19.4

USE OF THE ADVANCED REGIONAL PREDICTION SYSTEM (ARPS) FOR SPACE SHUTTLE WEATHER FORECASTS AT THE NWS SPACEFLIGHT METEOROLOGY GROUP

Timothy D. Oram * and Tim Garner
NOAA/NWS/SpaceFlight Meteorology Group
and Brian Hoeth

1. INTRODUCTION

The National Weather Service Spaceflight Meteorology Group (SMG) provides weather support for human space flight activities at Johnson Space Center. SMG's support includes providing weather forecasts for potential emergency abort landings following launch, and planned end-of-mission landings following the de-orbit burn and re-entry, for the Space Shuttle (Brody et al, 1997). The final preparations for either a launch or a re-entry attempt occur over about a 9-hour period with weather briefings at key decision points in the timeline. SMG issues the final weather forecast for potential emergency abort sites following launch approximately 15 minutes prior to launch (or about 40 minutes prior to the landing time if an abort were declared). SMG issues the final weather forecast for a re-entry about 90 minutes prior to the planned landing time.

The potential for mesoscale diagnostic and prognostic models to improve weather support for these final weather forecasts has long been recognized. In fact, the National Research Council specifically recommended the implementation of mesoscale analysis and forecast models following the *Challenger* accident (NRC, 1988). The rapid increase in processing power of workstations during the late 1980's and 1990's created the possibility that these models could be implemented on affordable workstations -- a consideration in any operational environment. Between 1995 and 2003, the NASA Applied Meteorology Unit (AMU) worked with the operational forecast offices at SMG and the 45th Weather Squadron to conduct evaluations of mesoscale models such as the Mesoscale Atmsopheric Simulation System (Manobianco et al, 1996) and the Regional Atmospheric Modeling System (Case et al, 2002b). The mesoscale forecast models were initialized with a larger scale model such as the Nested Grid Model (NGM) or Eta, but the local data incorporated into the models were either limited or insufficient to accurately depict the mesoscale features. The results from these initial evaluations were mixed. However, the need to improve the model initialization by incorporating more local data was a common theme of these studies' conclusions.

Through the work of the AMU, SMG sought to explore the use of a more comprehensive data assimilation system incorporating all available mesonet data surrounding Kennedy Space Center (KSC), the primary landing site for the Shuttle. The goal was to produce a mesoscale diagnostic system utilizing data at the highest spatial and temporal resolution possible. A by-product of this effort would be an analysis suitable for initializing a mesoscale model. The AMU was tasked to identify local data sources and develop a prototype data assimilation system using the Advanced Regional Prediction System (ARPS) (Case et al, 2002a). ARPS is a comprehensive multi-scale prediction system that includes: the ARPS Data Analyis System (ADAS), single-Doppler radar retrieval and data assimilation procedures, the prediction model, and post-processing packages and verification tools (Xue et. al 2003). The original AMU task focused solely on prototyping the configuration of ADAS for east central Florida. SMG then transitioned the ADAS prototype into operations for further operational testing and evaluation. SMG and the NWS Melbourne Weather Forecast Office (WFO) recently tasked the AMU to assist with the implementation of the prognostic component of ARPS.

This paper will describe the lessons learned during the preliminary deployment of ADAS into SMG's operations. In addition, the implementation of the latest version of ADAS and the ARPS forecast model configuration will be discussed. Finally, a recent case highlighting one of SMG's forecast challenges and the potential utility of ARPS is presented.

2. ADAS PROTOTYPE AND LESSONS LEARNED

Techniques Development Unit (TDU) Meteorologists at SMG are responsible for developing new forecast techniques and transitioning new tools into operations. The goals of the ADAS operational transition and evaluation were to a) transfer the AMU data assimilation prototype into SMG forecast operations, b) develop the expertise in the TDU to maintain the system, c) incorporate new data sources, and d) begin to exploit the diagnostic products to improve Space Shuttle landing forecasts.

2.1 ADAS Prototype

The prototype software consisted of ADAS from ARPS Version 4.5.2 with modifications by the Applied Meteorology Unit to better utilize the available data, and to eliminate some problems with the analysis identified by SMG and the Melbourne WFO. Some of the modifications included development of modules to read RUC 20-km and 40-km hybrid coordinate data in

*Corresponding author address: Timothy D. Oram, NOAA/NWS/Spaceflight Meteorology Group, 2101 NASA Parkway, Mail Code ZS8, Houston, TX 77058-3696; e-mail: timothy.oram@noaa.gov

GEMPAK format as a background field for the analysis, read the Kavouras format of NIDS radar products, process the KSC and Cape Canaveral Air Force Station (CCAFS) tower data processing, process Aircraft Communications and Reporting System (ACARS) weather data, and add capability to the program that converts the grid analysis from the ARPS native format to GEMPAK format (Case, 2003). The ADAS analyses were run on 10-km and 2-km resolution grids centered over KSC at 15-minute intervals. The Rapid Update Cycle (RUC) model provided the background field for the 10-km grid while the 10-km analysis provided the background for the 2-km grid. The analyses were output in a variety of formats: the native binary format, GEMPAK grid format, and a GRIB file that was created from the GEMPAK grid using N-AWIPS utility software. The GRIB file was ingested into the SMG Advanced Weather Interactive Processing System (AWIPS) via the Local Data Acquistion and Dissemination (LDAD) system. Forecasters could also use N-AWIPS software to display the data and selected parameters were routinely converted into GIF images for display using a web browser.

2.2 Lessons Learned

Some of the key findings regarding the quality of the analyses, the display of the gridded analysis, and maintenance of the system include:

- The continuity of weather features in the analyses was significantly impacted by the real-time data flow. Several modifications were required to data ingest scripts developed during the research phase to optimize the use of the data in real-time operations. In addition, the timing of the operating system's time scheduler ("cron") jobs to run the analyses had to be adjusted to fully utilize the available data.
- RUC hybrid data were used to overcome a limitation in the near-surface temperature analysis. However, missing background fields due to the large size of the RUC data and limited communications bandwidth was the most common cause of a missing analysis.
- The initial mesonet data sources from KSC provided data over a small portion of the 10-km domain and additional data was needed that provided better coverage throughout the analysis domain.
- Forecasters did not fully utilize the data until the data were integrated into AWIPS although various products could be viewed with N-AWIPS/GEMPAK or simple web pages with preset graphics.
- Maintenance and improvement of the ADAS analysis consumed a great deal of time. This is particularly true with any local modifications to the software.
- The Unix shell scripting languages used with "cron" to run the analysis cycle processes were cumbersome and difficult to troubleshoot when problems occurred.

3. CURRENT ADAS CONFIGURATION

The University of Oklahoma's Center for the Analysis and Prediction of Storms (CAPS) released the latest version of the ARPS software (ARPS 5.0.0 IHOP_5) in June 2003. The code was converted from FORTRAN 77 to FORTRAN 90 and several improvements were implemented. SMG determined that an upgrade to the latest version of ARPS and ADAS was required in order to best support the implementation of the prognostic ARPS mesoscale model.

During the three years of operation of the prototype, SMG developed access to new data sources. Figure 1 shows the current flow of data into the ADAS. The Unidata Local Data Manager (LDM) software is used as the preferred communications software for ingesting data from external sources and exchanging data between workstations running ADAS and the ADAS pre-processors. LDM is a very efficient communications protocol and can be used to trigger the processing of data as files are received. SMG's Man computer Interactive Data Access System (McIDAS) is used to ingest and serve satellite, surface, Florida Automated Weather Network (FAWN), Coastal Marine Automated Network (CMAN), ship and buoy data using its client-server software. Eta model GRIB files are retrieved from public servers using the File Transfer Protocol (FTP).

Two primary goals were established for the data ingest in the upgrade to the ARPS 5.0.0. First, SMG wanted to use standard formats that were already supported by ARPS/ADAS. The use of standard formats would help avoid the development and maintenance of local software. Second, emphasis was placed on ingesting Level 2 WSR-88D data from multiple Florida radars. SMG believed the high update frequency and volumetric scan from the multiple radar sites would have a more significant impact on the analysis than surface-based observations or limited point profiles of data such as provided by profilers. ADAS can directly ingest the Level 2 data provided by the LDM broadcast. However, a separate workstation is dedicated to receiving the other data sources that require preprocessing into ADAS formats. Satellite and surface data (METAR, CMAN, FAWN, ship, and buoy) are retrieved from a McIDAS server and reformatted while NOAAPort radar data are simply uncompressed. The Forecast Systems Laboratory Meteorological Assimilation Data Ingest System (MADIS) broadcast using LDM contains a wide variety of mesonet data, profilers, and ACARS data that can also be formatted for the ADAS data ingestors. SMG expects to develop data pre-processors for KSC mesonet data and selected data sets in the MADIS broadcast in the near future. After re-formatting, the pre-processor workstation broadcasts the data to the ADAS workstation using LDM.

The current ADAS configuration is a 178 by 178 horizontal grid with 45 vertical levels. The horizontal resolution is 4km with the center of the grid located at 28.0 North and 80.5 West. The ADAS analysis is run on a Dell PC with the RedHat 8.0 LINUX operating system. The scripts that run the processing for the analysis were completely re-written using the Perl scripting language to improve clarity and maintenance of the operational system. The use of the Perl scripting language also allows SMG to take advantage of Perl modules incorporated into the ARPS package that automate the creation of the namelist files needed to run the various ARPS/ADAS programs. The ARPS software supports a variety of models as the background fields including Eta 40-km and RUC-40km in GRIB format. However, the RUC 20-km output in GEMPAK format is not supported. SMG chose to use the Eta 40-km GRIB data as the background fields for ADAS and boundary conditions for ARPS. This choice was made based on the following considerations: the ARPS developers use the Eta model as their background and we expected that this commonality would provide us greater support if problems occurred, the model data pre-processor reported problems during testing with the surface and soil moisture parameters from the RUC GRIB files, and the software development and communications issues associated with RUC 20-km in hybrid coordinates were avoided. The ADAS workstation interpolates the Eta GRIB data to the ADAS domain to create both the background fields for the ADAS analysis as well as the boundary conditions for the ARPS forecast model.

4. ARPS FORECAST MODEL CONFIGURATION

The AMU performed a study to recommend possible hardware configurations to support mesoscale modeling using the ARPS model. In order to best utilize the ARPS forecast model for SMG's operational needs, it was determined that SMG needed to take advantage of the Message Passage Interface (MPI) features of ARPS (the "arps_mpi" program). SMG purchased a Beowulf LINUX PC Cluster to support the modeling effort (see Table 1 for the cluster's hardware specifications). In addition to the network interface described in Table 1, SMG also purchased a Dolphin Wulfkit Interface and the SCALI software needed to utilize the faster communications of the Wulfkit interface. The cluster is currently running the Red Hat Linux 7.3 operating system.

The original goal for the implementation of the ARPS forecast model was to provide a 12-hour forecast every 3-hours at 3-km resolution over most of Florida. However, testing of various ARPS configurations on the SMG cluster indicated that this goal was not achievable. SMG is completing work on a configuration to produce a 9-hour forecast every 3-hours at 3-km resolution over the same domain as the ADAS analysis. This forecast run takes nearly 3 hours to complete. In order to obtain a forecast in a timely enough fashion, it was determined that the "arps_mpi" runs have to use 35 processors, with 7 processors in the x-direction and 5 processors in the y-direction. These parameters, along with many other forecast parameters, are all configurable in the ARPS input file that is read in by the "arps_mpi" program. The ability to rapidly reconfigure the ARPS model run is a significant improvement of ARPS 5.0 over previous versions that forced the selection of grid dimensions at compilation.

As is the case with the ADAS runs, Perl scripts that are initiated by "cron" drive the ARPS model runs. The scripts determine the latest "top of the hour" (e.g. 0000Z, 0300Z, 0600Z) ADAS data, which is then used as the analysis for the ARPS forecast model. Similar to the ADAS output, the output of the ARPS forecast model is ingested into SMG's AWIPS LDAD in NetCDF format.

5. ARPS OPERATIONAL UTILITY

The Space Shuttle Weather Flight Rules, which document acceptable weather conditions for a landing, are more restrictive than typical aviation flight rules. A short summary of typical end-of-mission criteria for a daylight landing at KSC is listed in Table 2. Analysis of SMG forecast accuracy during missions and simulations, as well as forecaster experience, indicates that low cloud ceilings and convective initiation are two of the more challenging forecast problems at KSC.

The 29 October 2003 0900UTC model run is used as an example of the potential utility of the ARPS model for Space Shuttle landing operations and the challenge associated with evaluating if the model provides improved guidance for operational forecasts. A cold front passed KSC between 0500 and 0600 UTC. Thunderstorms and rain occurred between 0500 and 0714UTC and the ceiling lifted from 5000 feet (unacceptable for a Shuttle landing) at the time of frontal passage to 8500 feet (acceptable for landing) by 0800 UTC. At the time of model initialization, the KSC observer reported only 1/8th to 2/8th's cloud cover at 9000 feet. KSC model soundings from the 0000 and 0600 UTC runs of the Eta (not shown), and Model Output Statistics (MOS) from the GFS and NGM, indicated that the ceilings should end by 1200 UTC. The LAMP (Kelly and Ghirardelli, 1998) output from 0800 UTC forecast cloud ceilings to last until 1300 UTC followed by no restrictions.

Visible satellite images at 1215, 1515, and 1815 UTC are shown in Figure 2a-c. Visible satellite images are not available on the synoptic hours; images are only available 15 minutes prior to or after the hour. This same limitation impacts the ADAS analysis as well. The cold front and associated showers continued moving to the south-southeast and were located offshore of southern Florida by 1500 UTC. However, an area of low clouds developed in northeast Florida behind the front and moved south over KSC producing a broken cloud deck around 1500 feet between 1235 and 1355 UTC. Another ceiling developed at about 2500 feet between 1525 and 1727 UTC. The cloud area associated with these ceilings exhibited a great deal of variation throughout the time period and the authors believe most of the observed motion of the clouds was development of new cloud combined with dissipation of existing cloud rather than simple advection of existing clouds.

The 0900 UTC ARPS cloud and surface wind for the model initialization and forecast times corresponding to the satellite images run are shown in Figures 3a-d. The ARPS model seemed to accurately depict the progression of the front. In addition, the model predicted the presence of low clouds behind the front fairly well between 0900 and 1200 UTC. The spatial extent of the cloud area over northern and central Florida was over-forecast during this time period. Between 1200 and 1500 UTC, the model quickly dissipated the majority of the clouds over east-central Florida. The model poorly forecast the band of clouds observed between KSC and Daytona Beach along the east coast of Florida. The model continued to dissipate the low level clouds over the Florida peninsula between 1500 and 1800 UTC, matching the dissipation of the clouds seen in the 1815 UTC satellite image. In general, the model seemed to have more difficulty accurately depicting the location and extent of the clouds over the water as evidenced by the lack of cloudiness where it did occur over the Atlantic and the prediction of unobserved clouds over the Gulf of Mexico along the west coast of Florida. The fact that the 1400 UTC LAMP guidance also did not forecast any ceilings between 1500 and 1800 UTC reinforces the difficulty the various models and forecast guidance had in predicting this event. The ARPS model did no worse than other guidance on this day. Although the model did provide some indication of the progress of low clouds toward KSC between 0900 and 1200 UTC, forecasters desire more accurate depictions of cloud ceilings.

6. CONCLUSIONS AND FUTURE EFFORTS

The 29 Oct 2003 case described above illustrates the need for improved forecast guidance for Space Shuttle operations. National scale models and statistical guidance did not accurately depict the event. The ARPS model indicated the potential for the presence of the low ceilings following the passage of the cold front, although the details of the evolution of the clouds was not handled well. Further refinement of the ARPS configuration may improve the model forecasts.

The implementation of the ARPS/ADAS 5.0 at SMG is still in its infancy. The ARPS system provides verification tools that will be used to gather statistics regarding the performance of the model. Although objective verification statistics need to be collected, these measures should not be the only consideration for evaluating the utility of running the ARPS model locally. The true measure of the utility of the model is if the model provides the forecaster with improved guidance that results in more accurate launch and landing forecasts. Subjective evaluation of the model's utility by the forecasters as well as objective measures of the skill of the final forecasts also needs to be considered.

In the future, Level 2 WSR-88D data will become available from radars near the secondary landing sites at Edwards AFB California and Northrup Strip New Mexico. ADAS analyses and ARPS forecasts from these sites will be developed. Many of the data available in the MADIS broadcast were used in the prototype ADAS but have not yet been integrated into the current ADAS analyis. Addition of these data sources to the ADAS analysis requires the development of pre-processors and possibly some software modifications to ARPS/ADAS; this will hopefully be accomplished within the next year.

Finally, testing of the ARPS on the SMG Beowulf cluster indicated that the purchase of the high performance Dolphin Wulfkit interface may not have yielded as large of a model performance increase as had been hoped. The ARPS developers supported this conclusion. SMG may have achieved more performance at the same cost by purchasing gigabit ethernet connections between the nodes and buying more processors. In addition, the ARPS developers have found that the Intel FORTRAN Compiler produces a faster MPI model run when compared to the Portland Group Compilers. SMG is currently purchasing the Intel compilers.

7. ACKNOWLEDGEMENTS

The authors appreciate the invaluable assistance of Jon Case (NASA KSC/AMU), Dan Weber (CAPS), Ming Xue (CAPS), Keith Brewster (CAPS), Kelvin Droegemeir (CAPS), Mike Eilts (Warning Descision Technologies), John Carpenter (WDT), and Gene Bassett (WDT). The implementation of the prototype ADAS would have been impossible without Jon Case's hard work. CAPS and WDT provided the authors advice and assistance in understanding the ARPS model and developing a usable operational configuration.

8. REFERENCES

Brody, F. C., D. Bellue, R. Lafosse, and T. Oram, 1997: The Operations of the Spaceflight Meteorology Group. *Weather and Forecasting*, 12, 526-544.

Case, J. L., J. Manobianco, T. D. Oram, T. Garner, P. F. Blottman, and S. M. Spratt, 2002a: Local Data Integration over East-Central Florida Using the ARPS Data Analysis System. *Weather and Forecasting*, 17, 3-26.

Case, J. L., J. Manobianco, A. V. Dianic, M. Wheeler, D.E. Harms, and C. R. Parks, 2002b: Verification of high resolution RAMS forecasts over east-central Florida during the 1999 and 2000 summer months. *Weather and Forecasting*, 17, 1133-1151.

Case, J. L., 2003: Reference Guide for the Applied Meteorology Unit Source Code Modifications to ARPS Version 4.5.2. Available from NASA Kennedy Space Center Weather Office.

Kelly, D.S., and J.E. Ghirardelli, 1998: A General Overview of Methodology and Applications of the
.

Local AWIPS MOS Program (LAMP), a short-range forecast guidance product. *Preprints 16th Conference on Weather Analysis and Forecasting*, Phoenix, AMS, 437-439.

Manobianco, John, Taylor, Gregory E., Zack, John W. 1996: Workstation-Based Real-Time Mesoscale Modeling Designed for Weather Support to Operations at the Kennedy Space Center and Cape Canaveral Air Station. *Bulletin of the American Meteorological Society*: Vol. 77, No. 4, 653–672.

National Research Council, 1988: Meteorological Support for Space Operations, Review and Recommendations. Available from the National Academy Press, Washington, D. C., 77.

Xue, M., D.-H. Wang, J.-D. Gao, K. Brewster, and K. K.Droegemeir, 2003: The Advanced Regional Prediction System (ARPS), storm scale numerical weather prediction and data assimilation. *Meteor. Atmos. Physics*, 82, 139-170.

Table 1. Beowulf Linux PC Cluster specifications

	Master Node	**Slave Nodes**
Quantity	1	17
CPU	Dual Intel Pentium III 1.26 GHZ	Dual Intel Pentium III 1.26 GHZ
RAM	1 GB	512 MB
Hard Drive	120 GB	120 GB
Network	1 GB Ethernet	100 Base T

Table 2. Daylight, End-of-Mission Weather-related Flight Rules for Kennedy Space Center

Criteria	**Threshold**
Ceiling	8000 feet
Visibility	7 statute miles
Head-wind	25 knots
Average Tail-wind / Peak Tail-wind	10 knots / 15 knots

Thunderstorms, Precipitation, Lightning	None within 30 nautical miles of runway
Detached, non-transparent anvil	None with 20 nautical miles of runway

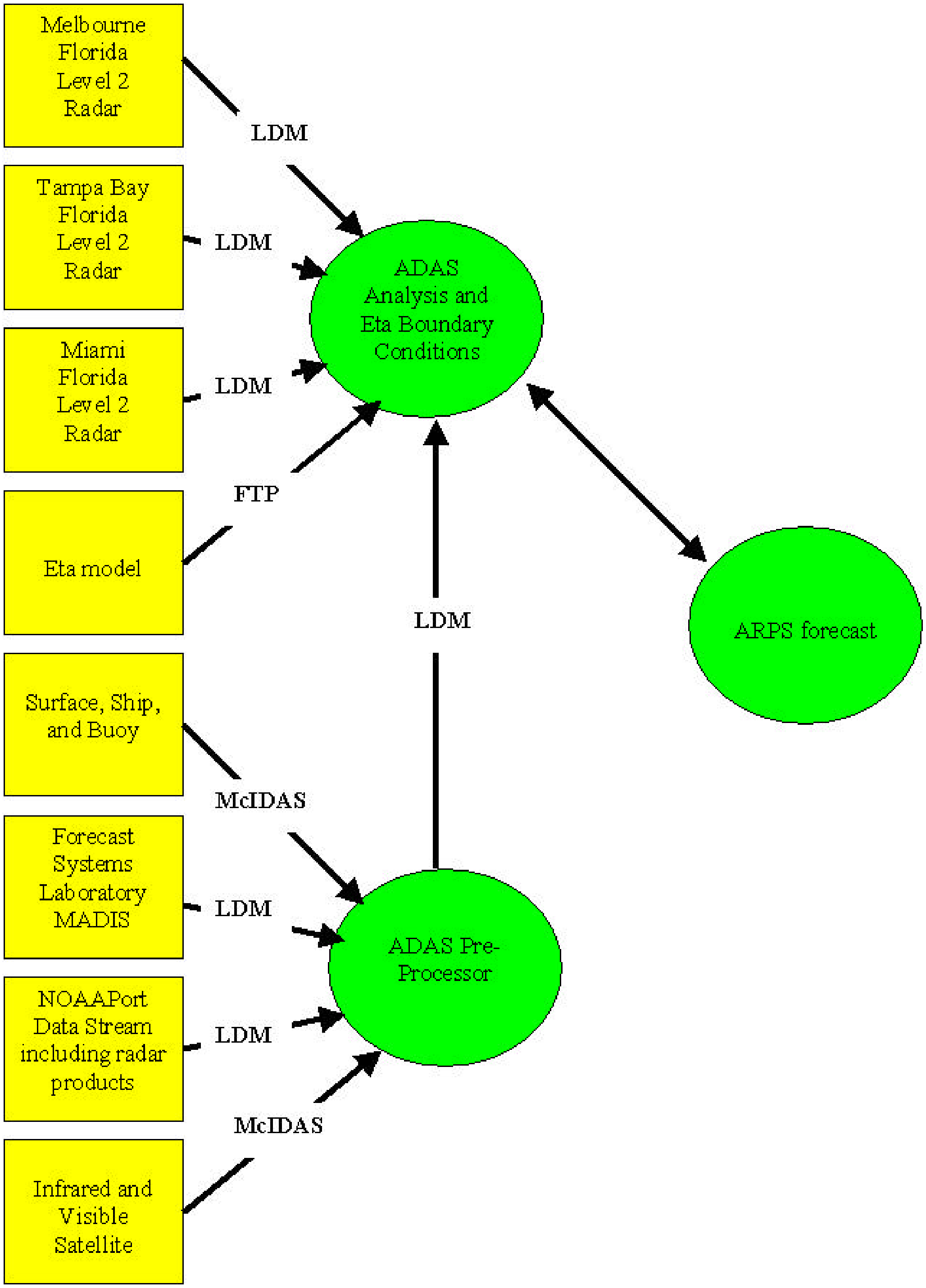

Figure 1. Data Flow for SMG ADAS and ARPS models

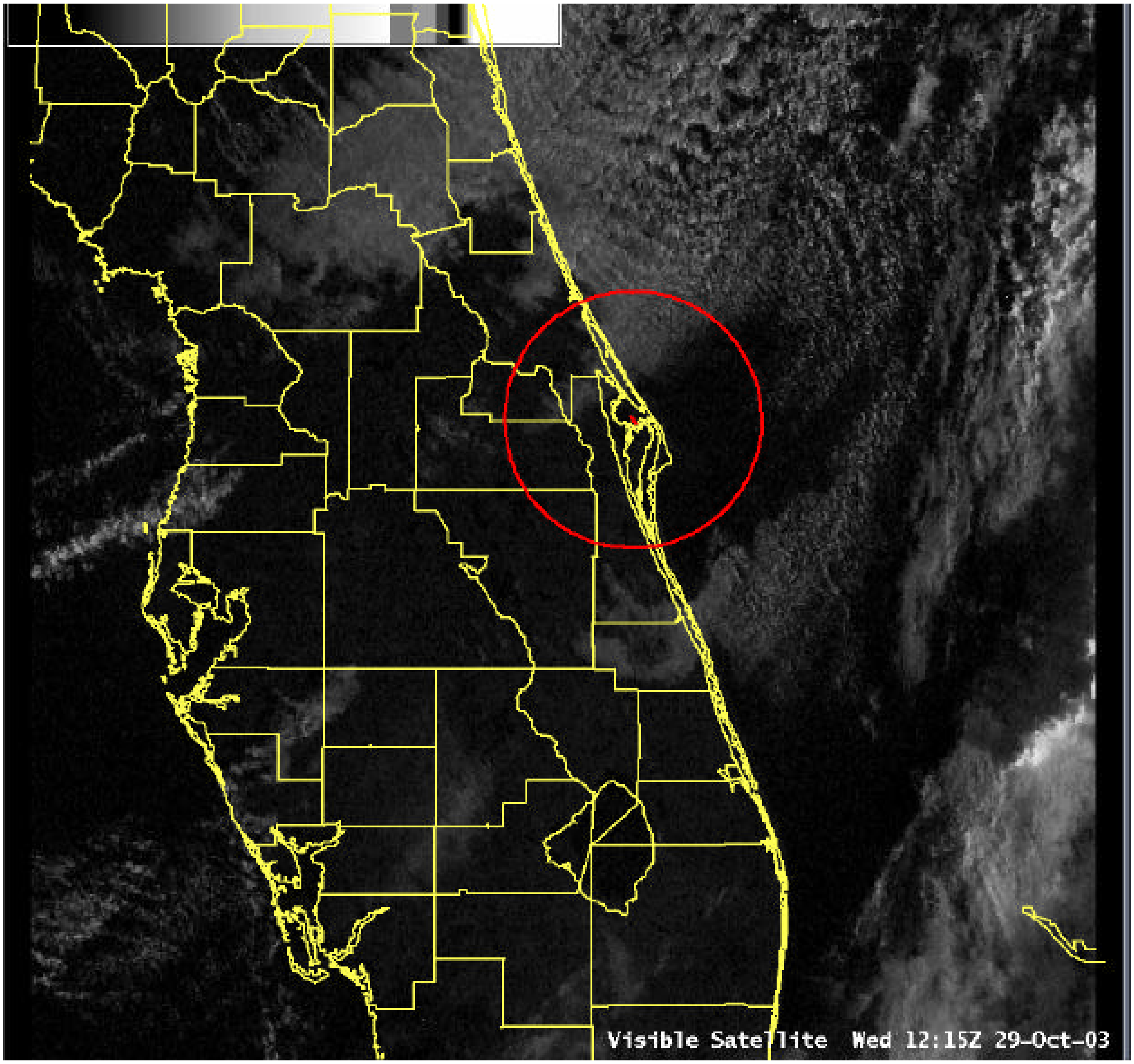

Figure 2a. 12:15 UTC 29 Oct 2003 Visible Satellite Image. The red circle is centered over Kennedy Space Center.

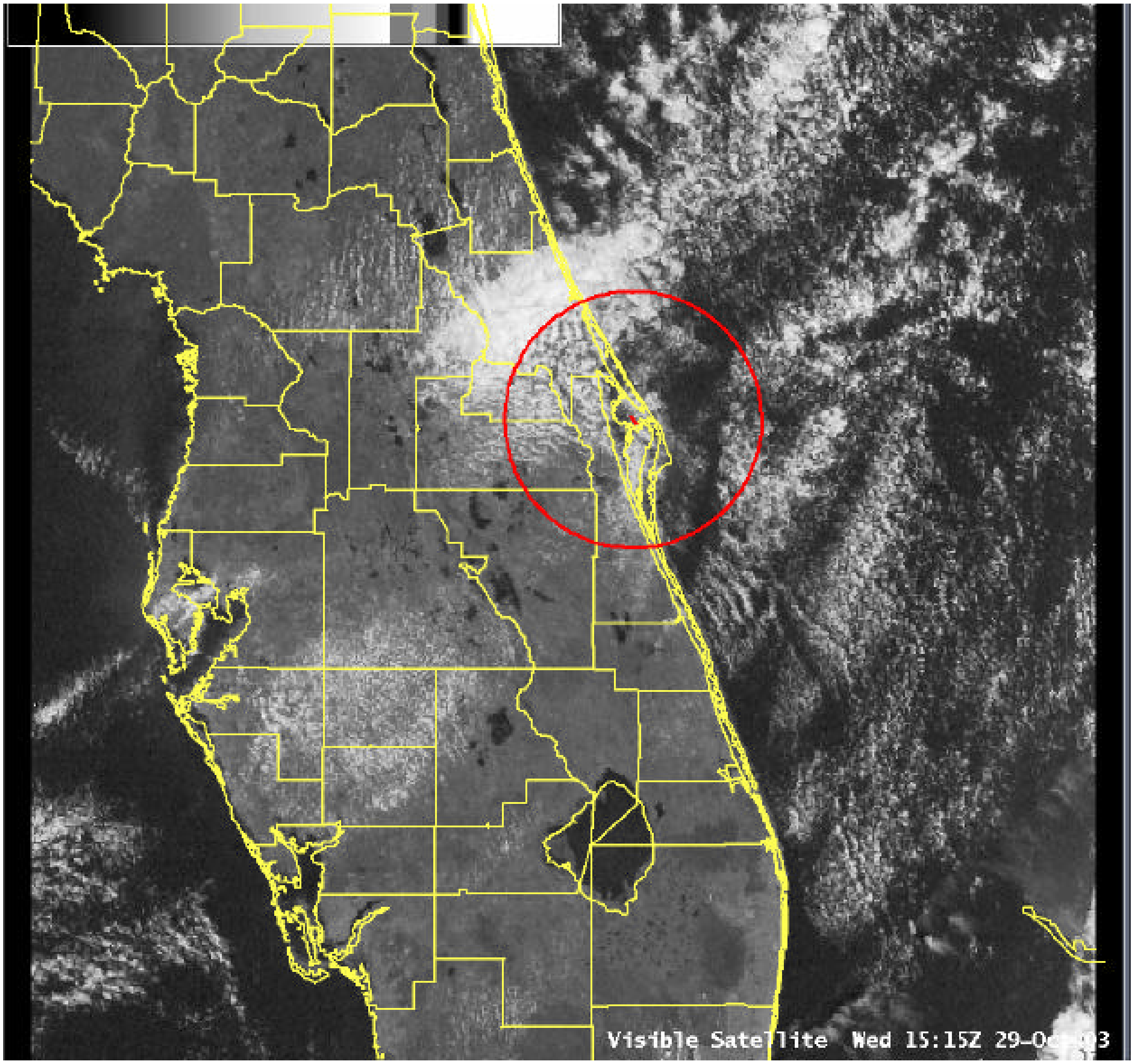

Figure 2b. Same as 2a except for 15:15 UTC 29 Oct 2003.

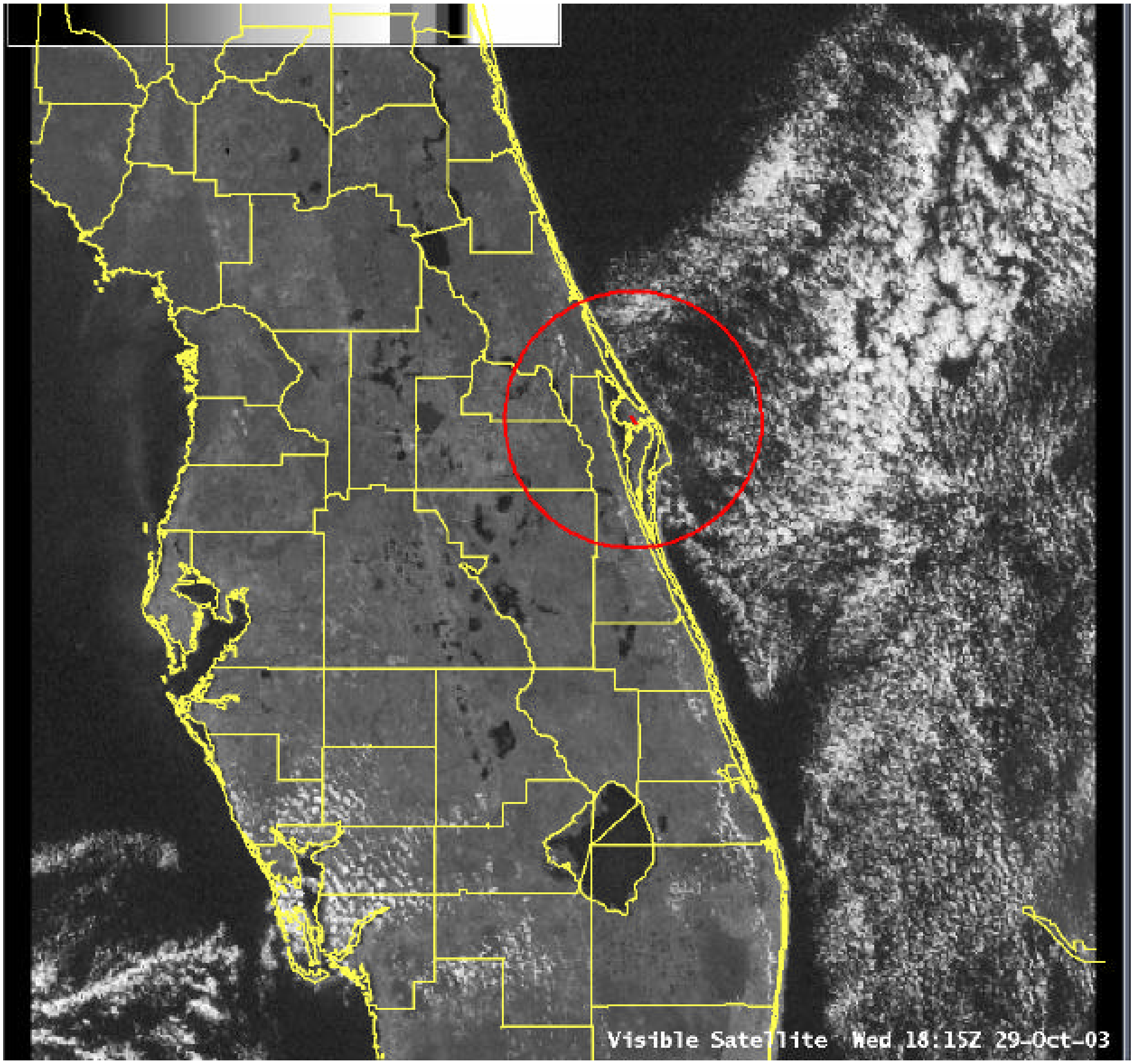

Figure 2c. Same as 2a except for 18:15 UTC 29 Oct 2003.

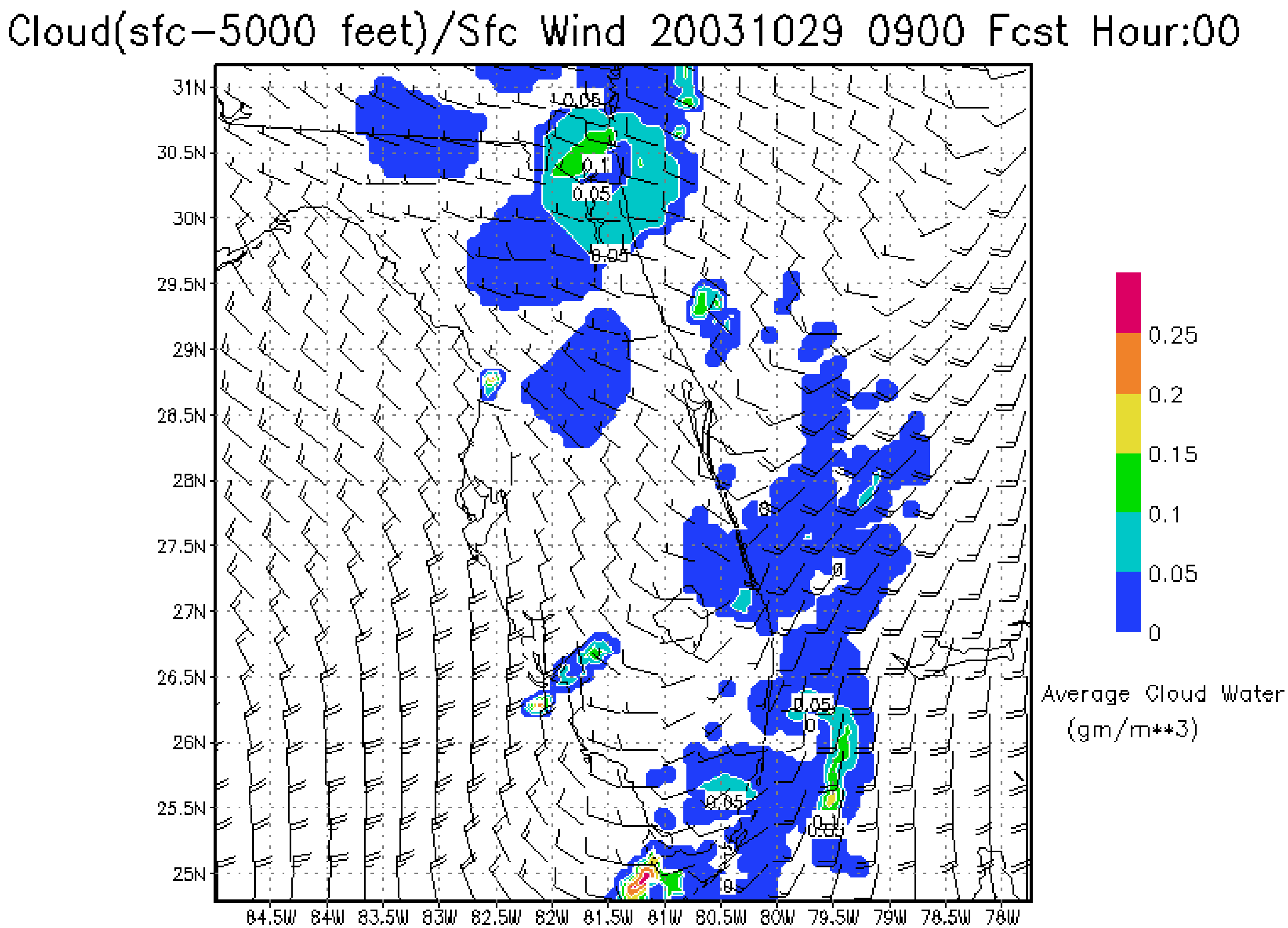

Figure 3a. ARPS cloud and surface wind initialization for 0900 UTC 29 Oct 2003. The cloud forecast is the layer average cloud water content between the surface and 5000 feet.

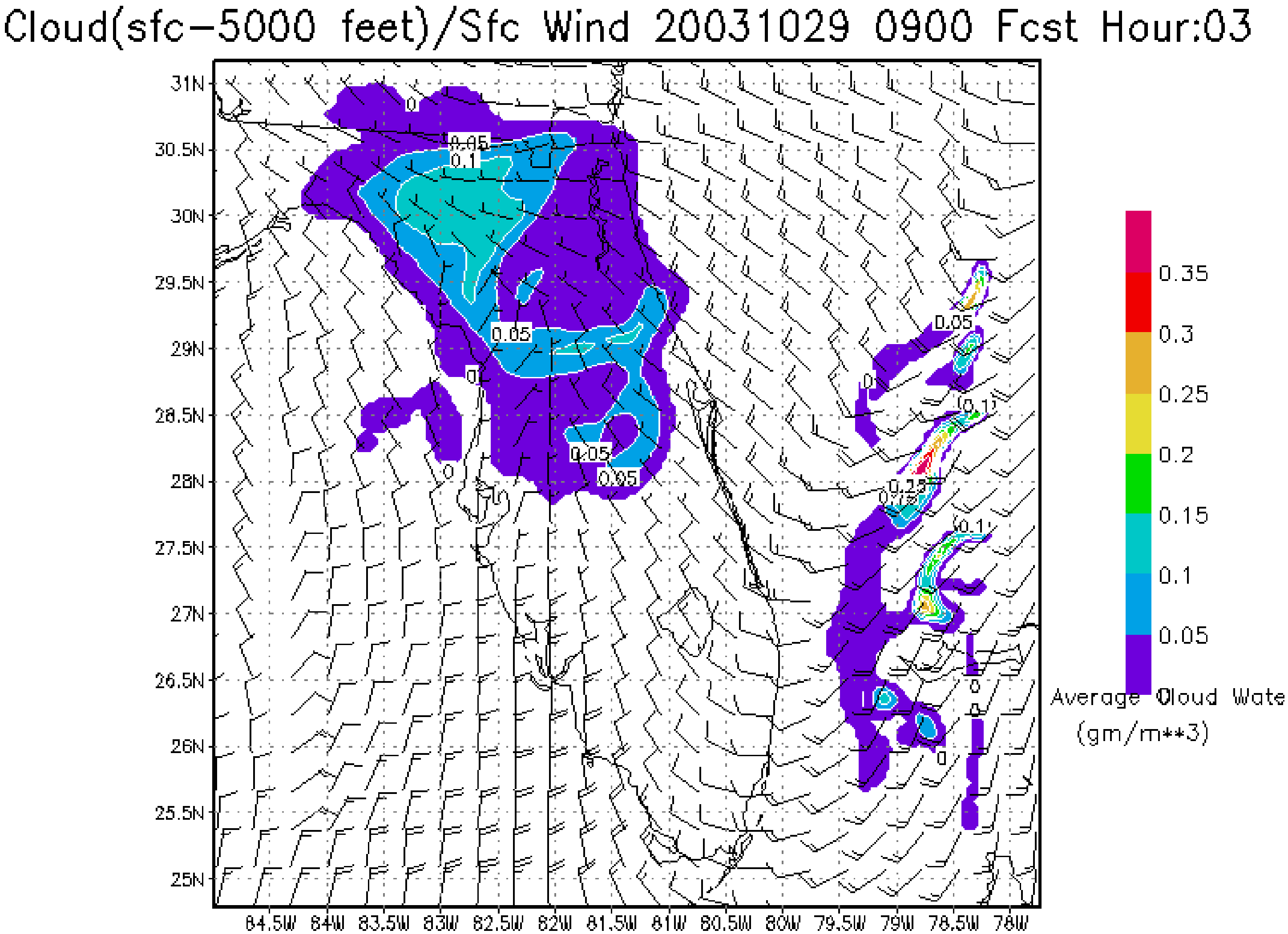

Figure 3b. Same as figure 3a except for 1200 UTC 29 Oct 2003.

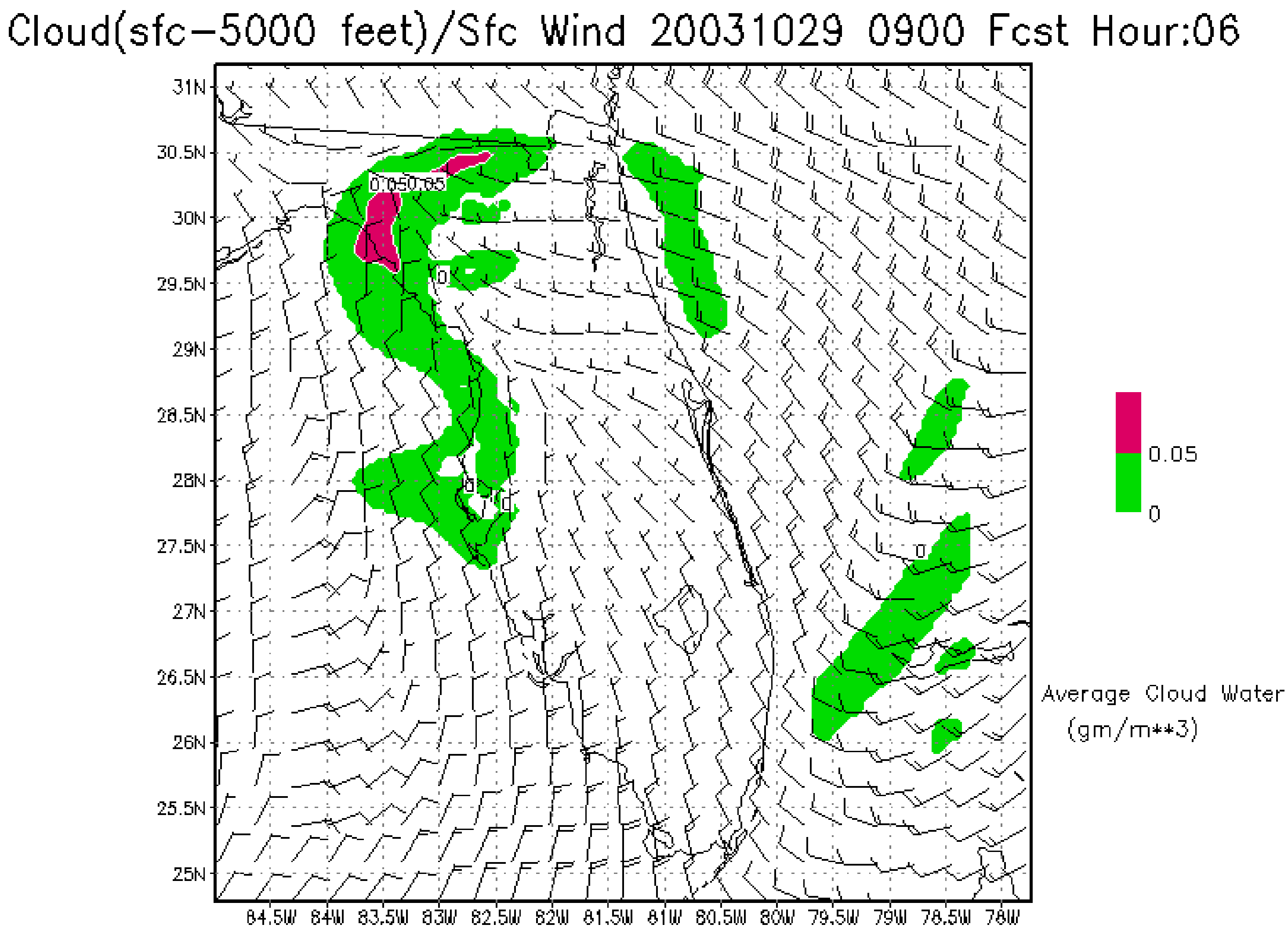

Figure 3c. Same as figure 3a except for 1500 UTC on 29 Oct 2003.

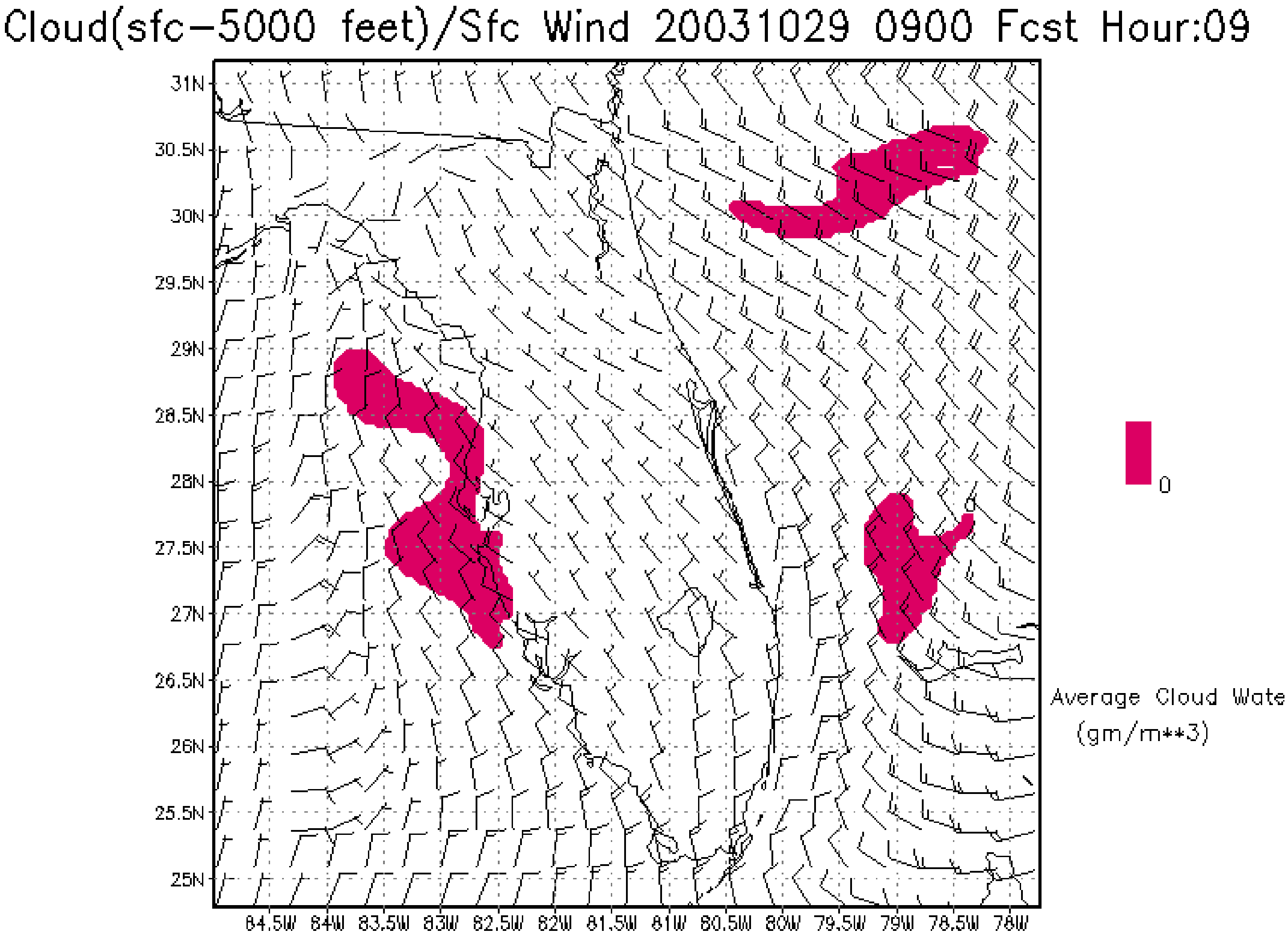

Figure 3d. Same as Figure 3a except for 1800 UTC 29 Oct 2003.