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THE POSITIVE IMPACT OF GOES-7 DATA IN THE LAPS WATER VAPOR ANALYSIS

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1. INTRODUCTION *

Horizontal Shape Matching (HSM) is an analysis technique used to incorporate structure into an analysis field based on variational methods (Sasaki 1958). Such variational techniques have been used in purely diagnostic (Achtemeier et al. 1986) and also prognostic applications (Chance 1986). At the Forecast Systems Laboratory (FSL) it is used diagnostically to insert satellite structure into a 10 km local water vapor analysis as part of FSL's Local Analysis and Prediction System (LAPS).

LAPS is a relatively new analysis system under development at FSL. The system addresses an anticipated need for analysis and modeling on the local scale that will arise in the AWIPS era. LAPS is designed to use both locally and nationally disseminated data, and its output can initialize local-scale models that address specific forecast problems. LAPS currently operates on a 10-km mesh approximately centered over Denver, Colorado. The square grid is 600 km on each side and the vertical coordinate is pressure with 50 hPa increments. The vertical grid begins at 1100 hPa and extends to 100 hPa. LAPS analyzes all state variables in separate three-dimensional and surface domains besides special fields such as aircraft icing threat. Additional documentation on the LAPS system can be found in McGinley et al. (1991).

FSL has operated LAPS with the HSM satellite insertion technique for two years. It is the only part of LAPS that uses Geostationary Operational Environmental Satellite (GOES) Visible & Infrared Spin-Scan Radiometer (VISSR) Atmospheric Sounder (VAS) data. This paper reviews the input data, the technique, and shows that the method applied to GOES-7 data provides measurable improvement to the water vapor analysis.

2. GOES-7 WATER VAPOR FIELDS

The fields used in this study to supply the gradient structure for our local-scale moisture analysis are described in Birkenheuer (1991) with a slight modification. This is briefly summarized here.

A physical retrieval algorithm adapted from the University of Wisconsin–Madison (Hayden 1988) generates temperature and dewpoint temperature profiles using FSL's national-scale Mesoscale Analysis and Prediction System (MAPS) (Benjamin 1991) analyses or forecast fields as a first guess and GOES-7 VAS radiance data. The sounding retrieval algorithm produces temperature and moisture profiles every 60 km in clear regions. Integrating the moisture soundings over three separate atmospheric layers provides vertical moisture structure. The set of layer precipitable water computations and their corresponding radiances form a sample from which the coefficients are derived through regression. The solved coefficient vector **c** is used in the following equation relating the measured radiances to layer precipitable water.

$$\mathbf{A}\mathbf{c} = \mathbf{s}, \qquad (1)$$

where **A** is an n X 12 matrix containing n observations of brightness temperatures (12 channels) from the satellite data for a given period and **s** is an n element vector containing integrated precipitable water values for a specified layer from the set of sounding retrievals. Coefficients are computed uniquely for each period and applied only to data of that same time.

Layer precipitable water fields at nominal satellite resolution of 16 km are then computed for each layer by applying (1) to the complete field of satellite radiances. The layer precipitable water fields are then bias corrected such that their integrated values agree with one of two available ground-based passive microwave radiometers operated by NOAA's Environmental Technology Laboratory (Guiraud et al. 1979).

Finally, to utilize the gradient structure from the satellite-derived layer precipitable water, a specific humidity field is derived at each layer's midpoint. The technique is described in more detail in Birkenheuer (1992a).

3. HORIZONTAL SHAPE MATCHING

The general form of the HSM comes about by minimizing a functional of the form:

$$J = \int\int \alpha(\nabla^2\phi)^2 + \beta(\phi_x - \phi_x^g)^2 + \beta(\phi_y - \phi_y^g)^2 + \gamma(\phi - \phi')^2 \, dx \, dy, \qquad (2)$$

where ϕ is the desired function, ϕ^g is the field containing gradient information, and ϕ' is a background field. The terms α, β, and γ weight the response of

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the Laplacian (smoothing), gradient structure, and background, respectively. The x and y subscripts denote partial derivatives. Note that the β term can be a function of x and y; this is because in our satellite application the β term depends on cloud cover. Values for β range from a maximum down to 0 in cloudy areas. This approach assures that the analysis excludes gradient information in cloudy regions that obscure clear-air satellite radiances.

The Euler-Lagrange equation that results after applying variational calculus to (2) has the form

$$\begin{aligned} \alpha\nabla^4\phi \;-\; \beta_x\nabla^2\phi_x \;-& \\ \beta_y\nabla^2\phi_y \;-\; \beta\nabla^2\phi \;+\; \gamma\phi \;=& \\ -\sum_{i=1}^{3}\Big[\beta_{ix}\nabla^2\phi^g_{ix} \;+\; \beta_{iy}\nabla^2\phi^g_{iy}& \\ +\; \beta_i\nabla^2\phi^g_i\Big] \;+\; \gamma\phi'.& \end{aligned} \tag{3}$$

This equation can be solved numerically using simple over-relaxation methods. Operationally, the coefficients used are $\alpha = 3.943 \text{ x } 10^6 \text{ km}^4$, β=3.395 x 10^4 km^2, and $\gamma = 1$. The technique to determine the coefficients is described in Birkenheuer (1992b). The summation term in (3) distributes the gradient structure from each of the three satellite-derived specific humidity levels described earlier into the particular LAPS level being analyzed. The HSM processing is done at one LAPS level at a time.

4. EVALUATION OF SATELLITE IMPACT THROUGH HSM

The primary purpose of this examination is to detect whether GOES water vapor gradient coupled into the LAPS moisture analysis through HSM have measurable positive impact. To achieve this goal, statistics compare different sets of analyses from April 1993 to present. The basic test statistic was the computed difference between the Denver RAOB dewpoint measurement and the dewpoint derived from the LAPS specific humidity analysis [t_d(LAPS) - t_d (RAOB)]. We focus on two time periods referred to as t_0 and t_{-1}. The set at t_0 refers to differences made at RAOB time, e.g., 1200UTC and 0000UTC. The set t_{-1} refers to difference made between the LAPS data one hour before sounding time with the RAOB data at sounding time, e.g., 1100UTC LAPS analysis dewpoint differenced against 1200UTC sounding data. The reason that one would expect this to be a "fair" test is that both t_0 and t_{-1} LAPS analyses do not contain RAOB data from that hour. Furthermore, soundings are typically launched at t_{-1} and data collected from that point up to t_0. From an analysis standpoint alone (where both t_0 and t_{-1} LAPS analyses were computed in the same way) one would anticipate that the t_{-1} would have an advantage, since the background field for LAPS one hour earlier would be based on a forecast field closer to initialization time. In our case we used MAPS to initialize LAPS; for example, the 1100UTC LAPS analysis would use a MAPS 2-h forecast initialized at 900UTC and the 1200UTC LAPS analysis would have used a MAPS 3-h forecast initialized at the same time for its background.

We subdivide these two datasets further by paying special attention to one set; the one in which the t_0 LAPS analysis has undergone HSM satellite modification and the t_{-1} set has not. As a control, we also have at our disposal the subset in which satellite data were not used at t_0. We can make one further classification in this analysis: between clear and cloudy scenes. The LAPS cloud analysis gauged cloudy conditions near the Denver RAOB site. If clouds existed anywhere in the column at the LAPS gridpoint corresponding to the Denver RAOB site, the sample was classified cloudy.

4.1 The clear situation

Table 1 shows the results obtained from the different sets of runs. Note first the figures from the "control" group. Comparing the clear bias error for roughly 2000 observations, both the t_0 and t_{-1} distributions had roughly the same bias of about 0.6 (°K), with standard deviations of about the same values as well, 4.1 to 4.2 (°K). This indicates that these distributions are the same. We also see a slight improvement in bias error and σ at t_{-1}, but the difference is subtle and not worth dwelling on except to speculate that it might be associated with the arguments presented earlier regarding the quality of the background field with respect to the MAPS forecast analysis time.

Looking now at the satellite modified t_0 and t_{-1} values, we note that the t_0 value receiving the satellite bias adjustment has an improved bias of 0.04 (°K) versus the t_{-1} value of 0.27 (°K). This is a relative improvement of 83 percent, but is it significant? To address this, two tests were performed on the distributions. First was a Student-t test that was applied in two different ways. One way assumed that the variances of each distribution were distinctly different. The Student-t statistic for this case was 2.82 representing a confidence level of 99.5 percent. Assuming that the variances were the same, the results were nearly identical. Therefore, we may assume that based on the Student-t test these are indeed separate distributions, truly showing a significant improvement.

The Kolmogorov-Smirnov test was also performed on the data. This approach simultaneously considers differences in variance and value. Here the probability of d (the computed statistic) being greater than observed was 0.019, and for this test, a strong significance level is indicated by 0.01 or smaller. Here this criterion is almost met. Coupled with the Student-t result, we can confidently state that there are two different distributions and the satellite modification results in a genuine positive impact.

Table 1. Statistical measurements comparing the dewpoint distributions

	Distribution time					
	t_0			t_{-1}		
	Sample	Bias (°K)	σ (°K)	Sample	Bias (°K)	σ (°K)
			Satellite modified t_0			
Clear	992	0.044	4.323	979	0.267	4.439
Cloudy	140	2.909	6.759	1080	0.434	4.625
			No satellite modifications ("control")			
Clear	2042	0.609	4.188	1997	0.579	4.112
Cloudy	1646	1.232	5.095	3457	0.832	4.561

4.2 The cloudy situation

Again we begin by looking at the cloudy subsets in the "control" group. Here we see that there were approximately one-half the number in the sample at t_0 versus t_{-1}. The bias statistics differ slightly, with the bias in t_0 slightly worse. The sample standard deviations are both greater than their clear counterparts. Again, as in the clear case comparison, we see no striking differences between the two time periods that we might attribute to anything except the one curious fact that the cloudy cases are about double at the earlier time.

Now looking at the satellite modified cloudy statistics, we first see that in approximately 10 percent of the cases the HSM step executed when the LAPS cloud analysis showed clouds over the Denver RAOB site. This is very different from the "control" group for the following reason. In the generation of the satellite water vapor fields, there is a check for the cloud fraction in the scene. If this is greater than 30 percent, the satellite water vapor fields are not produced. So we are not looking at extensive cloudy fields here. Furthermore, we are probably not looking at super clear cases either, but cases in between. So for the sample of about 140 measurements (representing about 14 soundings – estimating 10 levels per sounding) we have a situation where the field is partly cloudy and the satellite water vapor fields are generated and HSM is performed. And of this set, it is determined to be cloudy over Denver. The bias statistic in this situation is about 3 (°K) or about 6 times worse than the bias at t_{-1}. This by itself suggests that the HSM analysis does not handle the cloudy situation well. Both Student-t and Kolmogorov-Smirnov tests show that these are also very distinctly different distributions and the HSM analysis as applied for LAPS seems to do more harm than good in cloudy situations.

The major differences between the control and satellite modified subsets are that the control group includes both partly cloudy and complete overcast situations; whereas the satellite modified group contains *only* partly cloudy situations. This latter fact points to potential problems such as the handling of gradients near clouds and perhaps error in the exact location of clouds that might be due in part to the poor navigation that often occurs in geostationary imagery. Satellite navigation error on the order of 5 km could be very detrimental to a mesoscale water vapor analysis in a partly cloudy situation. We also are assuming that the RAOB balloon goes straight up and does not drift horizontally. In a partly cloudy situation it is likely to drift from inside a cloud to a region outside the cloud. This action would also lead to a positive bias in LAPS, as observed.

5. SUMMARY

From this study we conclude that the HSM insertion of GOES-7 gradient structure contributes positively to LAPS three-dimensional water vapor analysis. We also see that this is only true of situations for which clear skies are analyzed over the verification area, and that the HSM analysis in its current form may not perform well in cloudy situations. Future work should proceed in two fronts to reevaluate the cloudy cases with special attention to balloon drift, and explore the possibility of improving the behavior in cloudy regions by modifying the HSM weighting coefficients. The α term might need adjustment, since it dominates when there is no gradient data available and will modify the background field. Perhaps it has too great an effect in this situation.

It is indeed interesting that HSM reduces the bias but does not significantly improve the variance in the clear cases studied. Perhaps one way to interpret this evidence is to think of the HSM as pushing the analysis in the right direction but not quite aggressively enough. An increase in the β term in the HSM equation could possibly allow the gradient adjustment more influence in the result.

This study provides a benchmark for application of GOES-7 data in LAPS water vapor analysis. When GOES-I data are available we plan to adapt the LAPS water vapor analysis to this data source and make comparisons to assure that GOES-I is offering the best data possible.

6. ACKNOWLEDGMENTS

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