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7.4 Ongoing Development and Testing of Generalized Cloud Analysis Package within GSI for Initializing Rapid Refresh

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1. Introduction

The spin-up problem, which is due to the absence or improper initialization of the cloud and precipitation systems and related thermodynamical and dynamical features in the initial condition, is a critical problem faced by the short-range forecasts of aviation sensitive weather parameters and high-impact weather. To mitigate the problem, 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 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 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 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). A key aspect to the hourly RUC update is the cycling of all model variables, including cloud, hydrometeor, and land surface fields. The result of this process is an evolving mesoscale analysis that reflects the temporal sequence of observations, while allowing the model to propagate information forward in time. 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 systems in the RR, CAPS and GSD have collaborated to develop a generalized cloud analysis procedure within GSI, which combines the strengths of the both RUC (for stable clouds) and ARPS (for explicit deep convection) cloud analysis packages to improve the analysis of both stable layer and convective cloud and precipitation systems over a large domain.

In this paper, we first provide an overview of the cloud analysis, including a description of the observations used and an illustration of the procedure for

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updating the cycled cloud and hydrometeor fields. This is followed by a discussion of recent development work, including two key accomplishments: 1) an update to the operational RUC cloud analysis to more fully utilize METAR cloud observations and 2) the inclusion of a fully parallelized version of the generalized cloud analysis within the GSI. The latter accomplishment has facilitated an important milestone toward the NCEP operational Rapid Refresh implementation in 2009: namely the beginning of cycled forecasts utilizing the cloud analysis and available cloud observations (including METARs) over the entire Rapid Refresh domain. We conclude by discussing further plans for the general cloud analysis.

2. Cloud Analysis Overview

The components of the new generalized cloud analysis 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.

In cloud analysis, 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. Several cloud observation are used in the new cloud analysis package, which include:

- METAR cloud, visibility, and weather
- GOES cloud top temperature and pressure
- Radar reflectivity Mosaic
- Lightning ground stroke data

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

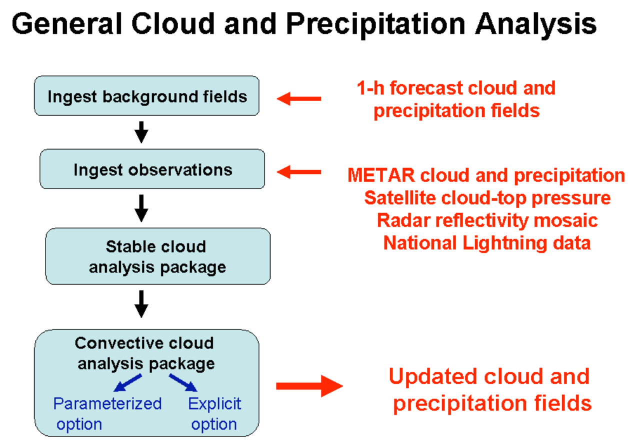

Fig. 1 Schematic diagram depicting the various modules and options within the general cloud analysis solver.

from background. An in-cloud temperature and moisture adjustment 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 cloud, hydrometeors fields, moisture and temperature 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.

For stratiform cloud specification, a schematic illustration from an experimental Rapid Refresh is presented in Fig. 2, which highlights: 1) the one-way nature of the various observations, 2) the use of the observational data to modify the evolving (cycled) cloud and hydrometeor fields. In the top panel a vertical cross-section of the background cloud ice + cloud water (Qi+Qc) field is shown. This background field is from the previous 1-h forecast. The middle panel depicts the cloud designation from the combination of observations. These include the METAR cloud information, GOES satellite-derived cloud top pressure, and the radar reflectivity data. The color depiction denoted the three possible states: YELLOW = observed clear, RED = observed cloudy, GREEN = unknown from observations. As can be seen from the middle panel, typically the GOES and METAR information capture the cloud top and bottom, leaving an unknown region in between. Radar

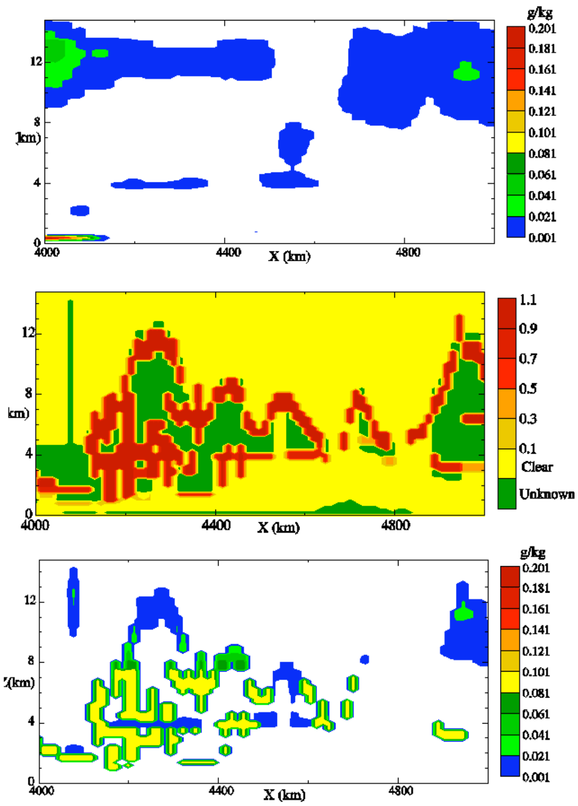

Fig. 2 Schematic example from 13 March 2006. Top panal shows cross section of background (from previous 1-h forecast) cloud ice + cloud water. Middle panel shows cloud designation from combined observations. Bottom panel shows cloud ice + cloud water field after modification.

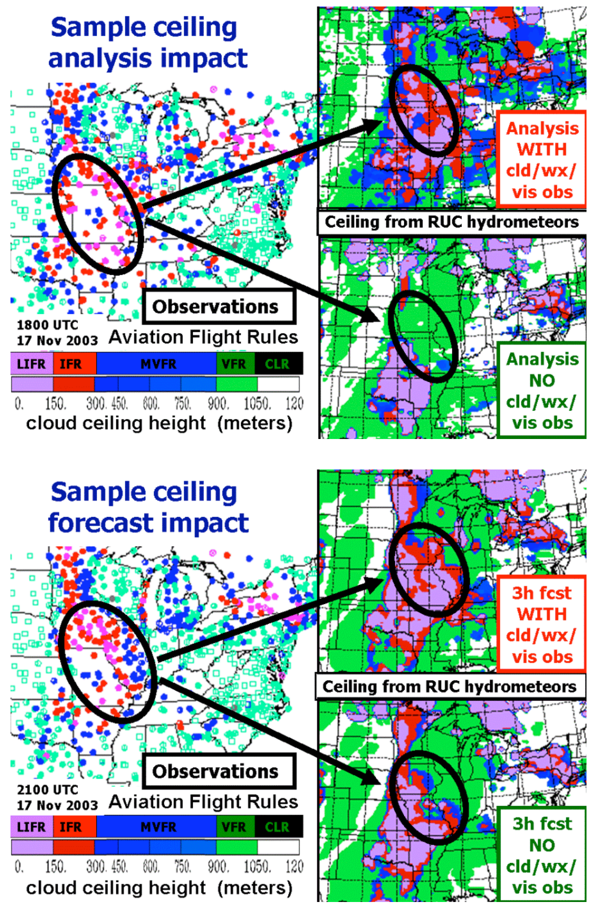

Fig. 3 (Left) Observed aviation flight rules at 1800 UTC and 2100 UTC 17 November 2003 and (right) Aviation flight rule derived from RUC analysis 3-h forecast with and without cloud analysis and 3-h forecast.

data are complementary and can fill in the gap to some degree. Logic exists in the cloud to handle a variety of special cases including radar echoes below the METAR cloud base (interpreted as rain falling from the cloud, no cloud building). The bottom panel shows the resultant Qi+Qc cross-section after the cloud analysis. As can be seen, background Qi+Qc has been removed in regions that are observed clear. In regions observed to have clouds, the background value is retained if it was non-zero, otherwise a value is specified as a fraction of the autoconversion threshold.

For low stratiform clouds, the cloud analysis is effective at projecting the METAR cloud and visibility information onto the cloud ice and water fields, resulting in an analysis that is consistent with the aviation flight rules ceiling values. This is quite important for aviation applications and is illustrated for a test case in the top panel of Fig. 3. Here the aviation flight rules derived from RUC analyses with and without the cloud analysis are compared with the corresponding observations. The differences are quite significant, with the cloud analysis matching the observations quite closely as expected. Retention of the analyzed cloud fields can be problematic, with internal model dynamics often rapidly overwhelming the initialized fields for dynamically active systems, such the one depicted in Fig. 3. Despite these difficulties, some model retention of the analyzed low level cloud fields is clearly evident in the 3-h forecast shown in the bottom panel, especially compared to the forecast without the cloud analysis.

3. Recent developments

Two major cloud analysis development tasks have recently been completed. The first is an upgrade to the operational RUC cloud analysis to more fully utilize METAR cloud observations and the second is the inclusion of a fully parallelized version of the generalized cloud analysis within the GSI. The latter accomplishment is a significant milestone toward the NCEP operational application of the Rapid refresh system.

3.1 METAR USE IN RUC CLOUD ANALYSIS

Routine evaluation of the NCEP operational RUC cloud analysis during the fall of 2007 revealed poor analysis fits to the METAR observed cloud properties. Analysis of the problem indicated that a high percentage of the METAR cloud observations (20-40%) were not being used in the cloud analysis due to correctable problems. A number use limit factors were found to be too restrictive. These factors included the vertical stability check, the model layer thickness check, and the background RH check. In addition, SCT/FEW cloud observations were not being used correctly, with no clearing up to BKN/OVC levels. The impact from correcting all of these features has been a marked improvement in the analysis and short-range forecast low-level cloud fields, as indicated by aviation flight rules and related verification. Fig. 4 shows a time series comparison of the CSI for the analysis and 1-h forecast of ceiling < 1000 ft. from the NCEP operational RUC runs (without the improvements) and the ESRL developmental cycle. Within the ESRL cycle, the improvements were introduced during the period from 14-25 November, 2007. The gradual improvement of both the analysis and 1-h forecast CSI during that period is quite clear, with continued superior performance after that. Based on these results, a crisis change was made in the NCEP operational RUC on 8 January 2008.

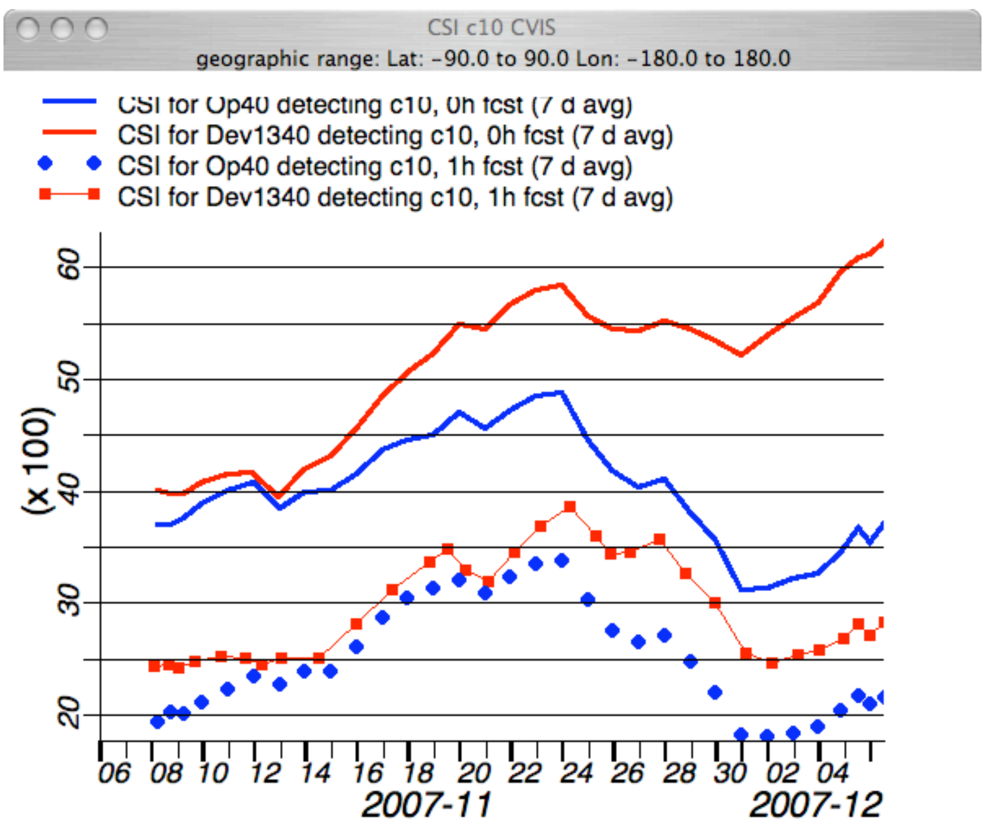

Fig. 4 Time series of CSI for ceiling < 1000 ft. (IFR conditions) for RUC analyses (solid) without the cloud analysis improvements (blue) and with the improvements (red). A similar comparison is shown for the RUC 1-h forecast (dotted). Improvements were made during the period from 14-25 November, during which the improvement in forecast skill can be seen.

3.2 ADDING CLOUD ANALYSIS IN GSI

As noted, previously developmental work is underway to replace the current NCEP operational hourly cycled RUC with the hourly cycled Rapid refresh (with a domain covering all of North American) in 2009. In the RR, the Gridpoint Statistical Interpolation (GSI) will replace the RUC 3DVAR analysis package. The GSI features an advanced satellite radiance assimilation, which is crucial for the RR because of the extensive oceanic coverage within the domain. An important task for the RR application of the GSI has been to incorporate the generalize cloud analysis.

This complex task, which included parallelizing the generalized cloud analysis, has recently been completed and we are now evaluating cycled analyses and forecasts produced by RR with the cloud analysis. The cloud analysis inclusion task was completed in a series of steps, with continual testing to confirm the accuracy of the results. Specific steps included adding the IO and parallel distribution of the background cloud and hydrometeors fields, adding the ingest and parallel distribution of the new observation (METAR clouds, satellite cloud-top pressure, and radar data) and inclusion of the parallelized clouds analysis. With respect to the radar data, a parallelized pre-processing program to map the reflectivity to the RR domain was written and optimized. Most recently, work is ongoing to supplement the radar reflectivity data with lightning from both the NLDN and the BLM Alaskan observations. Sample lighting data coverage plots will be shown later in this section. These lighting data (from the NLDN and Alaska) have processed and converted into reflectivity to additionally improve the analysis of thunderstorm analysis.

The whole cloud analysis has been updated to the latest GSI version, and is being successfully used in current real-time testing of the RR system. Two 6-h real-time cycles are currently being run and we have built an hourly cycling capability. Visibility, ceiling, and cloud-top plots have recently been added to the post-processing for the cycles and we have begun to examine the impact of the cloud analysis within the RR cycle.

Experiments are ongoing, but initial results indicate that the cloud analysis is functioning properly in the GSI and is successfully removing spurious cloud and precipitation and building missing clouds and precipitation. Further adjustment to the cloud analysis is expected, but we show three figures to document the initial results.

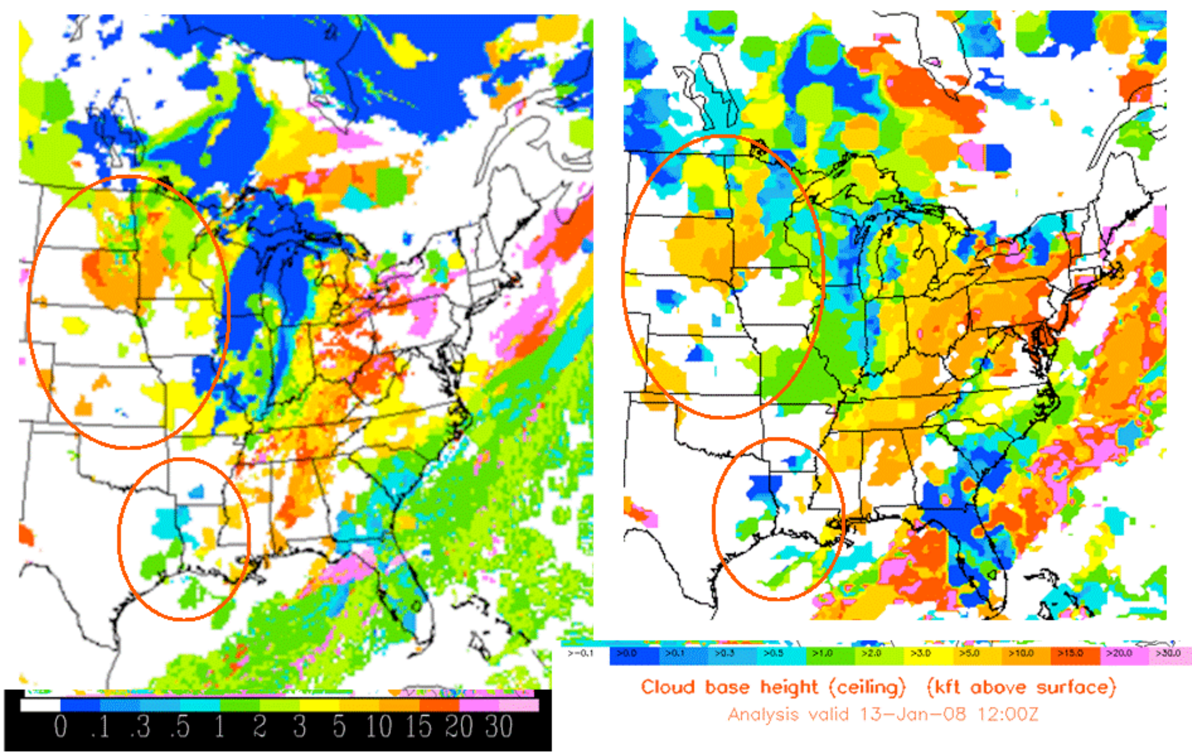

Fig. 5 (Left) Analyzed ceiling over the CONUS region for 12Z 13 January 2008 from RR 6 hour cycles and (right) the analyzed ceiling at the same time and region from RUC.

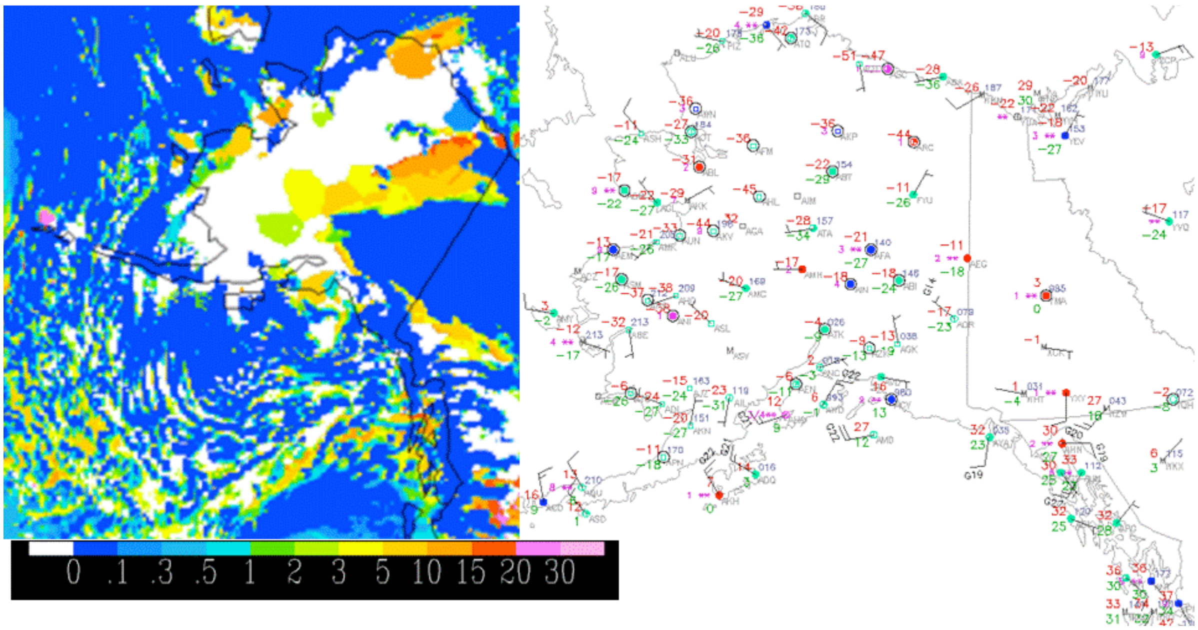

Fig. 6 (Left) Analyzed ceiling over Alaska for 12Z 13 January 2008 from RR 6 hour cycles and (right) the corresponding METAR observations

The first, Fig. 5, shows a comparison of RR and RUC analyzed ceiling for 12z 13 January 2008. As expected, the match is not perfect, consistent with the cycling using different model, similar characteristics can be seen in a number areas (indicated by ellipses). This confirms the initial successful implementation of the cloud analysis within the GSI for the Rapid Refresh cycle.

Fig. 6 shows a comparison of the same RR ceiling analysis over Alaska with METAR observations from 12z 13 January 2008. Again, a similarity of fields can be seen with low clouds in east central Alaska. In addition, the impact of individual METARs can be seen in the RR ceiling analysis. While these results are preliminary, they document an very important step in the RR cloud analysis development, the use of METAR cloud information over the Alaska region. Given the importance to Alaskan aviation of accurately forecasting the extensive low cloudiness in the region, further development and assessment of this aspect of the RR will continue to be a high priority.

Fig. 7, similar to Fig. 5, shows a comparison of RR and RUC analyzed cloud-top from the same 12z 13 January 2008 time, over the COMUS region. This analysis is primarily influenced by the background cloud fields and the satellite cloud-top pressure. Again a similarity between the RR and RUC analyses confirms the initial success of the coding to incorporate the general cloud analysis into the GSI for the RR cycle.

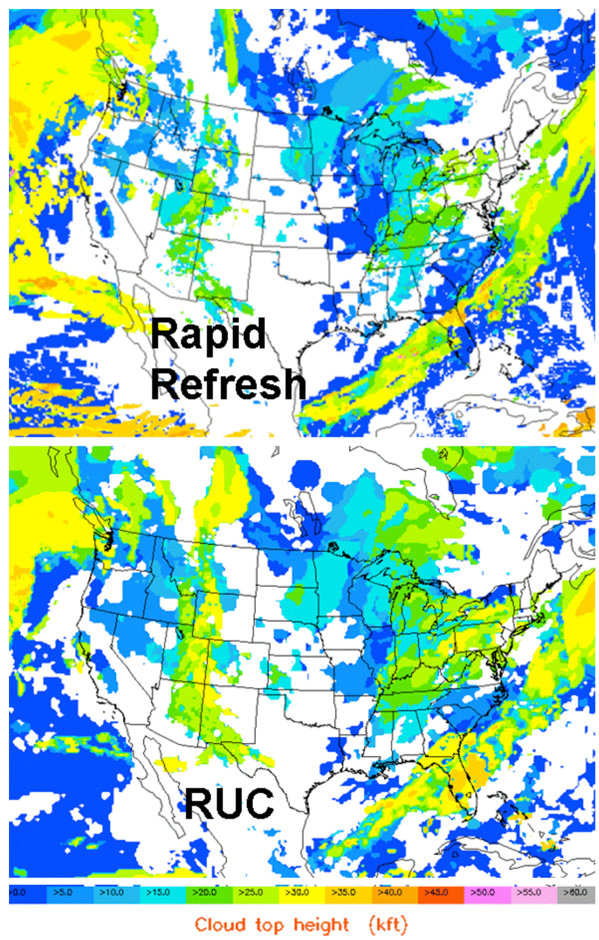

Fig. 7 (upper) Analyzed cloud-top height over the CONUS region for 12Z 13 January 2008 from RR 6-h cycles and (lower) the analyzed cloud-top height at the same time and region from RUC.

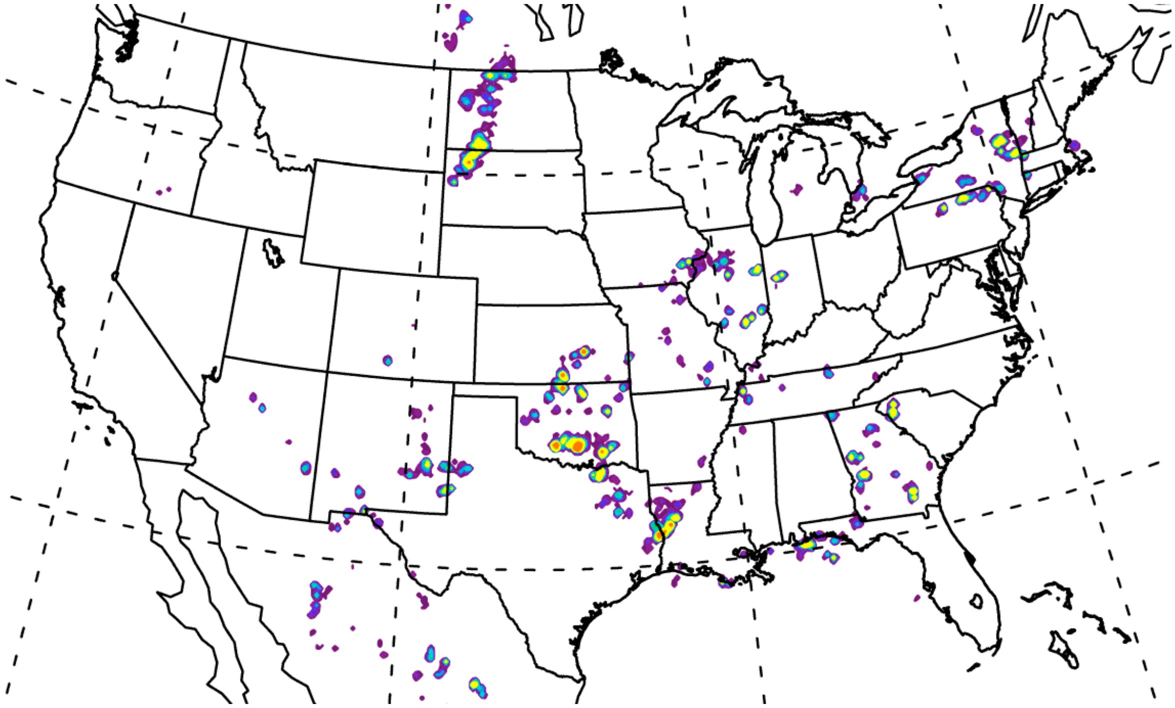

Fig. 8 Observed lightning ground stroke density distribution over CONUS domain at 00 UTC 10 July, 2007

A final aspect of the recent cloud analysis development work for the GSI, has been focusing on inclusion of the radar and lightning data in the RR.

A separate GSI pre-processing routine has been developed to parallel process the radar reflectivity mosaic tile data and interpolate it to the RR grid. A similar program has been developed for processing the reflectivity tiles at NCEP for use with the RUC hourly reflectivity assimilation. The lighting data from NLDN and Alaskan BLM have been processed and converted into reflectivity to additionally improve the analysis of thunderstorm analysis. This thunderstorm analysis capability complements the stratiform cloud analysis aspects described previously. As noted earlier, consistent with different model applications (parameterized vs. explicit convection) different thunderstorm analysis options exist for specification of cloud and hydrometeors, and in storm temperature perturbations.

More detailed assessments of the convective cloud analysis aspects will be presented in the future. We show here examples of the radar and lightning data coverage. Figs. 8 and 9 show NLDN lightning stroke density and radar reflectivity, respectively, over CONUS. As expected, there is a strong correlation between the fields, with the lightning data being skewed toward the more intense radar echoes. In the general cloud analysis algorithm, a simple linear relationship and assumed vertical profile are used to convert lightning stroke density into proxy 3D reflectivity data that complement the actual reflectivity data.

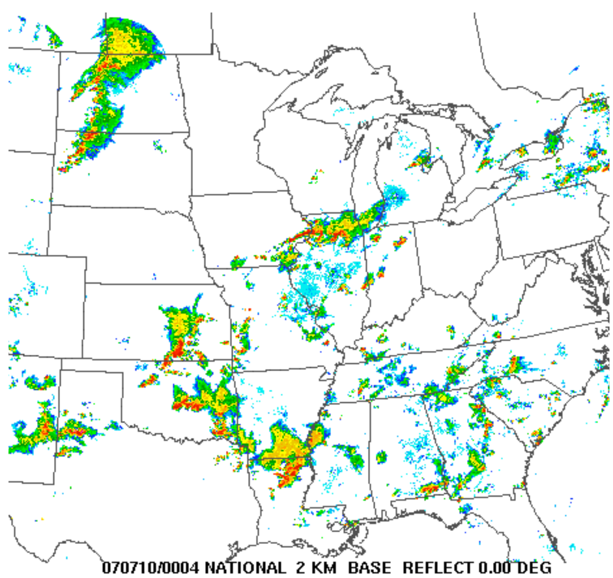

Fig. 9 Observed low-level radar reflectivity for 00 UTC 10 July 2008.

The combined reflectivity data (actual + proxy from the lighting data can then be used to modify cloud, hydrometeors and temperature in the cloud analysis or to specify latent heating-based temperature tendencies for use in the diabatic digital filter initialization.

Over the CONUS, the lightning data can be used to fill in radar data gaps, cover for missing radar data, and provide a selective enhancement for intense convection. For the RR domain, however, which covers all of North America and large areas of adjacent oceans, large regions exist with no radar data cover

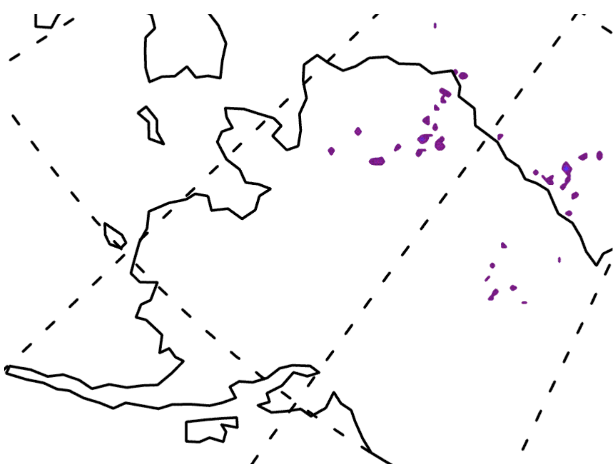

Fig. 10 Lightning ground stroke density for 00z 10 July 2008 over Alaska. Information from BLM data provided by the Alaskan Region National weather Service.

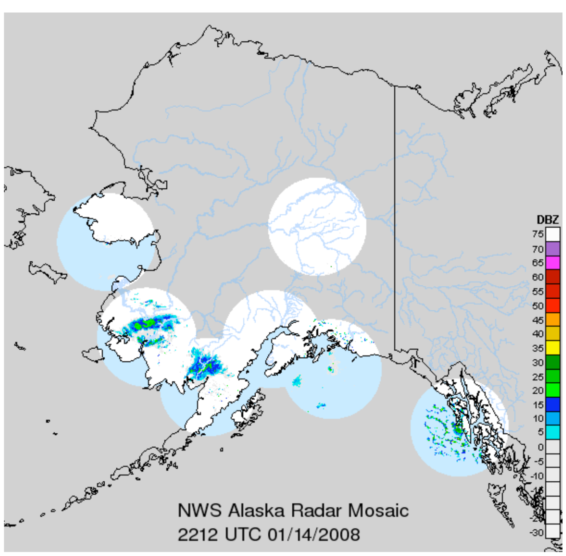

Fig. 11 Map showing low-level radar data coverage circles for the Alaskan WSR-88D radar network. Note, actual radar echoes are not time/date-matched with Fig. 10 and higher-level scans provide somewhat larger coverage

age. In these areas, lightning data become the primary observation source of convective activity. As such, we anticipate that lightning data will play a significant role in the RR cloud analysis over regions such as the Caribbean, Alaska and elsewhere.

Figs. 10 and 11 illustrate this potential for the Alaska region. For the past two seasons, the Alaska Region National Weather Service has provided us with a real-time feed of Alaskan lightning data from BLM sensors. Fig 10 shows the lighting ground stroke density for 00z 11 July 2008. For comparison, Fig. 11 shows the radar data coverage circles for the Alaskan WSR-88D radar network. Note, actual radar echoes are not time/date-matched with Fig. 10 and higher-level scans provide somewhat larger coverage. As can be seen , the Alaskan lightning data will be an important complement to the radar data, providing convective information of extensivce areas with no radar data coverage. We anticipate this will be an important data source during the summer convective fire season in Alaska.

6. Summary and Discussion

In this paper, we first briefly illustrated the cloud analysis procedure, with emphasis on the stratiform cloud analysis problem. We then summarized a recent upgrade to the operational RUC cloud analysis to make better use of METAR cloud information. We then described extensive new development and testing of the generalized cloud analysis procedure in GSI for Rapid Refresh. The new developments are mainly on the efficient, parallelized application of the cloud analysis in the RR cycled forecasts. 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 general cloud analysis scheme is running well in 6 hour cycles in big Rapid Refresh domain and preliminary 1-h cycled forecast experiments have been completed. Initial examination on the results over the full RR domain shows that the cloud analysis is able to improve precipitation prediction by reducing spurious precipitation, building up part of the weather system, and enhancing cyclonic precipitation. The ongoing cold season assessment, which has focused on stratiform clouds and precipitation systems, will be complemented by a warm season assessment, emphasizing convective systems.

Work to make the cloud and precipitation analysis more consistent for both stable and convective cloud systems, further refine the real-time parallel testing system, and examine the impact of the cloud analysis in a more systematic way is ongoing and we will report the results in the future.

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