P3.6

4D ASSIMILATION OF CLOUDY SATELLITE RADIANCES

T. Vukicevic, M. Sengupta, T. Vonder Haar , A. Jones, and F. Evans*

Cooperative Institute for Research in the Atmosphere (CIRA),
Colorado State University, Fort Collins, CO

*Program in Atmospheric and Oceanic Sciences (PAOS),
University of Colorado, Boulder, CO

1. INTRODUCTION

Statistical cloud properties are required to test and improve cloud parameterizations in weather prediction and climate models and to study the role of clouds in the atmospheric system. Cloud properties are also desired in the initial condition of weather models. Retrievals from site observations (e.g., the Atmospheric Radiation Measurements (ARM)), global satellite remote sensing measurements (e.g., International Satellite Cloud Climatology Project (ISCCP)) and simulations of cloud resolving models (CRMs) have been used to estimate statistical cloud properties though neither of the approaches have been fully successful. Retrievals performed at a single site are not representative of a large domain, while cloud analysis based on global satellite measurement retrievals do not have sufficient spatial resolution to resolve variability in cloud properties. Furthermore, additional information required for parameterization and understanding cloud evolution, such as advection of clouds and the relationship between clouds and atmospheric dynamics is not available from retrievals. The CRM simulations, on the other hand, provide cloud microphysical and associated dynamical properties but are poorly constrained with cloud observations.

It is possible to obtain the desired 4-dimensional analysis of cloud properties with an objective 4D data assimilation methodology that allows information from a cloud resolving model and cloud sensitive remote sensing measurements to be integrated. We have developed a 4D variational (4DVAR) data assimilation numerical algorithm for the Regional Atmospheric Modeling System (RAMS) with a cloud resolving capability. The entire 4DVAR algorithm with the model is designated the Regional Atmospheric Modeling and Data Assimilation System (RAMDAS).

This project is supported by the Army Research Lab and is intended to improve high resolution atmospheric state estimation of clouds in 4D. The current application of the new 4DVAR system emphasizes assimilation of cloudy satellite radiances from GOES imager IR wavelengths. The imager observations are selected for their high temporal and spatial resolution and strong sensitivity to clouds and water vapor.

2. 4DVAR DATA ASSIMILATION SYSTEM AND GOES IMAGER OBSERVATIONAL OPERATOR

The RAMDAS algorithm is described in detail in Vukicevic et al. (2004) and Zupanski et al. (2004). In summary it consists of 4 major components: 1) a nonlinear forecast model with cloud resolving parameterization, 2) an adjoint of the full forecast model, 3) an observational operator for visible and infrared satellite observations, and 4) a minimization algorithm. Here we are primarily interested in the cloud resolving model and the observational operator.

Clouds and precipitation in RAMS are explicitly predicted via a microphysics parameterization that features a one-moment scheme (mixing ratio) for cloud liquid water and a two-moment scheme (mixing ratio and number concentration) for six other hydrometeor types, including pristine ice, aggregates, snow, graupel, hail, and rain. The hydrometeor size distribution is approximated by a gamma distribution with a prescribed width.

The GOES imager observations are used via a set of forward and adjoint optical properties and radiative transfer models, described in detail in Greenwald et al. (2004). The principal features are: visible and infrared radiances computation in both clear and cloudy plane-parallel conditions using two different radiative transfer models, both of which handle multiple scattering. The operator also makes use of anomalous diffraction theory to estimate cloud single-scattering (i.e. optical) properties for all types of particles, including nonspherical ones. Extinction by gases is computed from the Optical Path TRANsmittance (OPTRAN) model.

3. ASSIMILATION OF GOES 8 IMAGER IR CHANNELS 4 AND 5

The GOES 8 imager observations at 10.7 μm and 12.0 μm (channels 4 and 5, respectively) were used in assimilation for a case with overcast mid to high cloud in a region centered at the ARM central facility in northern Oklahoma (USA). The forecast domain was 300 km^2, with horizontal grid resolution of 6 km and 84 vertical levels on a stretched grid with minimum spacing of 50 m and maximum of 500 m and the model top at 17 km. The RAMS initial and lateral boundary conditions were obtained from the operational regional weather analysis archive at NCEP with the horizontal grid resolution of 80 km and at standard pressure levels. The forecast model was first integrated for 15 hours starting at 00 UTC of March 21 2000. The data assimilation was then performed for two periods of one hour duration after 1100 UTC using the original forecast as the first guess (i.e., 1100-1200 and 1300-1400 UTC). Both periods were characterized with mid to high clouds in the observations (i.e., cold brightness temperatures) but the second window included fast cloud dissipation in half of the domain. The guess forecast contained thin ice cloud in the first period and no clouds in the second.

In the data assimilation experiments we tested: 1) the assimilation of single channels, 2) the simultaneous assimilation of channels 4 and 5 , 3) the sensitivity of assimilation results to observation frequency within the 1 h window (15 minute full resolution or 30 minute reduced resolution), 4) the sensitivity to model forecast or first guess and 5) the sensitivity to explicitly including (or not) the model error in the 4DVAR assimilation procedure. The results of the data assimilation experiments were analyzed using 5 different measures: 1) the cost function, 2) the 2D brightness temperature (Tb) distribution, 3) the domain wide error statistics in Tb, 4) the vertical profiles of cost function sensitivity to cloud and water vapor mixing ratio and 5) the analysis of the atmospheric temperature and humidity soundings and cloud radar reflectivity.

The cost function measure was used to verify convergence of each data assimilation experiment and relative accuracy of different experiments when the cost function definition was the same. The brightness temperature 2D distribution was used to verify spatial scales and patterns as well as tendency of either cloud build up or dissipation. In the third measure, the errors were defined as point by point differences between the observed and modeled Tb, thus defining a sample of errors for each observation time. The statistical parameters derived from the samples were: mean, median, root mean square, standard deviation and empirical pdf. The domain error statistics provide both a compact analysis of quality of the specific assimilation results and a crude estimate of errors to be expected from the cloudy radiance data assimilation for the given model, observations and cloud type. The vertical profiles of cost function sensitivity with respect to the hydrologic model variables are used to analyze differences between the impacts of two channels on the assimilation results. Of primary interest was vertical distribution of the sensitivity, its sign and amplitude ratio for the two channels. The vertical sensitivity profiles from locations with maximum absolute amplitude were compared.

The analysis of the cloud environment in the model before and after assimilation was performed by comparing the vertical soundings of temperature and water vapor mixing ratio between different experiments and against ARM observations at two locations. While one location (ARM Central Facility or CF) is included in the assimilation domain, the other (B4) is located at the edge of the outer-most model domain. The latter location could not be, therefore, impacted by the assimilation and the model solution in there was mostly dependent on the lateral boundary conditions. For CF, the cloud radar reflectivity was also used for independent verification of the assimilation results with respect to vertical extent of the clouds and cloud type.

4. RESULTS AND CONCLUSIONS

The data assimilation results for the 1100-1200 UTC period show:

1) The cloud resolving model responds very well in the 4DVAR data assimilation to the cloud sensitive IR imager observations in the case of full overcast by mid to high clouds. The model errors in Tb were reduced from around 30 K in average to less than 4K in the case of simultaneous assimilation of channels 4 and 5 with a frequency of 15 minutes.

2) The final model cloudy atmosphere is in very good agreement with the Tb observations in terms of spatial distribution as well as with the independent ARM sounding and radar reflectivity observations.

3) The statistical properties of final Tb errors in the assimilation domain show well behaved domain wide retrieval (Figure 1): small mean values in both channels (0.3 and 3.5 K, channel 4 and 5 wavelengths, respectively) and standard deviation of only about 6 K.

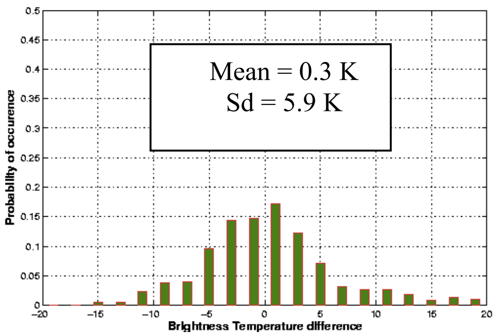
4) Channels 4 and 5 are highly correlated with respect to the cloud mixing ratio but the latter channel sensitivity to water vapor provides additional information in the mid troposphere that was effectively utilized in the assimilation.

5) The effect of including the model error in this case was faster cost function convergence but slightly larger mean and error variance in the domain error statistics.

In the second period (1300-1400 UTC) the model guess forecast was cloud free while the observations included full overcast with dissipating clouds. In the assimilation with both channels included the mid and high level clouds were triggered in the model due to modest sensitivity to water vapor in channel 5, but the full complexity of the observed evolution was not captured. The final Tb errors in the 1300-1400 UTC period were characterized with extreme cold and warm values unlike the errors in the first period.

The partial success in the second period is explained by the large first guess error and the insufficient information content of the observations relative to the cloud environment in the troposphere. The model first guess error resulted from persistently very dry lateral boundary conditions which could not be corrected with the GOES imager observations. These results suggest that moisture and temperature sounding observations are needed to further improve the conditions for cloud triggering in the assimilation.

(a)



(b)

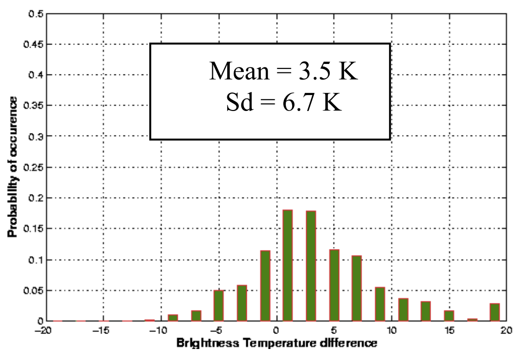


Figure 1. Final assimilation errors in the brightness temperature for the experiment with simultaneous assimilation of channels 4 and 5 with frequency of 15 minutes in the period 1100-1200 UTC, March 21, 2000: a) channel 4 Tb and b) channel 5 Tb.

REFERENCES

Greenwald, T., T. Vukicevic, and L. Grasso, 2004: Adjoint Analysis of an Observational Operator for Visible and Infrared Cloudy-sky Radiance Assimilation. *Q. J. R. Met. Soc.,* **130,** 685-705.

Vukicevic, T., T. Greenwald, M. Zupanski, D. Zupanski, T. Vonder Haar, and A. Jones, 2004: Method for explicit 3D cloud analysis by direct assimilation of visible and IR cloudy radiance. Accepted, *Mon. Wea. Rev.*

Zupanski, M., D. Zupanski, T. Vukicevic, 2004: CIRA/CSU Four-Dimensional Variational Data Assimilation System. Accepted, *Mon. Wea. Rev.*