Statistical Comparison Between Satellite-Derived Wind, Rawinsonde, and NOAA Wind Profiler Network Observations

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And

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Satellite winds provide a reliable estimate of global atmospheric motions in near-realtime throughout the troposphere and lower stratosphere with high time frequency and spatial coverage.

These winds are currently being used in a variety of applications:

1) NWP model assimilation to improve initial analysis and resulting simulations

2) Aviation route planning to avoid (or benefit from) regions with strong headwinds (tailwinds)

3) Cumulus cloud tracking to objectively recognize rapidly growing convective storms

4) Recognition of vertical wind shear near tropical cyclones

Atmospheric wind fields are highly variable in time and space (both horizontal and vertical), challenging our ability to effectively interpret and validate satellite winds, and their height assignments.
Objectives of This Research

Four components of this talk

1) Evaluate the natural spatial and temporal variability of atmospheric winds throughout the troposphere

2) Investigate the feasibility of using 6-minute resolution Wind Profiler observations as a “truth” standard for wind validation

3) Understand the speed and directional “error” characteristics of operational and experimental satellite winds over a variety of cloud types and flow regimes

4) Evaluate AMV height assignments, level vs layer mean motion
Benefit of High Resolution Co-Located Measurements

• 6-minute 404 MHz Profiler data at Lamont, OK has a vertical resolution of 250 m up to a ~16 km height
  - We can compare one Profiler scan (t=0 mins) to those at t+6, t+12, t+18…., t+180 mins at each of the 72 Profiler levels to evaluate temporal wind variability with height

• 4 to 6 sondes are launched per day at the Lamont site with a data reporting frequency of 2 seconds
  - The Profiler is fixed in position but records frequent data, as the sonde is carried away horizontally by the wind
  - This allows us to compare time-matched Profiler and sonde data at varying spatial separations (0-25. 26-50 km,….) to evaluate spatial wind variability

• Understanding natural wind variability allows us to: 1) understand limitations in interpolating between coarse observations, 2) optimize AMV validation match criteria and 3) improve upon NWP assimilation of wind observations
NOAA Wind Profiler Instrument

Winds estimated through quantification of Bragg scattering of Profiler radio signal within a layer
6-Minute Profiler Observations: Are They Accurate?

- There are two 404 MHz NOAA Wind Profiler Network data products

  - A 6-minute product, the maximum temporal resolution of the Wind Profiler
    - Minimal QC is applied by NOAA
    - This product is not used in operational forecasting or assimilation

  - An hourly product, comprised of a combination of multiple 6-min scans
    - 6-min scans that agree within a specified threshold are merged together to form a consensus averaged wind
      * Time stamping may not be representative
    - Product sent out worldwide via WMO GTS for global NWP assimilation
    - Also used in operational NWS forecasting activities
Two-sided quality control (QC) procedure

\[
\left( \frac{\left| \Delta V_{(T-(T-6))} \right| + \left| \Delta V_{((T+6)-T)} \right|}{2} \right) / \sqrt{\left| V_{(T-6)} + 2V_{T} + V_{(T+6)} \right|}
\]

Magnitude of vector change before and after

Square root of mean wind speed

Rejects reports which exceed two standard deviations* of this ratio

*(computed from a small data subset)

- 2-sided QC assures temporal consistency between Profiler wind observations
- Using the 2-sided QC, Vector RMS fit between each observation and those 6 minutes earlier and later was reduced by nearly 1 m/s, with ~95% of the data falling within 2 Standard Deviations at all levels
- Bulk fit between Profiler and rawinsonde observations were improved by ~8%
• Comparisons at all match distances are included here

• Profiler data at +/- 3 mins from the sonde observation are compared
  - For a 90 min sonde flight, QC’ed data from up to 15 Profiler scans can be compared
Spatial Variability of Atmospheric Winds

Data from April 2005-2006

Published accuracy of sonde wind observations
Temporal Variability of Atmospheric Winds

- Atmospheric winds vary by 1 to 1.5 ms\(^{-1}\) within a 1 hour period

- This time variability is larger at higher levels and longer time lags

- Daytime convective momentum transports within the PBL induce greater short-term variability relative to a stable nocturnal PBL
**Vertical Variability of Atmospheric Winds**

**Altitude Analysis**

Vertical variability highest in the PBL and at jet level, 7-8 ms\(^{-1}\) per 1000 m of height

Least vertical variability is evident in mid-troposphere, 6 ms\(^{-1}\) per 1000 m

Temporal variability built into this comparison…balloon ascent takes time
Summary: Comparison of “Truth” Measurements

- 6-min Profiler data is useful, after 2-Sided QC is applied

- Comparing obs from Profiler, which are a layer-mean flow, to a single sonde level may contribute some additional “error” into the stats

- Winds can vary significantly over space and time, and we must understand this variability in performing and evaluating validation studies, as well as interpolating between coarsely spaced observations

- The wind field varied by ~3 ms\(^{-1}\) from a 25 to 125 km radius at upper-levels

- Tropospheric winds varied by ~5 ms\(^{-1}\) within a 3 hour time window
• “Reasonable” match criteria (1 deg distance and 1 hour time), $\sim$4 ms$^{-1}$ of natural wind variability can be built into comparisons at upper levels

• Results are likely regionally dependent, but analysis can be repeated at other ARM sites with co-located instrumentation

• Results could have important NWP implications…spatial and temporal variability parameterizations are not incorporated well into data assimilation procedures, leading to some misrepresentation of the “actual” initial atmospheric state
Satellite Wind Validation
What are “Mesoscale” Winds ?

- An adjustment to the UW-CIMSS wind algorithm processing settings that allows for retrieval of very high density flow information

- Adjustments primarily geared toward tracking cumulus cloud features for convective storm nowcasting

- Primary differences between MESO and NOAA/NESDIS OPER winds include:
  1) Smaller targeting boxes (5x5 pixels compared to 15x15 (OPER))
  2) Greatly reduced dependence on a NWP-based first-guess background wind field, since NOGAPS does not explicitly simulate convective motions in global model
  3) VIS targets tracked to 100 hPa, compared to 600 hPa in OPER
  4) Reduced target gradient requirements in both VIS and IR
What are “Mesoscale” Winds ???
(cont’d)

• Processing setup relies heavily on feature tracking algorithm to depict atmospheric flows

• MESO processing method has the net effect of greatly increasing flow density, especially at smaller scales, at the expense of increased noise
GOES-12 1-4 km multispectral image sequences are used to:

1) objectively identify convective clouds

2) estimate cumulus cloud motions

3) and recognize rapidly developing convective storms as part of the CIMSS Satellite-based Nowcasting and Aviation Application Program (SNAAP)
AMVs Using Operational Settings (152 vectors)

Mesoscale AMVs (only 20% shown, 703 out of 3516 total vectors)

Using Operational AMVs

Using Mesoscale AMVs

Actual 30 min Cooling Rates
AMV Validation Methodology

- AMVs within 25 km of the Lamont, OK Profiler were found for a 1-year period (April 2005-2006)

- Three 15-min GOES images are used to compute AMVs, so 6-min Profiler data is averaged over a 30 min period to provide a fair comparison
  - 5 of 6 Profiler scans must be present and pass QC

- AMV and Profiler obs must be within 10 hPa in the vertical

- Match stats for all AMVs are shown, and are then separated into various categories to better illustrate AMV-Profiler difference characteristics
AMV to Profiler Height Assignment Histogram

AMV Height Assignment Histogram

GOES-12 AMV Pressure Height Assignment (hPa)

MESO AMV

OPER AMV
MESO/OPER Satellite Winds vs. 6 Minute Profiler

GOES-12 High-Density vs. NOAAProfiler Speed: April 2005-2006

MESO

GOES-12 High-Density vs. NOAAProfiler Direction: Final

GOES-12 High-Density vs. NOAAProfiler Component Differences: Final

GOES-12 Operational vs. NOAAProfiler Speed: April 2005-2006

OPER

GOES-12 Operational vs. NOAAProfiler Direction: Final

GOES-12 Operational vs. NOAAProfiler Component Differences: Final
Vector Difference Cumulative Frequency

Cumulative Frequency of AMV–NOAA Profiler Vector Difference Values

- 43% (65%) of MESO (OPER) AMV < 5 m/s
- 79% (95%) of MESO (OPER) AMV < 10 m/s
Validation Stats Summary: Speed Intervals

Positive Bias = GOES faster than Profiler

<table>
<thead>
<tr>
<th>Comparison Type</th>
<th>Number of Vectors</th>
<th>Directional RMS</th>
<th>Wind Speed Bias</th>
<th>Wind Speed RMS</th>
<th>Vector RMS</th>
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<tbody>
<tr>
<td><strong>MESO AMV</strong></td>
<td></td>
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<td></td>
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<tr>
<td>&lt; 10 ms⁻¹</td>
<td>2717</td>
<td>54.30</td>
<td>-.77</td>
<td>4.24</td>
<td>6.84</td>
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<td>10-19 ms⁻¹</td>
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<td>30-39 ms⁻¹</td>
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<td>40-49 ms⁻¹</td>
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<td>&gt; 50 ms⁻¹</td>
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<td>8.83</td>
<td>5.46</td>
<td>11.53</td>
<td>14.22</td>
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<td><strong>OPER AMV</strong></td>
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<td>&lt; 10 ms⁻¹</td>
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<td>39.77</td>
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<td>10-19 ms⁻¹</td>
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<td>6.31</td>
<td>6.60</td>
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## Validation Stats Summary: Spectral Channel

A large component of the high MESO IR vector RMS is from low-level (1000-700 hPa) targets

<table>
<thead>
<tr>
<th>Comparison Type</th>
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<th>Wind Speed RMS</th>
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<td><strong>MESO AMV</strong></td>
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<td>VIS only</td>
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<td>19.04</td>
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<td>4.25</td>
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## Validation Stats Summary: QC Parameters

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<th>Wind Speed Bias</th>
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<th>Vector RMS</th>
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<td>25.40</td>
<td>.82</td>
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<td>7.46</td>
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<td><strong>OPER AMV</strong></td>
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<td></td>
</tr>
<tr>
<td>50 ≤ QI score &lt; 75</td>
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<td>29.07</td>
<td>.54</td>
<td>5.37</td>
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<td>75 ≤ QI score &lt; 90</td>
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<td>14.13</td>
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<td>90 ≤ QI score</td>
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<td>9.18</td>
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<td>50 ≤ RF indicator &lt; 75</td>
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<td>7.73</td>
<td>-.06</td>
<td>3.09</td>
<td>3.85</td>
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</table>

Additional analysis shows first-guess winds have closer agreement with Profiler than AMV.
Summary: GOES-12 OPER/MESO vs. Profiler

Validation

- MESO AMVs derived fairly evenly throughout depth of troposphere, OPER mainly from the 450-150 hPa layer

- Slow vector (< 10 ms\(^{-1}\)) direction appears unreliable for both OPER and MESO

- Fast vectors (> 50 ms\(^{-1}\)) exhibit good directional agreement, but have much higher speed biases than average
  - Are large outliers influencing stats?

- Higher QC parameter scores improve AMV-Profiler agreement
  - NWP-based first guess has better agreement with Profiler than AMV
  - QC methods that ensure close agreement to NWP inherently improve AMV-truth comparison stats
Summary: GOES-12 OPER/MESO vs. Profiler Validation

• Current wind algorithm framework, coupled with today’s GEO satellite technology, may not be adequate for tracking mesoscale motions with comparable accuracy to those from the larger scale OPER processing
  
  - Navigation issues can impact slow wind speed/direction accuracy
  
  - Is this method too focused on the trees and has ignored the forest?….Is it possible that cloud/WV motions on such small scales may not be equal to the “true wind” as measured by sonde/Profiler?

• Sensitivity testing to target box size and image temporal resolution (7.5 to 60 mins) is underway

• One must decide whether better overall vector accuracy (OPER method) or increased flow detail (MESO method) would better suit his/her AMV application
Height Assignment
Evaluation
Evaluation of AMV Height Assignment Characteristics

• Satellites monitor clouds and water vapor gradient features that are advected through a sequence of images at a given speed and direction

• It may be unrealistic to assume that the motion of a cloud or coherent WV feature of significant depth would be controlled by flow along cloud top
  - Thin cirrus may be an exception
  - A layer-mean advective motion from within the cloud or over a depth of clear-sky is probably more reasonable

• AMVs are treated as point measurements in space in NWP models

Objective: To evaluate AMV-layer mean motion relationships for varying satellite channel, height assignment, and cloudy vs. clear conditions

Method for Addressing This: Compare 3.5 years of AMVs to layer-averaged sonde data from both the ARM SGP (GOES-12) and TWP sites (GMS-5, GOES-9, MTSAT)
Level vs. Layer of Best Fit Height Assignment

AMV Algorithm Height Assignment

Level of Best Fit

Layer of Best Fit

Pressure (hPa)

AMV-Sonde Vector Difference (m/s)
Layer of Best Fit Height Assignment: VIS+SWIR

- X = Water vapor intercept
- Asterisk = Histogram technique
- Diamond = CO2 slicing
- Star = Base technique
Layer of Best Fit Height Assignment: Water Vapor

- X = Water vapor intercept
- Asterisk = Histogram technique
- Diamond = CO2 slicing
Level of Best Fit Height Assignment

Level analysis: Search 100 hPa above and below the assigned AMV height and look for the minimum vector difference

High bias apparent for TWP assignments
Improvement from Level Best Fit Assignment

Question Addressed: How much would the AMV-sonde vector difference improve if the winds were assigned to their “Level of Best Fit”? 

~50% of AMV-sonde agreements would improve by less than 2.5 ms\(^{-1}\)

~80% would improve by less than 5 ms\(^{-1}\)
Layer of Best Fit Analysis

- Layer-mean motion approximation shows improved agreement relative to traditional single-level wind height assignment methods.

- AMVs for low-clouds correspond to a deeper layer motion than high clouds.

- Clear sky WV AMVs agree closest with a much deeper layer (150 to 225 hPa) than cloudy WV (50-75 hPa).

- West Pacific cloudy AMVs seem to correspond to deeper layers than those over CONUS.

- These results have important implications for NWP data assimilation in that we can better represent AMV information in models through vertical spread of wind information instead of point representation.

- Need to explore wind shear and upper-level moisture relationships.