Identifying the Uncertainty in Determining Satellite-Derived Atmospheric Motion Vector (AMV) Height Assignments

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Introduction and Motivation

- The proper analysis of tropospheric winds is an important prerequisite to accurate numerical model forecasts

- Advances in data assimilation and NWP in recent years are challenging AMV researchers and providers to improve the quality of their products

- AMVs are typically treated in current NWP with assumed or estimated observation errors, and as single-level data

Introduction and Motivation (continued)

- Although AMVs have mostly positive impacts on NWP, it has long been assumed that vector height assignments are a relatively large source of observation uncertainty

- Various approaches have been investigated to minimize the AMV height-assignment error (i.e. Schmetz et al 1993; Nieman et al 1993), and the impacts on NWP, such as spreading the AMV information over more than one level (Rao, Velden and Braun, 2002)

- The optimal approach to this AMV “information spreading” in NWP data assimilation is still relatively unknown because the vertical representativeness of AMVs has not been thoroughly specified by the data producers

- Based on guidance from CGMS IWWG Rapporteur Jo Schmetz, a renewed effort to better understand and specify AMV height assignments was initiated at IWW8 in Bejing

Introduction and Motivation (continued)

- **In this study we investigate large samples of multispectral AMV data, and through comparisons with co-located high-resolution ARM rawinsondes, we attempt to determine:**

1)An estimate of the true AMV observational error

2)An estimate of the fraction of AMV observation error attributable to height assignment uncertainty

3)The depth (layer) of troposphere over which AMV motions may be most representative given the present height assignment uncertainty

Caveat: ***This study examines AMVs produced from NESDIS-style retrieval methods. Therefore, the quantitative results are applicable to operational GOES and MODIS winds. However, the authors feel that conceptually the results should apply to AMVs derived at other national data processing centers.***

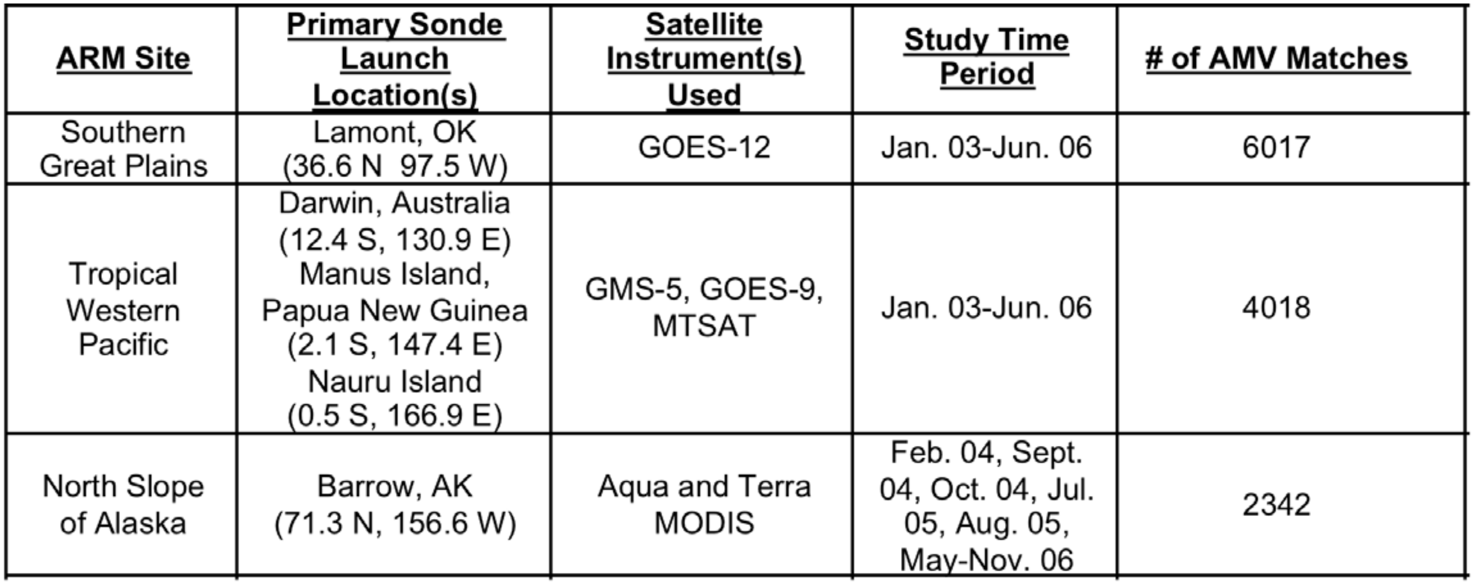
Data and Methodology

- **The AMV datasets were produced by the UW-CIMSS automated algorithm (Velden et al., BAMS, 2005), nearly identical to the code used to produce operational AMVs at NOAA/NESDIS (Daniels et al. 2002)**

- **AMV datasets are compared to rawinsonde wind observations collected by the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) program at three supersites**

- **Vaisala RS-92 sonde wind data is recorded every 2 seconds during sonde flight, providing observations at very high vertical resolution**

- Sonde accuracy: **0.5 ms^{-1} at SGP** (LORAN method)**, 0.2 ms^{-1} at TWP and NSA** (GPS method)



ARM Site	**Primary Sonde Launch Location(s)**	**Satellite Instrument(s) Used**	**Study Time Period**	**# of AMV Matches**
Southern Great Plains	Lamont, OK (36.6 N 97.5 W)	GOES-12	Jan. 03-Jun. 06	6017
Tropical Western Pacific	Darwin, Australia (12.4 S, 130.9 E) Manus Island, Papua New Guinea (2.1 S, 147.4 E) Nauru Island (0.5 S, 166.9 E)	GMS-5, GOES-9, MTSAT	Jan. 03-Jun. 06	4018
North Slope of Alaska	Barrow, AK (71.3 N, 156.6 W)	Aqua and Terra MODIS	Feb. 04, Sept. 04, Oct. 04, Jul. 05, Aug. 05, May-Nov. 06	2342

Match criteria: AMV must be within 50 km and 1 hour from sonde launch site/time

Data and Methodology (continued)

- **AMVs are initially assigned heights by the UW-CIMSS algorithm based on radiative properties of the tracked cloud or WV features using the following methods:**

  1) IR window

  2) Cloud base method

  3) CO_2 Slicing

  4) Water Vapor Absorption

  5) Histogram method

- **AMVs are then passed through a series of post-processing steps that edit or assign quality flags. Initially assigned heights may be adjusted slightly (“Auto Editing”) based upon better fit to a local 3-D analysis (Recursive Filter) of all nearby vectors.**

Data and Methodology (continued)

- **AMVs are first compared to the closest vertical sonde data point to evaluate the absolute accuracy of their initial “level-based” height assignments**

- **Next, to determine the true AMV observation error, we consider temporal and spatial wind variability parameters to estimate (and remove) the ‘matching error’**

- **Then, we evaluate the relative contribution of height assignment uncertainty to the true AMV observation error**

  - We identify the level of best AMV-rawinsonde match (or “fit”) to determine the accuracy possible if the height assignment error is minimized

  - We assume that the remaining AMV-sonde VRMS difference at the LBF is primarily due to targeting/tracking errors

- **Finally, we compute differences between AMV and rawinsonde when the rawinsonde winds are averaged over specified layers**

- Do the AMVs better correlate to a motion over a mean tropospheric layer, rather than a traditionally assigned discrete level?

Outline of Analysis Process

- **AMVs are first compared to the closest vertical sonde data point to evaluate the absolute accuracy of the AMVs at initial “level-based” height assignments**

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SGP	AMV Speed (m/s)	Sonde Speed (m/s)	AMV-Sonde Speed Bias (m/s)	**AMV-Sonde VRMS (m/s)**
Original AMV Height	21.50	21.91	-.41	**6.31**
Adjusted AMV Height	22.87	23.00	-.13	**5.75**

TWP	AMV Speed (m/s)	Sonde Speed (m/s)	AMV-Sonde Speed Bias (m/s)	**AMV-Sonde VRMS (m/s)**
Original AMV Height	10.21	10.68	-.47	**5.62**
Adjusted AMV Height	10.27	10.91	-.64	**5.27**

NSA	AMV Speed (m/s)	Sonde Speed (m/s)	AMV-Sonde Speed Bias (m/s)	**AMV-Sonde VRMS (m/s)**
Original AMV Height	16.29	17.17	-.88	**5.49**
Adjusted AMV Height	16.30	17.19	-.89	**5.36**

Baseline AMV Accuracies

AMVs here are simply compared to the closest sonde level (+/- 2 hPa), as would be done in common AMV validation studies

The ‘Adjusted AMV Height’ row reflects the AMVs that have passed through the Auto Editor (and best represent the NESDIS operational AMVs).

AMV assignment to adjusted heights improves AMV-sonde vector differences for ~60% of the matches (*not shown*)

We use these the adjusted AMV height values in the remainder of the study

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GOAL: Estimation of True AMV Observation Error

AMV OBSERVATION ERROR: The remaining AMV-sonde VRMS difference after removal of variability and sonde wind measurement error

AMV Observation Error is composed of targeting/tracking error and vector height assignment error

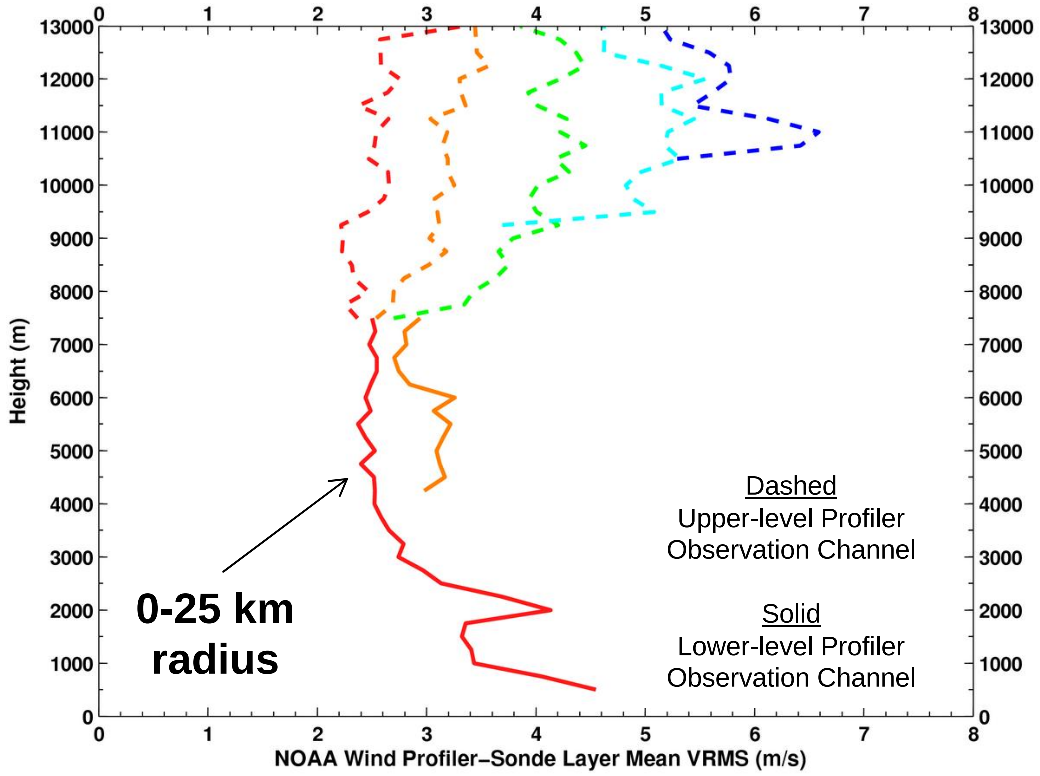
Observation Error (VRMS)
[From Kitchen (1989), QJRMS
and Schmetz (1993), JAM]

$$= \mathrm{SQRT}((\mathrm{ADJ\ HEIGHT\ VRMS})^2 - (\sigma_T^2 + \sigma_S^2 + \sigma_R^2))$$

σ_T=**Temporal Wind Variability (VRMS)**
σ_S=**Spatial Wind Variability (VRMS)**
σ_R=**Rawinsonde Error (VRMS)**

Rawinsonde error and AMV error at the adjusted height are known, so we will now determine the temporal and spatial wind variability

Data Matching Induced Errors: Spatial Variability



Maximum Spatial Variability at 11000 m

26-50 km radius = 0.7 ms^{-1}

51-75 km radius = 1.7 ms^{-1}

76-100 km radius = 2.7 ms^{-1}

>100 km radius = 3.1 ms^{-1}

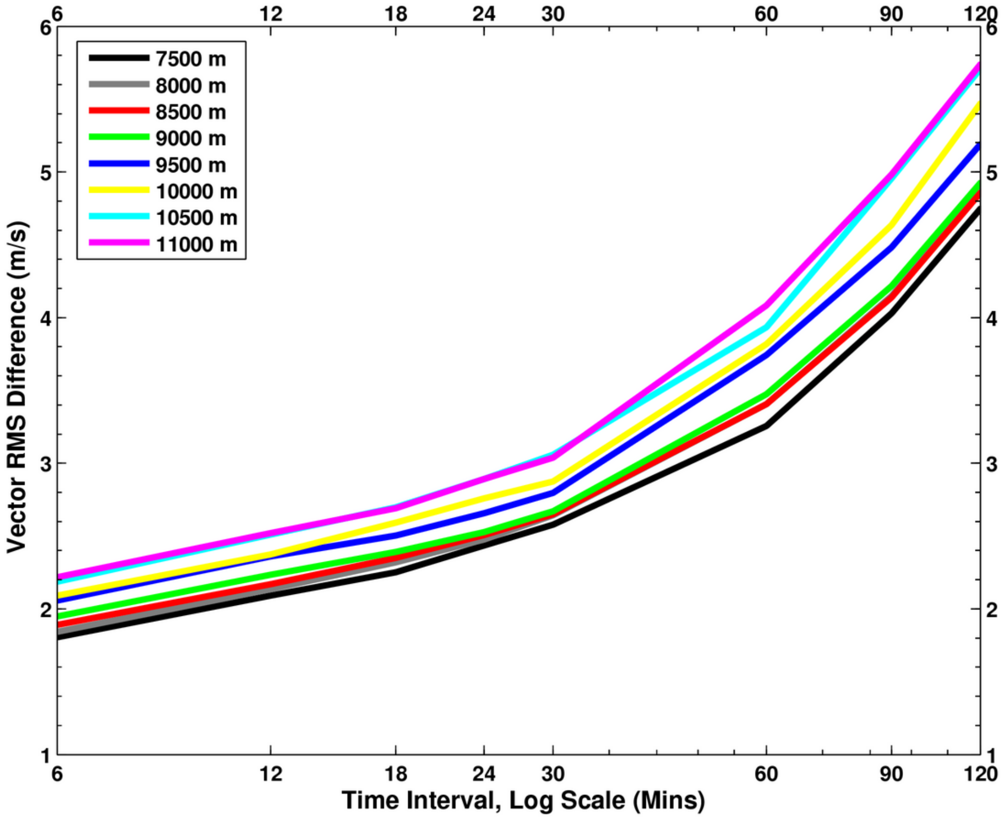
- **Sonde observations are compared to co-located 6-minute NOAA 404 MHz wind profiler observations over the Lamont, OK ARM (SGP) site for a 1-year period**

- We first compute VRMS between winds measured by stationary profiler and drifting/ascending sonde at 5 distance intervals from the profiler site

- Datasets are time-matched (+/- 3 mins), so differences are due primarily to spatial variability

- 0-25 km matches are considered a “perfect match”, so spatial variability at a given height is found by subtracting VRMS at greater distances from the 0-25 km VRMS

Data Matching Induced Errors: Temporal Variability



<u>**Maximum Spatial Variability at 11000 m**</u>

30 min Time Interval = 0.7 ms^{-1}
60 min Time Interval = 1.8 ms^{-1}
90 min Time Interval = 2.8 ms^{-1}
120 min Time Interval = 3.5 ms^{-1}

- **Time sequences of 6-minute NOAA 404 MHz wind profiler observations at the Lamont, OK ARM (SGP) site are compared for a 1-year period**

- The profiler remains in a stationary location, so differences between profiler observations within the 0-120 min period primarily result from temporal wind variability

  - We assume that instrument noise is represented by VRMS at the 6 min time interval. Temporal variability is found by subtracting the VRMS at various time intervals from the 6-min comparison

Summary of Data Matching Induced Errors

We assume that the SGP temporal/spatial variability stats are also applicable to TWP & NSA

Site	**Mean AMV-Sonde Comparison Height (Pressure)**	**VRMS Mean Spatial Variability (Separation)**	**VRMS Mean Temporal Variability (Separation)**	**VRMS Sonde Observation Error**
SGP	8300 m (350 hPa)	0.3 ms^{-1} (49 km)	1.3 ms^{-1} (69 min)	0.5 ms^{-1}
TWP	10300 m (270 hPa)	0.3 ms^{-1} (35 km)	1.2 ms^{-1} (53 min)	0.2 ms^{-1}
NSA	6500 m (430 hPa)	0.2 ms^{-1} (53 km)	0.6 ms^{-1} (35 min)	0.2 ms^{-1}

Results: Estimation of True AMV Observation Error

AMV OBSERVATION ERROR: The remaining AMV-sonde VRMS difference after removal of matching and sonde wind measurement errors

The AMV Observation Error is composed of targeting/tracking errors and vector height assignment error

Observation Error (VRMS)
[From Kitchen (1989), QJRMS and Schmetz (1993), JAM] = $\text{SQRT}((\text{ADJ HEIGHT VRMS})^2 - (\sigma_T^2 + \sigma_S^2 + \sigma_R^2))$

σ_T**=Temporal Wind Variability (VRMS)**
σ_S**=Spatial Wind Variability (VRMS)**
σ_R**=Rawinsonde Error (VRMS)**

$$\text{VRMS}_{SGP} = 5.57 \text{ m/s}$$

$$\text{VRMS}_{TWP} = 5.12 \text{ m/s}$$

$$\text{VRMS}_{NSA} = 5.32 \text{ m/s}$$

Outline of Analysis Process

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- **Then, we evaluate the relative contribution of height assignment uncertainty to the true AMV observation error**

  - We identify the level of best AMV-rawinsonde match (or “fit”) to determine the accuracy possible if the height assignment error is minimized

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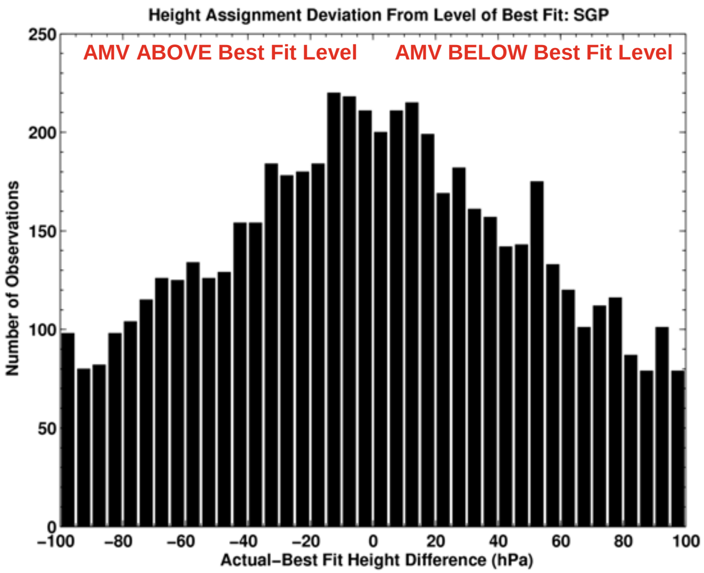
- Finally, we compute differences between AMV and rawinsonde when the rawinsonde winds are averaged over specified layers

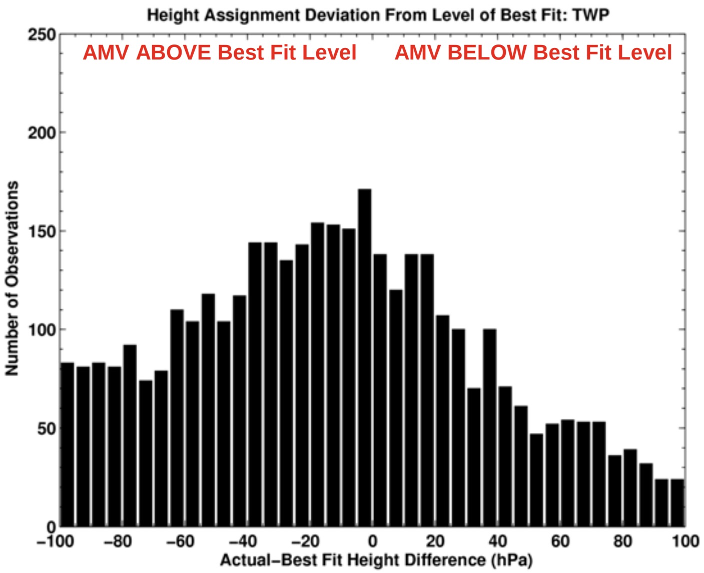
  - Do the AMVs better correlate to a motion over a mean tropospheric layer, rather than a traditionally assigned discrete level?

Level of Best Fit Height Assignment Comparison

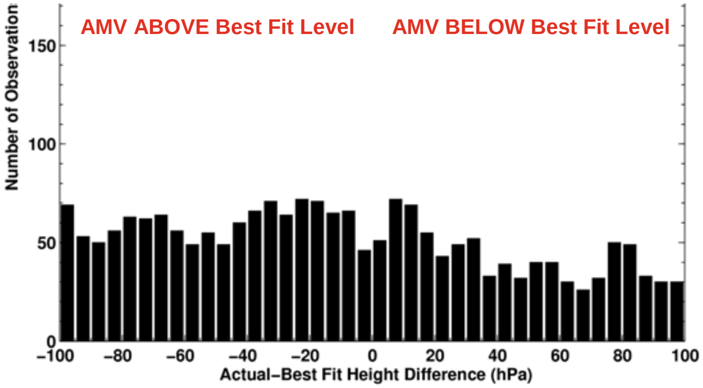
Oklahoma



Western Pacific



North Slope Alaska

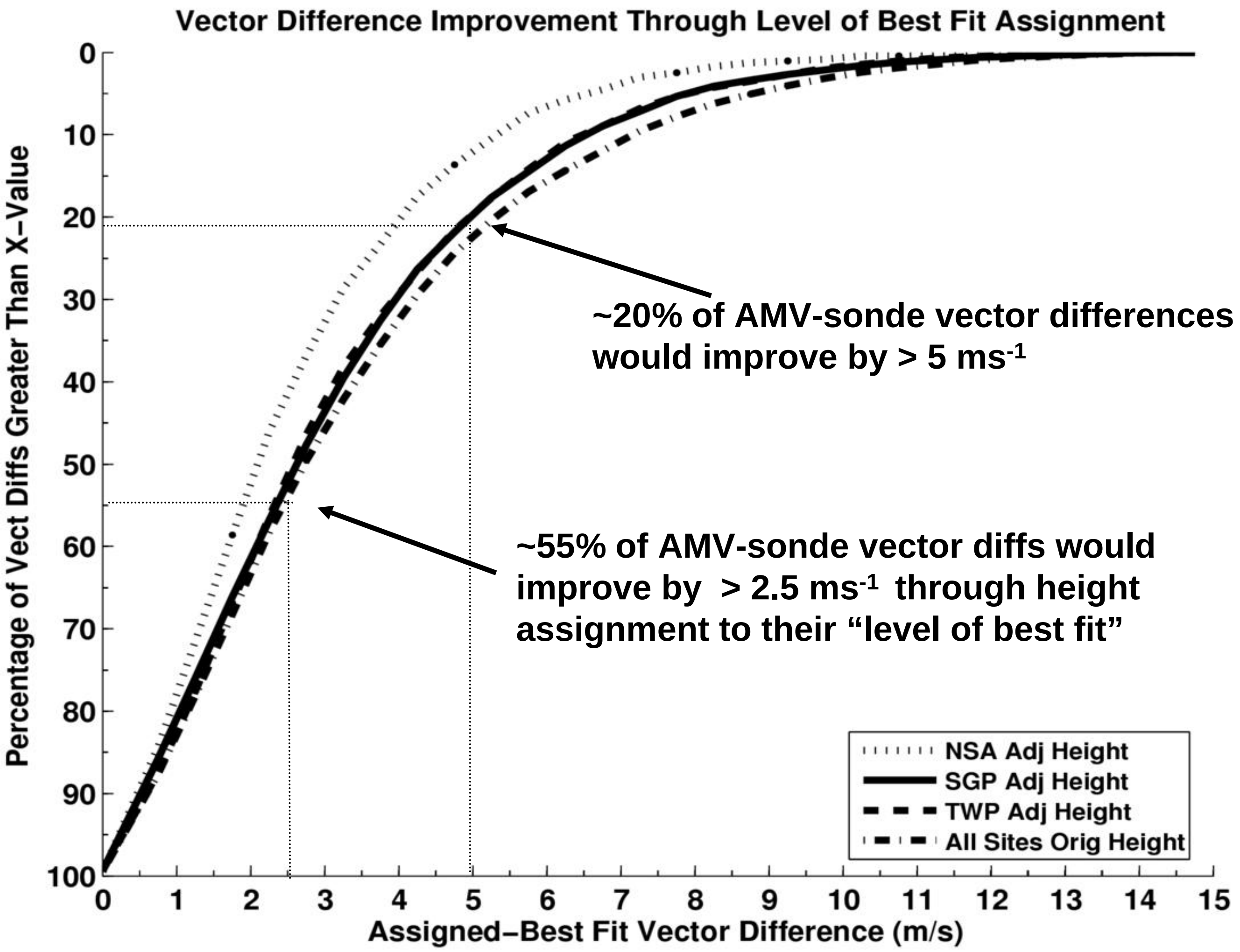


LEVEL OF BEST FIT DEFINED: The best possible “single-level” height assignment based on the satellite-observed feature motion

HOW TO COMPUTE LEVEL OF BEST FIT: Find the sonde level within +/- 100 hPa of the AMV height assignment where AMV-sonde VDIFF is minimized

Results: Level of Best Fit Height Assignment

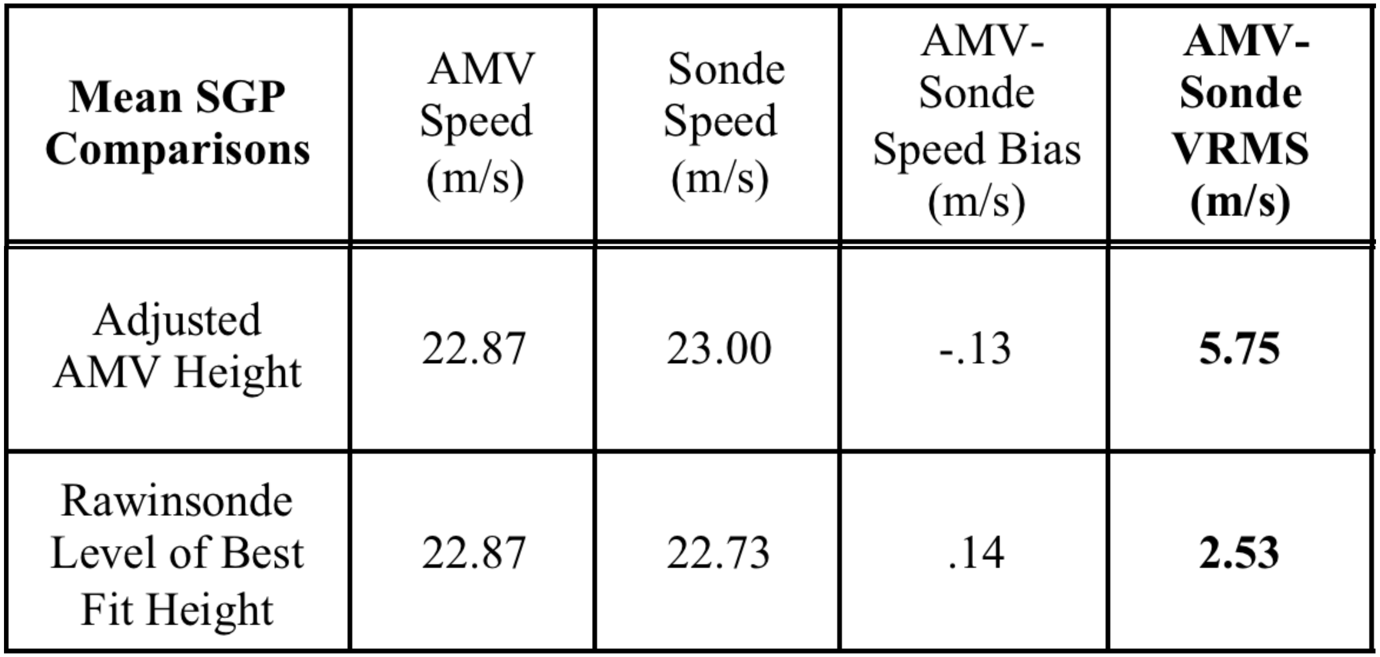
How much would AMV-sonde vector differences improve if the AMVs were assigned to their LBF?



~20% of AMV-sonde vector differences would improve by > 5 ms^{-1}

~55% of AMV-sonde vector diffs would improve by > 2.5 ms^{-1} through height assignment to their "level of best fit"

Results: Level of Best Fit Height Assignment



Mean SGP Comparisons	AMV Speed (m/s)	Sonde Speed (m/s)	AMV-Sonde Speed Bias (m/s)	**AMV-Sonde VRMS (m/s)**
Adjusted AMV Height	22.87	23.00	-.13	**5.75**
Rawinsonde Level of Best Fit Height	22.87	22.73	.14	**2.53**

Now that the VRMS at the LBF has been computed, we can estimate the relative contribution of height assignment to the total vector error

Estimate of Error From Height Assignment Uncertainty

$$\text{Fraction of Error From Height Assignment} = 1 - \frac{\text{VECTOR ERROR DUE TO TARGETING/ TRACKING}}{\text{VECTOR ERROR DUE TO TARGETING/TRACKING + } \underline{\textit{HEIGHT ASSIGNMENT}} \text{ } \textit{(AMV OBSERVATION ERROR)}}$$

$$\text{Fraction of Error From Height Assignment} = 1 - \frac{\text{SQRT}((\text{LBF VRMSE})^2 - (\sigma_T^2 + \sigma_S^2 + \sigma_R^2))}{\text{SQRT}((\text{ADJ HEIGHT VRMSE})^2 - (\sigma_T^2 + \sigma_S^2 + \sigma_R^2))}$$

σ_T=Temporal Variability (VRMS)
σ_S=Spatial Variability (VRMS)
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σ_T=Temporal Variability (VRMS)
σ_S=Spatial Variability (VRMS)
σ_R=Rawinsonde Error (VRMS)

NSA = 49%
SGP = 58%
TWP = 70%

- **Results clearly show that height assignment is a large fraction of AMV error**
- **Residual percentage of error is from the AMV targeting/tracking process**
- **The larger fraction of tracking error at NSA makes sense, since MODIS AMVs employ successive images at much greater time intervals (~100 mins)**
- **At SGP and TWP, target tracking is superior due to the higher frequency of available geostationary satellite images**
    - Height assignment is most important (relatively) in the tropics (TWP) where better cloud tracers (trade wind cumulus, and long-lasting cirrus) are often found

Outline of Analysis Process

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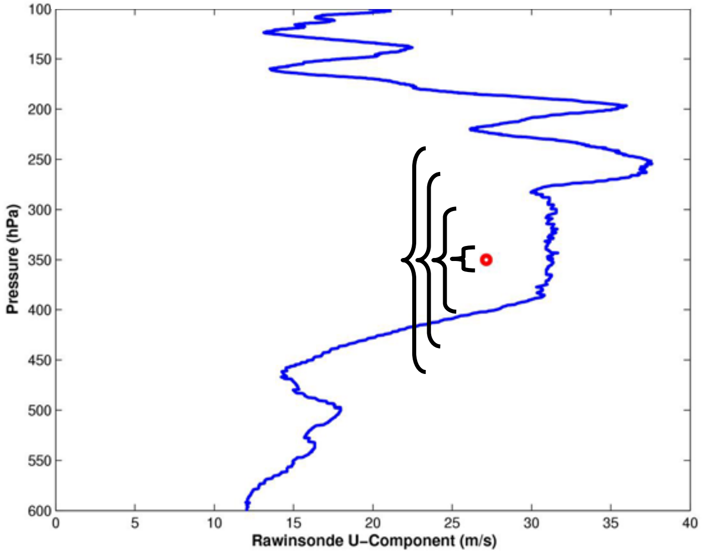
Investigation of AMV Height Assignments as Tropospheric Layers

Here we challenge the traditional constraint that AMVs are best associated/assigned to a discrete tropospheric level

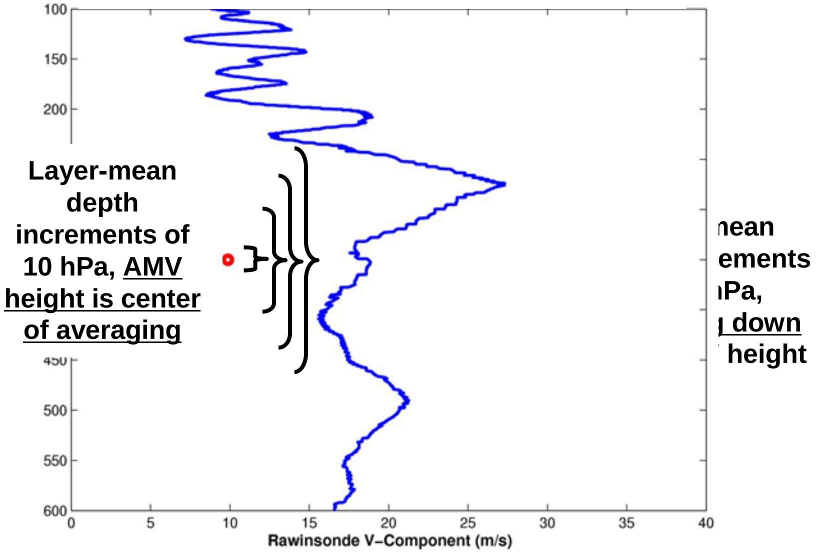
- **Starting at the AMV height assignment level, sonde wind component data are averaged over increasingly deep layers (exact method of averaging depends if targets are clear vs. cloudy – see illustrations below)**

- **VRMS difference stats are computed between layer mean sonde and AMV to evaluate the layer depth of best AMV-sonde agreement**

Clear-Sky WV U-Component



Clear-Sky WV V-Component



Layer-mean depth increments of 10 hPa, AMV height is center of averaging

Results: GOES-12 (SGP) AMVs - *Layer* of Best Fit

- **GOES-12 low-level AMVs (1000-600 hPa) best correlate to a 70-100 hPa tropospheric layer in depth**

- More difficult to evaluate low level vectors due to complex boundary layer and surface flows

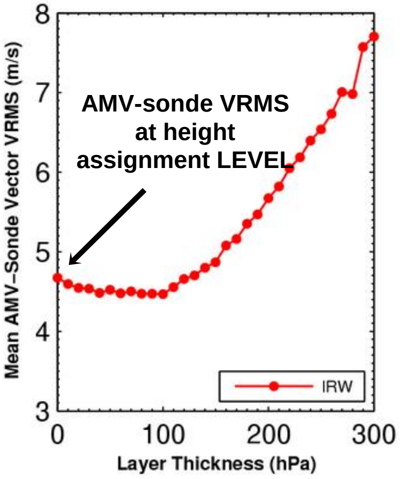
Upper-level cloudy IR and WV AMVs (above 600 hPa) agree best with a shallower layer, ~30-50 hPa in depth

- Layer of best fit improves agreement by 0.3 to 0.5 ms^{-1}

- **Clear-sky WV AMVs best relate to a much deeper layer, 150-200 hPa in depth**

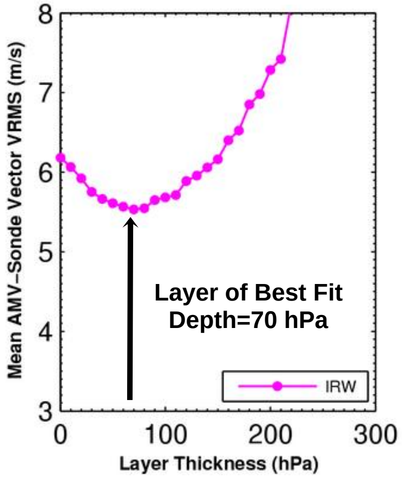
- Rao et al. (2002) show upper-level moisture content and/or gradients can modulate the layer of best fit depth for CSWV

Imager VIS



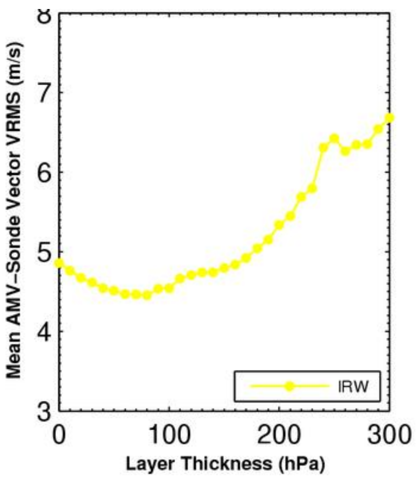
AMV-sonde VRMS at height assignment LEVEL

Imager SWIR

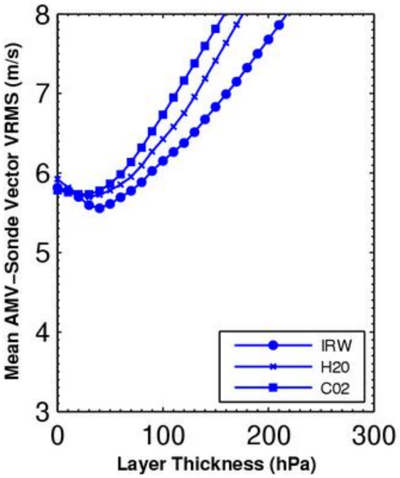


Layer of Best Fit Depth=70 hPa

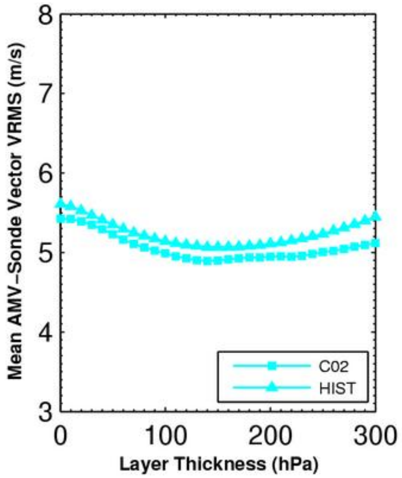
Imager Low-Level IR



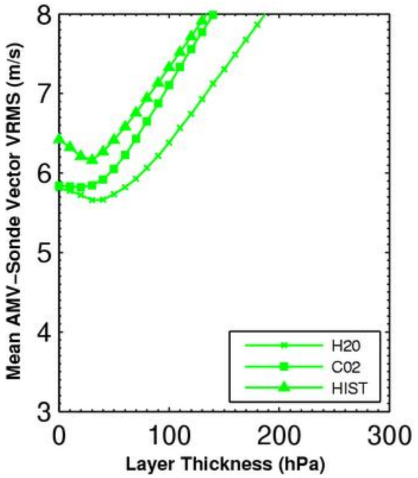
Imager Upper-Level IR



Imager Clear-Sky WV



Imager Cloudy WV



Results: Western Pacific (TWP) AMVs (GMS-5, GOES-9, MTSAT)

- **West Pac. AMV-sonde agreements generally closer than GOES-12, except for clear-sky WV**

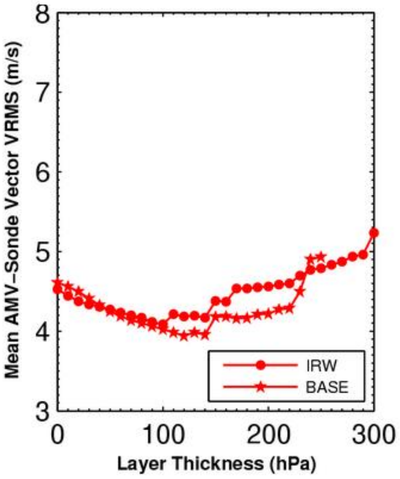
- **Upper-level cloudy IR and WV AMV layer depths similar to, but more pronounced than GOES (SGP)**

- Layer of best fit improves agreement by 0.5 to 0.8 ms^{-1}

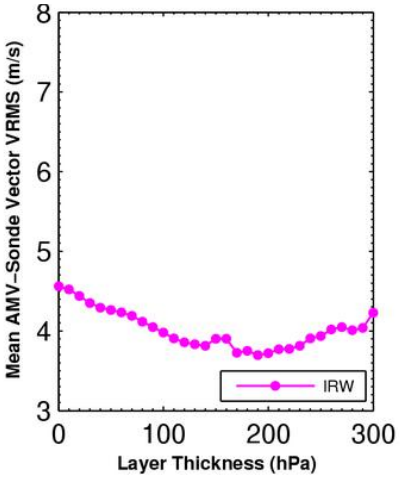
- **Clear-sky WV results similar to GOES-12**

- **Low-level AMV relationships less clear**

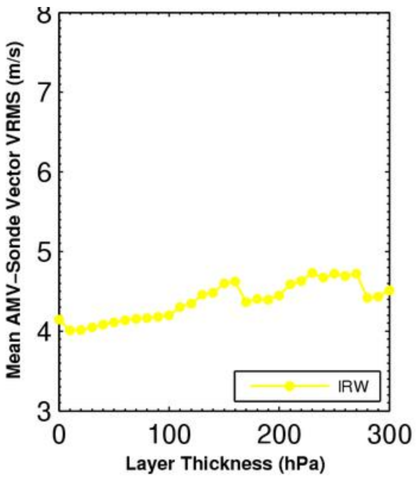
Imager VIS



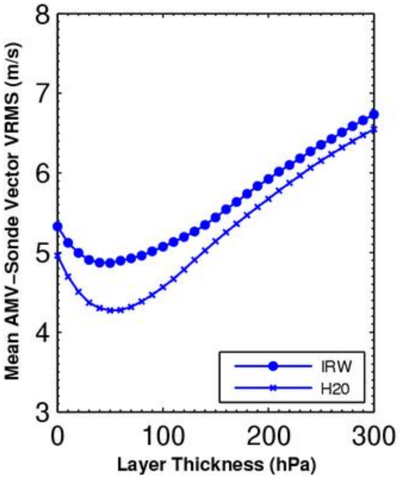
Imager SWIR



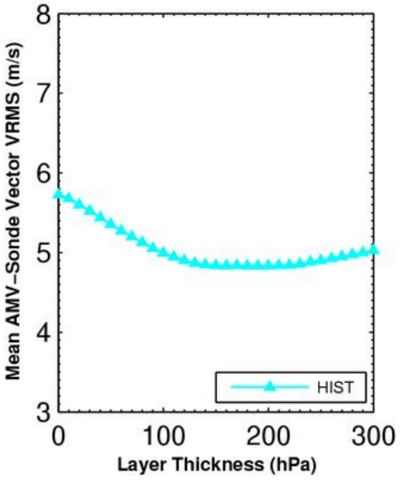
Imager Low-Level IR



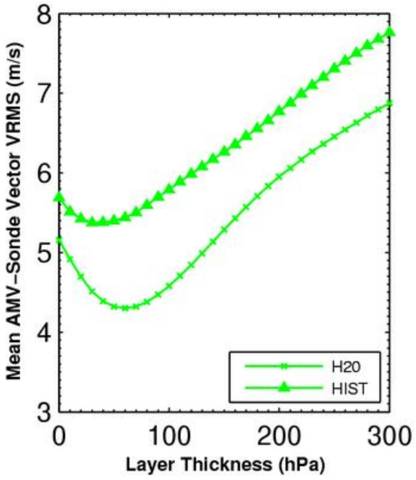
Imager Upper-Level IR



Imager Clear-Sky WV

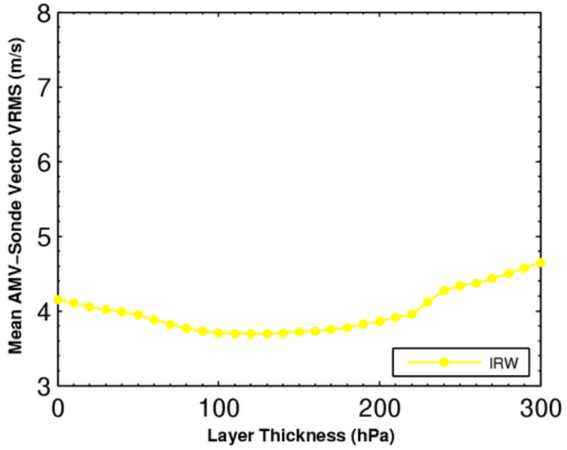


Imager Cloudy WV

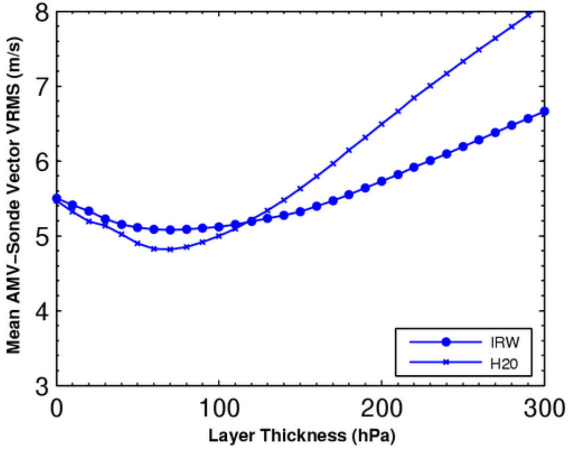


Results: Polar (NSA) AMVs (Aqua and Terra MODIS)

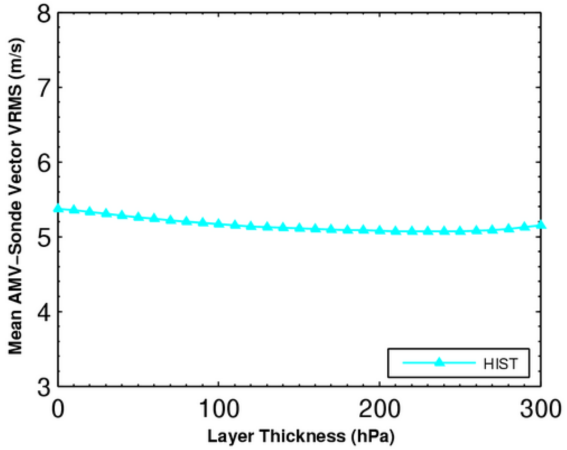
- Layer mean relationships are still suggested, however they are less clear. The characteristics of Arctic clouds, together with the extreme variability in flow regimes at higher latitudes, may be damping more definitive signals.



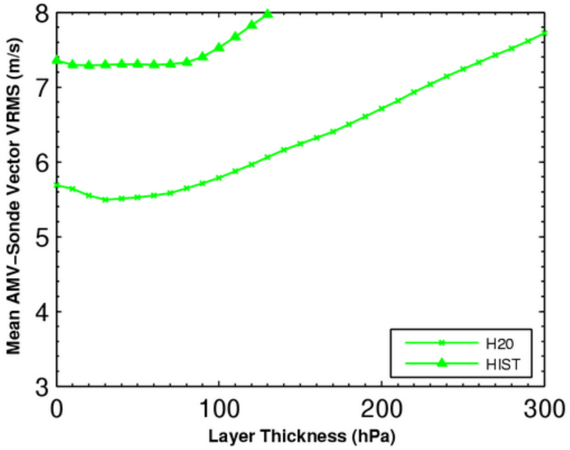
Low-Level IR



Upper-Level IR



Clear-Sky WV



Cloudy WV

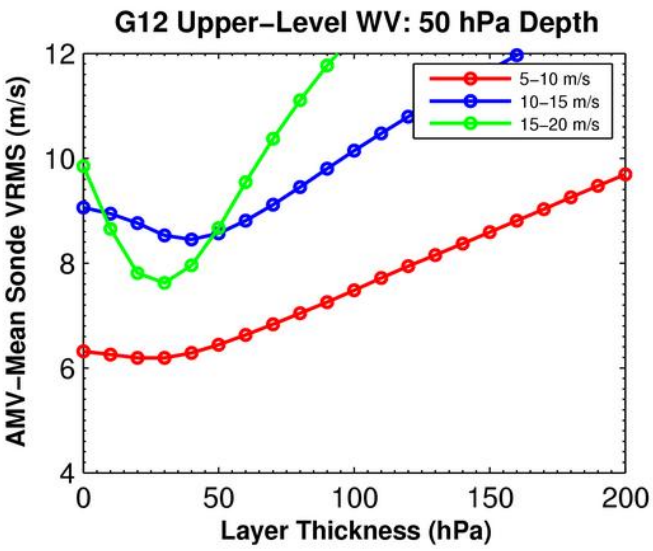
Results: Influence of Vertical Wind Shear: SGP/TWP

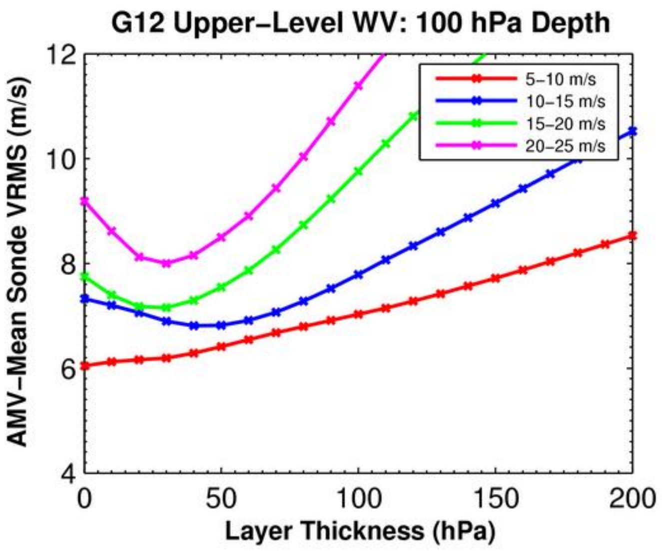
Uncertainty in AMV single-level height assignments is magnified in high vertical shear environments, since even small errors can result in large misrepresentations

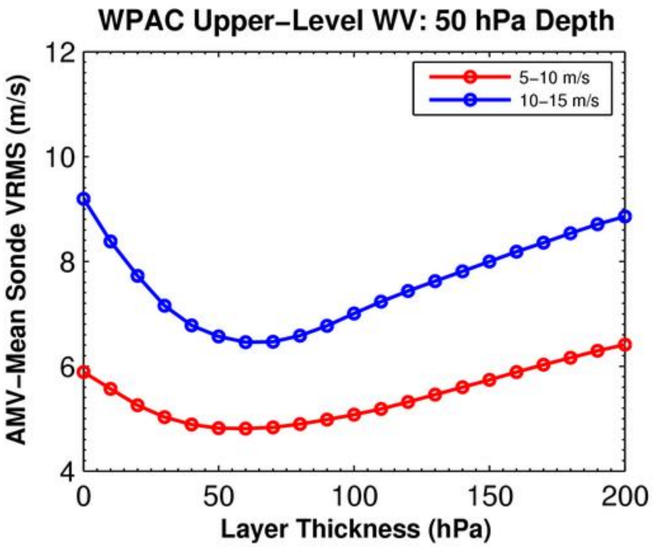
Higher vertical wind shear has major impacts:

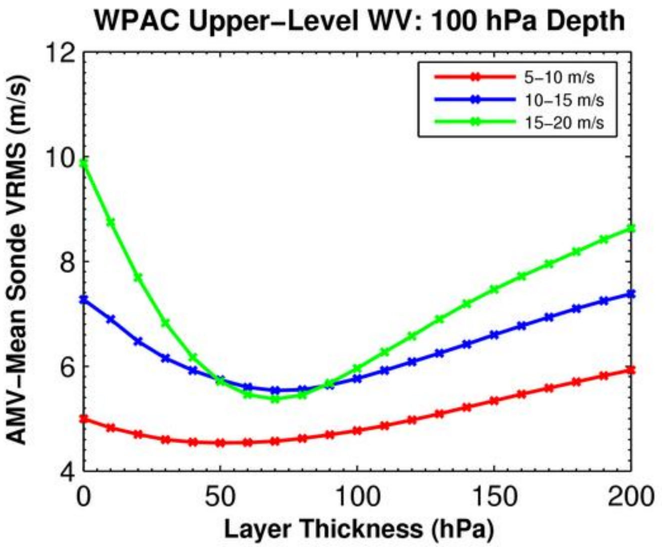
1) Increased AMV-sonde VRMS at AMV height assignment level

2) Reduction of VRMS using a layer-mean height representation has a more pronounced impact


G12 Upper–Level WV: 50 hPa Depth


G12 Upper–Level WV: 100 hPa Depth

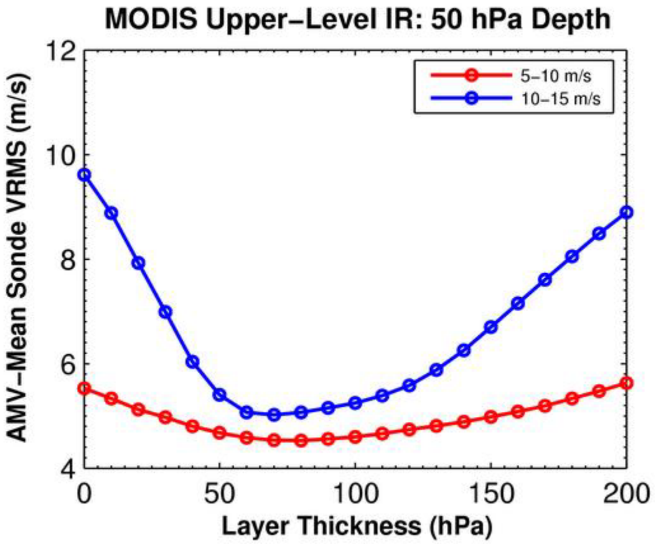

WPAC Upper–Level WV: 50 hPa Depth

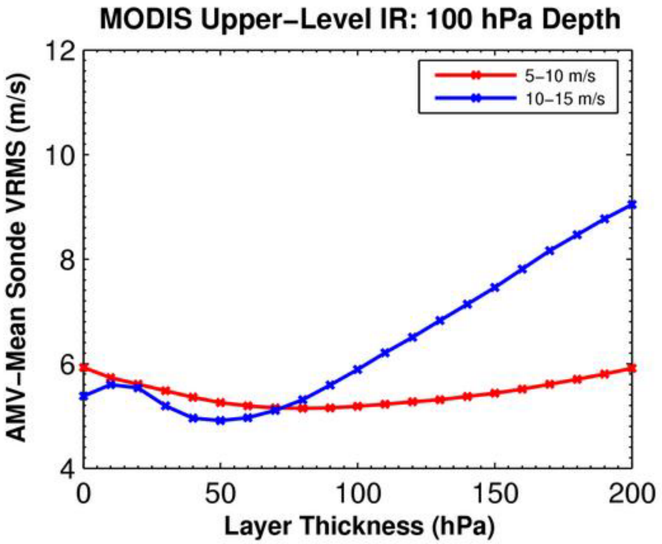

WPAC Upper–Level WV: 100 hPa Depth

Wind Shear=Vector Difference Between Sonde Wind at Layer Top and Bottom (50 or 100hPa depths)

Results: Influence of Vertical Wind Shear: NSA/MODIS

MODIS upper-level IR AMVs also show a lower layer-mean VRMS in high shear regimes, especially when shear is concentrated over a shallow depth





Clear-sky WV AMV-wind shear relationships are less evident (not shown)

A sufficient number of upper-level, high-shear cloudy WV matches were not available

Conclusions

Caveat: This study examined AMVs produced from NESDIS-style retrieval methods. Therefore, the quantitative results are applicable to operational GOES and MODIS winds. However, the authors feel that conceptually the results should apply to AMVs derived at other national data processing centers.

- **Based on a large sample of high-resolution rawindsonde information matched with collocated AMVs for three different geographic regions, we are able to estimate true AMV observation errors.**

- **Further analysis of AMV height assignments indicates that significant improvements in AMV-rawinsonde vector agreements are achieved by matching to collocated rawinsonde levels of ‘best fit’.**
  - From this analysis, we are able to show quantitatively that AMV height assignment indeed represents a large fraction of AMV error.

Conclusions (continued)

- **Since employing a level of best fit is impractical in operational applications, we show that some of this height assignment uncertainty can be overcome by treating the AMVs as representing finite tropospheric *layers*, rather than single discrete levels.**

  - Attribution of AMV information to a specified layer improves upon AMV-sonde agreement by ~0.3 to 1 ms^{-1} over original level-based assignments, with even larger improvements in high wind shear situations.

- **For a given AMV, the depth of best layer agreement is dependent on many factors:**

  1) Original vector height (Message: Accurate initial height assignment still important

  2) Spectral channel used for tracking

  3) Vertical wind shear magnitude

  4) Target scene type (i.e. clear vs. cloudy)

  5) Upper-tropospheric moisture content/gradients (WV winds - Rao et al. 2002

  6) Geographic region (i.e. tropics vs. polar)

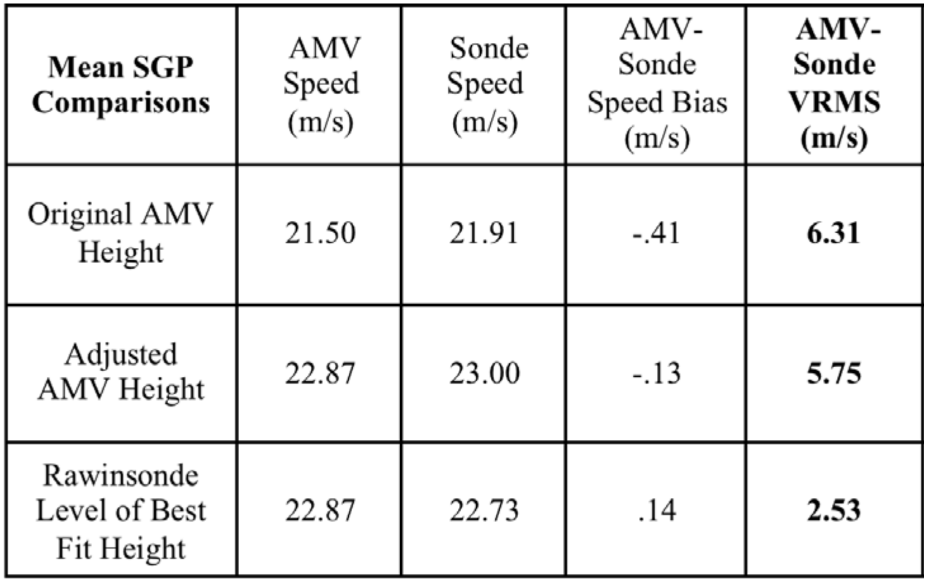
Implications

- **These results could be relevant to NWP data assimilation of AMVs, as they traditionally may not be well represented in numerical model analyses due in part to the elusiveness of a specified observational error, and also due to treatment as single-level observations**

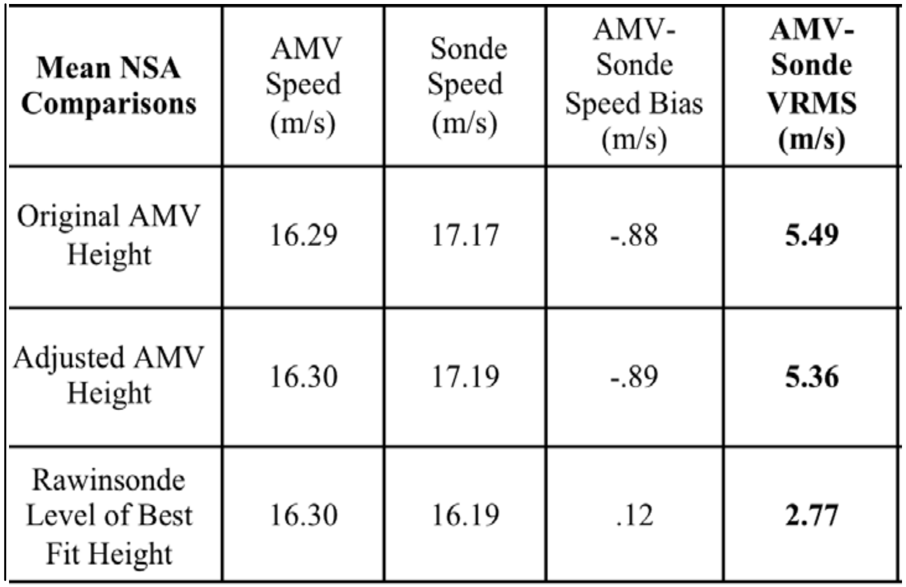
- **The findings should next be tested in NWP for analysis/forecast impacts, especially in data sparse and dynamically active (high shear) regimes**

Velden, C. S., and K. M. Bedka, 2008: Improved representation of satellite-derived atmospheric motion vectors by attributing the assigned heights to tropospheric layers. Conditionally accepted in *J. Appl. Meteor.*

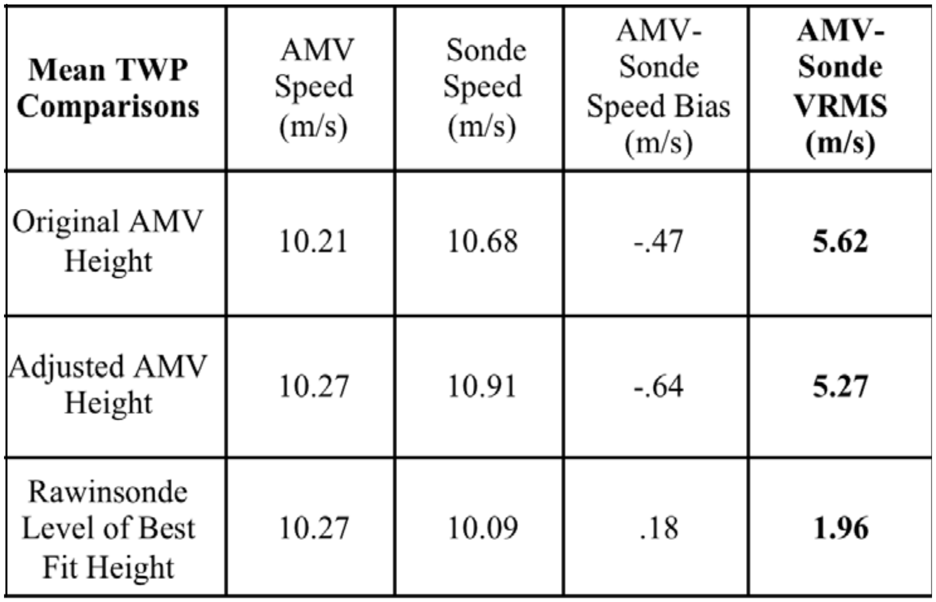
SUPPLEMENTAL MATERIAL



Mean SGP Comparisons	AMV Speed (m/s)	Sonde Speed (m/s)	AMV-Sonde Speed Bias (m/s)	**AMV-Sonde VRMS (m/s)**
Original AMV Height	21.50	21.91	-.41	**6.31**
Adjusted AMV Height	22.87	23.00	-.13	**5.75**
Rawinsonde Level of Best Fit Height	22.87	22.73	.14	**2.53**



Mean NSA Comparisons	AMV Speed (m/s)	Sonde Speed (m/s)	AMV-Sonde Speed Bias (m/s)	**AMV-Sonde VRMS (m/s)**
Original AMV Height	16.29	17.17	-.88	**5.49**
Adjusted AMV Height	16.30	17.19	-.89	**5.36**
Rawinsonde Level of Best Fit Height	16.30	16.19	.12	**2.77**



Mean TWP Comparisons	AMV Speed (m/s)	Sonde Speed (m/s)	AMV-Sonde Speed Bias (m/s)	**AMV-Sonde VRMS (m/s)**
Original AMV Height	10.21	10.68	-.47	**5.62**
Adjusted AMV Height	10.27	10.91	-.64	**5.27**
Rawinsonde Level of Best Fit Height	10.27	10.09	.18	**1.96**

After adjusting for match errors, we can compare the AMV-sonde VRMS statistics at the adjusted and LBF heights to estimate the relative contribution of height assignment to the total vector error