The Effect of using Digital Satellite Imagery in the LAPS Moisture Analysis

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ABSTRACT

The Local Analysis and Prediction System (LAPS) analyzes three-dimensional moisture as one component of its system. This paper describes the positive impact that simple 8-bit, remapped, routinely available imagery have on the LAPS moisture analysis above 500 hPa. A variational method adjusts the LAPS moisture analysis by minimizing differences between forward model-computed radiances and radiances from Advanced Weather Interactive Processing system (AWIPS) image-grade data from Geostationary Operational Environmental Satellite (GOES-8). The three infrared (IR) channels used in the analysis will be routinely available to AWIPS workstations every 15 min. This technique improves LAPS upper-level dewpoint, reducing dewpoint temperature bias and root-mean-square (RMS) error on the order of 0.5 and 1.5 K respectively as compared to Denver Radiosonde Observation (RAOB) data. Furthermore, it strongly exemplifies the objective analysis benefit of image-grade data, in addition to its well-known subjective utility.

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1. Introduction

The Local Analysis and Prediction System (LAPS) has been under development since 1990. This system combines nationally disseminated data with local data for real-time objective analyses of all data available to the local weather forecast office. The LAPS analyses are of suitable quality to initialize a local-scale forecast model that can address specific problems of a small forecast domain with greater detail than can be achieved with nationally disseminated model guidance (Snook et al. 1998). Currently LAPS is part of Advanced Weather Interactive Processing system (AWIPS) build 4.0, however, LAPS is not limited to AWIPS and is available as a stand-alone entity accessible for download on the world wide web (WWW).

The LAPS system is routinely tested with new data sources and innovative improvements in applying more “conventional” data that will be nationally disseminated. One of the newer nationally disseminated data sources is digital satellite imagery. The Forecast Systems Laboratory (FSL) has been receiving 8-bit satellite data for the past 4 years, and has successfully used 11-micron and visible data in its cloud and surface analyses (Albers et al. 1996). Recent testing using 8-bit image data as a source for radiances in the 6.7-micron band (GOES 8, channel 3), along with 11-micron and 12-micron bands (channels 4 and 5) for quality control, has shown positive results on the moisture analysis at levels above 500 hPa. This paper reviews the improvements shown in a recent test of the LAPS moisture analysis in which GOES 8 radiances from three of the four IR channels were used to adjust upper-level moisture (above 500 hPa).

2. LAPS

a. LAPS overview

During the 1980s FSL conducted forecast exercises to test its workstation prototypes. Forecasters were burdened with the impossible task of reviewing all the incoming data, made possible through new technologies, and producing timely forecasts. They simply received too much data to be able to monitor all the information that needed to be incorporated into forecasts with the prerequisites of timeliness and accuracy. All local data needed to be objectively analyzed in conjunction with nationally disseminated data. Conceived as a resolution to this challenge, LAPS was designed for the purposes of analyzing all local data in real time on an affordable computer workstation and using its own output fields to initialize local-scale forecast models. So far it has been interfaced with the Regional Atmospheric Modeling system (RAMS) model and version 5 of the Pennsylvania State/National Center for Atmospheric Research Mesoscale Model, MM5. A more detailed review of LAPS is available in McGinley et al. (1991).

LAPS integrates all state-of-the-art data as they become routinely available to a field forecast office. Advanced data include Doppler reflectivity and velocity fields, satellite data including Geostationary Operational Environmental Satellite (GOES) infrared (IR) image data in AWIPS format, wind profiler data, dual-channel ground-based radiometer data, and automated aircraft reports.

The specific humidity (SH) module is one of 17 LAPS algorithms that span all procedures from data preparation and quality control to actual analysis. The SH module is one of four major processes that are responsible for merging data and negotiating the final output field of atmospheric state variables considered analysis. In addition to state variables, LAPS also addresses highly specific analyses of special interest, such as aircraft icing threat.

b. Review of the LAPS moisture algorithm

The LAPS moisture algorithm is one of four major modules that process different meteorological variables. In routine operation, the surface fields, the upper-level winds, upper-level temperature, and three-dimensional cloud analyses have already run providing the moisture analysis data. The LAPS SH algorithm can be divided into fundamental steps: background setup, boundary layer treatment, the optional variational adjustment to GOES radiances (under test), cloud saturation, and quality control. Only the background setup and GOES radiance adjustment is presented here.

1) BACKGROUND SETUP

Like most analysis systems, LAPS needs a starting point which it modifies by adding information from other datasets. This background, or first guess field, can be an earlier analysis or a forecast model output. The moisture analysis is similar to most LAPS routines in that it uses a forecast from a large-scale model as the first-guess field. Any model supplying the necessary fields in a timely fashion will work. At FSL we have used the following model forecasts to initialize LAPS: Mesoscale Analysis and Prediction System (MAPS) and its operational counterpart the Rapid Update Cycle (RUC), the National Center for Environmental Prediction (NCEP) nested grid model (NGM), and the NCEP's spectral and Eta models. Some LAPS routines, such as the surface analysis, draw upon the previous hour's LAPS field for additional information. For the LAPS moisture algorithm, however, only model forecast backgrounds are used. First, a temporal interpolation is calculated. If RUC data are used, the SH fields are derived on the RUC hybrid vertical grid and then interpolated to the LAPS pressure grid from a RUC forecast valid at the desired LAPS analysis time. Following this, a horizontal interpolation using two-dimensional splines fills the LAPS 10 km field. As a last step, a simple supersaturation QC step assures that the interpolation process did not inadvertently generate supersaturated conditions.

2) VARIATIONAL ADJUSTMENT TO GOES RADIANCES

For this experiment, two LAPS analyses were generated, one with the GOES moisture analysis included (referred to as the "adjusted LAPS"), and with GOES excluded (referred to as "conventional LAPS"). The variational adjustment to GOES radiances is the only difference between the two runs. Any differences in output quality are related to this analysis component.

An essential ingredient of the variational method described here is the ability to model GOES radiances from the LAPS dependent variables. This forward model 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, which is used to determine the air-mass path and optical depth between the radiator 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.

In order to apply the forward model appropriately, a determination of clear and cloudy field-of-views (FOVs) needs to be made. 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 FOVs classified as clear.

Following the background and a clear FOV assignment, the algorithm assures that all the data needed for proper execution are present. These include channel radiances derived from the imagery, the LAPS cloud analysis output, the LAPS surface temperature output, and LAPS 3-D temperatures. The forward model also requires an ozone profile, along with moisture and temperature profiles above 100 hPa, which are all obtained from climatology.

Next, the forward model is run for the 11-micron "window channel," and that brightness temperature is compared to the measured value for the FOVs. An acceptance tolerance of +/- 2K is used to accept or reject FOVs that are close enough to the LAPS profile to be deemed representative of the atmosphere. A disparity in the channel 4 brightness temperature comparison indicates that the LAPS thermal profile is too far off, or perhaps it contaminated by clouds. This conservative test goes beyond simple cloud detection, assuring a reasonable initial match between forward modeled and measured radiances. The forward model check is very sensitive and in many ways eliminates thermal profiles that subsequent variational techniques will find difficult to deal with. Moisture adjustment is then avoided unless the thermal profiles are reasonable.

At this point, all grid points offering promise of moisture adjustment have been identified. If the domain is cloudy, the GOES adjustment is discontinued and returns unmodified moisture values, which are passed to the final QC step described in the next section. Assuming that some grid points have been classified as clear, the next step is a variational adjustment at those locations. 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 at a particular gridpoint is modified each iteration by a layer-dependent scale factor c, with the modified moisture profile becoming cw. The observed radiance derived from 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 (c) departure from unity (no change to the initial profile) is minimized. The second stabilizing term helps constrain the solution to be near unity and is more important when multiple layers are solved (not presented 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 are minimized in this technique. Thus, any improvement in the “dirty window,” channel 5, will also contribute to the solution. The method following Powell (1962) is used to minimize this function and typically required three to 10 iterations to converge. A limit of 50 iterations was set as the maximum number to attempt. If the limit was reached, the coefficient for that particular grid point was excluded from the algorithm.

A Barnes (1964) analysis is used to fill any cloudy or skipped grid points. A weighted average of the surrounding coefficients is computed where the weight is the simple inverse of the distance to each grid point that contains data. For totally clear conditions, this step is skipped, since the variational step has already solved for the coefficients at all locations. In very cloudy situations this step is fast because there are relatively few points to use in the weighting step, and relatively few weights to compute.

Following this inverse-weighting scheme, the coefficient field is smoothed using a spatial invariant filter; simply averaging the values in a 3x3 grid point window, and assigning that average to the window’s central grid location.

When the coefficients have been determined, they are applied to the SH field at each pressure level for which they are designated, and then the modified SH field is advanced to the final analysis step.

3) QUALITY CONTROL

The analysis concludes with cloud reconciliation in which the atmosphere is saturated where clouds are analyzed. The cloud field used is from the LAPS cloud analysis that runs prior to this analysis. Lastly, quality control is applied by assigning any supersaturated gridpoints saturated values. Supersaturation, though rare, can occur since the scaling is performed on specific (not relative) humidity.

3. Impact Study

a. Data Sources

The major inputs to the LAPS specific humidity analysis are model moisture forecasts (already described, i.e., RUC); LAPS surface pressure, temperature, and dewpoint temperature fields; LAPS three-dimensional cloud and temperature analyses; GOES sounding IR radiance fields (the new dataset evaluated here); ozone and high altitude moisture profiles used in the forward radiance model, and the intentional exclusion of RAOB data (excluded from the analysis but used for verification).

Prior to the analysis, 8-bit image data are prepared for the LAPS domain. The AWIPS data are extracted from the Satellite Broadcast Network (SBN) data format, and a file describing the satellite data for the specific LAPS domain is constructed. A value for the “representative” average brightness temperature for each grid point is computed from the 8-bit image data. A static enhancement function is used in this step. The representative average is one that takes into account LAPS grid spacing. LAPS is coded in such a way that when it is installed at a location, the domain size and grid spacing is a variable that can be uniquely defined for each particular installation. The grid spacing along with knowledge of the AWIPS image projection (Lambert) define how many pixels in the image will be averaged to represent data at each grid point. For example, if the grid spacing is 10 km, the pixels averaged will exist within in a radius of 5 km about each grid point. The averaging criteria are recomputed at each grid point based on the changing difference between the LAPS (polar stereo graphic projection with locally defined polar longitude) and the satellite imagery with a fixed Lambert or Polar Stereographic projection. Another dependence is the resolution of the satellite image. This can be 8 km in the case of the “Supernational scale,” 5 km using the FSL CONUS scale (used in our laboratory only), and 4-km IR with 1-km visible on the ECONUS or WCONUS AWIPS scales. It should be remembered that each of these projections are only “true” at some particular place in the image projection. This factor is taken into consideration when determining which pixels to average.

b. No RAOB Data

RAOB data are not used directly by the operational LAPS analysis in this test even though the current LAPS moisture algorithm has the capability of using RAOB data, so this capability was deactivated for this test. Therefore, it is proper to use the Denver 0000 and 1200 UTC RAOB data as a control to assess the effect of GOES radiance data on the Colorado LAPS moisture analysis.

c. Ozone and high altitude moisture profile

The GOES forward radiance model requires an ozone profile in addition to the temperature and moisture profiles. A climatological ozone profile is used for this part of the scheme. It is determined automatically within the forward model.

The forward model also requires a thermal and moisture profiles above 100 hPa extending to 1 hPa. These data are obtained from a simple climatology model and concatenated to the LAPS data (which extend to 100 hPa) to produce the model-dependent profiles. The climatological model is based on a function of season and latitude.

d. Computed statistics

The statistics used to describe analysis quality are based on differences between the analyzed dewpoint temperature and the observed Denver RAOB for the LAPS levels that coincide with the mandatory RAOB levels above 500 hPa. The mean of the differences will be referred to as bias error. More important is the RMS error, a measure of the mean squared deviation of the difference measurements about their respective bias. The analysis at and below the 500 hPa level was not modified by this technique. The statistics were computed only for mandatory levels to prevent the possibility of introducing discrepancies through interpolation of RAOB data. It is assumed that improvement at mandatory levels implies improvement at the intervening pressure levels.

Figure 1 shows the composite effect of adjustments to the LAPS analysis at 1200 and 0000 UTC April - August 1996. Plotted are the conventional LAPS analyzed dewpoint RMS, and the adjusted LAPS analyzed dewpoint RMS using GOES radiances extracted from SBN imagery. RAOB data for the times calculated were used only for the validation, not in the analysis. Improvements can be observed at all levels; however, RAOB data are only reliable to about the 200 hPa level (dotted line on the plot) at which the ambient temperature drops below -40C and RAOB hygrometer data become unreliable. Therefore, the region between 400 and 250 hPa is more significant. In addition to Figure 1, it is useful to examine a table of the compiled statistics for this time period.

Table 1: Error Statistics April - August 1996

Pressure (hPa)	Prevariational Bias (K)	Postvariational Bias (K)	Prevariational RMS (K)	Postvariational RMS (K)	Sample Size
400	0.723	0.286	2.592	0.976	134
300	0.902	0.352	2.802	1.296	132
250	0.918	0.379	2.614	1.226	132
200	0.817	0.347	2.334	1.127	131
150	0.897	0.465	2.847	1.672	128
100	1.125	0.621	3.326	2.005	130

The improvement in bias using the variation step reduces bias error roughly 60% between 500 and 200 hPa. RMS error is also reduced in this region by an amount ranging from 50% at 200 hPa to 60% at 400 hPa.

A definite moist bias is evident in LAPS at upper levels, which is improved by the satellite data. This bias has been traced to the LAPS background, which during 1996 was MAPS or RUC forecast data. What is significant is that the satellite image radiance data as used by LAPS worked to constantly dry the upper levels, thus compensating for the bias.

4. Example case

a. Two-dimensional field

A single case is presented here to illustrate the mechanics of the technique. Figure 2 shows a two dimensional analysis results at 300 hPa on 1200 UTC 14 May 1997. Figure 2a shows the SH field over the Colorado LAPS domain as prepared by the analysis directly before the variational step. A moisture gradient located at the northern edge of the domain indicates higher amounts of moisture to the north. Below this in the middle of the domain two features predominate. A maximum-over-minimum in the west and a minimum-over-maximum in the east.

Figure 2b, shows the scale factor adjustment as computed by the available satellite data in clear areas. The high over low observed in the west in figure 2a, is located near an adjustment that also indicates a high over low that has shifted farther south. The scaling field indicates that the values in the southern part of the domain are too moist and increases moisture in a region over the Colorado Eastern plains raising it by a factor of 1.35 (the greatest adjustment shown).

Figure 2c shows the product of the scaling term with the initial field. The result preserves the major features, but with their range of values changed and a slight shift of position. The region in the south is much drier, and the low feature over the eastern plains has risen in magnitude and been shifted to the east. The high-over-low feature in the west has shifted south and a new low center north of the high has been established directly south of the gradient at the north edge.

b. Comparison with RAOB data

Table 2 lists the comparisons of this case with the Denver RAOB at 1200 UTC. A scale factor of 0.992 was applied to specific humidity at all levels resulting in the dewpoints tabulated. It should be noted that even though the correction at this RAOB location was to dry the atmosphere (as is the overall result in Table 1) there are regions in this domain where the atmosphere is moistened.

Table 2: Analysis impact over Denver 1200 UTC 14 May 1997

Pressure (hPa)	Prevariational Dewpoint (K)	RAOB Dewpoint (K)	Postvariational Dewpoint (K)
400	241.3	231.5	239.2
300	228.2	223.1	226.4
250	216.7	214.3	215.0
200	210.4	205.3	208.8
150	206.2	200.1	204.7
100	210.4	196.7	208.9

5. Summary and recommendations

Digital GOES image data will soon be available to every forecast office with an AWIPS data feed, indeed they are also available via the WWW to forecasters at large. These data offer more than subjective views of cloud structure, dynamic processes, and real-time images of meteorological processes from above. As demonstrated here, they also have meaningful significance for inclusion of satellite radiance data in local objective analyses.

The technique, the data used in the analysis, and the statistical methods employed can be improved. The 8-bit GOES data could be replaced with either full resolution (10-bit) image data or, 13-bit sounder data. Sounder data not only provide the highest precision, but offer the opportunity of more channel selection which implies better vertical resolution.

Even though statistics were computed from a significant data set for Denver, Colorado, they might be improved by using more stations in the domain. This is now easier to do since we run a larger domain than that used here to compute the real-time data presented. Using more RAOB stations not only broadens the statistical database, it could possibly establish analysis quality with regard to domain dependencies. Satellite related gradients picked up by the analysis could also be better diagnosed.

The technique presented here is fundamentally a moisture retrieval using variational methods to achieve a better radiometric match by varying the moisture concentrations at upper levels. The real power of variational techniques is in combining datasets by using the error characteristics associated with each measurement, the optimum analysis attained by finding the best way to fit all data. It is conceivable given the computer resources that the analysis could incorporate satellite data for cloud, surface temperature, multilevel moisture and perhaps wind in a three dimensional variational configuration. The technique presented here lays the groundwork for expanding the technique in this direction.

In future work, we will apply the coefficients from the lower two layers in the analysis. Partitioning of the atmosphere into two upper-level layers instead of one offers one way to obtain more vertical structure from the analysis with minimal change to the algorithm. Future studies may also focus on quality of analyzed gradients since GOES imagery shows these effectively.

The current analysis excludes cloudy areas. If the analysis is eventually determined to focus solely on upper-level atmospheric moisture, it may be possible to include regions of low-level cloudiness from which the radiation can be characterized above the low-level cloud tops. This would provide better mesoscale detail in the upper-level moisture analysis.

Objective analysis methods are best served by high quality sounder data and applying sophisticated analysis techniques. However, in the context of the operational workstation environment, with limited CPU and real-time data capabilities, the technique presented here represents a novel way to exploit a data source that might otherwise be ignored for objective analysis. Future decisions on spacecraft design, operation, and capabilities (including the selection of the specific data subset to disseminate to field operations) should take this application into account. Improvements and usage of the satellites will be shortchanged if we presuppose that image data are useful strictly for subjective analysis.

REFERENCES

Albers, S., J. McGinley, D. Birkenheuer, and J. Smart, 1996: The Local Analysis and Prediction System (LAPS): Analyses of clouds, precipitation, and temperature. *Wea. Forecasting*, **3**, 273-287.

Barnes, S. L., 1964: A technique for maximizing details in numerical weather map analysis. *J. Appl. Meteor.*, **3**, 396-409.

Birkenheuer, D., 1994: The positive impact of GOES-7 data in the LAPS water vapor analysis. *Seventh Conf. on Satellite Meteorology and Oceanography,* Monterey, CA, Amer. Meteor. Soc., 400-403.

Hayden, C.M., 1988: GOES-VAS simultaneous temperature-moisture retrieval algorithm. *J. Appl. Meteor.*, **27**, 705-733.

McGinley, J.A., and S.C. Albers, 1991: Validation of liquid cloud water forecasts from the Smith-Feddes method derived from soundings and LAPS analyses. *Fourth Intl. Conf. on Aviation Weather Systems,* Paris, France, Amer. Meteor. Soc., 228-233.

McGinley, J.A., S. Albers, and P. Stamus, 1991: Validation of a composite convective index as defined by a real time local analysis system. *Wea. Forecasting*, **6**, 337-356.

Powell, M.J.D., 1962: An iterative method for finding stationary values of a function of several variables. *Computer J.*, **5**, 147-151.

Rogers, R.R., and A.P. Schwartz, 1991: Mesoscale fluctuations of columnar water vapor. *J. Appl. Meteor.*, **30**, 1305-1322.

Snook, J. S., P. A. Stamus, J. Edwards, Z. Christidis, and J. A. McGinley, 1998: Local-domain mesoscale analysis and forecast model support for the 1996 Summer Olympic Games. Submitted for publication in *Wea. Forecasting*.

Figure captions

Fig. 1. Plot showing the RMS error differences between LAPS with and without GOES data for the period between April and August 1996. RAOB data are valid to a approximately 200 hPa.

Fig. 2a. Shows the 300 hPa specific humidity field over the Colorado LAPS domain as prepared by the analysis directly before the variational step.

Fig. 2b. Shows the field of scaling factors applied to the 300 hPa level to adjust the moisture in clear areas.

Fig. 2c. Shows the adjusted 300 hPa moisture field (Fig. 2a adjusted by 2b).