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Title of the Investigation:

"Improvement of Operational Aircraft Icing Forecasts and Diagnoses by Assimilation of Satellite Cloud/Surface Properties in the RUC/WRF"

Decision Support through Earth Science Results

Integrated System Solutions for Applications of National Priority: Aviation

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Abstract

Liquid water path (LWP) is one of the key variables for diagnosing aircraft icing conditions and is currently represented poorly in the numerical weather prediction models, in particular the NOAA Rapid Update Cycle (RUC) model used by the FAA Aviation Weather Program for diagnosing and forecasting aircraft icing conditions. New NASA Earth Science products, available from analyses of Geostationary Operational Environmental Satellite (GOES) and Terra and Aqua MODIS data, include state-of-the-art estimates of LWP that are made available in a timely fashion. This proposal describes a plan to assimilate the Langley Research Center (LARC) GOES and MODIS cloud products into the RUC analysis to improve diagnoses and forecasts of aircraft icing conditions with potential impacts on general weather forecasts and other transportation methods. The work includes evaluation of the current state of the RUC condensate analyses and forecasts, the uncertainties in the LARC products relative to current RUC inputs, development of assimilation programs and hierarchies, and development of a prototype operational processing system. The results of this study will be the first step along a clear path for improving weather forecasts operationally in both the near-term and long-term using future advanced satellite sensors.

I. Project Plan & Approach

1. Introduction, Decision Support Tools: AWRF Products, CIP & FIP

Numerical weather forecasts and analyses by the NOAA Rapid Update Cycle (RUC) model and a future version, the Rapid Refresh (RR) using the Weather Research and Forecast (WRF) Model, are essential components of the FAA Aviation Weather Research Program (AWRP). The AWRP and the RUC (RR-WRF) are two of the four National Airspace System elements addressed by the NASA Aviation Application. The AWRP products (Fig. 1, center), which include the Current Icing Potential (CIP), Forecast Icing Potential (FIP), flight altitude winds and temperatures, and precipitation, constitute a set of decision support tools for improving aviation safety and flight planning over the continental USA (CONUS). Because the RUC is key to so many AWRP components, any significant improvements in its forecasts and analyses will have a substantial impact on both general and commercial aviation throughout the country via the AWRP products.

Currently, hourly 4-8 km resolution cloud properties are being generated at NASA Langley Research Center (LARC) under the NASA Advanced Satellite Aviation-weather Products (ASAP) Initiative. The products include liquid water path (LWP), cloud top height, cloud droplet effective radius r_{eff}, and icing probability and intensity among other parameters. These products are being integrated into the AWRP CIP to complement the RUC output and pilot Reports (PIREPS) currently being used to produce the CIP. The LARC products are based on near-real time analyses of Geostationary Operational Environmental Satellite (GOES) radiances using algorithms that derive similar products from the NASA Earth Science Enterprise (ESE) satellites, *Terra* and *Aqua* (Minnis et al., 2002, 2004a). The current configuration of the integrated system using the LARC and the RUC output in the AWRP products is shown as the blue arrows and black text in Fig. 1. The proposed changes to the system are indicated in red.

2. Project Objective & Approach

2.1 Background

The RUC currently assimilates a wide variety of data to analyze cloud parameters (Fig. 2) including the NESDIS cloud-top pressure and temperature product based on the GOES data, surface METAR cloud, ceilometer, and visibility observations, and radar reflectivity. RUC 1-h forecasts are currently used to differentiate between ice and water clouds (Benjamin et al., 2004a,b). These data are used to modify the hydrometeor mixing ratios forecast 1-hr earlier by the RUC. Efforts are ongoing to improve RUC forecasts of all parameters by assimilating new datasets as they become available (e.g., Benjamin et al., 2004c) and by moving to a higher resolution grid (Benjamin et al., 2004d).

The recently available NASA LARC satellite products (Minnis et al., 2004b) represent a significant advance in quantifying cloudiness in near-real time at high temporal and spatial resolutions. Determination of cloud phase each hour greatly exceeds the capabilities of the NOAA satellites that pass over a given area 2-4 times per day. LWP and ice water path (IWP) interpreted with state-of-the-art models can provide cloud thickness and hydrometeor constraints unavailable from the NESDIS cloud-top product, GOES radiances, and surface observations. Other LARC products such as cloud base and top heights and surface skin temperature are also new variables that have potential for assimilation into numerical weather analyses. By providing

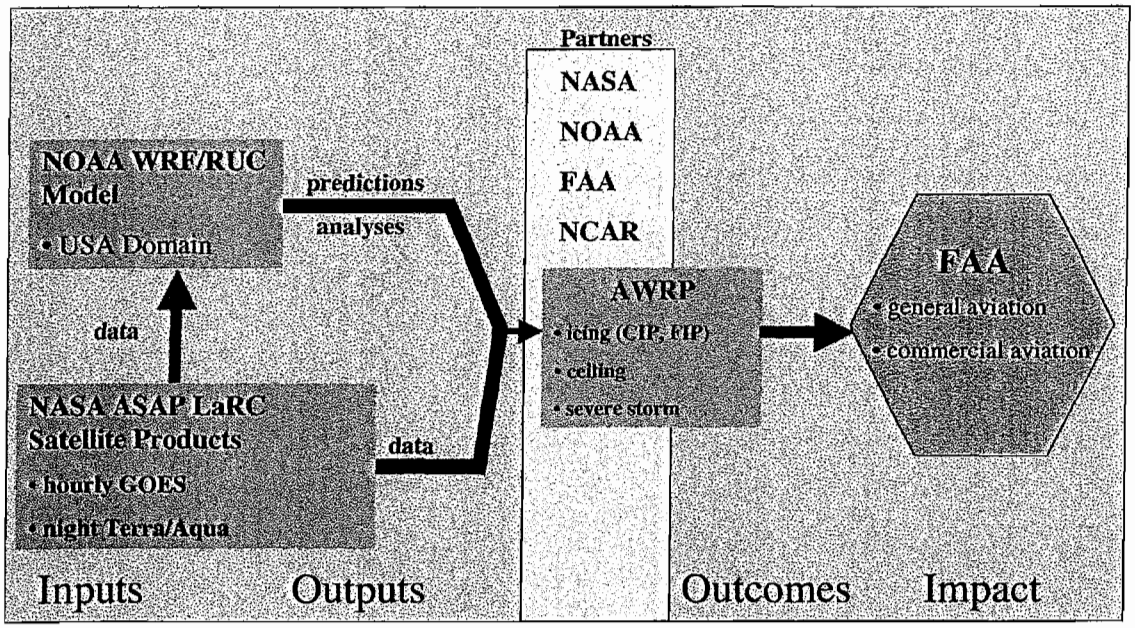

Fig. 1. The integrated system approach addressed here. The red arrow indicates the work that will be performed under this proposal to improve the output from the models with subsequent improvement in the outcome (CIP) and better information provided to the FAA.

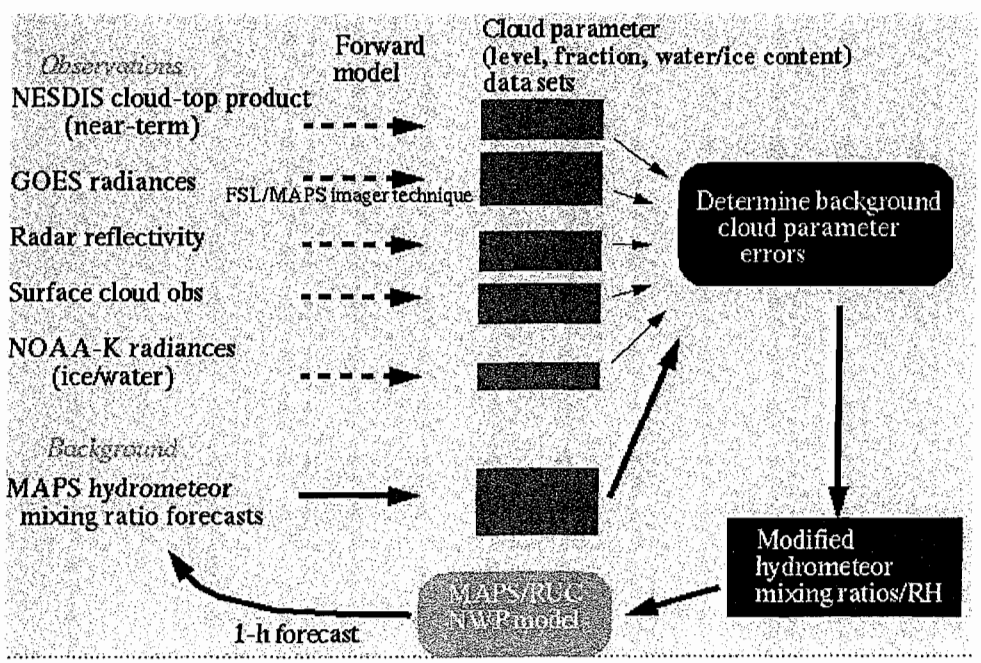

Fig. 2. Current cloud information assimilated into RUC for cloud analysis.

additional input from the GOES data, it should be possible to improve the RUC analyses and forecasts, thereby, leading not only to improvements in the CIP and FIP, but to various other decision support tools as mentioned below.

2.2 Objective and Impact

The objective of the research proposed here is to develop a system to assimilate near-real time cloud and radiation products from GOES, Terra, and Aqua into the RUC in order to improve the accuracy of RUC analyses and forecasts. The system will be designed to become a part of the operational RUC/RR-WRF models and will be compatible with future generations of weather satellites.

While this research will favorably impact the aviation decision support tools, it is uniquely important because the improvements in forecasting gained by this research will have a direct path to operational National Weather Service (NWS) model forecasts via the RUC/WRF and its developer group, the NOAA Forecast Systems Lab (FSL) led by one of the Co-Principal Investigators. The RUC system provides the highest frequency of forecasts of any NOAA models. Satellite data can have the greatest impact on high temporal resolution models because they can be used to update the model fields to match closely with the actual changes in continuous fields over the domain rather than to changes in discrete portions of the domain (i.e., surface observations). The research follows the natural progression of the RUC assimilation process that brought in the GOES cloud-top data and the other quantities indicated in Fig. 2. The RUC output is not limited only to aviation, but is applicable to many other societal concerns including other transportation systems, severe weather forecasting, energy management, and the broader NWS goal of developing a "situational awareness model." Thus, successful accomplishment of the proposed assimilation development will impact a broad range of decision processes to enhance a variety of societal outcomes.

2.3 Approach

The cloud product input for the assimilation is based directly on the algorithms developed for the ESE Clouds and the Earth's Radiant Energy System (CERES; Wielicki et al., 1996, 1998) and currently being used to analyze Moderate Resolution Imaging Spectroradiometer (MODIS) data taken form the *Terra* and *Aqua* platforms in addition to the GOES data for ASAP. The research proposed here will deliver a blended product using the ASAP GOES output for all times and CERES MODIS analyses taken at night. The latter analyses use the additional spectral channels of MODIS to provide more information at night, when the spectrally limited GOES imager has more difficulty detecting and interpreting cloudy pixels. Because the future GOES-R series of geostationary satellites will have imagers with spectral channels similar to those on MODIS, the framework for using the current GOES and MODIS data will be directly transportable to use with the GOES-R data stream when it becomes part of the operational system. Additionally, it will also be suitable for assimilating LARC-MODIS cloud products into the NWS forecast models over Alaska where GOES data are of limited utility.

The research proposed here will initially focus on assimilating one set of parameters, namely LWP and IWP because they are so important for precipitation and aircraft icing. Additional parameters will be examined for assimilation later after demonstrating the improvements gained by introducing the initial set into the RUC process. The approach will consist of four steps: evaluation, verification, validation, and benchmarking. *Evaluation will consist of statistical assessment of the current RUC output in terms of the analyzed and predicted*

fields via comparison with the LARC products. Verification will consist of determining the range of conditions when the LARC products are accurate enough for assimilation. Validation will consist of determining if the assimilation improves the analyses and forecasts sufficiently to warrant its use in an operational environment. The benchmarking will implement the assimilation in a pseudo-operational environment for a selected set of reference cases to determine the level of improvement in the decision support tools, i.e., the CIP and FIP. The gain in accuracy of the analyses and forecasts will be determined relative to the current levels using standard weather forecast evaluation techniques and though comparison with satellite data. In partnership with the ASAP and AWRP, improvements in the CIP and FIP will also be determined for the same selected time periods. The operational requirements for implementing the new process will then be determined for future incorporation of the new satellite datasets in the RUC/WRF models.

3. NASA Earth Science Datasets

Two datasets are considered here. The first consists of the ASAP LaRC cloud products that are derived from 4-km GOES imagery over the entire CONUS (Minnis et al., 2004). The second is composed of similar cloud products derived from 1-km MODIS data from Terra and Aqua by the CERES project. The algorithms used to analyze the data consist of two components: cloud detection (e.g, Trepte et al., 1999) and cloud property retrievals (Minnis et al., 1995, 1998, 2002, 2004b). The cloud detection algorithm for MODIS relies on the 0.65, 1.6, 2.1, 3.7, 10.8, and 12.0-μm channels during daytime, while at night and in sunlight near the terminator (twilight) it uses the 3.7, 6.7, 8.5, 10.8, and 12.0-μm channels. A subset of this algorithm is used for the GOES data using the available GOES channels: 0.65, 3.9, 6.7, 10.8, and 12.0 μm. For cloudy pixels, the visible infrared solar-infrared split-window technique (VISST; see Minnis et al., 1995, 2002) is used to determine cloud phase and derive cloud effective temperature Tc, effective droplet radius r_e or ice crystal diameter D_e, and optical depth OD. Values for LWP and IWP are simple functions of OD and r_e or D_e. Cloud effective height is determined by matching the value of Tc to the nearest RUC temperature profile. Cloud-top height z_t and thickness are estimated using a set of empirical functions (Minnis et al., 1990; Chakrapani et al., 2001). The thickness and z_t are used to estimate cloud base height z_b. The pressures corresponding to the cloud height parameters are also determined from the RUC profiles. Top-of-atmosphere shortwave albedos and outgoing longwave radiation are computed for all pixels while surface skin temperature is estimated for each cloud-free pixel. An aircraft icing probability and intensity index is also computed based on LWP, Tc, and r_e (Minnis et al., 2004).

The daytime part of the code is the most stable and robust and produces the highest quality products. At night and at twilight, much less information is available because the infrared channels saturate at a nearly constant brightness temperature value when the clouds become optically thick (OD > 6). The solar-infrared infrared split-window technique (SIST) is used at these times, but it mainly differentiates between optically thick and thin clouds and corrects Tc for semi-transparent clouds. Around twilight periods, the 3.7 (3.9) μm channel loses a lot of information because its solar-reflected signal tends to cancel its emitted signal so that low clouds become difficult to detect. For MODIS data, this is less of a problem because the 8.5-μm channel (to be on the GOES-R imager) is unaffected by the sun while having a similar emitted signal.

The 8.5-μm channel also provides some reinforcement for the nighttime cloud detection, so the CERES MODIS nocturnal cloud detection is more robust than that for the current GOES

channels. Figure 3 presents an example of the GOES phase determination, the MODIS brightness temperature differences (BTD) between the channels 29 (8.5 μm) and 31 (10.8 μm) and channels 20 (3.7 μm) and 31 as well as the GOES BTD between channels 2 (3.9 μm) and 4 (10.8 μm), BTD24 (Fig. 3c). BTD24 is much noisier than its MODIS counterpart (BTD20-31) making it difficult to identify (Fig. 3a) all of the supercooled low clouds in western Nevada, around the Great Salt Lake, and southern Idaho that are glaringly evident as negative (dark) values in Figs 3b and d. Consistency checks between BTD29-31 and BTD20-31 used in the CERES algorithm help identify such clouds with little difficulty.

The GOES products are currently produced every half hour by sampling every other line and pixel of the 4-km GOES data to enhance processing speeds. The results are available within 30-90 minutes after the image time, a delay that is only a function of the computer processing resources. The results are made available in gif and binary formats at the LaRC website (*http://www-angler.larc.nasa.gov/satimage/products.html*). The GOES-10 and GOES-12 data are ingested from the University of Wisconsin McIDAS system and analyzed separately, then combined to cover the entire CONUS over an area that roughly corresponds to the RUC domain. The programs are written in modular components facilitating upgrades to various subsystems as improvements are developed. The CONUS processing has been ongoing for more than 1 year and has been upgraded several times.

The CERES analysis has been applied to McIDAS-based MODIS data in near real time over the eastern US during field experiments (Minnis et al., 2004b) and is currently being applied globally at the NASA Langley DAAC in near real-time to MODIS data obtained from the NASA GSFC DAAC as part of the NASA Applications-supported FLASHFlux project (P. Stackhouse, personal communication). One of these two resources will provide data for the development of nighttime *Aqua* and *Terra* MODIS cloud products for this proposed assimilation effort.

Preliminary validation studies using in situ and surface radar and microwave radiometers indicate that the VISST-derived values of LWP (e.g., Dong et al, 2002) and IWP (e.g. Mace et al., 1998; Young et al., 1998; and Mace et al., 2005) are, on average, relatively unbiased for relatively thick stratus (OD > 10) and thin cirrus (OD < 6) clouds, respectively. Preliminary dual angle analyses using GOES-10 and 12 over stratus areas suggest that the LWP rms errors are on the order of 10 - 30%. Other validation efforts are continuing. Areas of concern for these products include the nighttime and twilight difficulties mentioned earlier in addition to retrievals over snow and in multilayered cloud conditions. Huang et al. (2005) found that the total condensate water path can be overestimated by up to 100% or more in overlapped ice-over-water cloud cases when the standard algorithms are used. The GOES and CERES algorithms will both be upgraded in the coming year to include multilayered cloud detection and analysis methods (e.g., Kawamoto et al., 2002; Chang and Li, 2005; Minnis et al., 2005) that should provide useful flags for data users and, possibly separate estimates of LWP and IWP in some cases. The CERES MODIS methodology includes an algorithm for more accurate retrieval of OD and LWP over snow fields based on the 1.6-μm channel that is unavailable on the current GOES imager, but will be part of GOES-R. These uncertainties and others will be taken into consideration during the Evaluation process.

We plan to work with two satellite datasets when executing the proposed research. The first dataset will consist entirely of LARC GOES output from algorithms in place in June 2005. At that time, the initial operational phase for the LARC ASAP cloud products will commence and the algorithm will be frozen for a year or more. During the following year, improvements

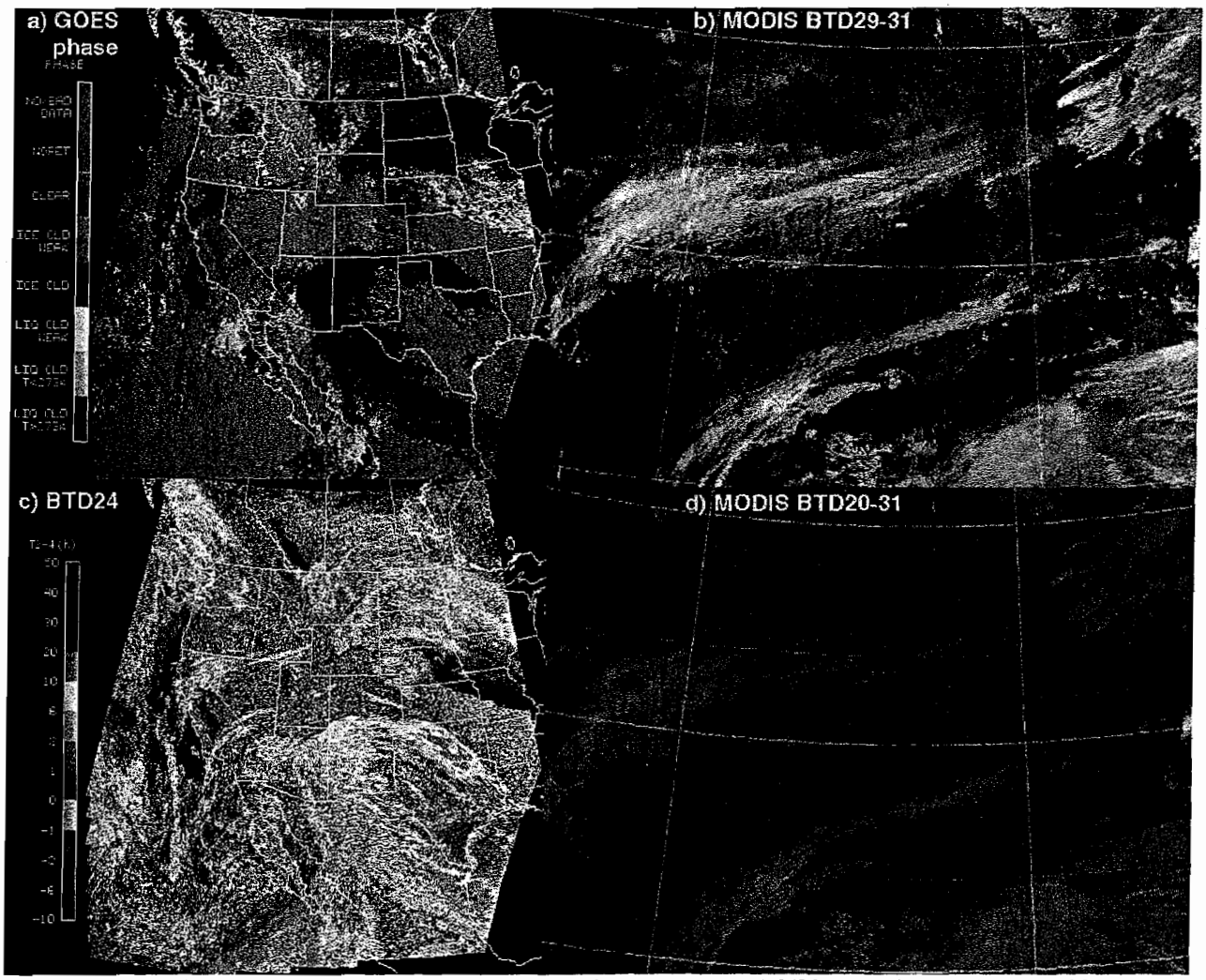

Fig. 3. Cloud phase and brightness temperature differences from GOES and Aqua MODIS, ~0900 UTC, 21 January 2005. (a) Dark blue - warm water clouds, light blue - supercooled water clouds, green - clear, red - ice clouds. (b) and (d) dark areas denote negative BTD. (c) Blues - negative BTD.

such as multilayer cloud detection and enhanced nighttime analyses will be finalized and the value of the MODIS retrievals will be determined. The second dataset then will be composed of results from the updated GOES algorithms and the MODIS retrievals. These datasets will be used in the evolution of the RUC cloud assimilation algorithm.

4. RUC Assimilation Process

Aviation and other transportation users have an urgent need for considerable improvement in predictions of clouds, fog, ceiling/visibility, and stable and convective precipitation. Beyond a few hours, model-based predictions of these sensible weather elements are the main source for forecaster guidance. Accurate model predictions of these elements requires accurate specification of cloud and hydrometeor fields in model initial conditions.

The RUC cycles at full-resolution five microphysical species (cloud water, cloud ice, and rain water, snow, and graupel) and has the capability for updating these fields from observations. A description of the RUC model parameterization for mixed-phase hydrometeors is in Benjamin et al. (2004b). In the operational RUC run at NCEP, the NESDIS GOES cloud-top data are used to update these fields yielding improved cloud initial conditions in the RUC (since 2002, described in Benjamin et al. 2004a). Further detail is described in Benjamin et al. (2002) and Kim and Benjamin (2001).

Each hour, the RUC cloud analysis utilizes the following sources of information as described:

- 1-h RUC explicit 3-D hydrometeor (cloud water, rain, ice, snow, graupel (forecast).
- GOES/NESDIS cloud top product (pressure and temperature) to build and clear clouds from 1-h forecast:
  - Building – add cloud water or ice, saturate water vapor.
  - Clearing – remove cloud water/ice, subsaturate.
  - Checks for convective/marine cloud situations.
- Checks for snow cover or nighttime situations with ambiguity for cloud cover presence or cloud level assignment
- METAR cloud level (broken and overcast levels only), and current weather and v visibility
- Radar reflectivity and lightning – used in FSL test versions of the RUC. (Only these have been used for building 3-D condensate field for initial conditions up to this point.)

Thus, an important problem for short-range numerical prediction is the initialization of cloud and hydrometeor fields. Clearly, satellite and radar data are important for specification of the three-dimensional cloud/hydrometeor field. Another important source of information that will be added to the operational RUC with the 13-km RUC package in spring 2005 is the sensible weather information (weather, clouds, ceiling, visibility) provided by surface METAR observations. This work with the RUC is part of a larger FAA-sponsored effort to improve ceiling and visibility forecasts over the USA (Herzegh et al. 2004). The goals in assimilating METAR ceiling and visibility observations are:

- Force near-match of RUC hydrometeor fields to current ceiling/ visibility observations.
- Improve accuracy of RUC short-range predictions for ceiling, visibility, and precipitation.

The present assimilation technique for METAR cloud and visibility is to augment the pre-existing RUC cloud analysis technique, in which 1-h forecast (background) 3-d hydrometeor fields are modified using GOES cloud-top data. The assimilation of ceiling/visibility data allows clearing and building of cloud (hydrometeor) layers, generally in the lower troposphere, sometimes down to the surface. The RUC assimilation of GOES cloud-top pressure and temperature (Benjamin et al. 2004a) is based on the creation of a 3-D gridded cloud logical field indicating volumes where: 1) it is known that clouds do not exist, 2) it is known that clouds do exist, or 3) the presence of clouds is indeterminate. The same logical structure used for GOES cloud assimilation is used again with METAR observations, resulting in a more accurate 3-d hydrometeor yes/no/unknown field. Cloud layers are identified with BKN, OVC, or VV (vertical visibility) observations.

A cloud layer depth of 50 hPa is assumed unless the same METAR observation reports precipitation, in which the depth is set at 150 hPa. Since cloud layers are assimilated on a height-relative basis, cloud depth is modified to account for intersection of mountains with cloud layers. For surface-based cloud observations, assumptions about the horizontal representativeness must also be made. In initial tests performed to date, surface-based cloud observations are assumed to be representative at up to 120 km in distance. These values can be refined in the future to be dependent on stability, the background relative humidity profile, and terrain elevation in the vicinity of the observation. METAR observations of clear conditions or ceiling levels higher than forecast are used to clear RUC analysis grid volumes. For assimilation of either satellite-based or surface-based cloud observations, assumptions must be made about the depth of the cloud layer detected.

This same data assimilation structure for the RUC cloud/hydrometeor analysis provides a starting point for assimilation design for LARC LWP and IWP retrievals. It is critical to provide inter-consistency between all of the observations to modify cloud/hydrometeor 3-dimensional fields. This inter-consistency will be used to include quality control methods with the proposed assimilation of IWP/LWP products.

During the work of this proposed project, the RUC will evolve to a new software structure with the Weather Research and Forecast (WRF) modeling system. In 2007, the current RUC software will be replaced with a new WRF-based version of the RUC to be called the Rapid Refresh (RR). The RR-RUC version will include incorporation of an assimilation code framework called the Gridpoint Statistical Interpolation (GSI) analysis. The RUC cloud/hydrometeor technique discussed above will evolve into the GSI analysis in the development of the RR model/analysis system. Thus, incorporation of the LARC LWP/IWP products initially into the current RUC cloud/hydrometeor assimilation technique will also be used in the GSI analysis for the RR-RUC system.

The revised cloud/hydrometeor assimilation technique including LWP/IWP data sets will require developing techniques for producing vertical condensate structure that is both consistent with the LWP/IWP data but also with observed cloud top (satellite) and cloud base (METAR) information. The revised technique will also include modification to divergent components of 3-D horizontal winds by using condensate values as proxy observations of vertical motion and/or by nudging toward condensate/radar observations within a diabatic version of the digital filter initialization (DFI) already used within the RUC (Benjamin et al. 2004a).

5. Technical Plan

5.1 Evaluation

The RUC condensate values need to be evaluated relative to the LARC products to determine initially where, when, and by how much the two quantities agree and disagree. Examples of some of the LARC GOES products are shown in Fig. 4 for 1500 UTC, 25 January 2005. The RGB image (Fig. 4a) combines the 0.65, 10.8, and 3.9-μm radiances to highlight snow (deep magenta), clear areas, water clouds (peachy colors and some white), and ice clouds (some white, gray, and light magenta). The VISST was used to analyze the clouds over areas with solar zenith angles (SZA) less than 80°, eastward of a line from southern Baja through North Dakota. To the west, the nighttime analysis was applied. This line is evident in Fig. 4c, which shows an abrupt change in r_{eff}. High ice (Fig. 4b, red) clouds dominate the western half of the domain (Fig. 4d), while low supercooled (Fig. 4b, light blue) and warm (Fig. 4b, dark blue) liquid water clouds cover large portions of the eastern half. These images highlight some of the problems noted earlier. Most of the clouds are properly diagnosed in the dark areas, but some errors occur in the twilight zone over Nevada and North Dakota. The values of r_{eff} are also poorly retrieved in the dark areas. Some snow-covered areas in eastern Canada are incorrectly classified as thin ice clouds. Some of the high clouds over the Midwestern USA probably overlap low-level water clouds. PIREPS in the areas with large values of r_{eff} (Fig. 4c, red) from Minnesota to Kentucky reported significant aircraft icing where the LARC icing algorithm diagnosed heavy icing (not shown).

Preliminary comparisons of the diagnosed LARC GOES and RUC LWP and IWP fields for 1500 UTC, 20 January 2005 are shown in Fig. 5. The RUC condensate fields are taken from an experimental version of the 13-km RUC, including NESDIS-GOES and METAR cloud assimilations. Some obvious differences are apparent in the LWP data, especially over water. The RUC indicates a large area with significant LWP west of Baja, while the LARC results and the RGB image (Fig. 4a) show few clouds even for nighttime. Further north, the RUC diagnoses clear sky conditions while the nighttime LARC analysis detects significant low cloud cover. The RUC LWP fields over the Gulf of Mexico and the tropical Atlantic are much less continuous than those from the GOES; IWP (Fig. 5d) appears to be overestimated in the same areas. The RUC LWP patterns off the Atlantic coast are similar to the GOES results but the magnitudes are too large. RUC diagnosed no LWP over southern Illinois where icing occurred and LWP was found by the LARC retrievals. It is clear from this initial example that the inclusion of the NESDIS-GOES and METARS data result in correct horizontal placement of a majority of the clouds. However, there are significant LWP errors in the current RUC analyses that can be reduced by assimilating the GOES cloud products, even at night.

The forecasts generated from the RUC analysis are impacted by the initial conditions as seen in the 2100 UTC results in Fig. 6. The 6-h forecast (Fig. 6b), based on the 1500 UTC analysis, maintains the large LWP values off the Baja and Atlantic coasts that are not supported by the LARC LWP retrievals (Fig. 6c). The 6-h forecast correctly places significant LWP off the Florida Gulf coast, but that LWP disappears in the 1-h forecast based on the 2000 UTC analysis. The LWP east of Florida is correctly reduced in the 1-h forecast, but much of the LWP over the northern Great Lakes is also eliminated. Because of a tendency to maintain the LWP fields in the model forecasts, assimilation of realistic values into the analysis should yield more accurate forecasts, if the assimilation is properly executed. This should be especially true for the short-term forecasts that become the basis for the next hour's analysis.

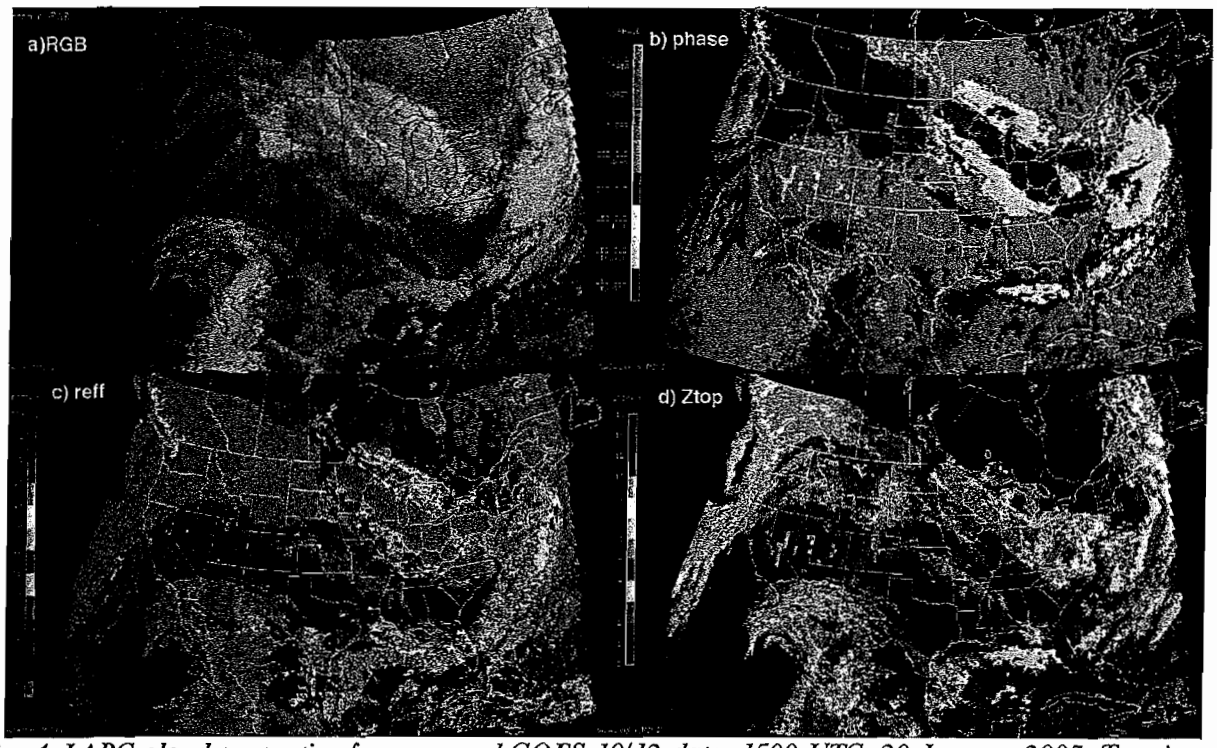

Fig. 4. LARC cloud properties from merged GOES-10/12 data, 1500 UTC, 20 January 2005. Terminator evident in left quadrant of (a).

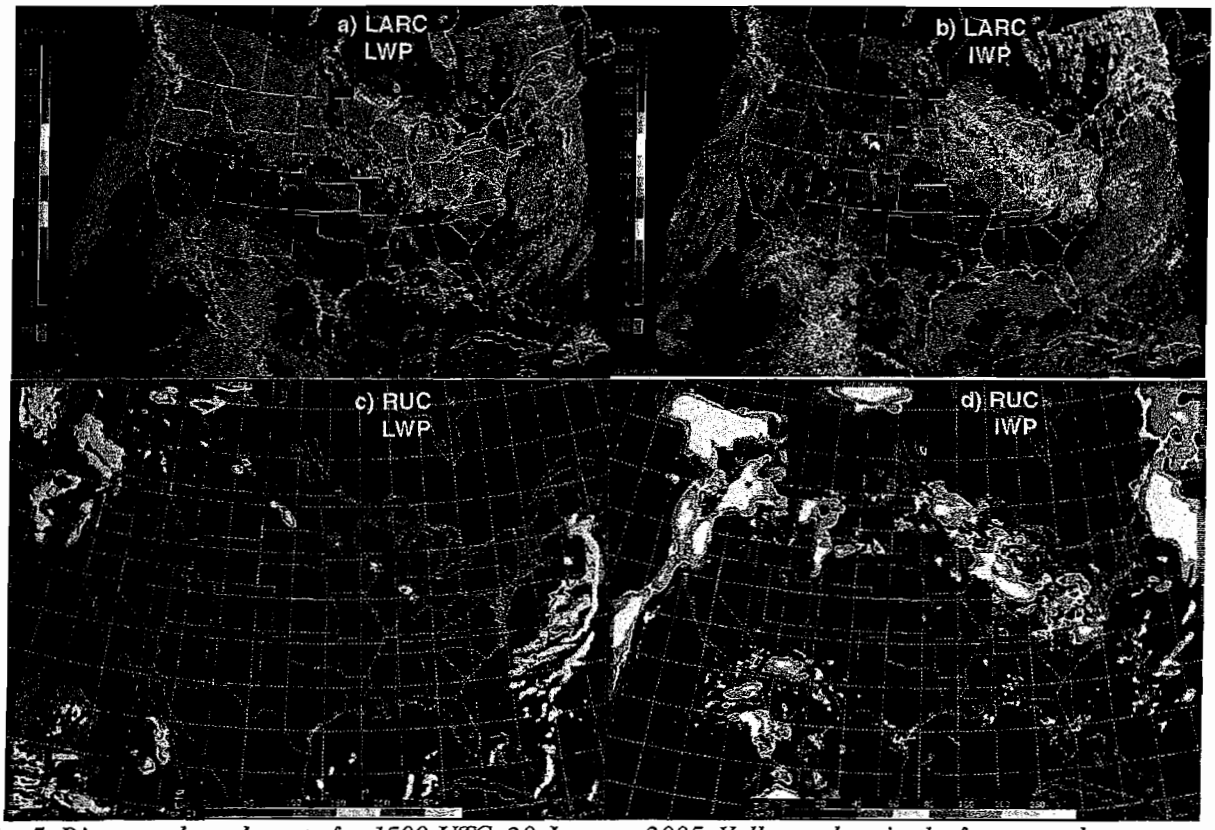

Fig. 5. Diagnosed condensate for 1500 UTC, 20 January 2005. Yellow values in the forecasts denote LWP > 250 gm^{-2}, but for (a) & (b), 250 < LWP < 300 gm^{-2}; red, LWP > 600 gm^{-2}.

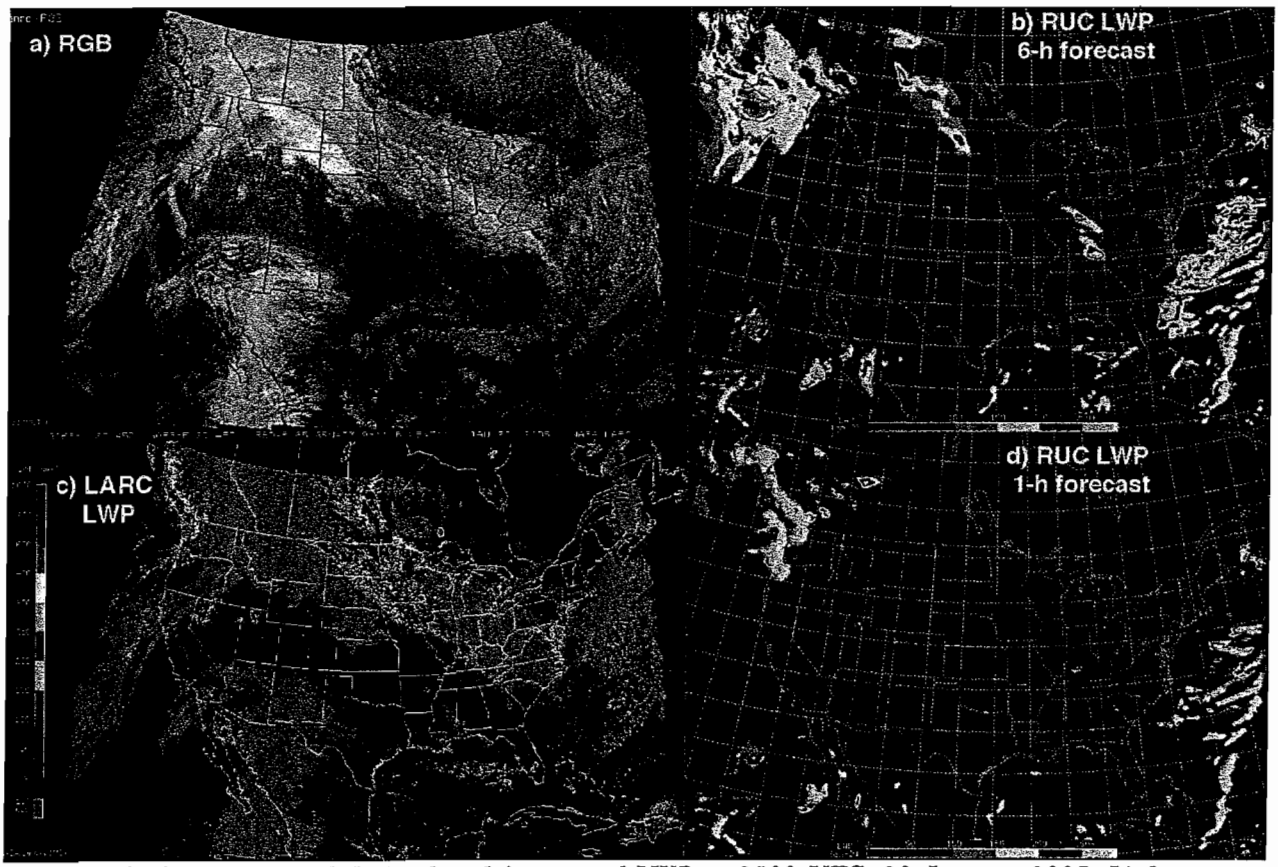

Fig. 6. GOES imagery and derived and forecasted LWP at 2100 UTC, 20 January 2005. Light green values in the forecasts denote LWP > 250 gm^{-2}, but for (b), 250 < LWP < 300 gm^{-2}; red, LWP > 600 gm^{-2}.

A comprehensive evaluation of the potential for the GOES products will be undertaken by comparing them with the RUC analyses and forecasts over selected time periods in different seasons. The comparisons will focus on the relative horizontal and vertical placements of the condensates and the magnitude of the differences, in addition to the frequency and location of total disagreement. The utility of the nighttime data for properly detecting low clouds like those off the Pacific coasts will also be examined in detail even though LWP data are not available. Comparisons of nocturnal low cloud locations from MODIS and RUC data will also be made to ascertain how much is gained by involving the MODIS results. Additionally, the locations of supercooled clouds diagnosed with the RUC analysis, forecasted by the RUC, and diagnosed from GOES data will be compared to the available PIREPS at relevant times to assess the potential value of having the satellite relative to nowcasting and forecasting aircraft icing conditions. In situ measurements from ASAP icing flights will also be used in the evaluation. The results from the evaluation will provide guidance for the next steps in this project.

5.2 Verification

Before incorporating the cloud data into the RUC, it is necessary to determine the accuracy of a given parameter over a wide range of conditions to guide the assimilation process in making decisions about when and where to rely on the results. The evaluation described above should provide information about where and when the RUC produces significant errors in the analysis so that the blending of the LARC cloud data with the other input (e.g., Fig. 2) can be optimized. This blending process will require detailed comparisons between the LARC products and other reference datasets including the current assimilation products and other reference sources such as the active and passive sensors at the DOE ARM site. The latter effort is ongoing under sponsorship of ARM program, while the former will be conducted as part of the research proposed here. An initial comparison of cloud base heights from the METARS ceilometers with their LARC counterparts is shown in Fig. 7. An examination of the heights reveals many areas of agreement to within 500 m, such as the Midwest, and other areas of disagreement such as central Alabama where multilayered clouds invalidate some of the satellite analysis assumptions. Comparisons like these and others with the NESDIS cloud-top height product will be crucial for deciding when and where to assimilate the LWP and IWP data.

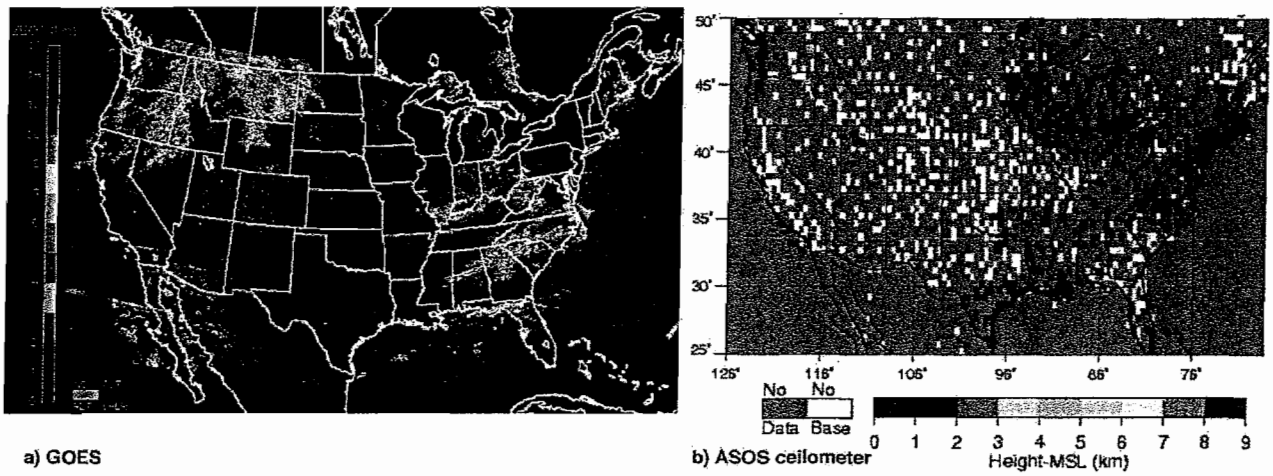

Fig. 7. Cloud base heights at 1845 UTC, 18 March 2004 from (a) LARC GOES analysis and (b) METARS ceilometer data.

When used in conjunction with the other input, the LARC product should facilitate both the vertical and horizontal placement of the condensate in the assimilation. For example, the METARS cloud base heights are interpolated or extrapolated from the surface locations out to 100 km from each site. The LARC product can be used to guide the interpolation/extrapolation because it reflects actual changes in the cloud fields from one location to the next. Similarly, the NESDIS cloud-top product sometimes has difficulty detecting low clouds and their height while the LARC sometimes has problems with high clouds. Thus, the LARC product can be used to determine where clouds occur that were missed in the NESDIS analysis.

Optimizing the location of the clouds is a critical first step prior to assimilating the condensate information. The information best suited to each data type will take precedence in deciding which dataset to use for a particular location. For example, the METARS cloud-base heights will generally trump the LARC values and also will be used to adjust the LARC results. The NESDIS top heights will take precedence for any clouds at pressures less than 600 hPa. Combining the LARC, METARS, and NESDIS information will provide valuable enhancements such as the locations of multilayered clouds where estimates of LWP and IWP are needed. Other comparisons of results with imagery will be used to establish the conditions, such as twilight, night, and snow as mentioned above, when the LARC products should even be considered In the proposed effort, systematic comparisons of the relevant parameters for different seasons will be used to develop the procedures for enhancing the input from other sources and to establish the criteria for using or not using the LARC products. The comparisons will be performed twice, once using the current LARC analyses and later using the updated GOES analyses that include a variety of improvements such as multilayered cloud analyses.

5.3 Validation

The primary validation of the improved RUC/RR forecasts will be through intensive case study evaluations for both winter and summer case studies. These case study evaluations will allow iterative

a) development of refined IWP/LWP products,
b) development of quality indicator fields for IWP/LWP grids to indicate level of confidence to be used in data assimilation,
c) development of a refined RUC/RR assimilation technique, including evaluation of the condensate values from RUC/RR analysis and consistency with the original LARC fields,
d) assessment of the effect on short-range (1-12h) model forecasts.

FSL will run parallel test periods of at least several days each in cold season and warm season to examine the impact of assimilating LARC IWP/LWP products. Parallel versions of the RUC 1-h cycle will be run for these periods with and without the IWP/LWP data, similar to the technique run for profiler impact by Benjamin et al. (2004e). This testing will evaluate changes in forecast skill for precipitation, cloud coverage, and cloud ceiling. FSL will also apply existing verification systems to evaluate effects on forecasts verified against upper-air rawinsonde (balloon) observations and against surface METAR observations. These verifications will be stratified, as necessary, to isolate anticipated effects of LWP/IWP data in local regions. The new RUC/RR forecast output will be compared with the original RUC forecasts as well as with the GOES realizations of IWP/LWP at the actual forecast times. While any gains in IWP/LWP

forecast accuracy are not likely to be accompanied by a degradation in some other forecast variable, it is critical to ensure that it does not occur.

The iterative process is summarized in the task schedule as two steps, versions 1 (V.1) and 2 (V.2). The first version uses the initial LARC GOES dataset and the second version uses the updated GOES plus MODIS dataset. This arrangement might actually consist of more steps depending on the speed of the development and testing of the various components. Work on the V.1 assimilation software will begin at the same time as the evaluation process. In developing the assimilation code, particular attention will be paid to the potential for transition into an operational environment to facilitate later conversion.

FSL and LARC will collaborate closely to select and evaluate the case studies. In addition to emails, the collaboration will include regular telecon meetings and project meetings with travel, as needed. Most of the meetings will take place in Boulder as reflected in the travel budget. Mr. Bill Smith (Co-I) will spend several weeks each year working directly with the FSL group to learn more about the assimilation process and to help develop interfaces between the RUC ingest system and the LARC products.

5.4 Benchmarking

The benchmarking process will be a more formal exercise similar to the validation worked described in the previous section. It will, however, extend into the decision support system to determine the impacts of the assimilation on the CIP and FIP. During the latter part of year 2 and until the end of the funding period, FSL and NASA will collaborate with the NCAR AWRP/ASAP team to evaluate the effects on the CIP/FIP products, specifically the horizontal, vertical, and intensity of aircraft icing, from experimental RUC and/or Rapid Refresh cycles run at FSL including the V.1 and V.2 assimilation of the LARC LWP/IWP products. As an objective measure, the benchmark effort will include comparisons with PIREPS and LARC GOES data at the realization times. Cases will be selected to include times when the NCAR team collected in situ data. The timing of the benchmarking as well as the other tasks are summarized in the Schedule section.

5.5 Expected Results and Future Outlook

Inclusion of satellite-retrieved condensate water path as an input variable in a numerical weather prediction model has not been accomplished before because the accuracy, sampling, and timeliness of the satellite retrievals and the sophistication of the weather models had not reached the levels appropriate for their merging. The state of the art in both areas, however, has reached the point where the potential benefits need to be identified and reaped. In the proposed research, we will produce a system for assimilating the LARC GOES and MODIS products into the RUC. This system will be designed for relatively easily transition into the RUC operational environment. The assimilation of the water path data should produce more accurate analyses and forecasts of clouds, locations of potential aircraft icing, and severity of the icing conditions. Additionally, more accurate representation of cloud condensate in the initial conditions should produce more accurate weather forecasts, in general, providing benefits to the multitude of activities that rely on weather information. The potential for including additional satellite parameters such as surface skin temperature will also be explored for future assimilation.

The final assimilation process, results, and the intermediate studies will be documented in conference papers and journal articles. A prototype code for ingesting and processing the LARC cloud data will be available for conversion to an operational environment.

The proposed research follows an evolutionary pathway making the best use possible of current NASA Earth Science datasets in an application critical to improving the safety of US air traffic. It provides the foundation for future integration of enhanced Earth Science products expected from more sophisticated sensors on upcoming satellites such as GOES-R. The enhancement of the RUC through the proposed research will also carry over the future operational numerical weather prediction models such as the RUC and WRF/RR. This proposal has focused on the CONUS domain, but other parts of North America could benefit from the results of this study. General aviation is a way of life in Alaska where icing conditions are frequently encountered but difficult to monitor and predict. Use of MODIS data and future NPOESS data is more suitable at high latitudes where GOES cannot view and Sun-synchronous satellites sample a given area several times each day. Furthermore, the WRF/RR will be expanded to include Alaska, so the assimilation process could also be adapted to include input strictly from the polar-orbiting satellites. In summary, the research proposed here is ideal for continued enhancement of aviation weather forecasts through the use of NASA-generated Earth Science datasets.

5.6 Management and Analysis Team

The proposed team is an interagency group utilizing the many years of experience in satellite cloud remote sensing at LARC and numerical weather prediction and assimilation at NOAA FSL. Dr. Patrick Minnis has been developing and applying methods for remotely sensing clouds and the surface for over 27 years. He pioneered the use of geostationary satellite data for objectively quantifying clouds and the radiation budget (Minnis and Harrison, 1984) and currently leads a group developing new techniques for remotely sensing clouds using a variety of satellites and imagers. Dr. Stan Benjamin has been actively involved in the study and development of numerical weather prediction models and data assimilation for over 20 years. During the last decade, he directed the development of the Rapid Update Cycle. Drs. Minnis and Benjamin will be jointly responsible for the overall direction of the proposed research.

Dr. Minnis will have overall responsibility for the satellite analyses and comparisons and construction of the prototype operational environment. Bill Smith (LARC), who has been analyzing satellite data for more than 15 years, is currently completing his PhD studies at the University of Wisconsin. He will be participating with the goal of developing a PhD dissertation on the assimilation of satellite cloud products with guidance provided by Dr. Benjamin. Mr. Smith will be directly responsible for the comparisons of the LARC cloud products with the NESDIS, METARS, and RUC datasets and will participate in the formulation and testing of the code to assimilate the LARC products. Louis Nguyen has been developing programming systems for ingesting, storing, and analyzing both geostationary and low-Earth orbit satellite data for nearly 15 years. He will be responsible for directing the development of the semi-operational environment for testing the LARC products and serving them to the RUC assimilation system. He will work closely with the FSL group to ensure that the satellite output will be provided to FSL in formats and resolutions developed using an open consensus approach with appropriate documentation to meet ISO standards. A full-time contractor will work with the LARC group to conduct comparisons and analyses as directed by the Co-PI and Co-I's and to develop programs and documentation as needed.

Dr. Benjamin will have overall responsibility for the assimilation studies and the development and assessment of the weather forecast products and metrics. FSL will hire a new data assimilation scientist to work at a 50% level on this project. The data assimilation scientist

will have experience in operational numerical prediction modeling, and in use of satellite observations. This scientist will be hired either through a Federal or a cooperative institute position.

The team will work closely with the FAA AWRP through its current ties at NCAR via the NASA ASAP program. The LARC group is already working with the NCAR RAP team to assimilate the LARC products directly into the CIP. Dr. Benjamin leads the AWRP Model Development and Enhancement PDT and also works closely with the NCAR/FAA group. Both the FSL and LARC group will work closely with the NCAR team to determine the impact of the improved analyses and forecasts on the CIP, FIP, and other air safety decision support tools. This proposed research has been endorsed (see letters of support) by Gloria Kulesa, the FAA AWRP Team Leader and John J. Murray, the Deputy Program Manager for Aviation Applications at NASA LARC.

Minnis and Nguyen also work closely with the LARC DAAC to acquire, process, and disseminate both GOES and MODIS data as part of the CERES team. Nguyen led the effort to consolidate the ingestion of GOES data at the DAAC for the CERES project and will be responsible for interacting with the DAAC to access FLASHflux output (near-real time analysis of MODIS and CERES data) and to develop a plan for transition of the GOES and MODIS data processing into an operational environment, possibly at the LARC DAAC, and for developing the real-time interface with the FSL assimilation system.

II. Task Schedule

2006:

Evaluation

- *Compare RUC-GOES WP*

Verification

- *Establish LARC data accuracy criteria*
- *Compare GOES, NESDIS & METARS (GNM) data*

Validation

- *Develop/test V.1 LWP/IWP assimilation code*

Documentation

- *Present RUC comparison results at natl conf*
- *Submit RUC-GOES comparison paper*

2007:

Evaluation

- *Establish prototype criteria for LARC WP use*

Verification

- *Compare GOES & MODIS results in night & snow*
- *Determine criteria for using MODIS data*
- *Compare NESDIS & METARS w/updated LARC*

Validation

- *Develop/test V.2 LWP/IWP assimilation code*
- *Develop hierarchy for assimilating GOES, NESDIS & METARS data*

Benchmarking

- *Work with AWRP/ASAP to benchmark CIP/FIP using V.1 LARC data assimilation*
- *Refine code of most mature components to operational standards*

Documentation

- *Present V.1. LWP assimilation & GNM comparison at natl conf*
- *Revise comparison paper*
- *Submit paper of V.1 assimilation results*
- *Submit paper comparing GNM data*

2008:

Evaluation

- *Compare RUC-GOES ztop, Tsfc, Tcld*

Verification

- *Compare NESDIS & METARS w/updated LARC*

Validation

- *Finalize hierarchy for assimilating GNM*
- *Test forecast/analysis w/ MODIS data*
- *Develop & test V3 LWP/IWP assimilation*

Benchmarking

- *Benchmark CIP/FIP using V.2 LARC data assimilation*
- *Design prototype system for transition to operations*

Documentation

- *Present V.2 LWP assimilation & GNM comparison at intl conf*
- *Revise GNM comparison & V.1 papers*
- *Submit paper of V.2 assimilation results*
- *Submit paper documenting V.2 input*

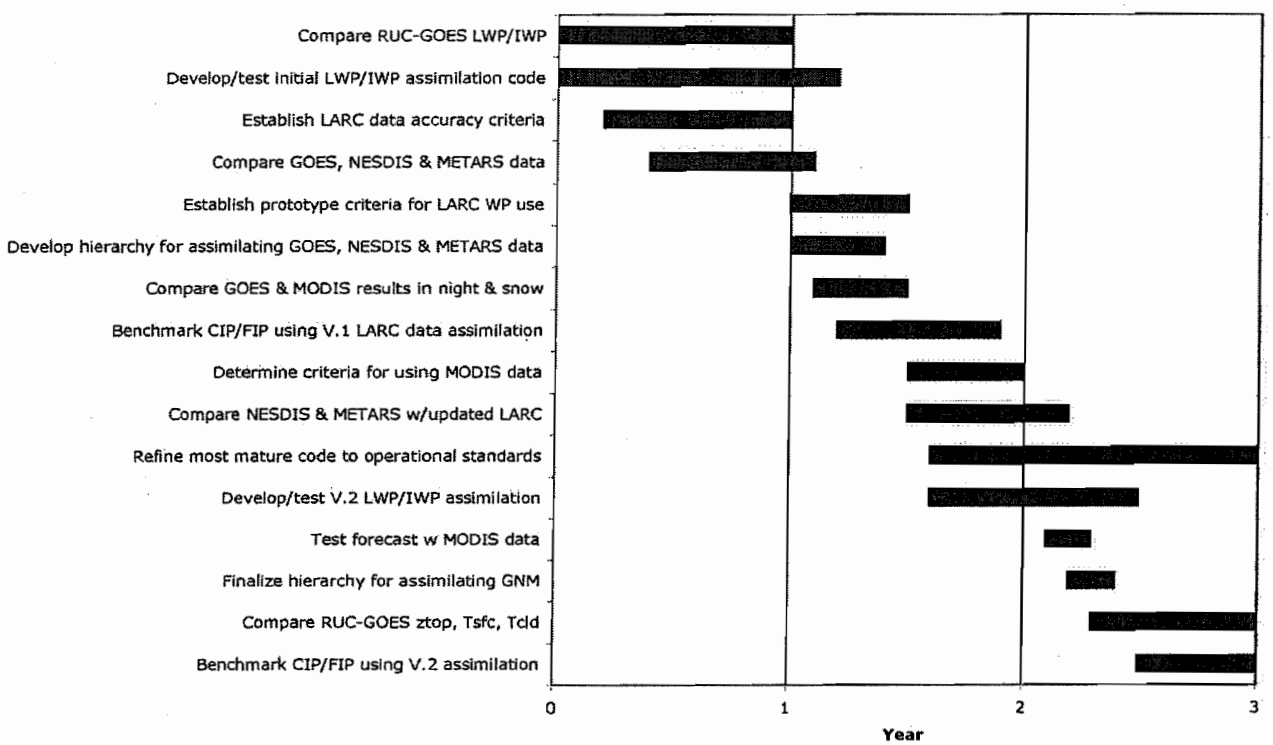

Fig. 8. Schedule of major tasks.

III. Performance Measures

The performance measures used here will consist of meeting milestones by projected dates, such as the tasks outlined in the schedule above and the documentation of the processes and results. The evaluation process will be judged a success if it determines that the LWP and IWP values for the "best" LARC products are significantly or insignificantly different than the current RUC output for both forecast and analysis products. If significant differences are found, the study will proceed to develop the criteria for using one or more components. Measures that will be used to judge when to use or not use the LARC products will include the uncertainties derived from the verification process and external validation efforts. The criteria will be adjusted using higher order products such that the use of LARC data will not introduce an error relative to those higher order (i.e., METARS or NESDIS cloud top) products for the locations and conditions for which they are most accurate. The criteria for assimilation will be adjusted until those errors are minimized. Significant improvement in one or more aspects of the CIP and FIP products with no degradation in other forecasted variables will constitute justification for considering this process for transition to an operational environment. Progress reports, published conference papers, and submitted journal articles will be used to document the progress of the research.

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