. CloudSat will provide new opportunities for measuring these elusive quantities, but as a non-scanning instrument, will have limited impact on data assimilation applications.

2.2 Issues concerning models

The diverse set of models and model components required for data assimilation have varying degrees of reliability. Atmospheric dynamics at horizontal scales larger than 100 km or so are typically handled quite well. Operational NWP models are able to predict the location in space and time of clouds associated with large-scale organized systems, but their skill degrades as the strength of synoptic forcing and/or amount of larger-scale organization decreases. Although the regions where strong dynamics tend to generate significant precipitation and clouds may be well delineated, quantitative reliability is currently lacking.

A long list of deficiencies in current forecast models and in the models used to relate observations to analysis fields was composed at the workshop. Modeling of some diabatic processes, particularly those associated with moist convection and the radiative effects of clouds remain unreliable. For example, the identical input provided to two different schemes commonly used for parameterizing moist convection can often yield precipitation rates differing by factors greater than two.

Even schemes apparently based on fundamental physics, such as “explicit microphysical precipitation schemes” are in fact highly parameterized with much accompanying uncertainty. Also, details such as cloud ice shapes and liquid drop size distributions that are relatively unimportant for predicting storm evolution but are critical for estimating radiative scattering remain typically unpredicted. Optimal use of radiance observations in cloudy regions may require new model considerations.

Uncertainties in physical parameterizations are many. The biggest issue is modeling sub-grid-scale precipitating convection. Other parameterizations needing improvements include modeling of shallow convective clouds associated with the planetary boundary layer, microphysics of cloud formation, surface exchanges of heat, moisture, and momentum under high wind conditions, and the overlap of multiple cloud layers for radiative calculations. These processes are generally multi (spatial) scale. They also do not operate in isolation, but strongly influence and are affected by others. These are among the reasons why progress in their development has been slow. Simply utilizing models having higher spatial resolution will not be sufficient to mitigate these deficiencies.

Observational knowledge is lacking on the statistical properties of clouds, including sub-grid variability of temperature, moisture, momentum, and the various forms of condensate. Little is known about turbulent, convective conditions.

The Cloud and Precipitation Modeling Group had several recommendations for improving the utility of the various models required for data assimilation:

- Construct several robust observational data sets for validating process models and components. Simulated data sets appropriately produced by cloud resolving models would also be very informative.

- Develop improved moist convective schemes that are compatible with data assimilation applications. This requires prediction of additional aspects of the processes as well as different additional validation.

- Develop suitable perturbation or tangent linear models and their corresponding adjoints. These adjoint models must be validated for their intended applications, not just in the limit of infinitesimal perturbations.

- Develop joint development programs involving the diverse sub disciplines within the atmospheric community: cloud and precipitation observations, modeling, and assimilation of observations. Current model development efforts within both the research and operational communities appear to be insufficient for a near-term step-wise improvement of the assimilation of clouds and precipitation. Truly useful application, validation and development of these models - that do not act in isolation - requires serious collaborations across the spectrum of disciplines.

2.3 Issues concerning radiative transfer

The development of fast, accurate IR and microwave radiative transfer (RT) models for clear atmospheric conditions has enabled the direct assimilation of clear sky radiances in NWP models. Many models also handle the scattering and emission processes that dominate cloud and precipitation RT. Some analytic Jacobian schemes, crucial components for data assimilation, have also been developed. Highest accuracy in RT through clouds and precipitation is achieved at microwave lower frequencies where cloud emission is dominant and is least sensitive to particle size distribution. The Joint Center for Satellite Data Assimilation (JCSDA) has developed a community radiative transfer model (CRTM) framework which will allow for faster implementation of new radiative transfer algorithms into operation

RT models currently suffer from several difficulties and limitations. Scattering by precipitation and clouds is a function of particle properties that are not currently predicted or diagnosed in NWP models. The spatial inhomogeneity of clouds and precipitation demands complex, time consuming techniques such as 3D Monte Carlo modeling for computing scattering. Uncertainties in surface radiative property modeling (e.g. emissivity and reflectivity) remain large in many geographical regions, particularly over land and ice. There are few comprehensive data sets for fully assessing the accuracies and performances of RT models.

Progress in modeling RT in clouds and precipitation can be accelerated by implementing the following recommendations:

- Construct sets of high-quality satellite and associated in-situ observations, the latter including condensate sizes and shapes, to fully assess RT model

performance. These can be provided by special field campaigns, the Cloudsat program (that will collocate Cloudsat observations with NWP model outputs and other satellite measurements), and ARM sites. Characterize the biases and standard deviations of simulated radiances.
- Determine mean particle size from satellite VIS/NIR and/or microwave observations or develop diagnostic and/or prognostic schemes in NWP models for mean particle size. Use this in forward model calculations in the operational NWP models.
- Develop, for clouds and precipitation, the especially fast radiative transfer schemes needed for complete 3D or 4D data assimilation systems that include many observation types. Speed, accuracy, memory requirements, atypical NWP input requirements, and general compatibility with other data assimilation components must all be considered.

2.4 Issues concerning assimilation

Precipitation estimated from radar data or inferred from satellite-observed cloud top temperatures has been assimilated in some operational or research models for many years. The assimilation techniques have been at best loosely based on modern inverse modeling or control theory. Success according to some measures has been demonstrated sufficiently to continue the practice. Generally, however, no improvements have been measured in subsequent forecasts beyond 1 day, or in some systems, beyond hour 6. More recently, such data have been included in the most currently accurate, variational data assimilation schemes, but with only neutral impacts on forecasts. With some critical portions of the infrastructure in place, however, these newer systems provide a firm basis for future improvements.

The primary impediment to assimilating cloud and precipitation observations is the fundamental difficulty of the problem. The range of space scales is broad (microphysical to planetary), as is the range of time scales. Many fundamental aspects of assimilating these data render them difficult to use. These include model and observation – including RT - error characteristics, with some of the error statistics extraordinarily large. Representativness errors are also very large and non Gaussian in common parameters.

The moist physics is highly nonlinear. The nonlinearity of the underlying relationships implies that some error statistics to be considered are not even approximately Gaussian. Nonlinearity also implies that assimilation schemes based on linear theory must be sufficiently modified, sometimes with little theoretical guidance. Usual assumptions of unbiased models and data and, in four dimensional contexts, the assumption of a perfect trajectory model, must be relaxed.

Precipitation and cloud formation depend strongly on less well observed and modeled aspects of the flow, including moisture convergence and convective parameterization. Some problems that have previously been considered solved, such as the employment of specific dynamical and physical balance constraints, need to be revisited as more is required of assimilation systems. A strong imposition of geostrophy, for example, may have been generally appropriate, but in regions of strong moist convection, distortion of the precipitation generating flow may be unacceptable for matching observations.

While some basic research is being conducted at a few operational centers, there are many basic issues not being investigated at all (such as reasonable characterization of predictability limits) and little such work is being conducted at universities. In the past, much such work has not been critically assessed leading to some confusion regarding what has been general demonstrated and what remains to be investigated.

Besides its inherent difficulties, progress in assimilating these data has been slowed due to insufficient examination of several fundamentals. While many implications of chaotic dynamics and physics have been explored since the advent of numerical weather prediction, others have yet to be considered. Particularly, knowledge of any limits of precipitation and cloud property predictability would help determine both appropriate goals and paths to attain them. More complete and critical assessment of past and current attempts to assimilate this data would help assessment of the importance of neglected issues and provide a firmer foundation to build upon with less confusion. Consistent use of common sets of metrics applied to precipitation and cloud forecast errors, analysis increments, and analysis residuals would help establish a basis of information to measure future improvements as well as insight regarding sources of error.

Although the assimilation problem integrates many issues, light can be shed on many aspects of the problem by isolating them. This requires sufficiently understanding the full problem so that the isolated context remains appropriate. Included are examinations of the Jacobians of physical parameterization schemes and forward models, adjoint-based sensitivity analysis, predictability characterization, statistical considerations in sub grid modeling, and better inclusion of statistical considerations in model development, including stochastic elements. These problems are ideally suited for traditional university research.

Recommendations to accelerate progress include:

- Compare background-derived estimates and observations differences (O-F statistics) for precipitation and cloud related variables to determine a current baseline estimate of information content

- Entrain model developers interested in design applications for data assimilation, including linearization, regularization, and simplification.

- Encourage data and model providers to seriously estimate the errors in their products or formulations.

- Develop prototype precipitation and cloud data assimilation systems even if the impact on skill associated with them is initially neutral.

- Conduct well designed and carefully interpreted predictability experiments to determine what increase of precipitation and cloud forecast skill is a realistic target and what specific kinds of improvements are required to attain that skill.

2.5 Overarching Recommendation

The assimilation of observations related to clouds and precipitation requires combined efforts among the observation, modelling and data assimilation communities. Although the NWP community in particular has attempted to develop much of the required expertise within itself, much greater and accelerated progress would be generated by entraining enhanced collaboration. The same is true for the other communities. Communication is currently difficult, with concepts considered basic within one community being foreign to another. The Workshop encourages the JCSDA, the major operational NWP centers, and appropriate funding agencies to support new and stronger collaborations and enhance opportunities for communication.

All Workshop presentations are posted on the JCSDA web-site at http://www.jcsda.noaa.gov/CloudPrecipWkShop/index.html

A Special Issue of the American Meteorological Society's Journal of the Atmospheric Sciences is in press for the publication of Workshop and additional papers on Assimilation of Satellite Cloud and Precipitation Observations in NWP Models.