5.17 Statistical Relationships Between Satellite-Derived Atmospheric Motion Vector, Rawinsonde, and NOAA Wind Profiler Network Observations

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1. Introduction. Satellite-derived atmospheric motion vectors (AMVs) are used within a wide variety of applications such as NWP model data assimilation, convective weather and tropical cyclone forecasting, and aviation flight planning. Qualitative evaluations of AMVs indicate that they realistically portray atmospheric flow patterns with reasonable speed and direction. Yet, little quantitative information exists to explain how AMVs and their variations in the vertical relate to the true atmospheric motion.

The focus of this presentation is to evaluate specially-processed GOES-12 mesoscale AMVs (Bedka and Mecikalski 2005) using two established ground-based in situ observing systems: a 404 MHz NOAA Wind Profiler and rawinsondes. Wind observations are matched in time/space with mesoscale (MESO) AMVs over the U. S. DOE ARM Southern Great Plains Central Facility at Lamont, OK, Routine operational (OPER) GOES-12 AMVs from NOAA/NESDIS (Velden et al 1997) are also incorporated into this analysis to compare and contrast RMS and bias statistics between OPER and MESO AMVs. In addition to an evaluation of AMV-Profiler vector RMS difference (VRMS) and bias, rawinsonde data is used to understand the characteristics of AMV height assignment through a “level of best fit” analysis.

2. Data and Methodology. GOES experimental MESO and NOAA/NESDIS OPER AMVs within 25 km of the Lamont, OK Wind Profiler site (LMNO2) were collected over a one year period from April 2005-2006, providing a database of 15332 MESO and 1132 OPER visible (VIS), water-vapor (WV), and infrared window (IR) channel vectors. MESO AMV processing is designed to better depict highly detailed flow regimes through the tracking of smaller cloud and WV features, adjustment of quality-control procedures that were developed to satisfy a coherent AMV field for larger-scale flow regimes, and minimization of the impact of a background wind analysis on the resulting AMV field. These adjustments in AMV processing have the net effect of increasing flow detail at the expense of greater noise in the AMV field. A more detailed discussion on the AMV data and processing methodologies is provided in Appendix A.

Quality-controlled six-minute resolution data from the Lamont, OK 404 MHz NOAA Wind Profiler are compared to GOES AMVs to validate AMV wind speed and direction. As a 3-image sequence of 15-min resolution GOES-12 data is used to compute AMVs, at least five of the six possible six-minute wind profiles within this 30-min window are averaged together (centered in time on the middle GOES image) to obtain a set of wind observations that is reasonable and “fair” to compare with GOES AMVs. It is understood that the Wind Profiler does not provide “truth” wind measurements, but merely offers stable, well-calibrated, high temporal resolution observations, which allow for a large sample size of co-located AMV-Profiler data. A detailed evaluation of Wind Profiler error characteristics at the Lamont, OK site is shown within this symposium by Petersen and Bedka (2006).

Vaisala RS-92 GPS-tracked rawinsonde (i.e. “sonde”) data is used to validate AMV height assignment. AMVs are compared to sonde data at levels extending from ±150 hPa below/above the AMV height assignment to understand the level of the atmosphere for which AMVs exhibit the closest agreement or “best fit”. We define the term “level of best fit” (LOBF) as the sonde sampling level at which the AMV-sonde vector difference is minimized. The purpose of this analysis is to identify the level in the atmosphere that an AMV “should” have been assigned to based upon the satellite observed cloud or water vapor feature motion, with the understanding that current generation AMV height assignment techniques are imperfect. At the LOBF, it is assumed that the remaining AMV-sonde vector difference is related to factors such as tracking errors within the AMV algorithm and spatial variability between the AMV and sonde locations. Vectors assigned to heights above 700 hPa are evaluated here to avoid spurious results that could arise from comparisons to highly varying winds often present near the surface and within the boundary layer. A rawinsonde is considered a match if the balloon is launched within 60 mins of the AMV time stamp. Four sondes are launched per day in normal operations at the SGP Central Facility. When supplemental sondes from intensive observation periods are added to the operational sonde database, quality controlled data from 1628 sondes are incorporated into this analysis.

3. Results. Figure 1 shows a comparison between NOAA Wind Profiler and GOES-12 AMV wind speed estimates for the one year period described above. The OPER AMVs yield far fewer matches, but exhibit much closer agreement with Profiler wind observations. These results are to be expected, as the OPER AMV processing method incorporates a high degree of vector editing and quality control. These post-processing techniques provide more “accurate” wind estimates
on average, but do not allow the OPER AMVs to capture the level of detail contained within the MESO fields (see Appendix A for an example of MESO AMV field detail). Positive speed bias indicates that both AMV processing schemes estimate wind speeds that are faster ($< 1 \text{ ms}^{-1}$) than that observed by the Wind Profiler. Higher mean OPER wind speeds reflect the fact that the majority of OPER AMV-Profiler data matches originate from upper-level ($< 400 \text{ hPa}$) IR and WV vectors, whereas a high percentage of MESO matches correspond to slower low-level VIS vectors. Additional discussion of this analysis is provided in Appendix B.

The histograms shown in Figure 2 represent the difference between MESO/OPER AMV height assignments and the level that these AMVs exhibited best fit to a sonde profile. The results reveal that, for both OPER and MESO, the AMV height assignments were essentially unbiased relative to the LOBF, with a nearly even distribution between being assigned above and below the LOBF. 40% (51%) of MESO (OPER) AMVs were assigned within 50 hPa of their LOBF, with 18% (22%) of AMVs being assigned within 20 hPa. Thus, it appears that the OPER AMV processing scheme yields slightly better height assignment results, yet neither scheme performs extremely well at assigning vector heights. Additional analysis and discussion related to AMV height assignment is provided in Appendix C.

In summary, when selecting an AMV processing scheme, one must evaluate whether greater flow detail (MESO method) or better relative accuracy (OPER method) will better suit his/her particular satellite AMV application.

**Figure 1:** Co-located NOAA Wind Profiler (x-axis) and MESO (y-axis, left) and OPER (y-axis, right) AMV wind speed observations. Scatter-point density is shaded in greyscale. RMS and bias statistics (in $\text{ms}^{-1}$) are shown in the lower right.

**Figure 2:** MESO (left) and OPER (right) pressure deviation from the AMV level of best fit for vectors of all channels above 700 hPa.

4. References


Appendix A

A.1. Mesoscale AMV Processing Methods

GOES AMVs have recently been shown to capture detailed mesoscale flow structures in the vicinity of convective storms, which can be used to compute convective cloud-top growth rates (Bedka and Mecikalski 2005, BM05 hereafter). Using the UW-CIMSS satellite AMV algorithm (Velden et al. 1997, 1998) to help diagnose a severe thunderstorm event over the U.S. Southern Plains, BM05 show that a modified mesoscale AMV processing methodology increases the number of vectors by a factor of 20 over typical operational methods. Examples of the MESO AMV field from this event are shown in Figure A.1 and within BM05.

The methodology for deriving mesoscale AMVs is explained in detail in BM05, but is summarized below. A 3-image sequence of 15-min temporal resolution GOES-12 1-km visible (VIS), 4-km 10.7-μm “infrared window” (IR), and 4-km 6.5-μm water vapor (WV) band data is used as input to the UW-CIMSS AMV processing algorithm. Targets are identified in boxes of adjustable size within the middle image of this sequence and are tracked both forward and backward in time using cross-correlation based feature matching. Suitable targets represent well-defined cloud features (VIS, IR), coherent cloud edges (VIS, IR), or brightness temperature (T_b) gradients in the WV channel. Two “sub-vectors” are computed and which are then averaged to arrive at a final vector motion for a given target.

The next step is to obtain an estimate of the height for each AMV. This is accomplished by a hierarchical scheme (Velden et al. 1998) that selects one of several available IR-based techniques: the “IR window” technique (Schreiner et al. 1993); the CO_2-slicing algorithm (Menzel et al. 1983); or the H_2O-intercept method (Szejwach 1982; Nieman et al. 1997).

The AMVs are then post-processed using objective quality control (QC) routines. These routines check the temporal and spatial coherence of the AMVs [the “quality indicator” (QI) technique, Holmlund 1998] and the fit of each individual vector to an objective analysis of the wind field [“recursive filter” (RF) analysis, Hayden and Purser 1995]. While an NWP model guess is used as a background for the objective analysis, the required fit of the final AMV field to the model first guess is reduced in mesoscale AMV processing because the model often cannot accurately resolve and represent the complex flow associated with (and induced by) convective clouds on the meso-γ (sub-grid) and meso-β scales due to grid resolution limitations.

Additional differences between operational and mesoscale AMV processing are described below. The principal goals of these adjustments are to increase the number of targets for subsequent tracking, and to relax the quality control constraints primarily developed to satisfy a coherent AMV field for larger-scale flow regimes. Both of these processing strategy modifications serve to increase the density and detail of the resulting AMV field to better depict mesoscale flow regimes.

- The size of the AMV targeting box is reduced from the default size of 15 x 15 to 5 x 5 pixels (~1-km (VIS) and ~4-km (IR) resolution per pixel).
- VIS targets are tracked through the entire depth of the troposphere and lower stratosphere (1000-100 hPa); this differs from operational processing, where targets are only identified in the lower- to mid-troposphere (1000-600 hPa).
- The maximum IR target T_b is increased from 250 to 285 K in order to allow tracking of lower-tropospheric cumulus clouds in warm boundary layers.
- The impact of the internal quality control on the resulting AMV field is greatly down-weighted through a reduction of the minimum required QI (50 vs. 60 (operational)) and RF (.01 vs. .50 (operational)) analysis score thresholds.
- Gross error checks that penalize directional and speed variations from the background guess field (typically 90° and 10 ms^-1) are turned off to further minimize the impact of the first-guess on the final mesoscale AMV field.
Figure A.1: GOES-12 mesoscale AMVs superimposed on VIS imagery within and near developing convection over Eastern KS at 2000 UTC on 4 May 2003. Green barbs represent AMVs within the 1000-700 hPa layer; blue barbs within the 700-400 hPa layer, purple barbs within the 400-100 hPa layer. Large blue arrows illustrate mid-level diffluent flow (left panel). Green barbs outlined by boxes illustrate convergent flow at levels below 900 hPa (right panel).

It is important to note here that, like any other observing system, satellite-derived AMVs are inherently unable to perfectly depict the “true” flow at any given point in the atmosphere, even if the AMV target characteristics (horizontal dimension, cloud-top opacity/emissivity) and their behavior in time are optimal. The underlying assumptions of satellite-derived motion estimation are that features move within a short-term image sequence at a constant height level, with speeds equal to the true atmospheric flow. The first assumption can be violated in convective cloud situations, especially if the image sequence separation time is large compared to the magnitude of vertical motions. The latter assumption is difficult to prove with the current generation observing systems as no “perfect” wind measurement device exists. Finally, vertical momentum transports occurring in “clear-air” (i.e. cloud-free regions) induced by cumulus cloud dynamics and phenomena such as boundary layer eddies and gravity wave circulations cannot be directly measured from satellite. These transports can alter the actual flow as measured by in situ rawinsondes or Wind Profilers.

The following bullets provide a brief summary of the target characteristics, time evolution behavior, and NWP first guess characteristics that would lead to an optimal AMV flow estimate using geostationary imagery. An appreciable portion of the AMV versus sonde and Profiler differences in this study are likely related to deviations from these guidelines. It should also be stated that rawinsonde/Profiler measurement errors, matching collocation induced errors, and atmospheric temporal/spatial variability also contribute to the differences shown in Appendix B.2.

Optimal AMV Target Characteristics:

- Steady-state cloud features neither growing nor decaying in the vertical, with sharp, coherent edges.
- Cloud and WV targets represent a single/shallow tropospheric level/layer.
- A VIS or IR target should fill an entire 4 km IR pixel, with an opaque cloud-top and an emissivity near 1, for the best application of the IR-based height assignment techniques.
- WV tracking targets representing a shallow layer of concentrated WV within the middle to upper troposphere (Rao et al. 2002), and exhibiting sharp horizontal gradients.
- Distinct appearance of target relative to the Earth surface (i.e. target much colder than surface, no surface snow or ice cover).
- Targets within ~60º of the satellite nadir point. Degredation can be expected outside of this radius towards the limbs of the satellite view.
Optimal AMV Target Tracking and Evolution Behavior

- Image temporal resolution: 5 mins for VIS/IR and 30 mins for WV.
- Coherency in the shape and motion of the target over the tracking interval (i.e. non-accelerating, subvector 1 speed equal to subvector 2 speed).
- Image-to-image geo-referenced co-registration accurate to within ~1 pixel.

Optimal NWP Background Guess Characteristics

- For the applications discussed in this study, mesoscale NWP model analyses with high spatial and vertical resolution to obtain accurate, representative temperature profiles for use in AMV height assignment.

A.2. Dataset Co-location Methodology

Two types of comparisons will be shown in Appendix B. One will include spatially and temporally collocated Wind Profiler and sonde information at each Profiler sampling level. This comparison is shown to demonstrate the relative accuracy and consistency of the 6-min Wind Profiler observations. As each sonde reports data from thousands of vertical levels, a large number of collocations exist, which allows for a robust analysis of the difference characteristics between these two instruments. Once proof of Profiler measurement consistency and accuracy has been established, a second set of comparisons is performed which includes GOES-12 OPER and MESO AMVs and Profiler data. The results of this comparison have been introduced in Figure 1, but will be expanded upon in Appendix B.2.

Details describing the Profiler-sonde comparison methodology are as followed. The time and location of the rawinsonde observation at each sonde level is compared to the time stamp of a Wind Profiler observation. Profiler observations within +/- 3-mins of the sonde observation and 2-hPa in the vertical are considered matches. As the sonde ascends with time, a Profiler observation temporally closest to the sonde observation is selected for comparison. Thus, for a 1-hour sonde flight, as many as 11 different Wind Profiler profiles are directly compared to the sonde data. An additional quality control procedure was applied to Wind Profiler data to ensure time consistency and coherence of the observations. This is described in detail by Petersen and Bedka (2006).

The second comparison focuses on the quality of GOES-12 AMV estimates relative to Profiler observations. The Wind Profiler was selected for this study because this instrument is a stable, well-calibrated, high temporal resolution observing system, which allows for large sample size of co-located AMV-Profiler data. In contrast, wind observations from rawinsonde may ultimately be considered more accurate, but they are only launched 4 times per day during normal SGP Central Facility operations, which greatly reduces the number of possible data matches.

Additional details describing the AMV-Profiler comparison methodology are as followed. AMVs within 25 km of the Lamont, OK Wind Profiler site are collected each time the UW-CIMSS algorithm is executed. MESO AMVs are processed every 30 mins during daylight hours, as these data are used primarily to compute convective cloud growth rates within an algorithm that depends upon GOES Visible channel information. OPER AMVs are processed every 3 hours during both the day and night. An AMV is matched in height with the closest Wind Profiler observation using a maximum vertical distance criterion of 10 hPa. The 404 MHz NOAA Wind Profiler samples the atmosphere at a 250 m vertical resolution, which corresponds to ~25 hPa in depth at the 850 hPa level, ~15 hPa at 500 hPa, and ~8 hPa at 200 hPa. AMVs above the 7500 m level are matched only with Profiler “high mode” observations, as a much greater number of high mode observations pass quality control checks than those from the low mode within the Profiler “overlap region” (from 7500-9250 m).

Appendix B

B.1. NOAA Wind Profiler-Radiosonde Comparison

A direct comparison between quality-controlled Wind Profiler and radiosonde wind observations is shown here to demonstrate that Wind Profiler can accurately depict atmospheric flow throughout the troposphere and lower stratosphere. The results of this comparison for a one-year time period are shown in Figure B.1. There were 45539 matches for this comparison, yielding a directional RMS difference of 17° and nearly unbiased wind speed observations with a VRMS value of 3.4 ms\(^{-1}\). The u- and v-component difference plot further demonstrates that good agreement exists
between data from these two observing systems in a bulk sense, with a relative maximum number of observation differences being near the zero value. Figure B.2 shows a comparison of Profiler and sonde wind observation VRMS with height and increasing sonde distance from the Profiler site. The highest VRMS values are present both within the boundary layer (surface to 800 hPa) and in the lower stratosphere (above 200 hPa). Agreement between the two observing systems decreases as the sonde is advected further away from the Profiler site, illustrating the existence of spatial variability in the wind field within a 125 km radius. A detailed discussion of Profiler and sonde data characteristics toward better understanding spatial and temporal atmospheric motion variability is provided by Petersen and Bedka (2006).

**Figure B.2.1.** Co-located NOAA Wind Profiler and sonde wind speed (left), wind direction (middle), and wind component differences (right) from April 2005-2006 at Lamont, OK. VRMS and bias statistics (degrees and m s\(^{-1}\)) are shown in the lower right portion of the left and middle panels. Scatter-point density is shaded by the color scale to the right of each panel.

**Figure B.2.2.** Co-located NOAA Wind Profiler and sonde VRMS with height (left panel). The number of data matches are shown in the right panel. Lines are colored by the sonde distance from the Profiler site and are defined by the legend in the right panel. Solid (Dashed) lines correspond to Profiler low (high) mode observations.

**B.2. AMV-NOAA Wind Profiler Comparison**

Table 1 provides a statistical comparison of MESO AMVs to Wind Profiler, separated by AMV type and height. The parameter “Vector RMS” is defined as:

\[
\text{vect}_\text{RMS} = \sqrt{\frac{1}{N} \sum_n (\text{vect}_\text{diff})^2}
\]

where \(u_{\text{diff}}\) and \(v_{\text{diff}}\) are the u- and v- wind AMV-Profiler component differences, vect\_diff is the combined vector magnitude of \(u_{\text{diff}}\) and \(v_{\text{diff}}\), and \(N\) is the total number of vectors in a given sample. “Vector Bias” is the mean vect\_diff between the AMV and Profiler data.

Table 1 shows that MESO AMVs within the lowest layer (1000-851 hPa) exhibit the highest directional RMS differences, as well as a reversal in speed bias compared to other layers. Vector biases are substantially higher for this layer than for the other three layers examined here, which is attributed to the higher directional RMS differences. Higher directional RMS differences indicate that both the u- and v-wind components are significantly different between AMV and Profiler, thus producing a higher mean vector difference (i.e. bias).

These results may be related to a couple issues. A high percentage of MESO AMVs from this layer are derived from VIS channel imagery. As the time period of this comparison falls within the “warm-season” over the U.S. Southern Plains, cloud “streets” composed of small cumulus often form during the early afternoon and dissipate during the evening. These clouds appear very similar to one another within VIS imagery, making it more difficult for the correlation matching procedures to distinguish coherent cloud tracers. This may explain some of the larger differences in wind direction. Also, during the afternoon hours, strong solar insolation aids in the development of turbulent eddies
within the convective boundary layer (CBL). These eddies draw higher momentum air downward, increasing the low-level wind speed. The Wind Profiler and can observe this process, as it is measuring flow from within the CBL, but the GOES satellite Imager does not have the needed vertical resolution, and this might be contributing to the negative bias in very low-level AMV speeds.

Another issue that may be leading to these results is related to limitations in VIS AMV height assignment accuracies for small (< 4-km width) cumulus clouds. VIS AMVs are generally assigned heights via the “IR window” technique, where the cloud-top 10.7-μm T_b is directly related to a NWP model temperature profile. When a VIS cloud feature does not fill an entire 4-km IR pixel, radiation from the earth’s surface also reaches the satellite sensor, causing the IR T_b assigned to the VIS cloud to be warmer than its true cloud-top temperature. Thus, the cloud is assigned a height which is likely too low (Bedka et al. 2005), causing the AMV to be compared with flow from the wrong Profiler and sonde level. A small VIS cloud feature may be tracked perfectly in this case, but the resulting AMV could still carry an observation error as a result of this issue.

Table 1 also indicates that MESO IR AMVs have a higher VRMS than their VIS and WV counterparts. It is important to note that, as IR and WV AMVs are primarily derived from upper-tropospheric features, they inherently observe flow of higher speed. Thus, one might think that WV and IR AMVs are more likely to possess higher RMS/bias values because they observe faster atmospheric flow. Surprisingly, WV AMVs have the lower vector RMS difference than those from the IR channel. WV directional differences are likely smaller because upper-tropospheric flow is quite smooth, with the tracked WV gradients being consistent in magnitude and orientation within a 3-image (30 min) sequence. VIS and IR cloud targets can evolve more rapidly, leading to difficulties in estimating the “true” atmospheric flow from a satellite perspective. IR AMV VRMS are highest overall which may be due to height assignment issues associated with errant assignment of semi-transparent cirrus clouds to the lower troposphere.

Table 1 reveals that OPER AMVs have significantly better agreement with Wind Profiler observations compared to the vectors from the MESO methodology. VRMS values for OPER AMVs are ~2.5-3 ms^-1 lower than those from the MESO scheme. It is important to note here that only 31 VIS OPER AMV matches were found here, so the results are dominated by data from the IR and WV channels, which exhibit lower directional RMS characteristics in both processing schemes. Low-level OPER AMVs exhibit the highest overall differences. This finding is consistent though
with the results from lower-tropospheric MESO AMV comparisons. Low-level OPER wind speed biases are higher and are of opposite sign than those from the MESO AMV scheme.

Appendix C

**AMV-Rawinsonde Level of Best Fit Analysis**

Figure C.1 shows the relationship between OPER AMV-sonde vector fits at the algorithm assigned AMV height and the remaining depth of a sonde profile. The IR AMV-sonde vector fit plot shows that the AMV algorithm assigned a height that was ~75 hPa above the LOBF at 375 hPa. Closer examination of IR AMV best fit curve reveals that this AMV appears to fit well with a layer of the atmosphere ~100 hPa thick, extending from 300 to 400 hPa. The AMV algorithm height assignment fell within this layer, yet LOBF analysis shows a large deviation of ~75 hPa from the LOBF, with a vector fit difference of ~.6 ms⁻¹. Thus, care must be taken when interpreting the results of this analysis, especially in terms of pressure deviations from the LOBF. The WV AMV best fit curve also shows that the AMV would fit well within a layer of ~80 hPa thickness. The AMV algorithm assigned this vector well outside of his layer and even further away from the LOBF, which yields a vector fit difference of ~3 ms⁻¹ and a pressure deviation of ~125 hPa.

Figure C.2 shows histograms of the vector fit improvement in that could have been yielded by height assignment to the LOBF for both MESO and OPER AMVs. The values shown in these histograms are analogous to the .6 (IR AMV) and 3 ms⁻¹ (WV AMV) actual-LOBF vector fit differences from the discussion above. This analysis shows that 89% (97%) of algorithm MESO (OPER) AMV vector differences were within 10 ms⁻¹ of the vector difference at the LOBF. 63% (80%) were within 5 ms⁻¹ of the LOBF. These results, coupled with the previously shown pressure deviation analysis in Fig. 2, indicate that more work needs to be done to properly assign heights to satellite AMVs. The results from Fig. C.1 may suggest that better overall AMV-sonde agreement would exist if AMVs were assigned to a layer of the atmosphere rather than a specific level.

**Figure C.1**: A comparison between the actual OPER AMV height assignment (red circle) and vector fit to a rawinsonde profile for an IR (blue line) and WV (green line) AMV.

**Figure C.2**: MESO (left) and OPER (right) vector fit deviation from the LOBF for vectors above 700 hPa in all AMV channels.

Appendix References


