P5.27A RADIANCE ASSIMILATION OF POLAR AND GEOSTATIONARY SATELLITE DATA IN LAPS

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1. INTRODUCTION

The Local Analysis and Prediction System (LAPS) was conceived in the late 1980s at the Forecast Systems Laboratory (FSL; McGinley et al. 1991). LAPS fills an anticipated need in the local forecast office. It has been apparent that the large data volumes generated from current and planned data acquisition systems overwhelm weather forecasters because it is impractical to review all available data soon enough to maintain timely forecast generation. An analysis system that integrates available real-time data produces a comprehensive synopsis of the atmospheric state in a timely fashion. Going beyond subjective application, the feasibility of forecasting with local-scale numerical models initialized from LAPS analyses has been demonstrated (Stamus and McGinley 1997).

FSL's operational LAPS analysis is typically performed on a 10-km mesh approximately centered over Denver, Colorado. The LAPS grid has ranged from 600 km on each side to a newer larger domain 1,250 by 1,050 km. The vertical coordinate is pressure with 50-hPa increments spanning 1100 hPa to 100 hPa; however, the pressure spacing is adjustable.

LAPS background fields are interpolated from large-scale global or regional models; typical choices have been the Rapid Update Cycle (RUC) or Mesoscale Analysis and Prediction System (MAPS) 60-km and 40-km national scale forecasts Benjamin (1991), the U.S. National Centers for Environmental Prediction's Eta, nested grid model (NGM), and the U.S. Navy Operational Global Atmospheric Prediction System (NOGAPS) models. LAPS routinely generates state variable analyses of *t, p, z, u, v, w*, and *q*; and can produce special fields such as three- dimensional (3-D) cloud distribution, cloud type, precipitation; and derived fields such as lifted index (LI), LI *x w*; and integrated precipitation over time. In addition, LAPS can serve special needs of the user, e.g., aviation forecast problems.

This paper reviews recent progress in utilizing the different satellite data sources and forward models for LAPS analysis applications.

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2. RADIANCE DATA USED IN LAPS

At its inception, LAPS was designed to address the local forecast/nowcast problem, aimed at severe weather, rapid updates, and the merging of high frequency data sources (e.g., radar data) into a frequently updated analysis. For this reason, it was natural to develop LAPS with a Geostationary Operational Environmental Satellite (GOES) interface.

Since then, demands have changed, and domains have now been analyzed outside of the range of GOES coverage in places such as Bosnia, China, and more domains are planned for other overseas applications (i.e., Sydney 2000 Olympic Games). These activities, external to the United States, lack the GOES coverage that we have depended on for years. LAPS is currently being configured to utilize other geostationary platform data such as Meteosat and GMS, but even with these capabilities, a polar capability appears desirable.

GOES data have many advantages, one of them being the exceptional temporal continuity that is especially vital in local-scale analysis and monitoring for severe weather. However, when using analyses for model initialization, polar satellite data can offer significant benefits in data-sparse areas, especially if the model runs are initialized at a time coincident with a polar pass. Available at all locations on the globe including our laboratory, polar data are attractive for development because they can be checked out in-house and their performance could be anywhere in the world. Code maintenance also becomes standardized since one satellite (or type of satellite) is involved. Furthermore, we can test the polar data alongside GOES and apply experience with GOES to the polar infrared (IR) and exploit the microwave sensing unique to polar craft.

The experience to date has been with IR data, which is the focus of this paper. Eventually, the logical progression of our work is to follow the Television and IR Operations Satellite (TIROS) high-resolution infrared sounder (HIRS) with TIROS microwave sounding unit (MSU) data and then explore Defense Meteorological Satellite Program (DMSP) data. Thus, we will eventually be utilizing microwave satellite data in LAPS. The selection of the forward models studied parallels this development. This work provides a foundation for combining satellite data of all types and the algorithms now being developed must handle navigation and integration of heterogeneous data (at least IR, visible, and microwave). This paper also addresses the progression from an iterative variational scheme to more contemporary matrix solutions with the ultimate objective to utilize one model to support all data types from most platforms.

GOES data can effectively support LAPS from both direct readout (10-bit) and low-precision radiances inferred from 8-bit imagery. Birkenheuer (1996) documents FSL's experiments with using satellite broadcast network (SBN) 8-bit image data to supply its algorithms with satellite brightness temperatures. Imager data were initially used since they are readily available for Advanced Weather Interactive Processing System (AWIPS) and are directly applicable to the local forecast office using current data sources supporting AWIPS. With a better source of digital radiance imager data (10 bit instead of 8 bit), it is conceivable that the positive impact could be extended further. This study demonstrates that the 13-bit sounder data from GOES is superior to imager data in the GOES variational technique.

TIROS data used in LAPS originate from high-resolution picture transmission (HRPT) files. In particular, the TIROS ingest software processes the TIROS Operational Vertical Sounder (TOVS) information, which provides radiation measurements in 19 IR spectral regions from the shortwave (4.3 μ) to the longwave regions, as well as the visible wavelength (0.69 μ).

An intermediate processing step exists between the LAPS ingest and the raw HRPT files. The primary function navigates the data to earth locations (latitude and longitude) and computes the brightness temperatures for each IR channel using the interactive TIROS processing package (ITPP). The LAPS ingest software directly reads the ITPP-produced files and computes the mapping transform for each HRPT file. Because the TOVS data resolution is approximately 42 km along the satellite track, this mapping is not time-consuming and requires about 2 minutes to process each intermediate file.

3. FORWARD MODELS AND ANALYSIS TECHNIQUES

To date, LAPS has used two primary approaches for radiance data assimilation. Both methods are 1-D variational techniques, modifying portions of the vertical column one grid point at a time. In the case of GOES data, the radiances are densely spaced enough for the 10-km analysis to allow an analysis at each grid point, using the choice of nearest neighbor or averaged clear radiances values.

In the case of TIROS data, the field-of-view (FOV) is such that only the LAPS grid point closest to the center of the FOV is analyzed. The results from the ensemble of analyses are spread throughout the LAPS grids by conventional analysis techniques such as Barnes (1964).

3.1 University of Wisconsin Model (GOES Application)

The forward model used for GOES assimilation produces a simulated radiance based on temperature, moisture, and ozone profiles along with the temperature of the surface or cloud top, and the pressure of that radiating surface (i.e., surface pressure or cloud top pressure whichever applies). Also needed are the zenith angle, used to determine the airmass path and optical depth between the FOV and the satellite. The forward model used for this work was obtained from the University of Wisconsin--Madison and it is described in Hayden (1988). The forward model coefficients used for this study were vintage late 1995, furthermore, this model is not configured to produce a Jacobian for matrix solutions.

In order to apply the forward model variationally, clear and cloudy FOVs need to be determined. The LAPS cloud analysis is used to identify clear and cloudy LAPS grid points (Albers et al. 1996). The analysis presented here is only working from the FOVs classified as clear. The cloudy FOVs probably can be used; however, further research and refinements are needed to exploit cloudy and especially partly cloudy regions.

The functional evaluated at each grid point has the form,

$$J = \sum_{i=3}^{5} [R(t, o, cw)_i - R_i^o]^2 + (c-1)^2 \qquad (1)$$

where the goal is to determine the optimum coefficient (c), where c is a scaling factor for the moisture corresponding to the atmosphere between 500 and 100 hPa. No modification is made to the moisture profile anywhere else in the column. The forward model radiance (R) for a specific channel i is a function of LAPS temperature profile (t), ozone climatology profile (o), and the unmodified LAPS mixing ratio profile (w) and the scaling coefficient c. The moisture profile used in each run of the forward model is the modified moisture profile denoted by cw, where each level of w has been scaled by the level-dependent coefficient c. The observed radiance derived from AWIPS image data is designated as $R^o{}_i$, where subscript i indicates the imager channel number.

The first term in the functional maximizes agreement between the forward model and observed radiance at the expense of only modifying the water vapor profile. The second term adds stability and gives more weight to solutions in which the coefficient's departure from unity (no change to the initial profile) is minimized. The second stabilizing term, helping constrain the solution to approximate unity, is more important when multiple layers are solved (a case not considered here). Weights based on error characteristics can eventually be added, but for now the two terms have equal weight. Error statistics become more important when the functional grows in scope to include other data sources (i.e., Radiosonde Observation (RAOB) data).

Note that differences in all three channels, not only the moisture channel, are minimized in this technique. Thus, any improvement in the "dirty window," imager channel 5, will also contribute to the solution. The Powell (1962) method used to minimize this function typically required three to 10 iterations to converge. Here the maximum number of iterations was set at 50, and if this limit was reached, the coefficient for that particular grid point was excluded from the algorithm.

Once the coefficients are determined, they are applied to the specific humidity field at each pressure level for which they are designated. The modified specific humidity field is then advanced to the final analysis step.

3.2 RTATOV (Polar Application)

To perform the polar experiments for LAPS, the forward model/variational solution was selected to be RTATOV, a radiative transfer model obtained from the European Centre for Medium Range Weather Forecasts (ECMWF). RTATOV solves both the forward model problem plus the Jacobian "K matrix," adjoint, and tangent linear operators. Here the gradient matrix is used to solve a 1-D or 3-D variational solution to reconcile the analyzed thermal and moisture profiles with measured satellite radiances. This model was selected because it embraces a state-of-the-art approach to radiance assimilation and can effectively be formulated for use in a homogeneous or heterogeneous analysis situation. Here it was only applied homogeneously to the moisture profile; future applications will be heterogeneous by expanding the functional to include other data sources and their respective forward models.

The functional used to minimize the radiance data against the background is:

$$J = (x - x^b)^T C^{-1}(x - x^b) + (y^m - y(x))^T E^{-1}(y^m - y(x)) \quad (2)$$

The 1-D minimum variance solution is applied after Eyre (1989) using:

$$x = x^b + CK^T(E + KCK^T)^{-1}(y^m - y(x^b)) \quad (3)$$

where x^b is the background vertical profile vector containing thermal and moisture data from modified model background data along with climatology above 100 mb. C is the covariance error matrix of the background, K is the gradient matrix from RTATOV, E is the covariance error matrix for the HIRS channel data, y^m is the measured radiance vector, and $y(x^b)$ is the forward modeled radiance vector computed from the background vertical profile using RTATOV.

The solution is only applied in clear areas even though methods exist to handle clouds in the model. We selected this approach for convenience, since we are using the model for the first time. For cloud detection we rely on the LAPS cloud analysis that uses GOES data in its current formulation.

4. RECENT VARIATIONAL ANALYSIS EXPERIENCES WITH GEOSTATIONARY AND POLAR DATA

The positive results using GOES imager data to enhance both moisture analyses and local forecasts have been shown (Birkenheuer 1998a). Recently the iterative variational approach has been applied to 13-bit GOES sounder data, demonstrating additional improvement over those obtained using radiances derived from 8-bit image data. These solutions used three comparable channels (10, 8, and 7) from the GOES 9 sounder instrument that correspond to the GOES 9 imager channels (3, 4, and 5). Therefore, improvement is likely due to better data precision, signal-to-noise ratio, and better modeling of the sounder radiances.

Figure 1a plots the specific humidity bias error, with the most notable improvement at 400 hPa. The imager analysis bias is shown as dotted lines and the sounder bias error in solid lines. The reported value at 350 hPa represents only 2 data points (since 350 is not a mandatory RAOB pressure level), and the remaining points represent statistics from 64 comparisons made from mid-December 1997 through early February 1998, pooling both 1200 and 0000 UTC validation times.

Figure 1b contrasts the imager and sounder RMS errors. Following 1a, the imager RMS error is indicated by the dotted line, and the sounder-based result by the solid line. Here we see a very consistent reduction throughout the column except at 400 hPa, where there is substantially more improvement in RMS error.

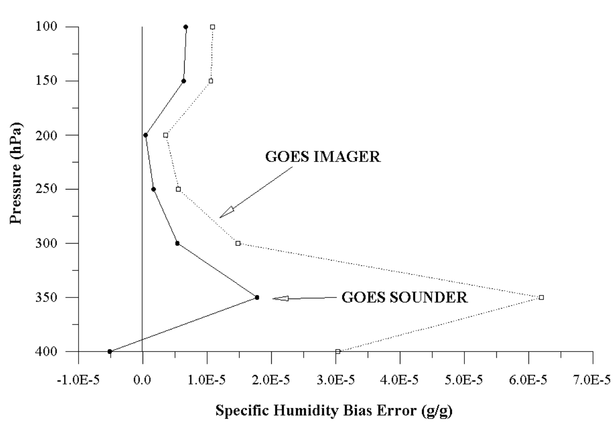

Fig 1a. Plot of specific humidity bias error (g/g) with pressure over the portion of the LAPS analysis that is modified using GOES 9 data. Imager and sounder results errors are computed using Denver RAOB data. A total of 64 cases comprise the sample except for 350 hPa, which only had two cases for the time interval studied.

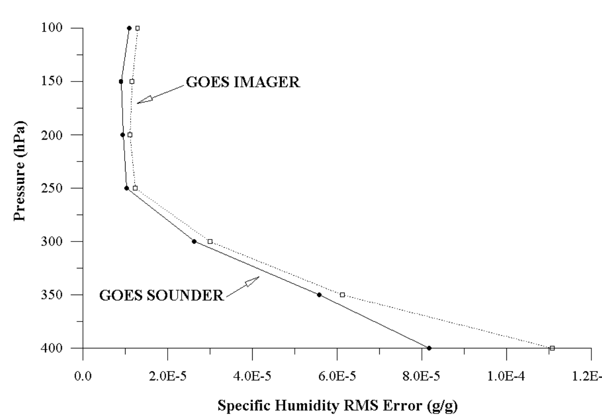

Fig. 1b. Plot of specific humidity RMS error (g/g) for the same cases as in Fig 1a.

Overall, for the entire atmosphere between 400 and 100 hPa, the analyzed bias error using imager data was 1.287×10^{-5} compared to 2.599×10^{-6} g/g from sounder-based moisture analyses, reduction in moisture bias was a striking 80%. The RMS error statistics are also improved with sounder RMS error of 3.592×10^{-5} compared to the imager RMS error of 4.826×10^{-5} g/g, an overall improvement of about 25%.

Work is ongoing in applying matrix solutions to our analysis; these methods are not yet mature enough to replace our iterative scheme. Initial experiences with RTATOV are discussed in Birkenheuer (1998b). The major finding was that mesoscale structure can be derived from the method, but consistent improvement in analysis quality has yet to be demonstrated from a large data sample. The RTATOV work is now on hold while LAPS is configured for Optical Path Transmittance (OPTRAN; McMillin et al., 1995).

5. SUMMARY AND PLANS

To date we have had the greatest success and most experience applying GOES radiance data to LAPS using iterative variational schemes for moisture enhancement. We are steadily progressing to the more versatile variational approaches. In the summer of 1998 we hope to apply the variational minimization analysis not only to the moisture analysis but also to the thermal analysis. The matrix methods currently being explored will enable us to bring together multiple data sources, and to solve for multiple variables, eventually producing the best solution for a wide set of data types.

One candidate for replacing the iterative GOES method is RTATOV coupled with OPTRAN as its forward model component in its more natural coordinate system. OPTRAN is currently being configured to interface to LAPS. The expectation is to devise one model that will support the large variety of satellites and sensor data providing efficient maintenance while serving a host of satellite needs.

In the meantime, it is unfortunate that GOES sounder radiances remain beyond the reach of the local forecast office. LAPS will remain configured to use GOES imager data for its source for radiometric satellite data in AWIPS; however, until sounder radiances can be offered to the local forecast office, LAPS will not realize its full potential from GOES. When LAPS is operated in a location where it can receive sounder radiance, the techniques are in place to put these data to effective use.

Future plans now include refining the LAPS GOES analysis techniques to utilize more of the sounder channels. Care is required to offset the improvement that more data add to the analysis against the longer processing times incurred when processing more channels.

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