CGMS-35, NOAA-WP-22
Prepared by C. Velden
Agenda Item: II/5
Discussed in WGII

PROGRESS IN NOVEL STUDIES ON THE HEIGHT ALLOCATION OF AMVS TO LAYERS

In response to CGMS Action 34.20

This paper investigates the assignment of altitude heights to satellite-derived atmospheric motion vectors (AMVs), commonly known as cloud-drift and water vapor (WV)-motion winds. The traditional practice of assigning AMV heights to discrete tropospheric levels is shown to be inadequate, and a superior methodology is achieved by representing the AMV motion in terms of tropospheric layers. Large volumes of multispectral (IR, VIS and WV) AMV datasets are compared to collocated rawinsonde wind profiles collected by the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) program at three geographically-disparate sites: the U.S. Southern Great Plains, the North Slope of Alaska, and the Tropical Western Pacific. These comparisons reveal that RMS differences between matched AMVs and rawinsonde wind values are minimized if the rawinsonde values are averaged over specified layers. In other words, the AMV value better represents a motion over a tropospheric layer, rather than a discrete level. The layer characteristics are specifically identified according to AMV height (high-cloud vs. low-cloud), type (spectral bands, clear vs. cloudy), geo-location, height assignment method, and amount of environmental vertical wind shear present. The findings have potential important implications for AMV data assimilation and NWP.

PROGRESS IN NOVEL STUDIES ON THE HEIGHT ALLOCATION OF AMVS TO LAYERS

Christopher Velden and Kristopher Bedka
Cooperative Institute for Meteorological Satellite Studies (CIMSS)
University of Wisconsin-Madison

1. INTRODUCTION

The proper specification and analysis of tropospheric winds is an important prerequisite to accurate numerical model forecasts. The retrieval of atmospheric motion vectors (AMVs) from satellites has been expanding and evolving since the early 1970s (Menzel 2001; Velden et al. 2005). Most of the major meteorological geostationary satellite data centers around the globe are now producing cloud and water vapor tracked winds with automated algorithms using imagery from operational geostationary satellites. Contemporary AMV processing methods are continuously being updated and advanced through the exploitation of new sensor technologies, and innovative new approaches. It is incumbent upon the research community working in AMV extraction techniques to ensure that the quality of the current operational products meets the needs of the user community. In particular, the advances in numerical weather prediction (NWP) in recent years have placed an increasing demand on data quality. With remotely-sensed observations dominating the initialization of NWP models over regions of the globe that are traditionally data-sparse, the motivation is clear: the importance of providing *high-quality* AMVs becomes crucial to their relevance and contributions toward realizing superior model predictability. The improved data assimilation methods now emerging from the NWP community are challenging the AMV researchers and providers to advance the quality of their products.

Accurate NWP requires observations for representing the initial state of the atmosphere and for updating the model through data assimilation. Over oceanic regions, where significant weather is common, conventional data sources are especially scarce. Thus, AMVs are useful for NWP because they can provide information in these important regions that might otherwise lack in accurate observations.

AMVs are derived by tracking either cloud or WV features (sharp edges or radiance gradients) in sequential images of multispectral satellite imagery. For example, cloud features detected in the infrared (IR) and visible (VIS) channels. AMVs from IR typically capture flow features in both the upper and lower troposphere; AMVs from VIS generally are used to depict motion in the lower troposphere. WV features are followed in cloud-free scenes using the WV channels that are present on most of the current operational environmental satellites (Velden et al. 1997). Therefore, the full complement of multispectral AMVs can provide wind data coverage over most of the globe, most of the time.

Many studies have shown the positive impact that AMVs can have on NWP. For example, GOES AMVs were assimilated into the Geophysical Fluid Dynamics Laboratory (GFDL) hurricane prediction system to determine their impact on simulations of Atlantic hurricanes (Soden et al. 2001). In over 100 cases, the GOES AMVs dramatically reduced a persistent westward bias common in the GFDL model. Furthermore, the AMVs were able to depict more accurately vorticity gyres in the environmental flow, which led to significant improvements in track position at all forecast times. A study using the European Centre for Medium-Range Weather Forecasts (ECMWF) system showed that AMVs are also beneficial to simulations of systems other than hurricanes (Kelly, 2004). In another study, the Navy Operational Global Atmospheric Prediction System (NOGAPS) was used to investigate the impact of targeted dropsondes and satellite winds on model analyses and forecasts of North Pacific weather events (Langland et al. 1999). It was found that the satellite data had a more positive impact on the forecast errors than did the dropsonde data. This was a result of the large area covered by the satellite data and the high temporal resolution. In fact, positive impacts such as those just discussed have led to the routine assimilation of AMVs, to varying degrees, in most operational models.

AMVs are typically treated as single-level data, that is, the AMV wind speed and direction are assigned by the processing algorithms to a determined/estimated pressure height, and these are used by the NWP data assimilation systems. Although as noted above that AMVs have had large positive impacts on NWP, the representative vector heights have proven to be a relatively large source of error (Nieman et al. 1993; IWW8 2006) because the satellite sensors actually sense radiation emitted from a finite layer of the troposphere rather than just one specific level. Thus, problems in data assimilation can arise because of the difficulty in accurately representing the measured motion of a layer by a single-level value. This type of discrepancy is especially prevalent in clear-air WV winds in which a sharp radiometric gradient signal (e.g., a cloud) is not usually present (Velden et al. 1997; Soden et al. 2001; Rao et al. 2002).

The height-assignment problems discussed above, and the potential impact on NWP when assimilating AMVs, is the primary motivation for this research. Although various approaches to minimize the height-assignment problem have been investigated, such as spreading the information over more than one level (Rao et al. 2002), the best manner in which to do this is still relatively unknown because the vertical representativeness of the AMVs has not been examined thoroughly. To this end, we investigate the vertical representativeness of these data by comparing them with collocated rawinsondes and attempting to determine the depth (layer) of troposphere over which the AMVs may be representative. This information may then used in numerical model simulations to determine the potential forecast impact.

The data and methodologies used in this study for the determination of the vertical representativeness characteristics of the AMVs are described in section 2. Section 3 presents results of the comparisons with rawinsonde observations. Section 4 briefly discusses the implications of the findings and offers potential application directions.

2. DATA AND METHODOLOGY

2.1 Datasets

The AMV datasets used in this study are produced by the UW-CIMSS automated algorithm that is nearly identical to the code used to produce operational AMVs at NOAA/NESDIS (Daniels et al. 2002). Therefore, the results are robust in terms of operational applications, and consistent in the regional comparisons discussed in the next section. To investigate regional variations, we examine AMVs produced from both geostationary and polar-orbiting platforms (Velden et al. 2005; Key et al. 2003). The algorithm employs successive image triplets using Visible (VIS), Shortwave IR (SWIR), Water Vapor (WV), and IR Window (IRW) spectral channels. The basic algorithm methodology is described in Velden et al. 1998. The final AMV pressure-altitude assignments are derived from first passing the targeted features through a series of height assignment routines based on the radiative properties of the cloud or WV features (Nieman et al. 1993, Schmetz and Holmlund 1992) to produce an initial set of estimated height values. These values are then passed through an automated quality control procedure (Velden et al. 1998) that can adjust the heights slightly based on a best fit of each vector to a local 3-dimensional analysis of all the AMVs in the immediate vicinity. In the investigations reported on in the next section, there was little difference in the layer-average results using both the initial and final height values, other than the final (adjusted heights) yielded superior rms differences with rawinsondes. Therefore, only the results based on the final heights are presented in Section 3, and will be referred to later in the text as the originally-assigned AMV heights.

The 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: the U.S. Southern Great Plains (SGP), the North Slope of Alaska (NSA), and the Tropical Western Pacific (TWP). The advantage in using ARM rawinsonde data is that wind observations are collected at a very high vertical resolution, every 2 seconds during the balloon flight, allowing for a large number of winds to be included in the layer-mean calculations. Most global rawinsonde observations are only recorded at mandatory and significant levels, which can be spaced far apart in the vertical and would likely be inadequate for this study. For informational purposes, the errors in these rawinsonde winds are estimated to be ~.5 ms^{-1} (LORAN method at SGP) and .2 ms^{-1} (GPS method at TWP and NSA). The primary rawinsonde launch locations within these ARM sites are summarized in Table 1, in addition to the satellite instrumentation used to acquire imagery over three regions, the time period for the comparisons, and the total number of available AMV-rawinsonde matches. The NSA study period for MODIS Aqua and Terra AMVs differs from that of SGP and TWP because an insufficient number of rawinsondes were launched before June 2006, so the period was extended until Nov. 2006.

2.2 Comparison Methodology

For this study, an AMV is considered for a comparison match with a rawinsonde when it is located within 50 km and one hour from the rawinsonde observation. For each match, the AMV speed and direction is compared to layer-mean rawinsonde wind observations for layers ranging from 10 to 300 hPa in thickness. Rawinsonde winds are accumulated within the layer of a specified thickness, the u- and v-components are averaged, and then the vector difference between the layer-mean rawinsonde and AMV is computed. AMV-rawinsonde vector differences are further separated into categories: satellite imaging channel, original height assignment level, height assignment technique, geographic location (ARM site), and clear-sky versus cloudy target type (for WV AMVs). Vector root mean square (VRMS) difference statistics are computed for each of these categories against layer depth increments increasing by 10 hPa (up to 300hPa). For the same (homogeneous) sample of matches, AMV-rawinsonde VRMS stats are also computed for the rawinsonde level closest to the original AMV height assignment. This is done so that the potential reduction in error by assuming a layer representation vs. the original single-level can be assessed.

The computation of the layer-mean is done differently depending on the scene type from which the AMV was derived. For clear-sky WV AMVs, the original height assignment represents the center of the layer-mean computations, as the signal detected by the WV channel (broad spectral response function) originates from a deep atmospheric layer (Weldon and Holmes 1991; Velden et al. 1997). For vectors derived by cloud tracking, the original vector height assignment represents the upper limit of the layer-mean computations, as it is assumed that a remotely-sensed cloud target is normally advected by flow at and below cloud top. For lower-tropospheric cloud-drift AMVs, (i.e. below 700 hPa), the layer-mean cannot include winds over the full 300 hPa thickness range, so the rawinsonde near-surface wind represents the lower-limit of the layer mean computations. For upper-tropospheric AMVs, the upper bound of the layer-mean (and original cloud target height assignments) is 100 hPa, to limit the potential influence of flow from within the stratosphere.

ARM Site	**Primary Sonde Launch Location(s)**	**Satellite Instrument(s) Used**	1 **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

Table 1. The primary rawinsonde launch locations within the indicated ARM sites, the satellite instrumentation used to acquire imagery over three regions, the time period for the comparisons, and the total number of available AMV-rawinsonde matches.

3. FINDINGS

3.1 Originally-assigned AMV height level vs. rawinsonde level of best fit

Before considering the layer results, it is of interest to examine the characteristics of the originally assigned single-level AMV heights to what we will refer to as the level of best fit (LBF). The LBF is the level of minimum AMV-rawinsonde vector difference, limited to +/- 100 hPa from the original AMV height assignment (constrained to limit spurious results from rawinsonde winds far from the actual tracer height that just happen to match up the best). Fig. 1 shows the distribution of originally-assigned AMV height deviations from the corresponding LBFs. Negative height differences correspond to vectors being assigned higher than the level of best fit. The results show a ”normal” distribution over the SGP site, but a tendency for the TWP AMVs to be assigned higher heights relative to the best fit level. Distinct maxima are present at the ends of the distributions, indicating best AMV-sonde agreement with a level far from the actual height assignment (which may or may not be a true representation). The significance of the height assignment on the AMV observation error is evident from Fig. 2. The improvement in AMV-sonde vector difference yielded by theoretically re-assigning the AMV heights to the LBFs: ~50 % of AMV-sonde vector differences would improve by at least 2.5 ms^{-1}, while ~20 % would improve by more than 5 ms^{-1}. This remarkable result is consistent for both the SGP and TWP site comparisons.

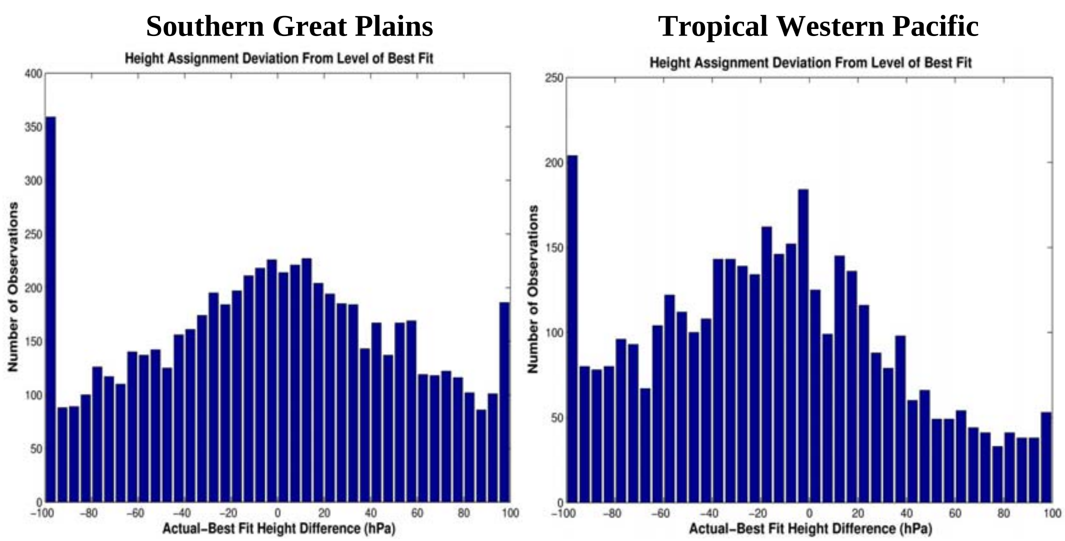

Fig. 1. The distribution of originally-assigned AMV height deviations from the corresponding LBFs. Negative height differences correspond to vectors being assigned higher than the level of best fit.

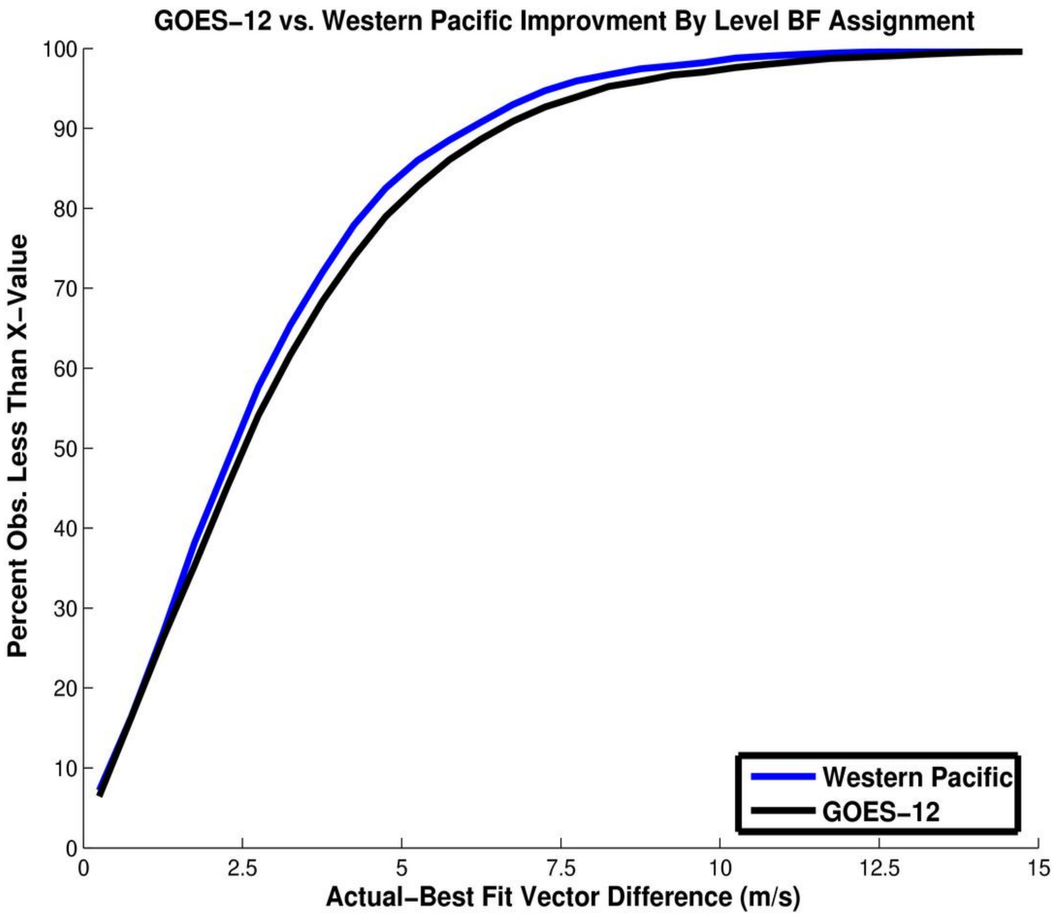

Fig. 2. The improvement in AMV-sonde vector difference yielded by theoretically re-assigning the AMV heights to the LBFs: ~50 % of AMV-sonde vector differences would improve by at least 2.5 ms^{-1}, while ~20 % would improve by more than 5 ms^{-1}.

3.2. Originally-assigned AMV height level vs. rawinsonde layer of best fit

Having established the importance of proper height attribution to AMVs, we now examine the AMVs in terms of the tropospheric *layer* their motion best represents. The AMV-rawinsonde comparisons are plotted as VRMS differences for the various rawinsonde wind averaged over the layer thickness categories (10-300hPa, in 10hPa increments), and are represented by the curves in Figs. 3-5 (with the corresponding single level-based VRMS values plotted on the y-axis).

The results presented in Figs. 3-5 consistently indicate that better AMV-rawinsonde matches occur when a layer-averaged rawinsonde wind is considered instead of a single-level. The curve minima (match improvements) are on the order of 0.5 to 1m/sec lower than the corresponding single level values. These results strongly indicate that AMVs are better represented by tropospheric layer-average winds, and these layer depths are specifically identified in terms of AMV qualities in Figs. 3-5. The major findings are summarized as follows:

- Lower-level (600-1000hPa) AMVs over land (SGP) best correspond to a layer depth of ~70-100 hPa. Over marine regions (TWP), these vectors better correspond to a depth of ~150-200 hPa, although the curve minima are less defined. This general finding relates well to previous studies which showed that marine AMV motion at or near cumulus cloud base (rather than the cloud tops usually assumed as the AMV heights) best corresponds to the overall cloud motion (Hasler, 1979; Spinoso 1997). In high latitudes (NSA), the results are less conclusive, but suggest a slight tendency to a thicker layer (200-250 hPa). The local vertical shear characteristics and variability are likely playing a role in the regional differences, and this aspect is discussed in a later section.

Upper-level (100-600hPa) cloud-tracked AMVs generally correspond to a shallower layer (~30-60 hPa) than that from low-level tracers. Most of the upper-level tracers are cirrus clouds, which are often shallow and advect in higher shear environments. Thus, these AMVs correlate best with a shallower layer flow. TWP AMVs agree with a slightly deeper layer than those over SGP, which is likely related to differing shear characteristics, coupled with the tracking of thicker cirrus plumes associated with higher WV amounts over the tropics. The depth of best fit layer appears to be independent of the tracer height assignment technique employed. The exception to the above generalizations is apparent in the NSA domain, where again the results are less clear. The characteristics of Arctic clouds, together with the extreme variability in flow regimes at higher latitudes, may be washing out definitive signals in this region.

- Upper-level clear sky WV AMVs over all three domains agree closest with a thicker layer of ~150-250 hPa. As Rao et al. (2002) show, the precise depth of this layer is likely modulated by upper-tropospheric moisture content.

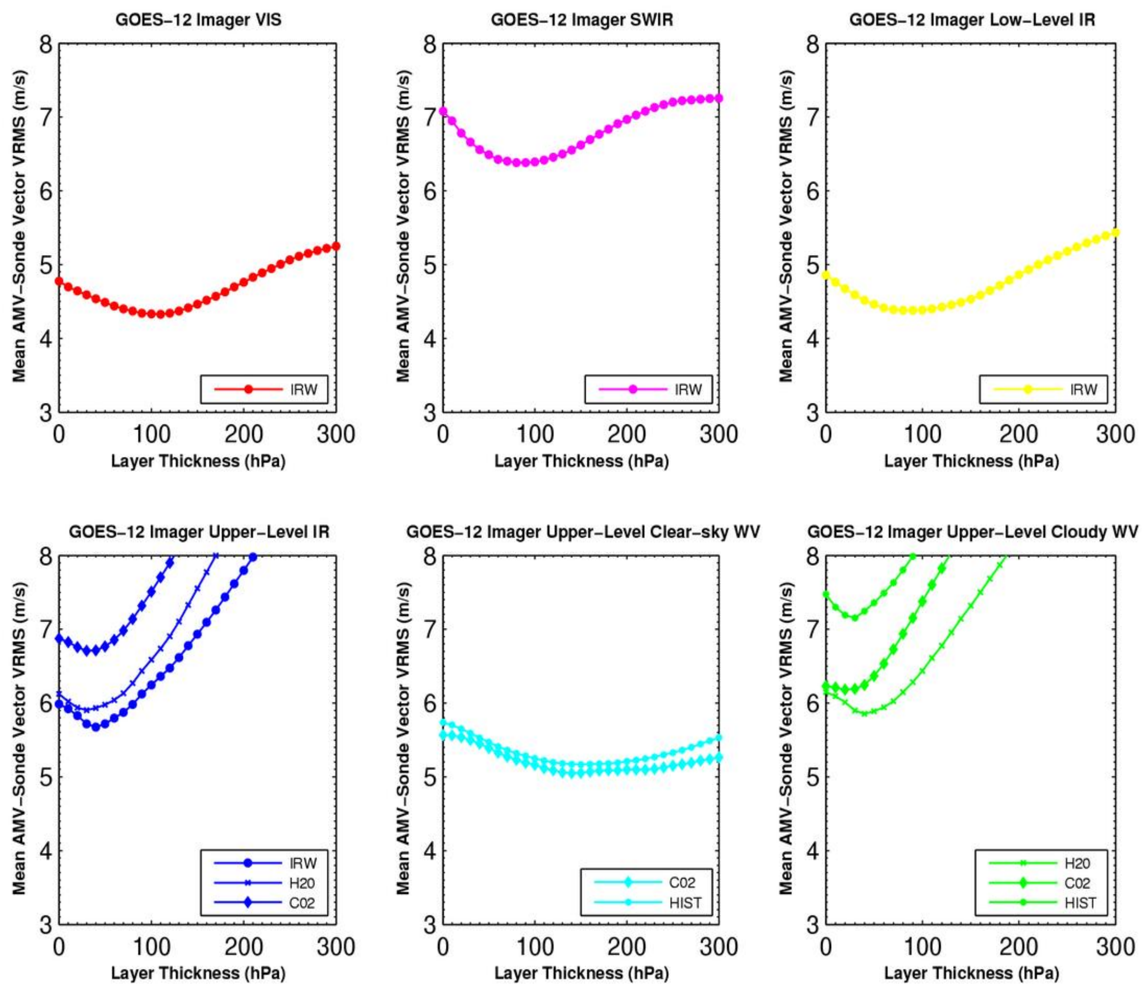

Fig. 3. The GOES AMV-rawinsonde comparisons are plotted as VRMS differences for the various rawinsonde wind averaged over the layer thickness categories (10-300hPa, in 10hPa increments), and are represented by the curves (with the corresponding single level-based VRMS values plotted on the y-axis), and for various cloud height assignment methods.

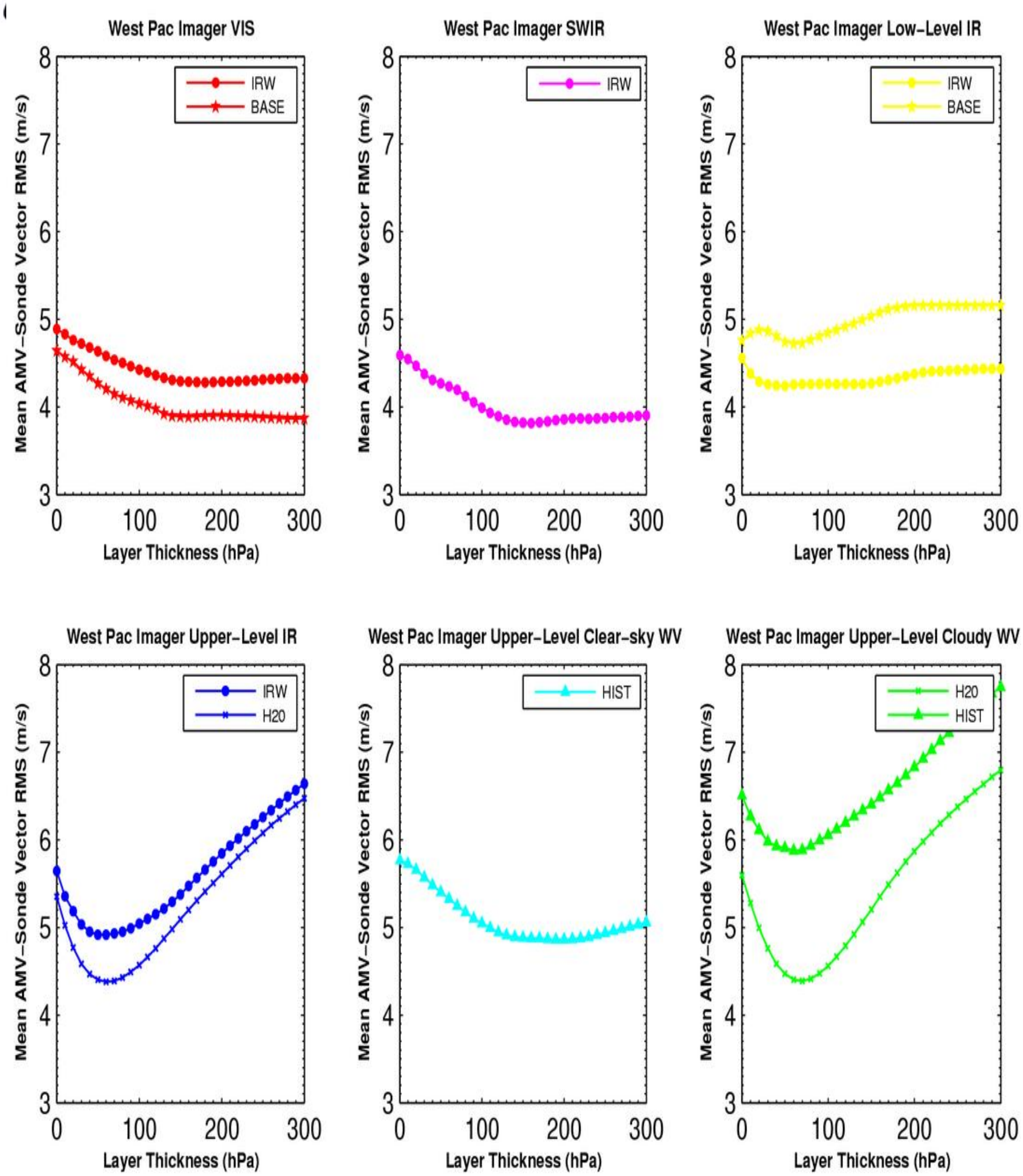

Fig. 4. Tropical Western Pacific AMV-rawinsonde comparisons are plotted as VRMS differences for the various rawinsonde wind averaged over the layer thickness categories (10-300hPa, in 10hPa increments), and are represented by the curves (with the corresponding single level-based VRMS values plotted on the y-axis) and for various cloud height assignment methods.

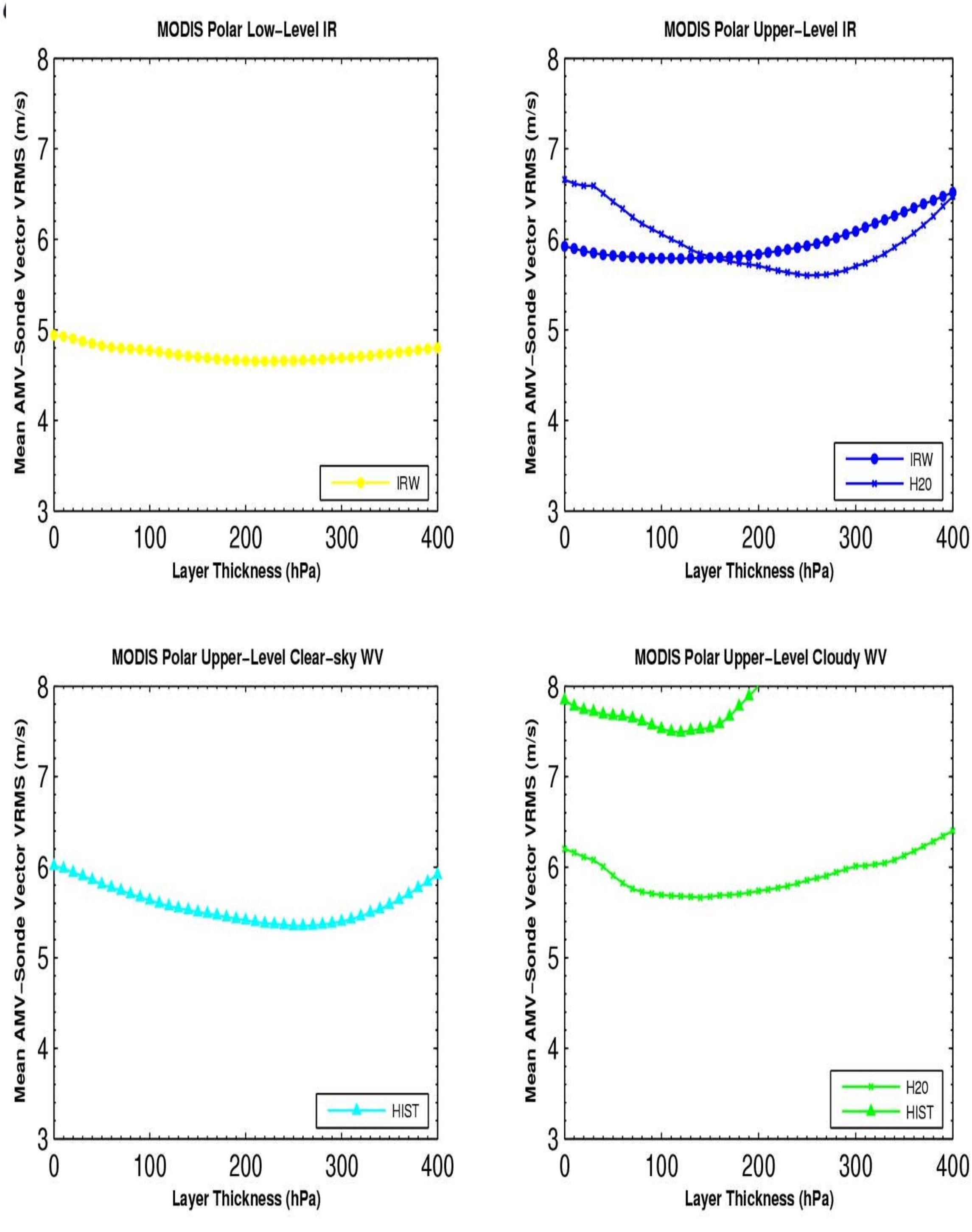

Fig. 5. North Slope Alaska MODIS polar AMV-rawinsonde comparisons are plotted as VRMS differences for the various rawinsonde wind averaged over the layer thickness categories (10-300hPa, in 10hPa increments), and are represented by the curves (with the corresponding single level-based VRMS values plotted on the y-axis) and for various cloud height assignment methods.

Effects of vertical wind shear

The term "wind shear" here refers to the vector difference between two selected rawinsonde levels, of which we vary the depth between them. Analyses of AMV-rawinsonde differences with respect to varying shear regimes are shown in Figs 6-9 (Only SGP and TWP results shown). Generally, in situations with little tropospheric vertical shear, the AMV matches within the respective layers are all quite similar. Thus, an AMV could agree just as well with one layer depth versus another. In this case, assimilating the vector as a level based motion at the original algorithm height assignment would be acceptable.

The most substantial impact occurs when there exists a high vertical shear over a relatively shallow depth (<= 100 hPa), usually found in the upper troposphere. At SGP, for 15-20 ms^{-1} of shear over 50 hPa in both IR and WV, assignment to a shallow layer ~30 hPa in depth can improve the AMV-rawinsonde agreement by up to 2.5 ms^{-1}. At TWP, for high shear-low depth situations, layer-mean assignment improves agreement by up to 2-4 ms^{-1}. In higher shear situations, the rate of VRMS increases dramatically with deeper layer depth, illustrating the importance of an accurate initial AMV height assignment in high shear situations. Conversely, there appears to be less relationship between low-level AMV and clear-sky WV AMV layers of best fit, and the magnitude of vertical wind shear.

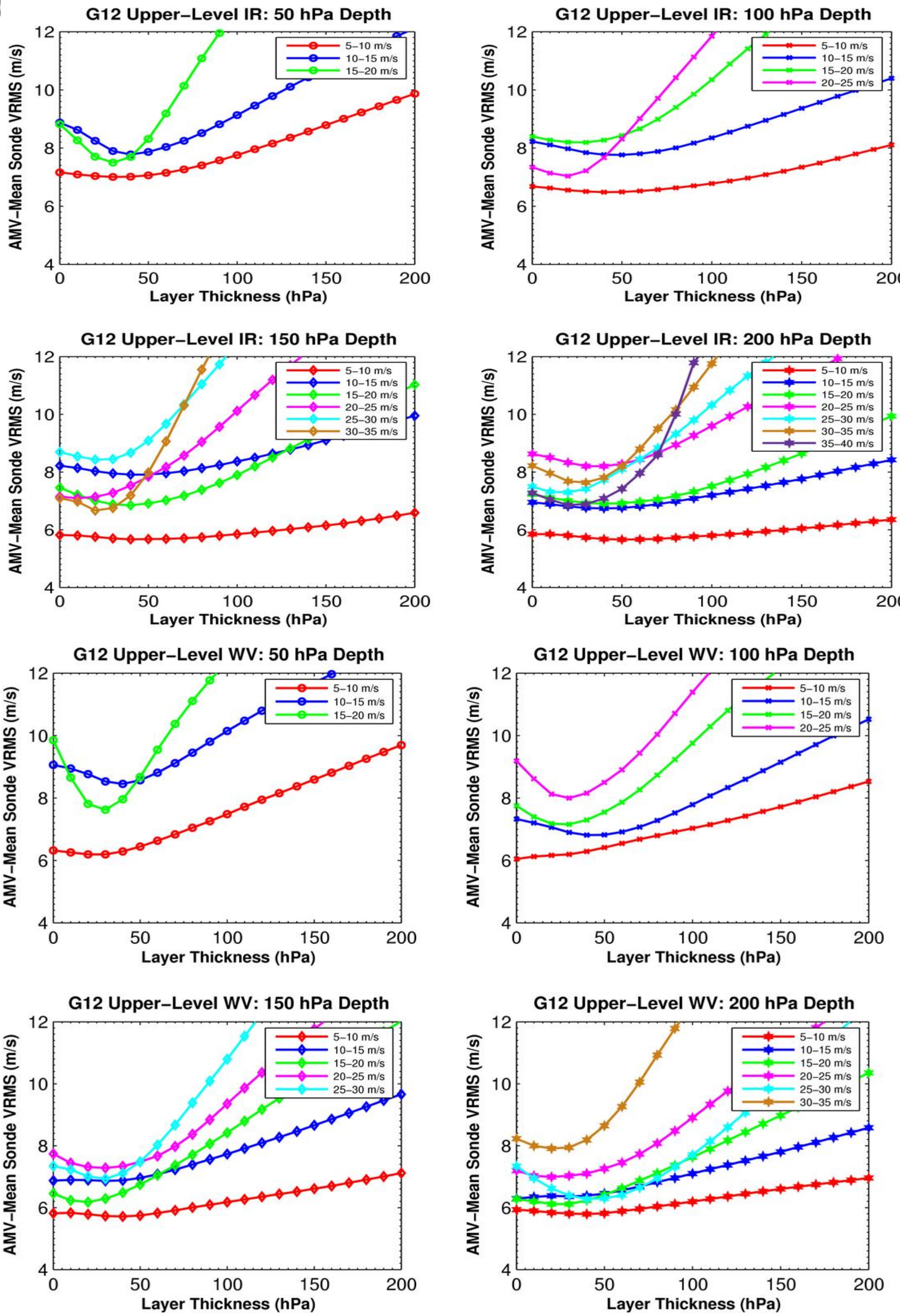

Fig. 6. Analyses of GOES upper-level AMV-rawinsonde differences with respect to varying vertical wind shear regimes (curve colors). The term "vertical wind shear" here refers to the vector difference between two selected rawinsonde levels, of which we vary the depth between them.

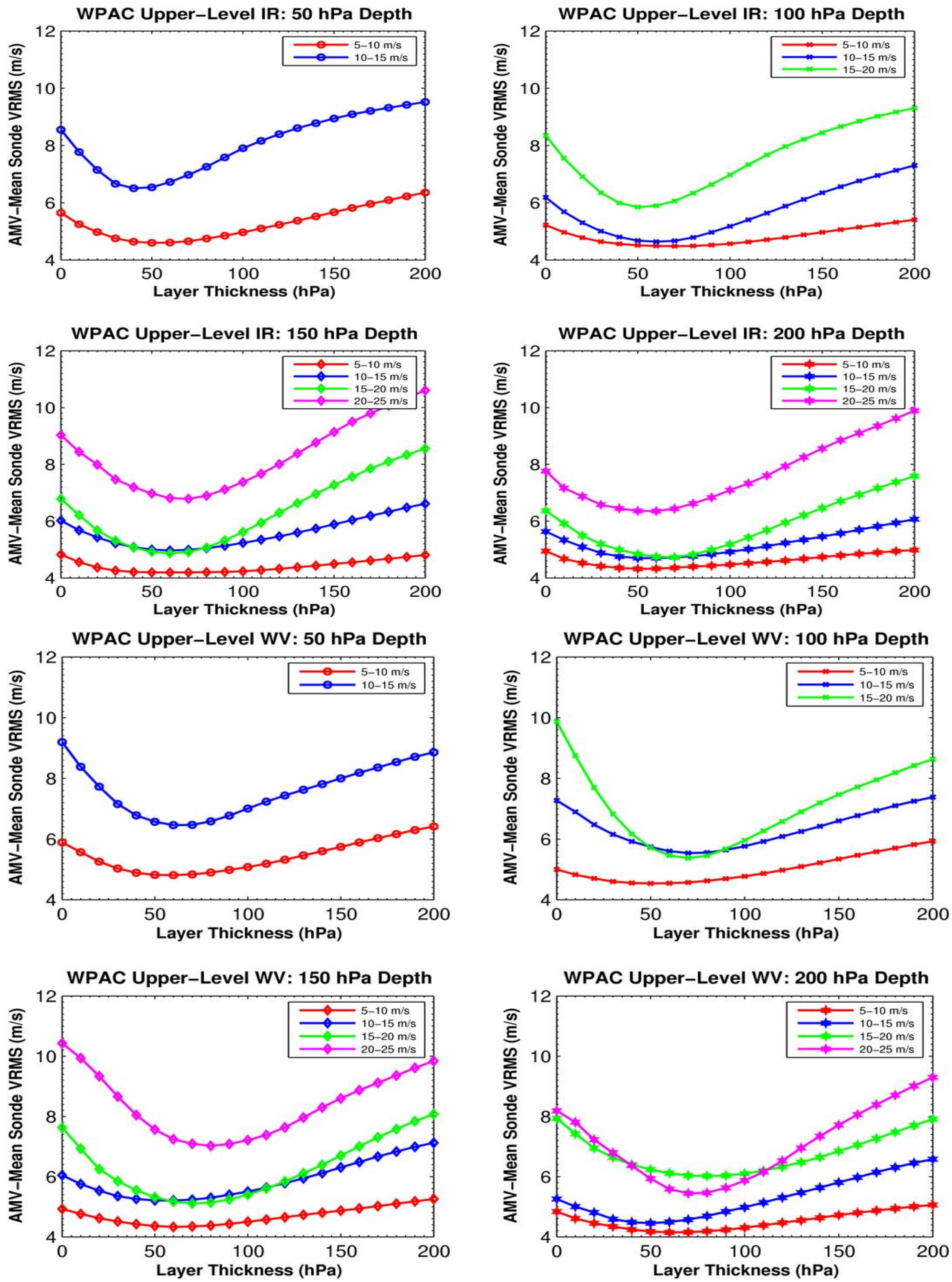

Fig. 7. Analyses of TWP upper-level AMV-rawinsonde differences with respect to varying vertical wind shear regimes (curve colors). The term "vertical wind shear" here refers to the vector difference between two selected rawinsonde levels, of which we vary the depth between them.

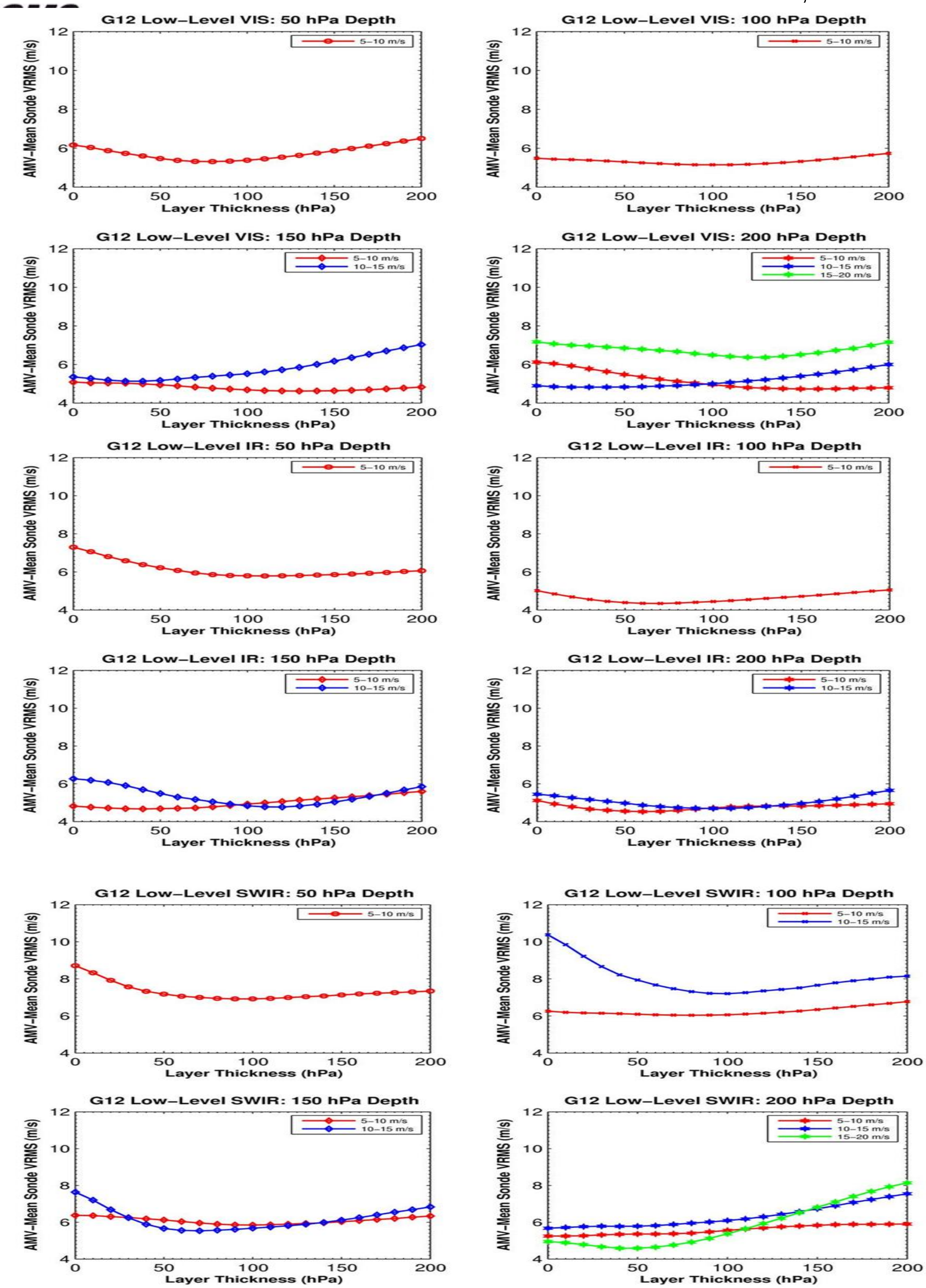

Fig. 8. Analyses of GOES lower-level AMV-rawinsonde differences with respect to varying vertical wind shear regimes (curve colors). The term “vertical wind shear” here refers to the vector difference between two selected rawinsonde levels, of which we vary the depth between them.

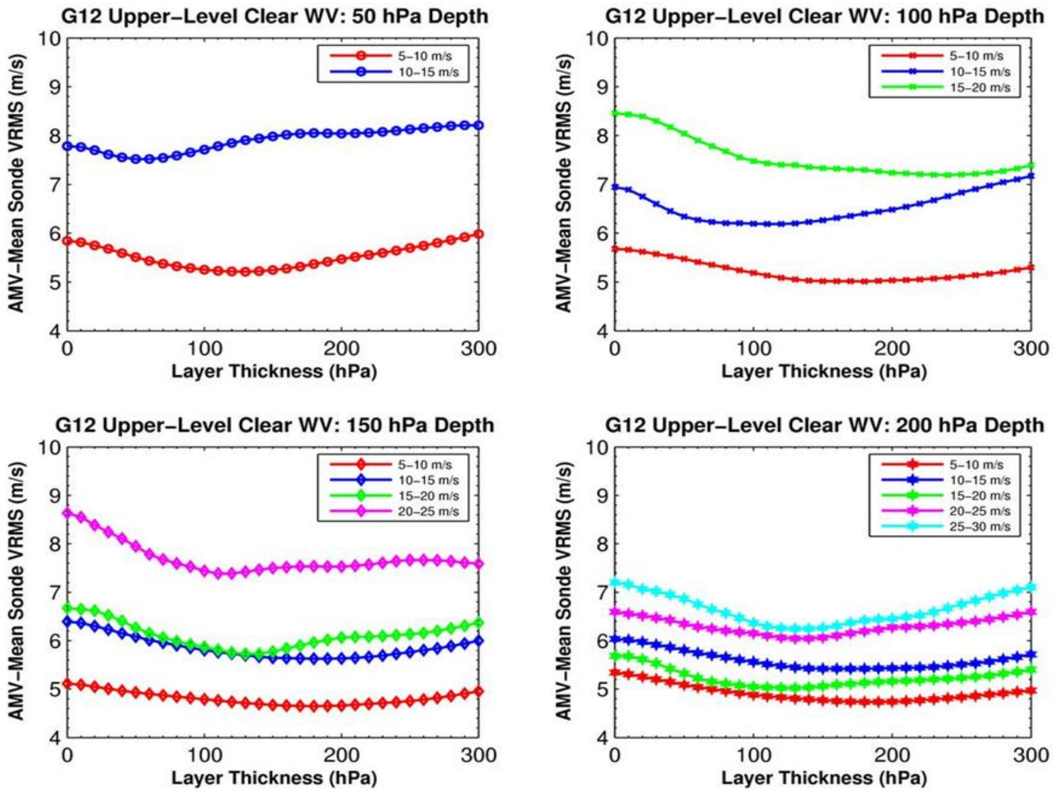

Fig. 9. Analyses of GOES upper-level Clear sky WV AMV-rawinsonde differences with respect to varying vertical wind shear regimes (curve colors). The term "vertical wind shear" here refers to the vector difference between two selected rawinsonde levels, of which we vary the depth between them.

4. IMPLICATIONS

The findings in this study clearly show quantitatively what has been believed for quite some time with respect to the representativeness of AMVs; vector height assignment is an important contributor to the quality of AMVs, and that the AMVs represent finite *layers* of tropopsheric flow, the depth of which are dependent on many factors. This is very relevant in a practical application sense as AMVs have traditionally not been well represented in numerical model analyses via single-level data assimilation. While the current more sophisticated objective analysis systems (i.e. 3DVAR) include vertical spread functions of various data inputs, for AMVs these are not well known or understood. Therefore, the influence of AMV data is often constrained in the vertical, and has less chance of making an impact on the initial analysis. The results in this study should next be tested in NWP to asses the potential impact on the analysis and subsequent model forecasts, especially in data sparse and dynamically active regimes.

5. REFERENCES

Daniels, J., C. Velden, W. Bresky, A. Irving, and K. Turner, 2002: Status and development of GOES wind products at NOAA/NESDIS. *Proc. of the 6th Int. Winds Workshop,* Madison, WI, 71-80. Copies available from EUMETSAT, Am Kavalleriesand 31, D-64295, Darmstadt, Germany.

Hasler, A.F., W.C. Skillman, W.E. Shenk, and J. Steranka, 1979: In situ aircraft verification of the quality of satellite cloud winds over oceanic regions. *J. Appl. Meteor.*, **18**, 1481−1489.

International Winds Workshop 8, 2006. Bejing, China. Proceedings available on DVD from EUMETSAT Publications, Am Kavalleriesand 31, D-64295 Darmstadt, Germany.

Kelly, G., 2004: Observing System Experiments of all main data types in the ECMWF operational system. *3rd WMO Num. Wea. Pred. OSE Workshop,* Alpbach, Austria, edited by Jean Pailleux and Horst Boettger, WMO Tech Report no. 1228, available from the WMO Secretariat, 7bis, avenue de la Paix, CH-1211, Geneva 2, Switzerland.

Key, J., D. Santek, C. S. Velden, N. Bormann, J.-N. Thepaut, L. P. Riishojgaard, Y. Zhu, and W. P. Menzel, 2003: Cloud-drift and Water Vapor Winds in the Polar Regions from MODIS. *IEEE Trans. Geosci. Remote Sens.,* 41(2), 482-492.

Langland, R., and Coauthors, 1999: NORPEX-98: Targeted observations for improved North American weather forecasts. *Bull. Amer. Meteor. Soc.,* **80**, 1363-1384.

Menzel, W. P., 2001: Cloud tracking with satellite imagery: From the pioneering work of Ted Fujita to the present. *Bull. Amer. Meteor. Soc.,* **82**, 33 - 47.

Nieman, S., J. Schmetz, and P. Menzel, 1993: A comparison of several techniques to assign heights to cloud tracers. *J. Appl. Meteor.,* **32**, 1559-1568.

Rao, A., C. Velden, and S. Braun, 2002: The vertical error characteristics of GOES-derived winds: Description and experiments with NWP. *J. Appl. Meteor.,* **41**, 253-271.

Schmetz, J., and K. Holmlund, 1992: Operational cloud motion winds from Meteosat and the use of cirrus clouds as tracers. *Adv. Space Res.,* 12 (7), 95-104.

Soden, B. J., C. S. Velden, and R. E. Tuleya, 2001: The impact of satellite winds on experimental GFDL hurricane model forecasts. *Mon. Wea. Rev.,* 129, 835-852.

Spinoso, C., 1997: The measurement of wind velocity from geostationary satellite observed radiances. PhD. Thesis RMIT (Royal Melbourne Institute of Technology) University, 268 pp.

Velden, C. S., C. M. Hayden, S. Nieman, W. P. Menzel, S. Wanzong, and J. Goerss, 1997: Upper-tropospheric winds derived from geostationary satellite water vapor observations. *Bull. Amer. Meteor. Soc.,* **78**, 173-195.

Velden, C. S., T. L. Olander, and S. Wanzong, 1998: The impact of multispectral GOES-8 wind information on Atlantic tropical cyclone track forecasts in 1995. Part 1: Dataset methodology, description and case analysis. *Mon. Wea. Rev.,* **126,** 1202-1218.

Velden, Christopher; Daniels, Jaime; Stettner, David; Santek, David; Key, Jeff; Dunion, Jason; Holmlund, Kenneth; Dengel, Gail; Bresky, Wayne and Menzel, Paul, 2005: Recent innovations in deriving tropospheric winds from meteorological satellites. Bulletin of the American Meteorological Society, Volume 86, 205-223.

Weldon, R. and S. Holmes, 1991: Water Vapor imagery interpretation and applications to weather analysis and forecasting. NOAA Tech. Report NESDIS 57, NOAA/NESDIS, 5200 Auth Rd, Wash. DC 20233, 213pp.