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P2.5 Development and Testing of a New Cloud Analysis Package using Radar, Satellite, and Surface Cloud Observations within GSI for Initializing Rapid Refresh

Ming Hu[1], Steve Weygandt[3*], Ming Xue[1,2], and Stan Benjamin[3]

[1]Center for Analysis and Prediction of Storms, University of Oklahoma
[2]School of Meteorology, University of Oklahoma
[3]Global System Division, Earth System Research Laboratory, NOAA

1. Introduction

The spin-up problem, which shows as the significant delay in the development of cloud and precipitation at the early stage of a model forecast, is a critical problem faced by the short-range forecasts of aviation sensitive weather parameters and high-impact weather. The spin-up problem is due to the absence or improper initialization of the cloud and precipitation systems and related thermodynamical and dynamical features in the initial condition and therefore can be mitigated through improving the analysis of such features, which include in-cloud temperature, moisture, and cloud and hydrometeor fields. However, the cloud and hydrometeor fields are typically poorly analyzed by most analysis systems even though surface METAR, satellite, radar, and other observing systems provide a great deal of cloud and precipitation information. The spin-up problem is also responsible for the inability of numerical weather prediction (NWP) models to beat extrapolation-based nowcasting systems for very short-range precipitation forecasting (Wilson et al. 1998).

To initialize cloud and precipitation systems as well as associated temperature and moisture fields using surface, satellite, and radar observations, both the Center for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma and the Global Systems Division (GSD) of the NOAA Earth System Research Laboratory have developed semi-empirical cloud analysis packages within their mesoscale numerical forecast systems, namely the Advanced Regional Prediction System (ARPS, Xue et al. 2000; Xue et al. 2001; Xue et al. 2003) of CAPS and the Rapid Update Cycle (RUC, Benjamin *et al.* 2004a; Benjamin *et al.* 2004c) of GSD, respectively.

The ARPS cloud analysis has evolved from that of the Local Analysis and Prediction System (LAPS, Albers et al. 1996) with significant modifications documented by Zhang (1999) and Brewster (2002). It was used with the WSR-88D data through frequent intermittent assimilation cycles in several studies of tornadic thunderstorms at horizontal resolutions of 3 km or higher (Xue et al. 2003; Hu et al. 2006; Hu and Xue 2007a) and been recently applied to initializing WRF also (Hu and Xue 2007b) Those studies clearly show that the cloud analysis procedure can effectively build up storms in the initial condition and therefore reduce the spin-up problem.

The RUC cloud analysis is used by the operational RUC run at the National Centers for Environmental Prediction (NCEP, Benjamin *et al.* 2004b). It is formulated to update 5 fully cycled cloud (water and ice) and precipitation (rain, snow and graupel) species. Observations used include GOES cloud-top data and surface cloud, visibility and current weather information. Experimental versions of the RUC cloud analysis run at GSD have also included 2D radar reflectivity and lighting data (Benjamin et al. 2004b; Weygandt et al. 2006a,b). The experiments show the use of the RUC cloud analysis improves the analysis and forecast of aviation weather sensitive elements. More recently, a procedure for dynamically initializing ongoing precipitation systems based on national radar reflectivity mosaic data has been developed for the RUC and is in real-time testing (Benjamin et al. 2007; Weygandt and Benjamin 2007).

The frequently updated guidance produced by RUC (using the latest observations within a mesocale analysis and prediction system) has been used heavily for short-range forecast applications, mainly for aviation, storm forecasting, and other transportation areas (Benjamin *et al.* 2006). Building upon this success, a new system, known as the Rapid Refresh (RR), is being developed in GSD to replace RUC with a WRF-based short-range forecast system. The new RR is able to cover a larger area including Alaska, Canada, and Puerto Rico and use more high-frequency observations over the wider areas. In RR, NCEP Grid-point Statistical Interpolation (GSI, Wu et al. 2002) is being used to analyze conventional data and initialize one of the WRF-ARW cores.

To improve the initialization of the cloud and precipitation system in RR, CAPS and GSD have

* *Corresponding author address:* Steve Weygandt, NOAA/GSD, R/E/GSD, 325 Broadway, Boulder, CO 80305, Stephen.weygandt@noaa.gov

collaborated to develop a generalized cloud analysis procedure within GSI. During this period, a case study of a Central Plains storm cluster on 23 May 2005 (Hu and Xue 2007b) was conducted to investigate the impact of the ARPS cloud analysis procedure with WSR-88D radar reflectivity data on the forecast of the storm cluster when it is used within GSI framework and with the Advanced Research WRF (WRF-ARW, Skamarock et al. 2005) as forecast model. After that, the ARPS and RUC cloud analysis packages were incorporated into a GSI framework and tested individually with a case of squall lines striking the central US on 13 March 2006. More recently, a prototype of the new generalized cloud analysis procedure that combines the strengths of the both RUC (for stable clouds) and ARPS (for explicit deep convection) cloud analysis packages has been developed to improve the analysis of both stable layer and convective cloud and precipitation systems over a large domain.

The components of the new generalized procedure are shown in Fig. 1. The ingest of the cloud and precipitation observations and the 1-h forecast cloud and hydrometeor fields (from the previous RR cycle) is followed by the stable cloud analysis solver and the convective cloud analysis solver. Recognizing the different treatments of convection within numerical forecast models, the convective cloud package includes a choice of modules: one for a model setup with parameterized convection and one for a model setup with explicitly resolved convection. Consistency between the cloud analysis packages with the model microphysics is also sought.

This paper documents some details of the new cloud analysis procedure and some verification experiments using the 13 March 2006 squall line case under the RR configurations. Section 2 describes the observations used in the cloud analysis. In section 3, the 13 March 2006 squall line case is briefly introduced. The new cloud analysis procedure is described in detail in section 4 with the analysis of testing experiments. The impacts of the cloud analysis used in assimilation cycles are briefly described in section 5 and a summary of the results is given in section 6.

2. Cloud and Precipitation Observations

Many meteorological observations include either direct cloud and precipitation elements or information related to them, but no one single observation or even the complete set of available observations can fully describe the state of all ongoing cloud and precipitation systems. Furthermore, many of the cloud observations provide a “one-way” look, where cloud information above or below an observed cloud layer is unknown. To accommodate this aspect of cloud

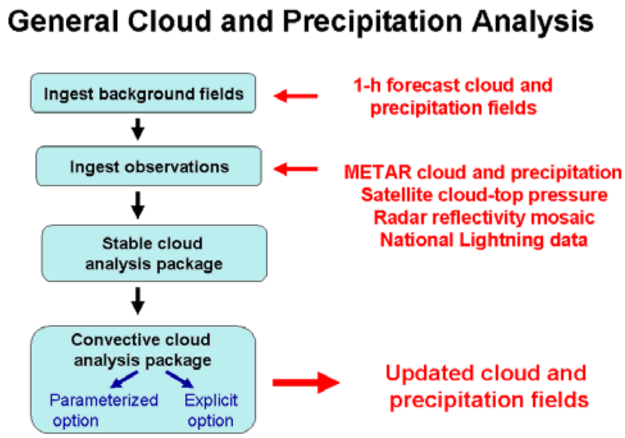

Fig. 1 Schematic diagram depicting the various modules and options within the general cloud analysis solver.

observations and facilitate update of the background fields (cloud building or clearing) only where the observations warrant, the cloud observations are blended together and used to distinguish three classifications: 1) observed clear, 2) observed cloudy, 3) clouds unknown from observations. This composite observed cloud information field is then blended with the background cloud information to produce an optimal estimate of the 3D cloud and precipitation fields. In this section, we will introduce the main observations used in the current cloud analysis procedure with their characteristics related to the cloud analysis.

2.1 METAR DATA

METAR data are typically generated once an hour and some of them come from an Automated Surface Observing System located at airports, military bases and other sites and some are from augmented observations or from trained observers or forecasters. On 1 June 1996, METAR replaced the Surface Aviation Observation (SAO) and becomes the primary observation code used in the United States to satisfy requirements for reporting surface meteorological data.

A regular METAR contains a report of basic atmospheric elements such as wind, temperature, dew point, and barometric pressure together with weather information such as precipitation type and trend, cloud height and cover, lightning, and visibility.

The METAR data used in current cloud analysis are from the operational NCEP BUFR data file ingested in GSD and include cloud amount and the height of cloud base for up to 3 layers, horizontal visibility, and current weather. Before the cloud analysis, METAR data are decoded and digitalized.

2.2 SATELLITE DATA

Satellites can provide a comprehensive view of cloud systems on a scale not possible by other means, especially in the area that has limited human activities like ocean and desert. But most of current satellite data contains only one level of cloud observation and need to be used with other cloud observation to generate a column of cloud. In this study, satellite cloud products from the NOAA National Environmental Satellite, Data, and Information Service (NESDIS), which is included in the same NCEP BUFR file as METAR data, are used in the analysis. GEOS cloud top temperature, cloud top pressure, and cloud cover that distributed in a 1 by 1 degree horizontal grid are ingested through decoding the BUFR file and then interpolated into the analysis grid.

2.3 RADAR DATA

As the only operational platform capable of providing observations of spatial and temporal resolutions sufficient for resolving convective storms, the operational WSR-88D Doppler radar network of the United States (Crum and Alberty 1993) is a key source of data for analyzing precipitation in cloud analysis, especial for convective precipitation. Although the radar network has covered the most of US continental domain horizontally, its spatial coverage is often incomplete and usually only observes a very limited set of parameters, the most important being the radial velocity and reflectivity. Still, radar reflectivity provides a high-resolution source to quantitatively determine the distribution of hydrometeors based on radar reflectivity factor equations.

The radar reflectivity used in the cloud analysis is a national (CONUS) 3D radar mosaic grid with a 1-km horizontal resolution over 30 vertical levels and a 5-minute update cycle. The data are generated by the National Severe Storm Laboratory (NSSL) by combing base level data from all available radars (NEXRAD, Canadian Radar, TDWR, gap radars) at any given time, performing quality control, and then combining reflectivity observations from individual radars onto a unified 3D Cartesian grid (Zhang et al. 2005, Langston *et al.* 2007) These reflectivity data can be read in and interpolated into analysis grid by the GSI and then be directly used in cloud analysis. National mosaic radar data are not routinely available at operational centers at this time, but efforts are underway to make them available at NCEP.

2.4 LIGHTNING DATA

Lightning ground stroke data from the National Lightning Detection Network (NLDN) can provide thunderstorm information in areas without radar coverage and are used as a proxy for reflectivity in the cloud analysis in regions where reflectivity data are not available.

3. March 13, 2006 Central US Squall Case

From 15 UTC March 12 to 09 UTC March 13, 2006, a strong surface low propagated through central US with its center starting from southeast Colorado, through Kansas, and ending at northeast Missouri. Associated with the strong low was a strong cold front moving east-southeastwards through Southern Plains and a strong warm front moving northwards. A dryline also existed ahead the cold front and moved eastwards during this period. Strong synoptic forces encountering convective-favorable environments produced a series of violent squall lines in central US. 140 tornadoes were reported during this severe weather event which caused 10 fatalities and significant property damages.

Among several squall lines that occurred during the day, the one used to test our scheme here was initiated along northeast Oklahoma, east Kansas, and northwest Missouri at around 2330 UTC 12 March and entered its mature stage from 0100 UTC 13 March. This squall line lasted only 5 hours and then was replaced by another stronger squall line which formed right behind it. The satellite IR image at 0015 UTC 13 March in Fig. 2 shows the cloud pattern and distributions in the continental US domain at the initial stage of the squall line.

4. New Cloud Analysis Package in GSI

4.1 GENERAL OVERVIEW

The goal of the cloud analysis package is to blend all available cloud and precipitation observations with background cloud and precipitation information to obtain an optimal 3D description of cloud and precipitation fields for initializing a numerical prediction model. In addition to modifying background cloud water and cloud ice based on the observational data, hydrometeors can be deduced within precipitation region based on radar reflectivity factor equations with the help of environment elements from background. An in-cloud temperature and moisture ad

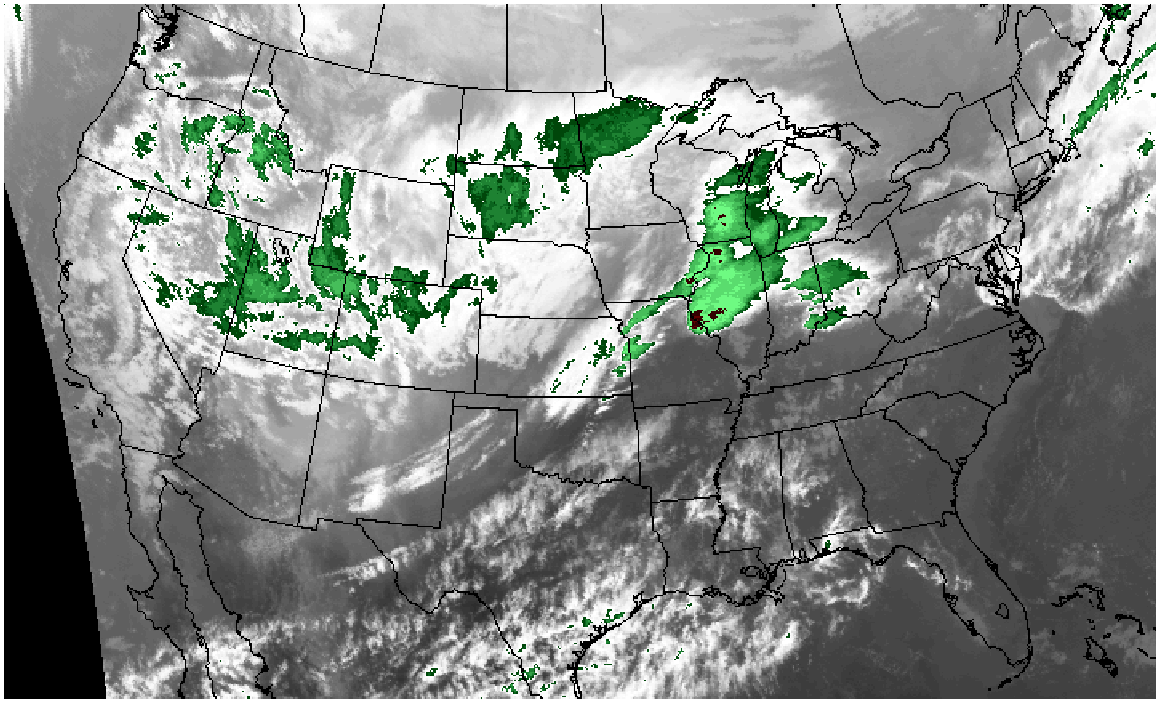

Fig. 2 GOES12 IR observation at 0015 UTC 13 March 2006.

justment procedure (consistent with the thermodynamical and microphysical fields within the cloud) can then be completed or the temperature tendency applied during a model pre-forecast integration.

The specific details of how the temperature, moisture and hydrometeors fields are adjusted varies greatly depending on whether convection in the model is explicitly resolved (grid resolution < ~ 5 km) or parameterized. Within the new generalized analysis, this reality is reflected by including a choice of algorithms as shown in Fig. 1. The generalized algorithm is still undergoing development and we describe and illustrate in this section how various components of the algorithm work. Initial results for some of the modules are shown without the use of background field, but development is ongoing to make full use of background fields.

4.2 CLOUD COVER ANALYSIS

a) Procedure

The METAR observations are used first to decide the cloud cover. Because the observation only gives the heights of cloud base and cloud amounts in each cloud layer, the analysis has to decide the spread and depth of the each cloud layers to make an initial 3D cloud cover. Currently all METAR observed cloud is assumed to be stratiform cloud with 300 m depth without precipitation and 1000 m with precipitation in sight to form a cloud cover profile. In each cloud layer, the cloud cover is decided by cloud amount observation that companied with each cloud base. If there is a dry layer or inversion, the cloud is removed. After getting all cloud profiles, the cloud cover in each grid point is decided by looking for the nearest cloud cover profile within a radius of 120 km. For the purpose of specifying hydrometeors, cloud building is done for observations of broken or overcast. Alternatively, a fractional cloud coverage can be specified that is later used in a cloud type diagnosis.

The reflectivity data that have been interpolated onto the analysis grid are then used to add more cloud cover information. When a grid has a reflectivity larger than a specified threshold and is located above the cloud base, cloud cover is added.

The NESDIS cloud products of cloud top temperature and pressure are further used to complete the 3D structures of the cloud cover. With a cloud top distribution, we either can decide the height of the cloud top or can find clear column to remove all possible overanalyzed cloud in previous steps. Again, the cloud observed by satellite is assumed to be a stratus and a thin layer is added underneath of each top and a removal process is conducted above each observed cloud top. In the use of satellite observations, major effort is devoted to the quality control of the observations to ensure a confidence of the cloud level and clear areas.

The last step of cloud and precipitation distribution analysis involves weather observation from METAR. When fog is observed, the lowest 2 layers of grid will be set to cloudy. The capability to specify deep cloud from a METAR observation of a thunderstorm also exists.

A component of the ARPS cloud analysis package is a cloud typing algorithm, which utilizes cloud temperature, cloud thickness, and background stability. Temperature is used to decide the level of the cloud (low, middle, or high), stability for types of cloud (stratus versus cumulus), and thickness for distinguishing cumulonimbus from all other cumulus.

b) Example of cloud cover analysis

To illustrate the impact of each observation type on the aggregate observed cloud cover, the horizontal extent of the cloud coverage diagnosed from each observation type is shown in Fig. 3a-d. For comparison, Fig. 3e shows the sum of the background cloud ice and cloud water fields. The cloud distributions depicted by satellite and METAR observations match

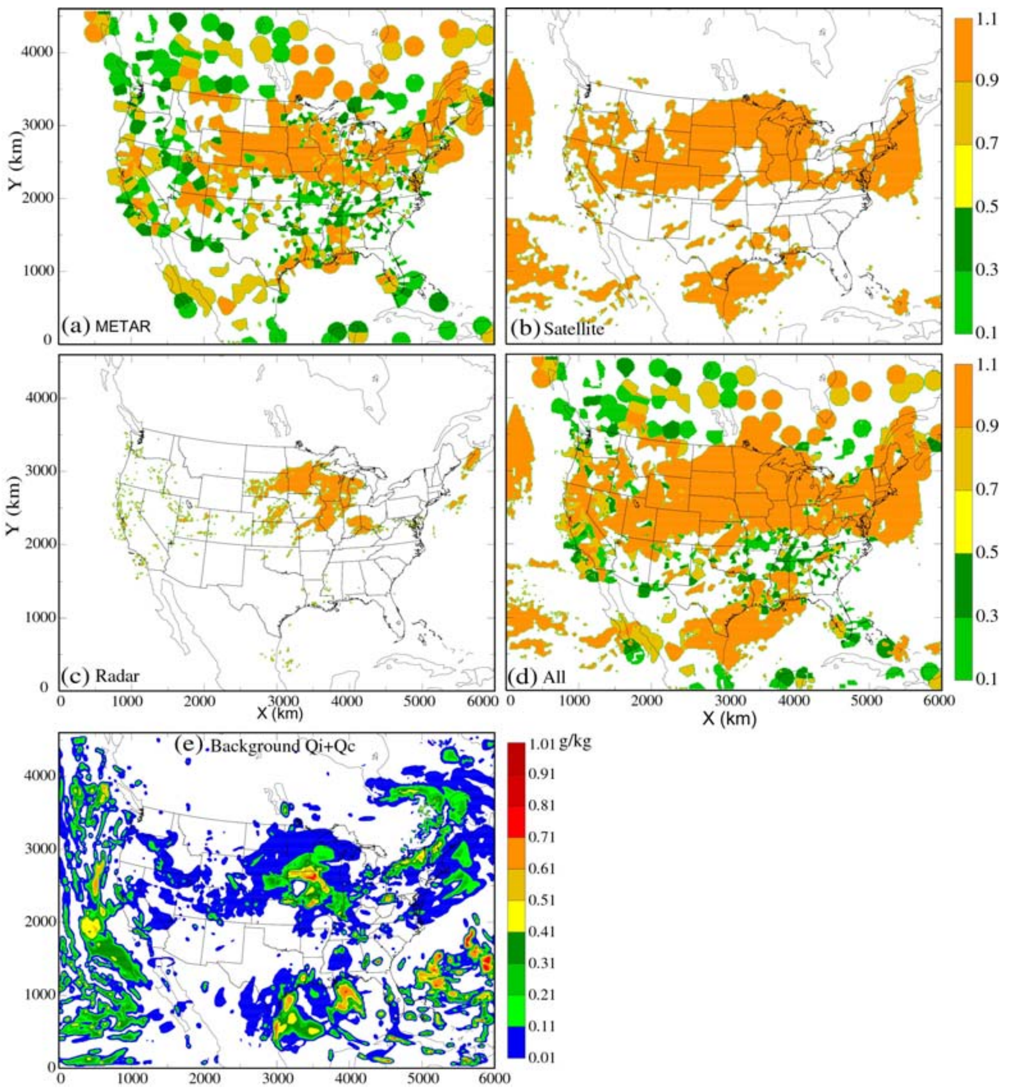

Fig. 3. Composite cloud cover (column maximum) indicated from various observations in the generalized cloud analysis: (a) METAR data only, (b) Satellite (NESDIS cloud products) only, (c) radar (NSSL mosaic reflectivity) only, and (d) all the above three data sources. e) background (1-h model forecast) cloudwater + cloud ice field.

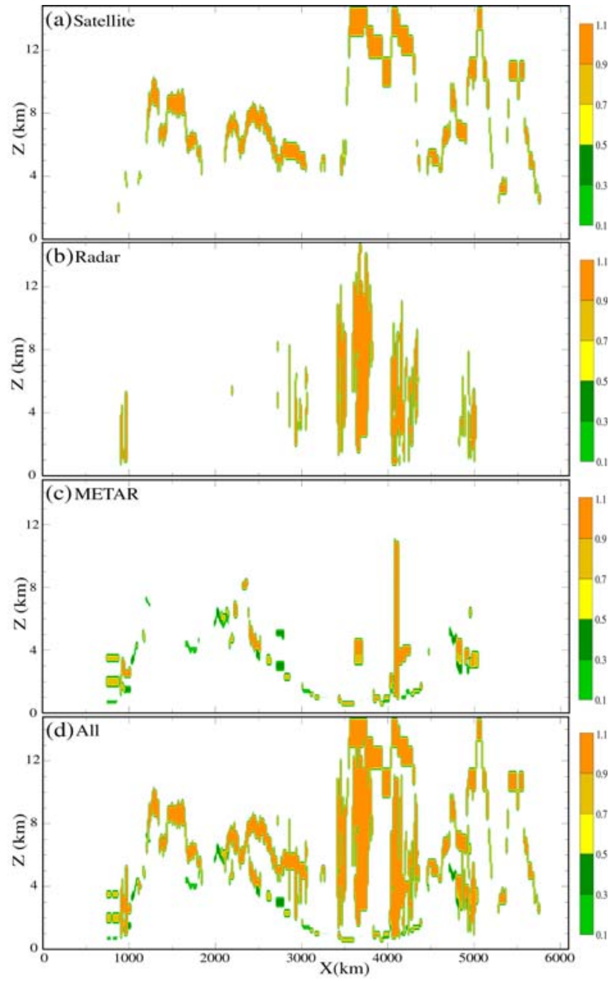

Fig. 4 West-East cross section of the analyzed cloud cover along the center of each panel in Fig. 3

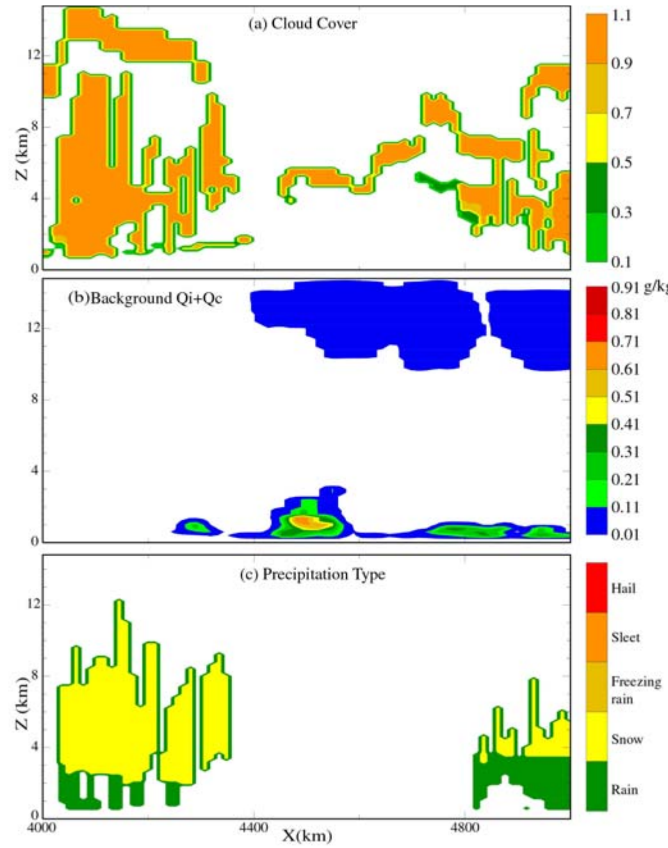

Fig. 5 Zoomed in west-east cross section of a) cloud cover deduced from all observations, b) the background cloud water and cloud ice fields and c) precipitation type deduced from the radar data and background temperature field. In a), regions where cloud cover is unknown are not indicated.

qualitatively with the cloud distribution implied from the background cloud ice and cloud water and from the IR satellite image (Fig. 2). In particular, two east-west oriented cloud bands are shown, one covering most of the Northern US (associated with the cyclone and fronts) and another one only covering the western of Gulf of Mexico coast. As Fig. 3a shows, isolated METAR observations in data sparse region results in circular regions of observed cloud cover. Overall the agreement between the background cloud fields and composite cloud observations is quite good.

Fig. 4 shows a west-east cross section of the contributions from each of observations. The Satellite and METAR define the cloud top and base, respectively, with a thin layer added beneath or above (Fig. 4a and Fig. 4c), while radar observation fills in the middle (Fig. 4b). Several additional aspects can be seen in Fig. 4: 1) the high cloud base between 1000 to 3000 km that is because of the elevated terrain across the Rocky Mountain; 2) the deep cloud around 4100 km deduced from the METAR observations (Fig. 4c) likely reflects a reported thunderstorm; 3) unlike other observations, radar data contributions can extend over a large vertical layer (Fig. 4b); 4) when all the observation are used, a more coherent, though still incomplete picture of the 3D cloudiness field emerges (Fig. 4d).

Fig. 5 shows a zoomed in section of the cross-sections, with a depiction of clouds deduced from all the observations, as well as the background cloud information, and the precipitation type deduced from the reflectivity and background temperature fields. From this figure, we can see that the observations provide a significant enhancement to the background fields. The precipitation type analysis shows a simple pattern, with snow above the freezing line and rain below (Fig. 5c).

4.3 CLOUD WATER AND CLOUD ICE

Two approaches for quantifying the amount of cloud ice and cloud water are being explored. The first, potentially more applicable to deep convection, assumes an air parcel rises from cloud base to top along a moist-adiabat, in which the liquid water that condenses in each layer is used as initial guess of the liquid water mixing ratio. In reality, this liquid water mixing ratio is significantly diluted by the entrainment of dry air into the parcel. This entrainment effect is considered through a curve that is generated based on the cloud types. The final cloud water and cloud ice is based on this diluted liquid water mixing ratio and environment temperature. In the second approach, potentially more suitable for stable layer clouds, the cloud and ice mixing ratios are specified as a fraction of the auto conversion threshold.

As an example for the first approach, the analyzed cloud water and cloud ice (deduced from all the observations, but without a background field) are plotted in Fig. 6 along an east-west cross section through the grid that has maximum hail mixing ratio. The vertical distribution of cloud is reasonable: cloud ice occurs at high levels and cloud water at low levels with a mixed layer located from 6 to 8 km.

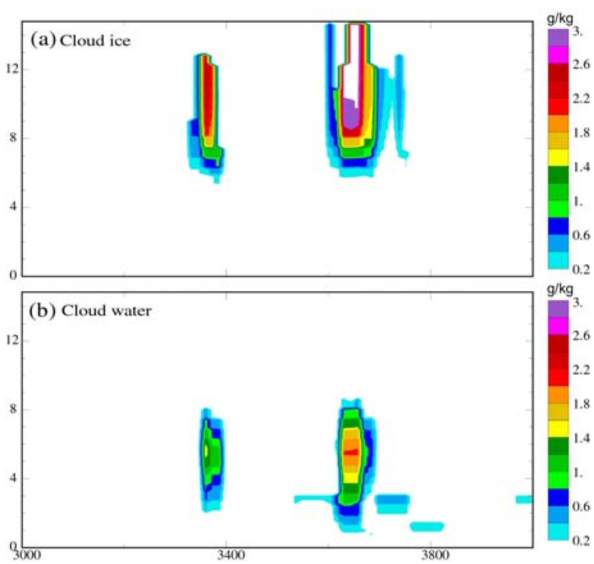

Fig. 6 West-East cross section of analyzed cloud water and cloud ice from all observations, but without a background field. The cross section is through the section that has the maximum hail mixing ratio.

4.4 RETRIEVAL OF HYDROMETEORS

Hydrometeors are retrieved based on the radar reflectivity observations by inverse radar reflectivity factor calculations with the help of precipitation types and environment temperature. Three hydrometeor retrieval schemes are available in current new cloud analysis package, which are named as KRY scheme, SMO scheme (Hu et al. 2006), and Thompson scheme according to the radar reflectivity factor equations on which the scheme is based. The last two schemes are based on a bulk microphysical schemes designed by Smith, Myers and Orville (1975) and Thompson (2004).

The analysis results of hydrometeors using the SMO scheme are illustrated in Fig. 7 along the same west-east cross section as Fig. 6. Similar to cloud distribution, the snow are all located in high altitude and rain in low altitude but they is an overlap layer. Two small hail areas are located in the middle level among the strong right cell.

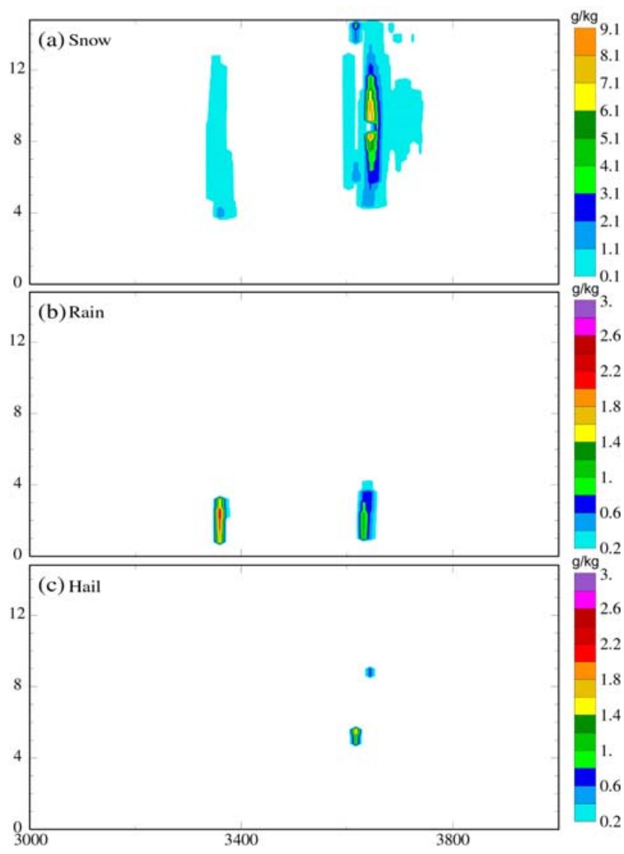

Fig. 7 West-East cross section of rain, snow, and hail deduced from all the observations. The cross section is picked to through the section that has maximum hail mixing ratio.

4.5 IN CLOUD TEMPERATURE ADJUSTMENT

Specification of hydrometeors for precipitating systems tends to have little impact on the resultant model forecast, unless the associated mass and velocity fields are also modified. In cloud warming offsets the negative buoyancy caused by hydrometeor loading and evaporation and induces an associated vertical circulation (low-level convergence / upper-level divergence) that helps to maintain the precipitation system. Multiple methods exist for this adjustment of the mass and velocity fields. Within the ARPS system two procedures (Brewster 2002) are available for adding a positive temperature perturbation to the cloud region (which in turn induces the updraft and sustains the development of precipitation system). The first, known as the latent heat (LH) scheme, relies on the latent heat release from the condensation of increased cloud water. The second, known as the moist adiabatic (MA) scheme uses a moist-adiabatic temperature profile of a lifted air parcel that is one of thermodynamic elements needed in the calculation of cloud water and ice. These two schemes were tested in detail for a supercell case in Hu and Xue (2007a). An alternative formulation currently being tested in the RUC (Benjamin et al. 2007, Weygandt and Benjamin 2007) uses a latent heating rate calculated in the cloud analysis to prescribe a temperature tendency that is applied during a pre-forecast diabatic digital filter adjustment.

5. Cloud Analysis Impact in Assimilation Cycles

To study the impacts of cloud analysis when used in a cycled RUC CONUS environment, four experiments with assimilation cycles for the 13 March 2006 central US squall lines case, which are from 0000 to 1000 UTC 13 March at 1-h intervals, were conducted. Within each cycle, 1-h forecast of WRF-ARW, which has the Thompson microphysics and Grell-Devenyi ensemble cumulus schemes turned on, is started from either regular GSI analysis without cloud analysis or with the inclusion of one of three cloud analysis procedures implemented in GSI. These three procedures are, respectively, based on the RUC and ARPS cloud analysis packages, and the new generalized package described earlier. The RUC cloud analysis emphasizes the use of satellite and METAR data for more stable precipitation systems while the ARPS cloud analysis has mostly been tuned and tested with the radar and METAR data for convective systems.

Experiments are ongoing and initial analysis of the experiments shows that the cloud analysis is helpful in removing spurious cloud and precipitation along the Gulf Coast, but was not able to generate the proper intensity for the active squall-line across the Midwest. Further adjustment to the cloud analysis is needed to improve the impact of cloud observation on the model forecast for the 13-km resolution RR grid.

6. Summary and Discussion

In this paper, a new cloud analysis procedure developed within the GSI framework is documented in detail with an introduction on major cloud and precipitation observations. The new scheme combined the strengths of the ARPS and RUC analysis packages and is able to analyze both stable layer and convective clouds and precipitation fields at the same time over in a large domain. Cloud and precipitation observations from three sources, namely satellite, radar, and METAR, are used together in the new cloud analysis procedure to generate a complete 3 dimensional description of cloud and precipitation.

The new cloud analysis scheme is tested using the 13 March 2006 Central US squall line case. The primarily verification of each components of the package such as cloud cover and type analysis, precipitation type analysis, cloud water and ice analysis and hydrometeors analysis is successful. A set of 3 experiments with cycled assimilation that use cloud analysis as a analysis component are conducted to study the impacts of cloud analysis through comparisons with a parallel experiment without cloud analysis. Initial examination on the results shows that the cloud analysis is able to improve precipitation prediction by reducing spurious precipitation, building up part of the squall line, and enhancing cyclonic precipitation. But the cloud analysis shows much lesser impacts on the forecast than it did in the experiments conducted by Hu and Xue (2007a, b) on a 3 km horizontal resolution grid. The resolution is likely an important reason for the lesser impacts but other reasons such as the microphysical schemes used in the model forecast, the settings of adjustable parameters in the cloud analysis, and role of background in the analysis also need to be carefully tuned for the special resolution and model configurations.

Work to make the cloud and precipitation analysis more consistent for both stable and convective cloud systems and to set up a quasi-operational parallel testing system for examining the impact of the cloud analysis in a more systematic and objective way is ongoing and we will report the results in the future.

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