ASSESSING THE QUALITY OF HISTORICAL AVHRR POLAR WIND HEIGHT ASSIGNMENT

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Abstract

Radiosonde stations are sparsely distributed in the polar regions, and reanalysis wind fields are adversely affected as a result. Given that at least ten numerical weather prediction centers worldwide have demonstrated that satellite-derived polar winds have a positive impact on global weather forecasts, a polar wind data set spanning more than 20 years was generated using Advanced Very High Resolution Radiometer (AVHRR) data to at least partially fill the spatial gaps. The overall quality of the historical AVHRR winds is relatively good, with biases of 0.1 to 0.8 ms^{-1}, depending on the level. However, a major limitation to AVHRR derived winds is the absence of water vapor and CO_2 channels, so only the 11 μm window channel can be used for wind vector height determination. The Infrared Window Channel method has been shown to work well for opaque clouds, but can have significant limitations in semitransparent or sub pixel clouds.

Statistical estimates of the pressure height error have been made through comparisons with radiosonde winds using two best-fit height assignment techniques. Both techniques produced similar results, indicating that the AVHRR historical winds have a noticeable positive pressure height bias overall. Statistical comparisons by season and layer have also been made. Finally, an investigation of the relationship between cloud optical depth and pressure height error was undertaken to determine the impact of cloud opacity on height assignment. Although a number of factors complicate the analysis, clouds tracers with small optical depths are expected to result in large height assignment errors.

INTRODUCTION

Numerous studies have reported on recent changes in climate over the Arctic and parts of the Antarctic (Serreze et al., 2000; Turner et al., 2006; Wang and Key, 2005b; Comiso, 2003). A major tool used to diagnose climate changes over the polar regions is an atmospheric reanalysis, such as the ones generated by the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) and the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-40 reanalysis products. However, it has also been shown that the reanalyses have relatively significant errors in their wind fields over the Arctic (Francis, 2002), likely due to the paucity of wind observations for assimilation over this region of the globe (Key et al., 2003). Therefore, climate change studies would benefit greatly by reducing the uncertainty in these Arctic analyses.

Because winds derived from polar orbiting satellite imagers have been used to improve weather forecasts (Key et al., 2003; Velden et al., 2005), they could also be used to improve the reanalysis wind fields. For multi-decadal reanalyses, the Advanced Very High Resolution Radiometer (AVHRR) on-board NOAA satellites is a suitable candidate due to its relatively long and stable record since 1981. In this paper, the reprocessed AVHRR polar Atmospheric Motion Vector (AMV) height assignments are compared to radiosonde wind profiles from the Integrated Radiosonde Archive (IGRA) to access the quality of the height assignment. A description of the height assignment method and flaws in using the method are given.

BACKGROUND

Francis (2002) examined differences between NCEP/NCAR and ECMWF reanalysis winds and collocated radiosonde winds (or rawinsondes) that were not assimilated in the reanalysis fields, using data from the LeadEx (1992) and CEAREX (1988-89) experiments. It was found that both reanalyses exhibit large biases in the zonal and meridional wind components, being too westerly and too northerly by 25-65%. It has already been shown that the assimilation of MODIS polar winds in numerical weather prediction models has significantly improved medium-range forecasts of geopotential height over not only the Arctic and Antarctic, but also in the Northern and Southern Hemisphere extratropics (Key et al., 2003). Based on this success a polar wind dataset spanning more than 20 years (1 January 1982 to 31 August 2002) has been generated using AVHRR Global Area Coverage (GAC) data from NOAA satellites. Unlike MODIS, AVHRR does not have a water vapor channel, and therefore produces fewer wind vectors at middle and upper levels over the Arctic and the Antarctic than the MODIS datasets. However, the length of the AVHRR availability makes it more appealing for improving deficiencies in the climate reanalysis fields. The tracking algorithm employed for AVHRR is very similar to that used for MODIS infrared (IR) and Geostationary Operational Environmental Satellites (GOES) winds. This method is described in depth by Nieman et al. (1997).

VALIDATION

The traditional approach in determining the quality of satellite-derived winds is to compare them to observed winds from collocated radiosondes (Holmlund, 1998 and 2001; Nieman et al., 1997; Velden et al., 1997). Validation statistics for AVHRR polar winds compared to radiosonde winds from the IGRA (Integrated Global Radiosonde Archive) are given in Table 1. The comparisons cover the area north of 60° latitude over the periods of 1 August 1988 to 21 May 1989 and 8 March to 22 July 1992. Only collocations with the radiosonde and AVHRR wind vector within a radius of 100 km in the horizontal, 50 hPa in the vertical, and 1 hour in time are used in the validation statistics.

Table 1 indicates that for the Arctic region, the AVHRR wind speed bias and RMS differences for three tropospheric layers are close to what is observed from geo-satellite-derived AMVs (Nieman et al. 1997). However, the vertical distribution of the AMVs is prominently mid-level, the opposite of lower latitude AMV fields produced from geo satellites. Over the Arctic it is obvious that with increasing height in the atmosphere, the RMS speed differences increase. The speed RMS increases from 4.98 m s^{-1} at low levels to 7.57 m s^{-1} at upper levels. The direction RMS decreases in quantity, or improve in quality, with increased height, decreasing from 65.17° at low levels to 42.40° at upper levels. The direction bias is greatest at upper levels at +1.48°, and smallest at low levels with direction bias of –0.49°. Overall, AVHRR is counter-clockwise of the RAOB winds at low and middle levels and more clockwise at upper levels. The speed biases are slightly positive (AVHRR +0.10 m s^{-1}) at low levels, negative at middle levels (AVHRR -0.29 m s^{-1}), and positive at upper levels (AVHRR +0.77 m s^{-1}). The normalized (by RAOB speed) root mean squared (NRMS) differences (correlation coefficients) decrease (increase) from 0.68 (0.62) at low levels to 0.37 (0.81) at upper levels, demonstrating that the overall quality of the winds increases from lower to upper levels.

Additionally, we compare the AVHRR and ERA-40 winds to collocated rawinsonde observations that have not been assimilated into the ERA-40 reanalysis, providing an independent assessment of how well the AVHRR and ERA-40 winds compare to one another. Rawinsonde data provided by two Arctic field experiments, CEAREX and LeadEX, which were used in the Francis 2002 study, is also employed here. As is mentioned by Francis (2002) and indicated in Table 2, the ECMWF has a significant positive speed bias in Arctic regions that are void of assimilated radiosonde data. Table 2 also indicates that AVHRR winds have a positive speed bias overall. However, the magnitude of the speed bias is 0.41 m s^{-1}, which is much smaller than the 1.64 m s^{-1} bias for ERA-40. In addition, the AVHRR winds have smaller RMS speed differences than ERA-40. However, it is also observed that the ERA-40 has a slightly smaller direction bias and RMS difference. The direction bias is noticeably better in ERA-40 at low levels: +2.19º compared to –9.61º for AVHRR (Table 2). At middle levels, AVHRR winds had a noticeably better direction bias of -0.09º compared to -7.22º for ERA-40. The smaller speed bias and RMS difference of AVHRR over ERA-40 suggests that the AVHRR winds have the potential to be assimilated into future ECMWF reanalysis products to help correct the positive speed bias that exists. In addition, the same positive speed bias is observed in the NCEP/NCAR reanalysis over the Arctic. Therefore, AVHRR winds could also improve that reanalysis product.

Table 1: **AVHRR wind statistics when compared to RAOB winds over the Arctic.**

	Low Level (< 700 hPa)	*Mid-Level (700 – 400 hPa)*	*Upper Level (> 400 hPa)*
Speed RMS	4.98 m s^{-1}	5.18 m s^{-1}	7.57 m s^{-1}
Speed Bias	+0.1 m s^{-1}	-0.29 m s^{-1}	+0.77 m s^{-1}
Avg. Speed Diff.	3.64 m s^{-1}	3.81 m s^{-1}	5.40 m s^{-1}
Direction RMS	65.17°	52.55°	42.40°
Direction Bias	-0.49°	-0.71°	+1.48°
Avg. Direction Diff.	46.1°	34.01°	25.07°
Mean AVHRR Spd.	7.42 m s^{-1}	11.17 m s^{-1}	21.04 m s^{-1}
Mean RAOB Spd.	7.32 m s^{-1}	11.46 m s^{-1}	20.28 m s^{-1}
NRMS	0.68	0.45	0.37
Correlation Coeff.	0.62	0.8	0.81
Sample Size	6449	21375	2589

Table 2: **Statistical comparison of the Arctic region AVHRR winds and ERA-40 reanalysis winds to collocated radiosonde winds from CEAREX and LeadEx that have not been assimilated into the reanalysis. Due to the sparsity of upper level (above 400 hPa) collocations (within 100 km and 50 hPa) of AVHRR with ERA-40, the layer statistics of mid and upper levels are combined.**

	Low Level (<= 700 hPa)		*Middle and Upper Levels (>700 hPa)*		**Total (All Levels)**	
	ERA-40	*AVHRR*	*ERA-40*	*AVHRR*	*ERA-40*	*AVHRR*
SPD RMS	5.85 m s^{-1}	5.68 m s^{-1}	7.74 m s^{-1}	7.61 m s^{-1}	6.69 m s^{-1}	6.55 m s^{-1}
SPD Bias	+1.45 m s^{-1}	-0.19 m s^{-1}	+1.92 m s^{-1}	+1.28 m s^{-1}	+1.64 m s^{-1}	+0.41 m s^{-1}
Avg. SPD Diff.	4.06 m s^{-1}	3.77 m s^{-1}	5.08 m s^{-1}	5.16 m s^{-1}	4.47 m s^{-1}	4.34 m s^{-1}
DIR RMS	52.02°	53.20°	53.83°	58.01°	52.79°	55.21°
DIR Bias	+2.19°	-9.61°	-7.22°	-0.09°	-1.66°	-5.70°
Mean SPD	6.90 m s^{-1}	5.26 m s^{-1}	9.11 m s^{-1}	8.47 m s^{-1}	7.79 m s^{-1}	6.56 m s^{-1}
Mean RAOB SPD	5.45 m s^{-1}		7.19 m s^{-1}		6.15 m s^{-1}	
Collocations	350		243		593	

METHODOLOGY

Due to AVHRR not having water vapor or Carbon Dioxide channels, the primary method used for height assignment determination is the Infrared Window Channel (WIN) method that utilizes the AVHRR channel 4 (10.30 – 11.30 μm) brightness temperatures (T_b). First, a T_b gradient is calculated in an 11 by 11 box of pixels, with each pixel being 4 km. If the T_b gradient is equal to or greater than 7° K, a target is determined to exist. Next, the 25 % coldest pixels are averaged to come up with a guess target temperature. Finally, this temperature is compared to the nearest background (ERA-40) temperature profile in a top to bottom of the atmosphere approach to come up with a linearly interpolated pressure height assignment for the target.

However, potential problems exist with this method that needs to be addressed. The target (cloud feature in the IR channel) is assumed to be an opaque object. However, this is not always the case (Figure 1) when the object is semi-transparent, having a small optical depth. For example, a cloud feature with an optical depth of 1.5 will have a transmission of 22 %. If the surface is warmer than the cloud feature, as is in most cases, will produce a height assignment lower in altitude or higher in pressure than the actual feature being tracked. During the Arctic winter or over the Antarctic it is possible to have a cloud feature that is warmer than the surface, and in these cases the assigned height would be too high in altitude or too low in pressure. Additional problems could arise if a cloud feature being tracked exists below the temperature inversion, or if the target box includes both surface and cloud features with the 25 % coldest pixels including both cloud and surface features.

The level of best-fit is determined by comparing the AVHRR AMV to a collocated (100 km and 1 hour time separation) radiosonde wind profile interpolated to 10 mb resolution. The primary technique used is a cost function (equation 1) that uses pressure (P_{diff}), temperature (T_{diff}) and vector differences (V_{diff}) between the AVHRR AMV and radiosonde wind profile to come up with the pressure height that has a minimum function value, which is determined to be the best-fit height assignment (Straka et, al. 2007).

$$C = (w_1 * \text{abs}\,(V_{\text{diff}})) + (w_2 * \text{abs}(P_{\text{diff}})) + (w_3 * \text{abs}(T_{\text{diff}})) \quad (1)$$

For this comparison, the weights were determined to be .55, .15 and .30, for w_1, w_2 and w_3 respectively. The pressure difference was normalized by 1000 and the temperature difference by 10.

The cost function method was compared to another best-fit method that determines the pressure height location of the minimum vector difference to be the best-fit. It was found that the cost function produced a similar result, with the distributions of both methods being nearly guassian and a noticeably positive pressure bias for the AVHRR AMV height assignments (Figure 2). The minimum vector difference method had a 30 mb larger RMS difference and 15 mb larger bias due to it not having temperature or pressure difference constraints.

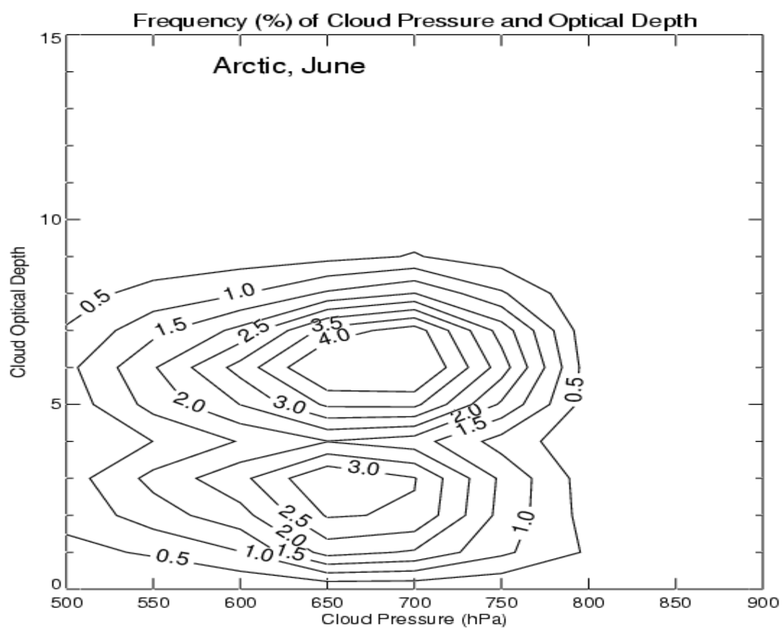

Figure 1: **Frequency of optical depths at specific pressure levels (hPa) Over the Arctic during June.**

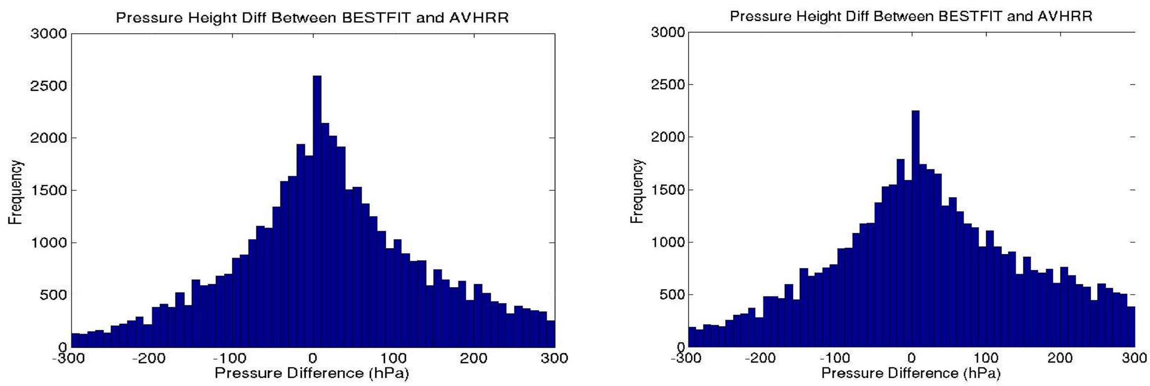

Figure 2: **Histogram plots of pressure difference (AVHRR AMV Height – Best-fit Height) for Cost function approach (left) and minimum vector difference approach (right).**

RESULTS

AVHRR AMV height assignments over the Arctic were compared to best-fit height assignments from the cost function method. It was found that overall AVHRR heights are too low in altitude or too high in pressure by + 33 mb on average, with an RMS difference of 162 mb (Figure 2).

Next, the pressure differences were partitioned into seasons: winter – December, January and February (DJF), spring – March, April and May (MAM), summer – June, July and August (JJA) and autumn – September, October and November (SON). It was found that the biases and RMS differences for spring, summer and autumn were fairly similar, with autumn having a slightly smaller bias and RMS difference. For winter, however, the bias and RMS difference were noticeably smaller than the other seasons (Table 3).

Furthermore, the pressure differences are partitioned into the atmospheric layer that they were assigned: low levels – below 700 hPa, middle levels – 700 to 500 hPa and high levels – above 500 hPa. For the layer segment of research, biases are calculated for pressure differences that occur in a +/- 200 hPa range, to eliminate methodology bias caused by the best-fit being limited to a re-assigning height no lower than 900 hPa. It was found that the RMS height difference decreased from lower to high levels, such as seen with direction and NRMS difference in Table 1. Moreover, there is a noticeable positive height bias at low and high levels, while the bias at middle levels is only slightly positive, and is indicated by the near normal distribution given in Figure 3.

Finally, the pressure differences are partition by season and atmospheric layer (Table 3). It was found that the smallest RMS difference for low and middle levels occur during the winter, however, for high levels the largest RMS difference occurred during the winter. The largest RMS difference at low levels occurred during summer, while for high levels the smallest RMS difference occurred during the summer. The minimum bias for all levels occurred during winter, with the bias at middle levels during winter being slightly negative, which is the only situation where a negative bias is observed. The largest positive biases occur during the summer for middle and high levels, with the summer bias at low levels being only slightly smaller than the maximum positive bias that occurs during autumn for low levels. The 200-hPa range biases indicate that the smaller biases tend to occur during the winter months, with the larger biases tend to occur during the summer months. This is indication that surface emission associated with semi-transparent cloud features is possibly having an effect on the height assignments.

A comparison of pressure height differences versus optical depths from APP-x was attempted. It was found that no concrete indirect relationship existed. However, for best-fits that occur at upper levels there are noticeably more pressure differences less than 200 hPa for optical depths greater than 4.5 (Figure 4). Likely reasons for no indirect relationship being found are the difficulty in determining optical depths at cloud edges and the inability to separate out targeting and tracking errors from height determination errors.

Table 3: **On the top is the overall seasonal statistics of pressure height differences between AVHRR and best-fit height assignments from radiosondes. Below is seasonal statistics partitioned by atmospheric layer: low levels (<700 hPa), middle levels (700 to 500 hPa) and high levels (above 500 hPa). Atmospheric layer biases are calculated for only pressure differences less than 200 hPa**

SEASON	**BIAS**	**RMSE**
Winter (Dec-Jan-Feb)	+14.39	154.17
Spring (Mar-Apr-May)	+41.70	167.59
Summer (Jun-Jul-Aug)	+40.26	164.91
Autumn (Sep-Oct-Nov)	+37.49	163.97
Low Levels		
Winter	+2.07	169.99
Spring	+8.72	209.09
Summer	+16.18	226.16
Autumn	+16.37	199.14
Middle Levels		
Winter	-1.84	166.69
Spring	+1.85	175.22
Summer	+3.88	170.79
Autumn	+0.21	172.15
High Levels		
Winter	+12.24	141.78
Spring	+14.60	134.16
Summer	+17.41	131.18
Autumn	+16.15	137.48

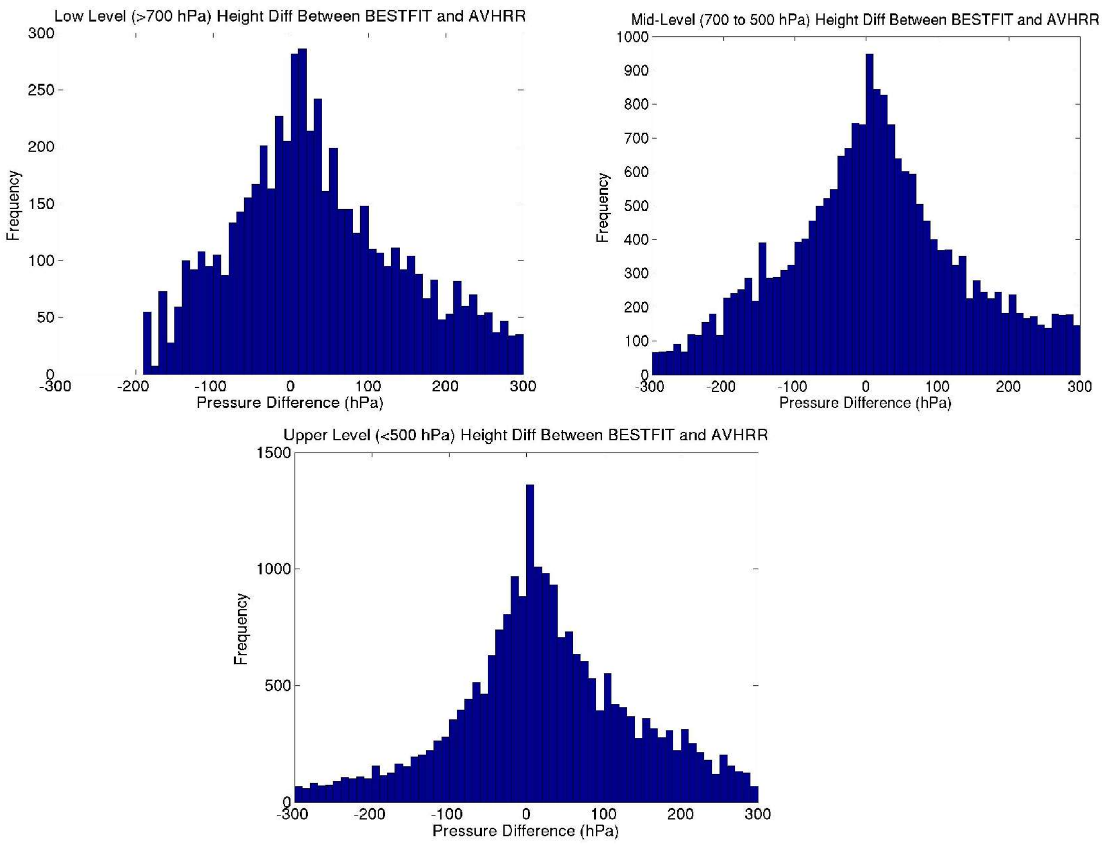

Figure 3: **Histogram plots of pressure difference between AVHRR AMV and Best-fit Heights separated into atmospheric layers. Upper left plot is for low-levels (> 700 hPa), upper right plot is for middle levels (700 to 500 hPa) and below plot is for high levels (<500 hPa).**

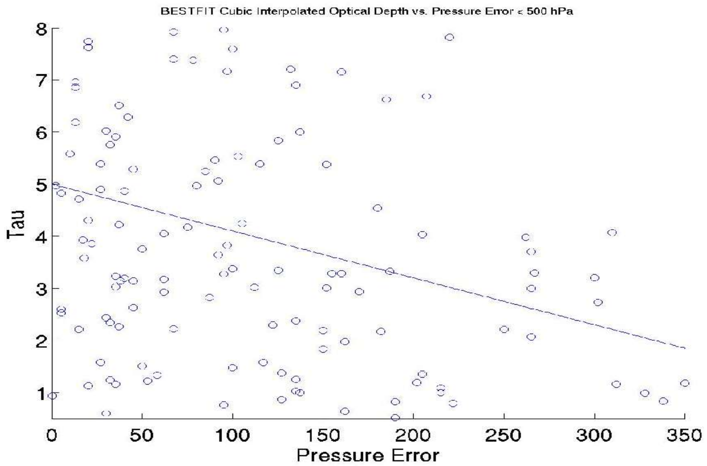

Figure 4: **Scatter plot of Pressure Error (AVHRR AMV height – Best-fit height) versus Optical Depth from APP-x for best fits that are above 500 hPa.**

SUMMARY AND CONCLUSIONS

The proven ability to track atmospheric motions using satellite imagery, the data's positive effect on NWP and the observed errors in reanalysis wind fields over the polar regions have led to the production of a 20-year dataset of winds over the polar regions using the AVHRR instrument on NOAA polar-orbiting satellites. The AVHRR winds represent atmospheric motions derived by calculating the displacement of individual cloud features in successive 11 μm infrared channel imagery. Due to AVHRR not having water vapor or Carbon Dioxide channels, the only viable method used for determining cloud motion feature heights is the WIN method. This method takes the target temperature, which is an average of the 25 % coldest pixels, and compares it to a nearby background temperature profile (ERA-40) to find the pressure height where the background and target temperatures agree to come with an AMV height assignment. This method should work fine for opaque clouds, but should have problems with semi-transparent clouds due to surface emission not being taken into account.

Validation of AVHRR and ERA-40 winds compared to collocated rawinsondes not assimilated into the reanalysis from the LeadEx (1992) and CEAREX (1988-89) Arctic field programs indicates that the AVHRR winds overall have a smaller speed bias by over 1 m s^{-1} and RMS by 0.14 m s^{-1}, but slightly larger directional differences. General comparisons of AVHRR winds to collocated RAOBs show that the quality of the winds over the Arctic is on par with operational winds produced from geo satellites, with the largest differences below 700 hPa and the smallest above 400 hPa. The normalized root-mean-squared errors and correlation coefficients of the wind vectors decrease (increase) with height, also indicating that the overall quality of the wind vectors increases with height.

The quality of the AVHRR AMV height assignments is determined by the use of a Cost function that weighs pressure, temperature and vector differences separately to come up with a best-fit height assignment. Overall, it is discovered that AVHRR AMV heights are on average assigned too low in altitude, with the smallest bias and RMS difference occurring during the winter. When partition into atmospheric layer, it is found that the RMS difference decreased with height. For middle and high levels the bias was slightly higher for summer compared to other seasons. The bias only becomes negative during the winter at middle levels. At low levels the RMS difference is noticeably higher for the summer, however, for high levels the RMS difference is highest during winter and smallest during the summer, which is the opposite as observed at low levels.

From simulations, cloud tracers with small optical depths are expected to result in large height assignment errors (Borde and Dubuisson, 2007). However, no indirect relationship was found due to the complexity of determining optical depths at cloud edges, where optical depth gradients are strong and irregular, and that it is very difficult to separate tracking and targeting errors from height assignment errors. If we are able to do so, a relationship between optical depth and pressure height error can possibly be made.

REFERENCES

Borde, R. And Dubuisson, P 2007: Cloud top height estimation using simulated METEOSAT-8 radiances. *Proceedings-SPIE the International Society for Optical Engineering*. **6745**, 13

Comiso, J.C., 2003: Warming Trends in the Arctic From Clear Sky Satellite Observations. *J. Climate*, **16**, 21, 3498-3510.

Francis, J.A., 2002: Validation of Reanalysis Upper-Level Winds in the Arctic with Independent Rawinsonde Data. *Geophys. Res. Lett.*, **29**, 9, 29-1-29-4.

Holmlund, K., 1998: The Utilization of Statistical Properties of Satellite-Derived Atmospheric Motion Vectors to Derive Quality Indicators. *Weather and Forecasting*, **13**, 4, 1093-1104.

Holmlund, K., C.S. Velden, and M. Rohn., 2001: Enhanced Automated Quality Control Applied to High-Density Satellite Winds. *Monthly Weather Review*, **129**, 3, 517-529.

Key, J.R., D. Santek, C.S. Velden, N. Bormann, J. 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. Rem. Sens.*, **41**, 2, 482-492.

Nieman, S. J., W. P. Menzel, C. M. Hayden, D. Gray, S. T. Wanzong, C. S. Velden, and J. Daniels. (1997) Fully Automated Cloud-Drift Winds in NESDIS Operations. *Bull. Amer. Meteorol. Soc.*, **78**, 6, 1121-1133.

Serreze, M. C., J.E. Walsh, F.S. Chapin III, T. Osterkamp , M. Dyurgerov, V. Romanovsky, W.C. Oechel, J. Morison, T. Zhang, and R. G. Barry. 2000: Observational Evidence of Recent Change in the Northern High-Latitude Environment. Climate Change. 1st ed. Vol. 46. The Netherlands: Kluwer Academic, 159-207.

Straka III, W., M. Forsythe, J. Daniels, J. Key, D. Santek and C. Velden. 2007: *Joint 2007 EUMETSAT Meteorological Satellite Conference and the 15th Satellite Meteorology & Oceanography Conference of the American Meteorological Society*. Amsterdam, The Netherlands. 24-28 September, 2007. SESSION 3: Operational Applications.

Turner, J., T.A. Lachlan-Cope., S. Colwell, G.J. Marshall, and W.M. Connolley. 2006: Significant Warming of the Antarctic Winter Troposphere. *Science*, **311**, 5769, 1914-1917.

Velden, C., J. Daniels, D. Settner, D. Santek, J. Key, J. Dunion, K. Holmlund, G. Dengel, W. Bresky, and P. Menzel. 2005: Recent Innovations in Deriving Tropospheric Winds From Meteorological Satellites. *Bull. Amer. Meteorol. Soc.*, **86**, 2, 205-223.

Velden, C.S., C.M. Hayden, S. J. Nieman, W. P. Menzel, S. Wanzong, and J. S. Goerss. 1997: Upper Tropospheric Winds Derived From Geostationary Satellite Water Vapor Observations. *Bull. Amer. Meteorol. Soc.*, **78**, 2, 173-195.

Wang, X. and J.R. Key. 2005b: Arctic Surface, Cloud and Radiation Properties Based on the AVHRR Polar Pathfinder Dataset Part II: Recent Trends. *J. Climate*, **18**, 14, 2575-2593.