2004 / 2005 Report on NOAA/NESDIS Satellite-Derived Winds

SUMMARY AND PURPOSE OF DOCUMENT

This paper summarizes the current NOAA/NESDIS operational wind product suite that includes the high density cloud-drift winds from the GOES imager, water vapor motion winds derived from the GOES sounder, and cloud-drift and water vapor winds from the MODIS instrument aboard NASA's Terra and Aqua satellites. Research and development activities involving new satellite-derived wind products and improvements to existing satellite-derived wind products are also summarized.

ACTION REQUESTED: NONE

2004/2005 REPORT ON NOAA/NESDIS SATELLITE-DERIVED WINDS

Jaime Daniels[1], Wayne Bresky[3], Chris Velden [2], Jeff Key[1], David Santek[2] and W. Paul Menzel[1]

[1] - NOAA/NESDIS/STAR

[2] - Cooperative Institute for Meteorological Satellite Studies
Madison, Wisconsin

[3] – Raytheon Information Solutions
Lanham, Maryland

1. Introduction

NOAA/NESDIS and the Cooperative Institute for Meteorological Satellite Studies (CIMSS) continue collaborations aimed at improving the quality of Atmospheric Motion Vectors (AMVs) derived from NOAA's Polar and Geostationary Operational Environmental Satellites as well as from NASA's Terra and Aqua polar orbiting satellites. Active areas of winds research include: investigating optical flow approaches to the problem of feature tracking, the derivation of AMVs from rapid scan GOES imagery, and the derivation of AMVs from the Moderate Resolution Imaging Spectroradiometer (MODIS).

2. Status and Performance of Operational Wind Products

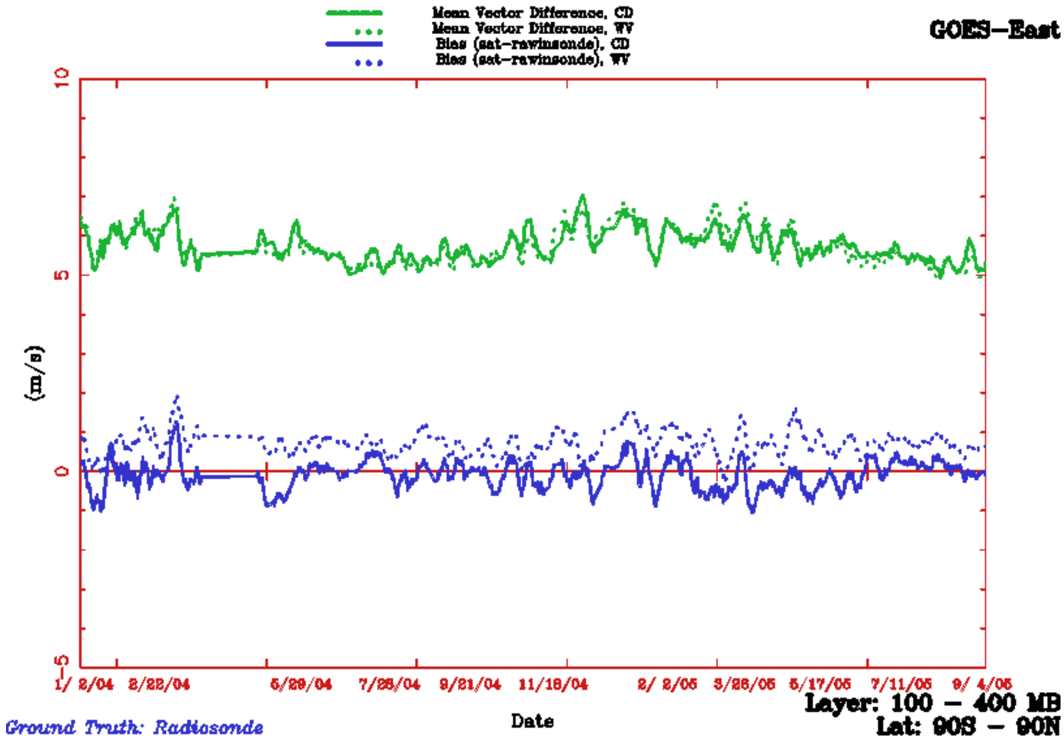
During the period 2004-2005, NOAA/NESDIS continued to generate Longwave Infrared (LWIR) cloud-drift wind and water vapor wind products from GOES-12 (GOES-E) and GOES-10 (GOES-W). Satellite-derived wind products added to the production suite at NOAA/NESDIS during this time period included the GOES night-time, low-level 3.9 µm shortwave infrared (SWIR) cloud-drift winds and the polar LWIR cloud-drift wind and water vapor wind products from the Terra and Aqua spacecraft. Operational production and distribution of the 3.9 µm SWIR AMV products began on 27 July 2004. All of the NOAA/NESDIS AMV products shown in Table 1 are encoded into the World Meteorological Organization (WMO)-sanctioned Binary Universal Form for the Representation (BUFR) of meteorological data and distributed over the Global Telecommunication System (GTS). The last column of Table 1 lists the WMO headers used to uniquely identify each of these NESDIS AMV products. *NOAA/NESDIS plans to begin distribution of the Terra and Aqua MODIS AMVs over the GTS on September 19, 2005*. NOAA/NESDIS also distributes the GOES AMVs to the NOAA/National Weather Service's (NWS) Advanced Weather Interactive Processing System (AWIPS) which gives NWS field forecasters digital access to these AMV products. Through the use of AWIPS graphics tools and capabilities, the NWS forecaster can integrate the AMV products with other data sources that include model output, rawinsondes, and aircraft reports.

Like other satellite producers, NOAA/NESDIS continues to rely on collocated AMVs and rawinsonde observations to assess and monitor the quality the AMVs. Time series of verification statistics can be found at: http://www.orbit.nesdis.noaa.gov/smcd/opdb/goes/winds/html/tseries.html. Figure 1 (top) shows time series of daily (at 00Z and 12Z) verification statistics (satellite-rawinsonde mean vector difference and wind speed bias) for upper level (100-400mb) GOES-12 LWIR cloud- drift winds and water vapor winds in the Northern and Southern Hemispheres for the period January 2004 – August 31, 2005. Figure 1 (bottom) shows a time series of verification statistics for low level (700-100mb) GOES-12 SWIR and LWIR cloud-drift winds. The verification statistics for GOES-10, while not shown, show similar results.

Wind Product	Frequency (Hours)	Image Sector(s)	Image Interval (minutes)	GTS WMO Header
GOES IMAGER				
LWIR (11um) Cloud-drift	3	RISOP	7.5	JACX11- GOES-E JCCX11- GOES-W
	3	CONUS	15	
	3	Extended NH: SH	30	
SWIR (3.9um) Cloud-drift	3 (Night-time)	RISOP	7.5	JQCX11- GOES-E JRCX11- GOES-W
	3 (Night-time)	CONUS	15	
	3 (Night-time)	Extended NH: SH	30	
Water Vapor (6.7um)	3	Extended NH; SH	30	JECX11- GOES-E JGCX11- GOES-W
Vis Cloud-drift (0.65um)	3 (Daytime)	RISOP	7.5	JHCX11- GOES-E JJCX11- GOES-W
	3 (Daytime)	PACU/CONUS	15	
	3 (Daytime)	Extended NH; SH	30	
GOES SOUNDER				
Sounder WV (7.4um)	3,6	CONUS/Tropical	60	JKCX11- GOES-E JMCX11- GOES-W
Sounder WV (7.0um)	3,6	CONUS/Tropical	60	JNCX11- GOES-E JPCX11- GOES-W
TERRA/AQUA MODIS				
LWIR (11um) Cloud-drift	2	NH; SH (Poleward of 65^o Lat)	100	JBCX11- Terra JICX11 - Aqua
Water Vapor (6.7um)	2	NH; SH (Poleward of 65^o Lat)	100	JFCX11- Terra JILX11 - Aqua

Table 1: GOES Imager/Sounder and Terra/Aqua MODIS atmospheric motion vector products generated by NOAA/NESDIS

Like the GOES AMV wind products, the quality of the Terra and Aqua MODIS wind products are monitored via comparisons with collocated rawinsonde observations. While the number of rawinsondes observations in the Arctic and Antarctic regions is limited, the comparison statistics that are generated still provide useful information on the quality of the MODIS AMVs. Figure 2 (top) shows time series of daily (at 00Z and 12Z) verification statistics (satellite-rawinsonde mean vector difference and wind speed bias) for mid level (400-700mb) Aqua LWIR cloud-drift winds and water vapor winds in the Northern Hemisphere for the period January 2004 – August 31, 2005. Figure 2 (bottom) shows the time series of verification statistics but for mid-level (400-700mb) Aqua LWIR cloud-drift winds and water vapor winds in the Southern Hemisphere. The verification statistics for Terra MODIS AMVs, while not shown, show similar results.



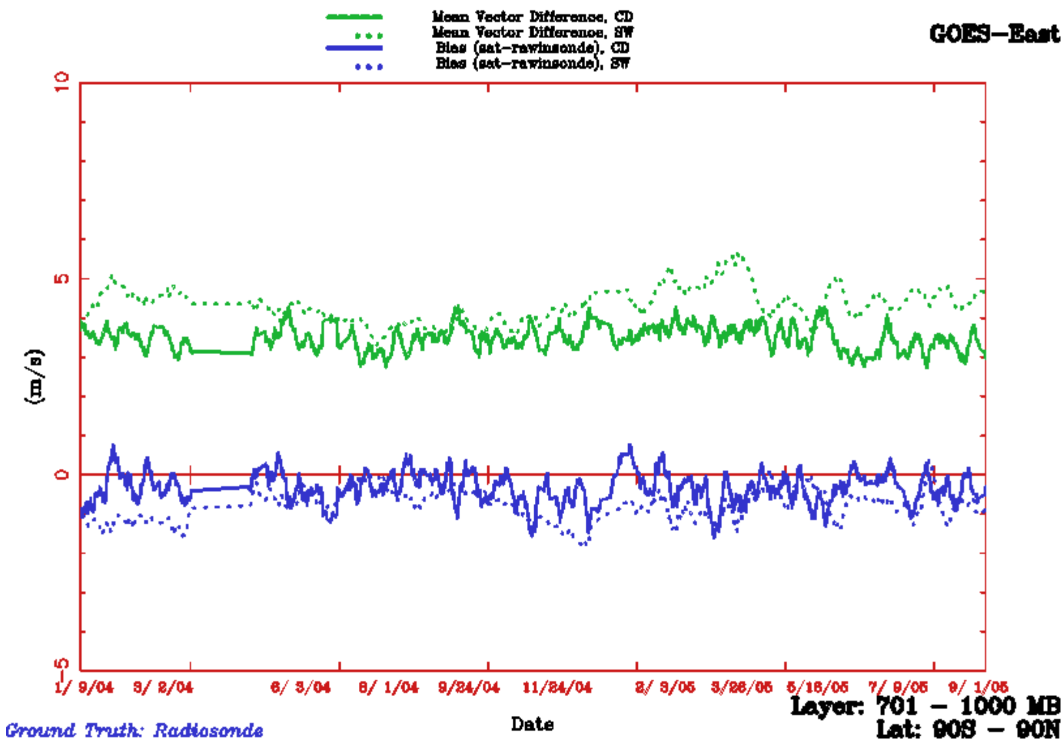
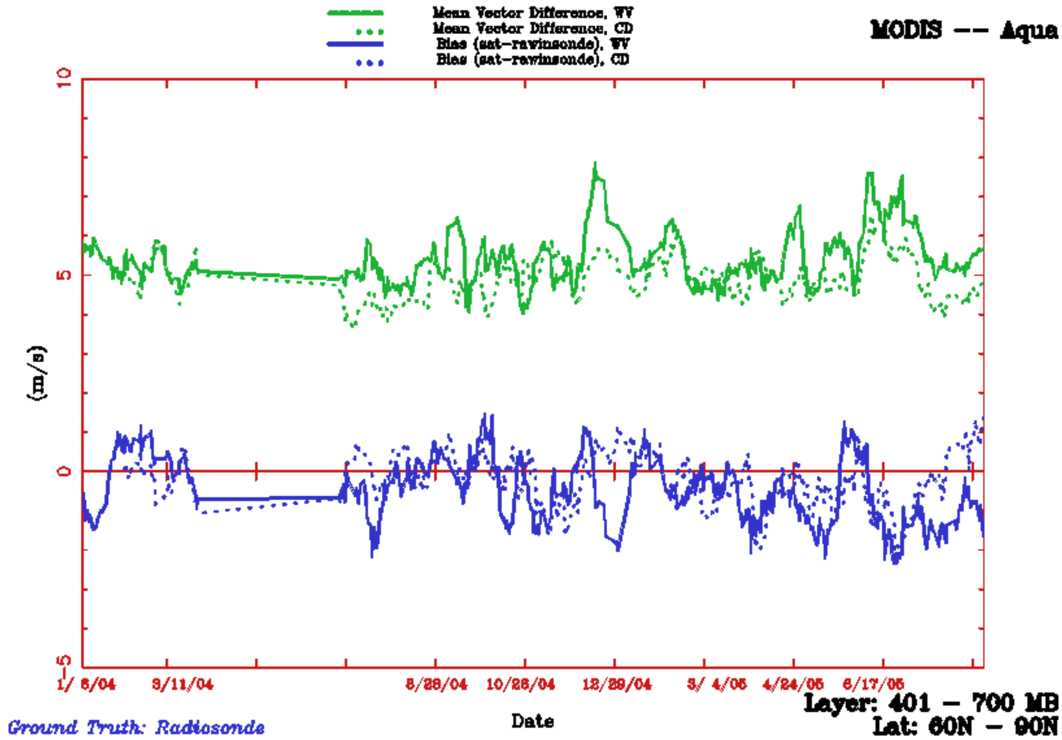


Figure 1. Mean vector difference and speed bias (sat-rawinsonde) for GOES-12 upper level (100-400mb) LWIR cloud-drift and WV winds (**top**) and lower level (700-1000mb) LWIR and SWIR cloud-drift winds (**bottom**).



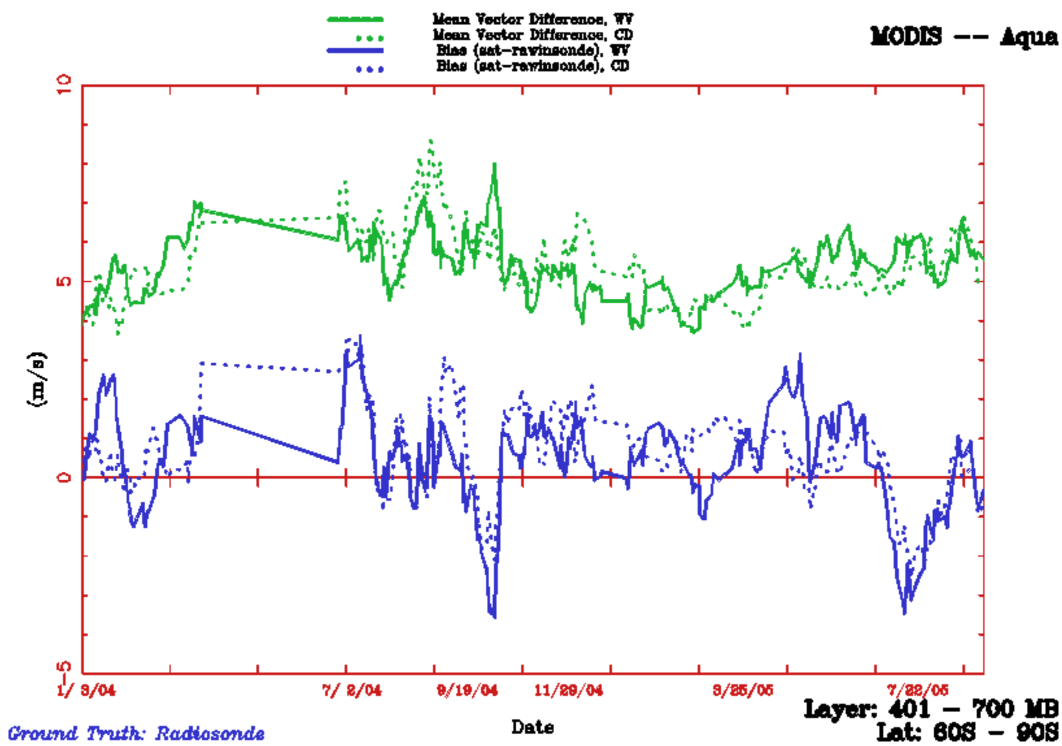


Figure 2. Mean vector difference and speed bias (sat-rawinsonde) for NHEM Aqua MODIS mid level (400-700mb) LWIR cloud-drift and WV winds (top) and SHEM Aqua mid level (400-700mb) LWIR and SWIR cloud-drift winds (bottom)

3. Research and Development Activities

3.1 Quality Control

As part of a Joint Center for Satellite Data Assimilation (JCSDA) effort, the Expected Error (EE) quality control approach developed at the Australian Bureau of Meteorology (LeMarshall et al, 2004) is being integrated within the operational winds processing system at NOAA/NESDIS and will be applied to both GOES and Terra/Aqua MODIS AMVs. The EE quality flag, which is an estimate of the AMV root mean square error in meters per second, is calculated from the wind speed components, the wind shear, the pressure and the elements that make up the Quality Indicator (QI) (Holmlund, 1998, Holmlund et al, 2001). The coefficients for each of these terms are generated using least squares regression and are tuned for each AMV type using colocated radiosonde observations. Preliminary results for the Aqua-MODIS IR cloud-drift wind products in the Northern Hemisphere for May-July 2005 are shown in Figure 3 which shows a scatter plot of the predicted error versus the actual and model background errors. The results indicate that the EE method does quite well in estimating the error associated with the real-time Aqua MODIS IR cloud-drift winds. NOAA/NESDIS plans to add the new EE quality control flag to the AMV BUFR template. The addition of this new AMV quality flag, together with the AMV quality flags that already exist in the BUFR template, are expected to allow NWP users to improve their ability to preferentially select the highest quality AMVs that will be used in their operational data assimilation schemes.

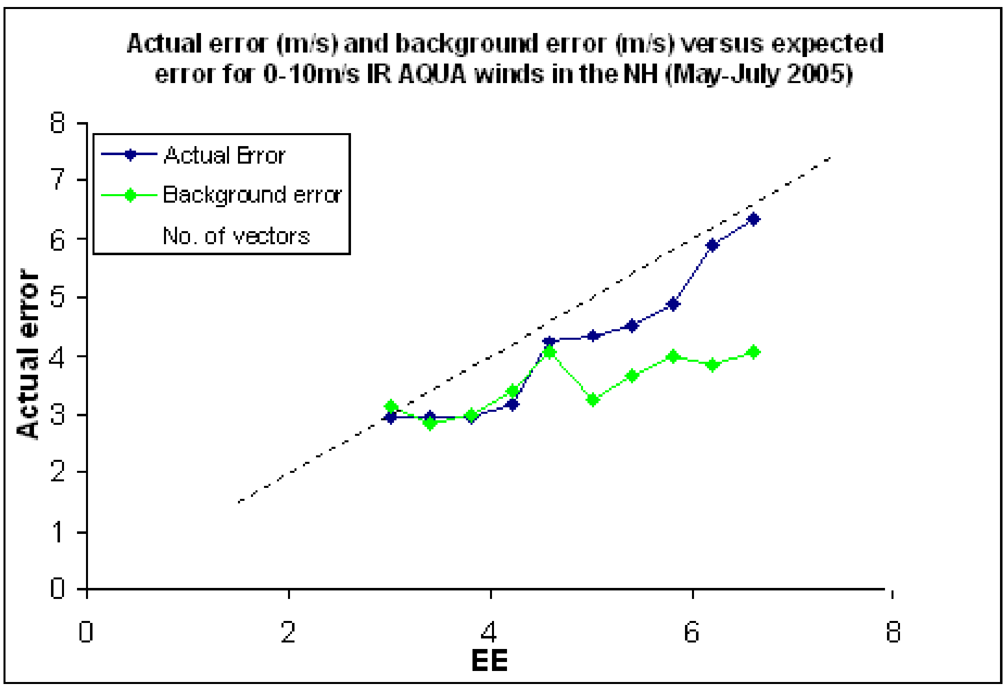


Figure 3. Estimated Error (EE) versus actual and model background error (m/s) for Aqua MODIS IR cloud-drift winds (0-10 m/s) in the Northern Hemisphere (May – July 2005)

3.2 Investigation of Optical Flow Approaches

In the computer vision field, optical flow is one of the standard techniques in computing motion vectors from two subsequent images (Sonka et al, 1993). At the past two International Winds Workshops (IWW6, IWW7) the Working Group on Methods recommended that further investigation and development of new feature tracking techniques, such as optical flow, be done. A suggested goal of such an effort would be to compare the performance of the optical flow techniques to the standard correlation methods used in AMV processing today. A long term goal would be to adopt an optical flow algorithm that was demonstrated to benefit certain AMV products.

Numerous optical flow approaches and algorithms are documented in the literature (Barron, et al, 1994). The optical flow algorithm being tested at NOAA/NESDIS is described in Lucas and Kanade, 1981. This algorithm has been incorporated into a test version of the vector calculation program**.** The test version is being used to generate wind fields over an entire image domain. Wind fields which have been generated using this optical flow algorithm are being compared to wind fields generated by the control, correlation-based method of tracking that has been used at NOAA/NESDIS for some time. It is anticipated that as the time interval between images is shortened, the optical flow algorithm will produce a superior wind estimate. Preliminary results of the optical flow approach using GOES-11 5-minute data are very encouraging. Figure 4 shows GOES-11 visible cloud-drift winds (not quality controlled) generated from 5-min imagery using the standard correlation matching (control) and optical flow (test) algorithms. While there is some convergence of the optical flow vectors toward the vectors generated using the standard correlation method, much work remains to be done. The correlation based tracking method performs quite well when tracking the motion of a field of small cumulus clouds; the optical flow method struggles a bit more in this situation. The optical flow approach, however, performed quite well when tracking was done using the 6.7um water vapor band. Table 2 presents a statistical comparison of raw wind fields from both methods (optical flow and correlation matching) against radiosonde data and shows lower RMS errors using the optical flow estimate. There is, however, a significant slow bias in the optical flow wind field which will need to be addressed if this algorithm is to become a viable method of tracking. More testing is being done and will be done in the upcoming months to attempt to remove this slow speed bias.

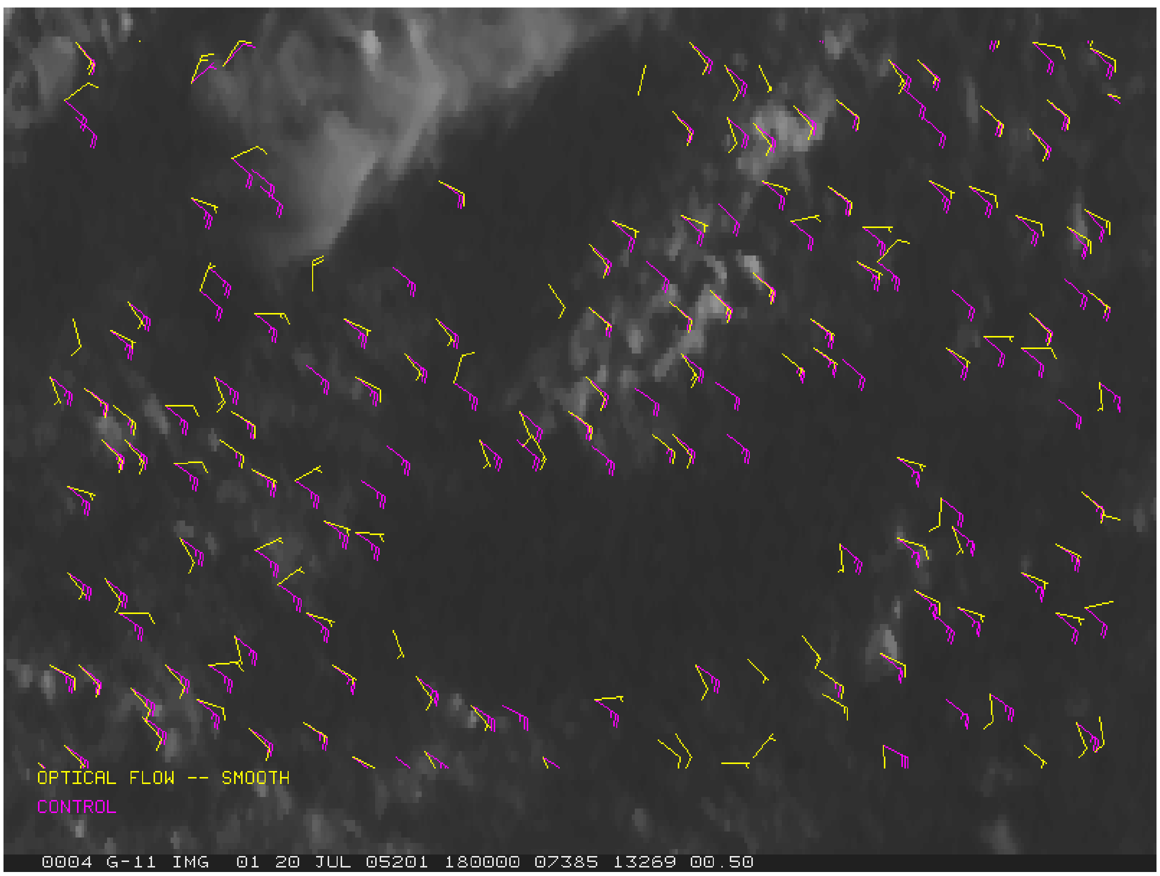


Figure 4. GOES-11 visible cloud-drift winds (not quality controlled) generated from 5-min imagery using the standard correlation matching (control) and optical flow (test) algorithms.

Statistic	Correlation Matching	Optical Flow	Raob

Mean Vector Difference (m/s)	6.28	5.63	
Normalized RMS	0.95	0.87	
Sat-Raob Speed Bias (m/s)	-0.38	-1.81	
Speed	7.37	5.93	7.76
Sample Size	149	149	149

Table 2. Comparison statistics between collocated GOES-11 raw water vapor winds (all levels) generated using correlation matching and optical flow tracking and rawinsondes at 00Z on August 3, 2005.

3.3 Polar Winds from MODerate Resolution Imaging Spectroradiometer (MODIS) data

Use of MODIS Winds in Operational Forecast Systems

Given the sparsity of wind observations in the polar regions, satellite-derived polar wind information has the potential to improve forecasts in polar and sub-polar areas. Eight numerical weather prediction (NWP) centers have performed model impact studies and found that, overall, the impact of the MODIS polar winds is positive. Most centers have demonstrated a positive impact in the Arctic and Antarctic as well as the extratropics of both hemispheres, though the magnitude of the impact varies among the centers. The following NWP centers are currently assimilating the MODIS winds in their operational forecast systems:

- European Center for Medium-Range Weather Forecasts (ECMWF)
- NASA Global Modeling and Assimilation Office (GMAO)
- (UK) Met Office
- Canadian Meteorological Centre (CMC)
- Japan Meteorological Agency (JMA)
- US Navy, Fleet Numerical Meteorology and Oceanography Center (FNMOC)

The National Centers for Environmental Prediction (NCEP) and Deutscher Wetterdienst (DWD) are using the winds in experimental systems. NCEP will begin operational use by the end of 2005.

Combined Terra and Aqua MODIS

At present, winds from the Terra and Aqua satellites are generated separately. Some improvements in wind quality and timeliness could be obtained by combining imagery from the two satellites into the same processing stream. Utilizing the combined Terra/Aqua MODIS data stream will require that imagery be corrected for parallax, as the two satellites will view the same cloud or water vapor features from different angles. Without a parallax correction, errors in location, and therefore wind speed and direction, can be significant. A parallax correction method has been developed and is being tested. Routine wind processing using the combined data stream is expected to begin in the first half of 2006.

Direct Broadcast MODIS Winds

The MODIS polar winds product typically lags the observing time (the time MODIS views an area) by 3-5 hours. The lag is largely due to the delay in the availability of the level 1B MODIS data, which are acquired through a NOAA computer system at the NASA Goddard Space Flight Center. The lag also includes a delay of 100 minutes because three consecutive orbits is used to derive the winds, and the final time is assigned that of the middle orbit. The 3-5 hour delay is too long for many regional or limited area data assimilation systems. It may be possible to reduce the delay by obtaining data from direct broadcast (DB) sites, with the added benefit of providing local forecasters with real-time wind information.

A system to generate the MODIS winds with direct broadcast MODIS data has been developed and implemented at McMurdo, Antarctica. All processing is done on site. An X-band antenna was purchased by the U.S. National Science Foundation and installed in January-February 2005, with wind production beginning in April. Figure 5 gives an example of the direct broadcast polar winds over Antarctica. While statistics are still being compiled and the system is being refined, it appears that winds can be generated with a delay on the order of 2 hours (again, including the offset time for middle image targeting) rather than 3-5 hours. Direct broadcast sites in Norway, Sweden, Finland, and Alaska are also being considered for direct MODIS acquisition. Real-time results for McMurdo are available at http://stratus.ssec.wisc.edu/products/db/mcmurdo.

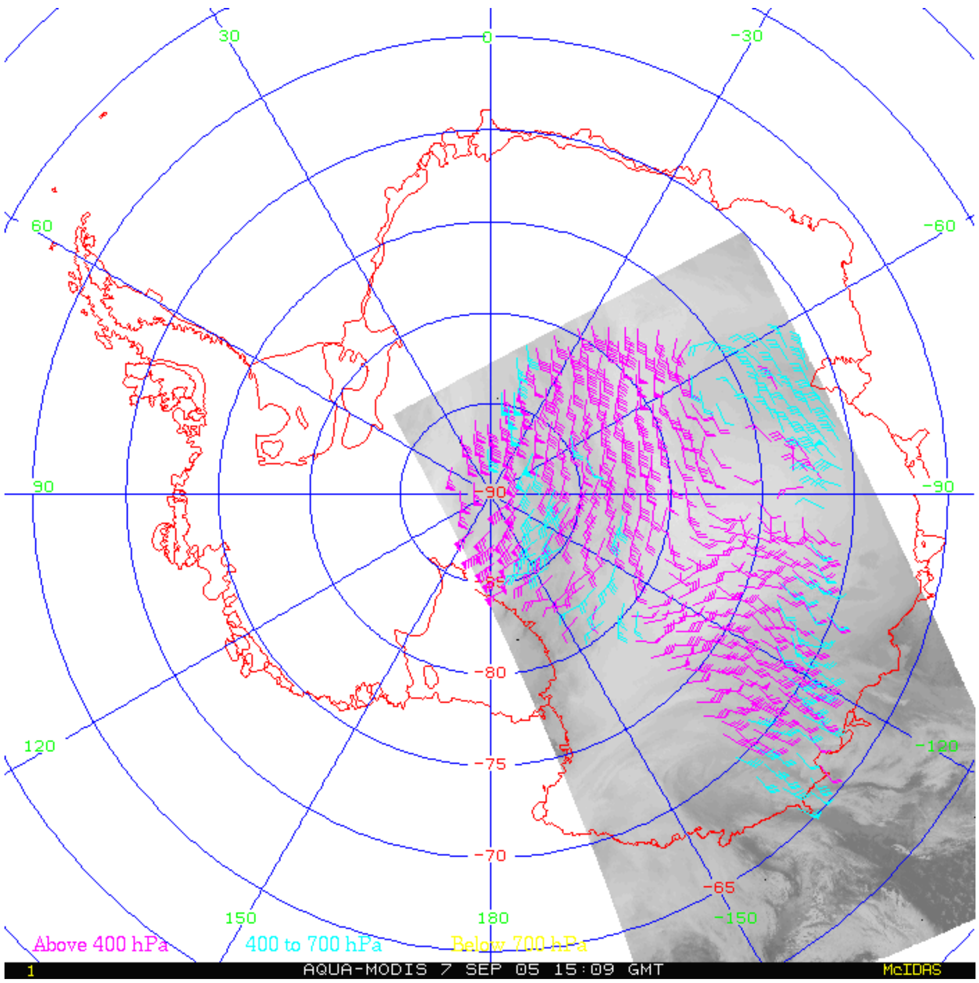


Figure 5. Winds generated from direct broadcast Aqua MODIS data obtained at McMurdo, Antarctica, on 7 September 2005.

3.4 Winds from Rapid-Scan Imagery

In the United States, GOES has been used in operational forecasting for quite some time. Forecasters recognize the additional detail that can be captured from more frequent imaging in events associated with rapidly changing cloud structures. The value of more frequent imaging is evidenced by the inclusion of a 15-minute update cycle over the Continental United States (CONUS) sector in the current GOES schedule, and by the multitude of special National Weather Service (NWS) operational requests for more frequent sampling at 7.5 minute intervals (Rapid-Scan OPerations, RISOP). On occasion, special periods of Super-Rapid-Scan Operations (SRSO) have been requested by the research community. The SRSO allow limited-area coverage of one-minute interval sampling over meteorological events of interest.

Recently, special GOES RISOP periods have been collected during several field programs and research initiatives designed to maximize observational abilities in regions of high-impact weather events. Some examples include the NASA Tropical Cloud Systems Program (TCSP) in Figure 6, the Atlantic Thorpex Regional Campaign (ATReC) in Figure 7, and the TROpical Predictability EXperiment (TROPEX) in Figure 8. In ATReC and TCSP, the datasets were used in real time in mission planning and/or directing aircraft to targets of opportunity. In TROPEX, the datasets will be used in targeted observing strategy experiments run by modelers at the Naval Research Laboratory. In all three cases, it is expected the enhanced datasets will be employed in case study analyses and numerical model impact studies. Further details on the use of rapid scans, and other recent satellite-derived winds innovations can be found in Velden et al. (2005).

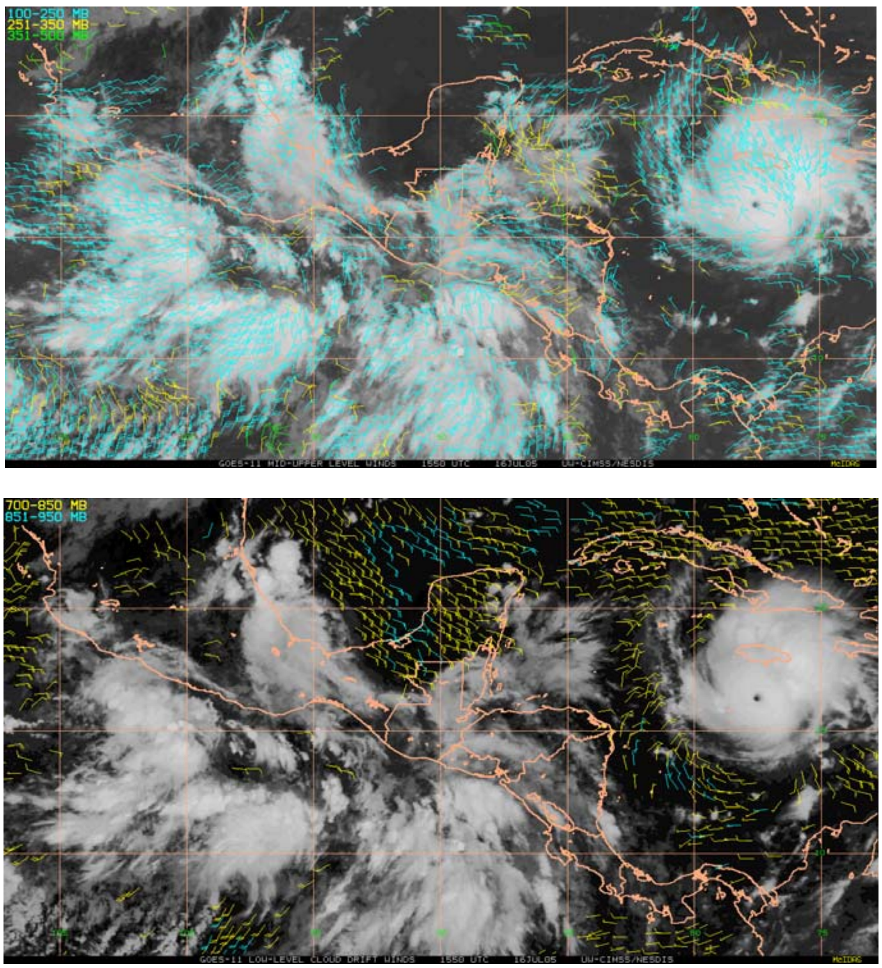


Figure 6. GOES-11 rapid-scan winds during TCSP, 16 July, 2005. Top: Upper-level winds; Bottom: Low-level vectors.

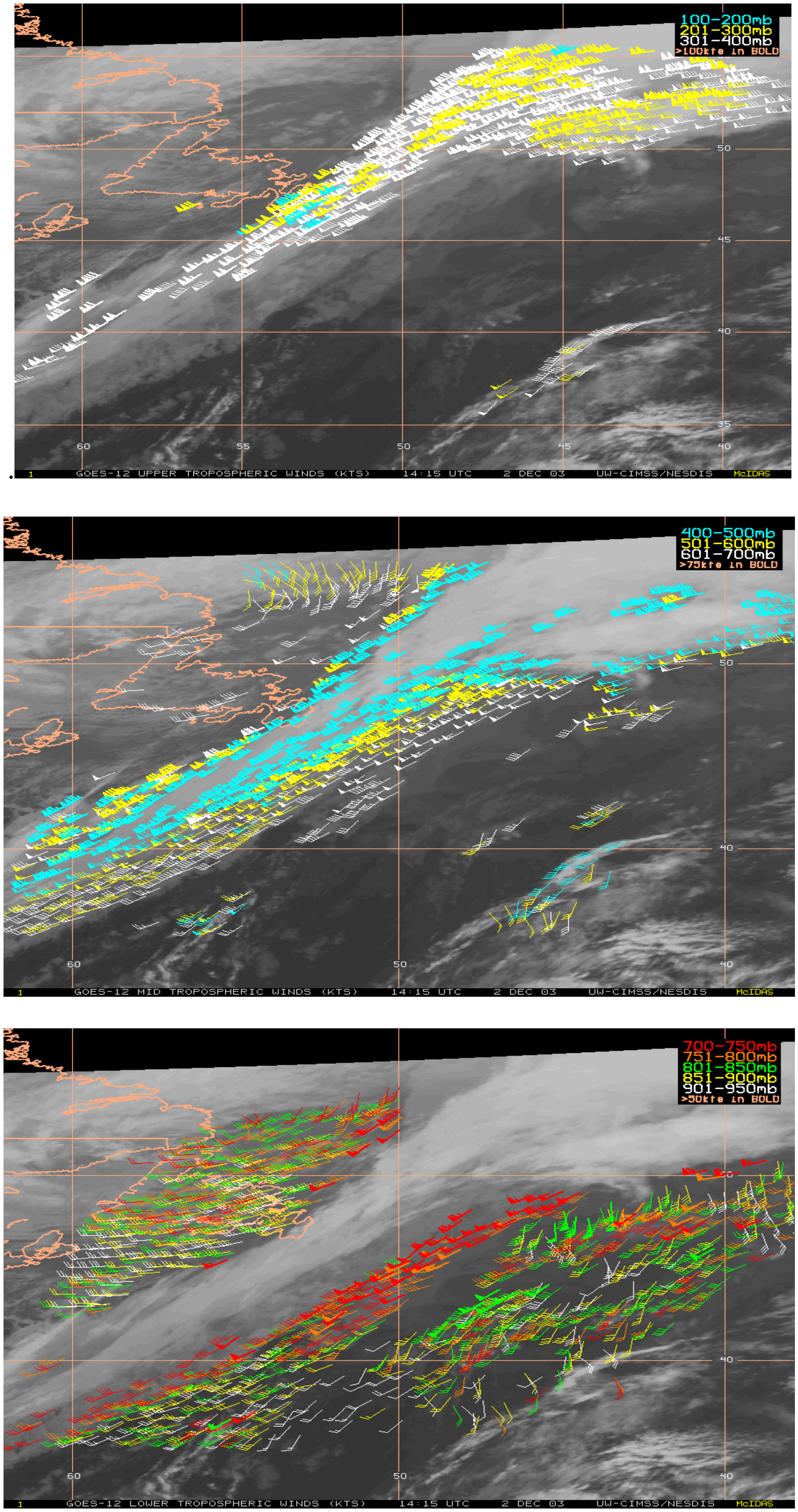


Figure 7. GOES-12 rapid-scan winds during ATReC, 2 December, 2003. Top: Upper-level winds; Middle: Mid-level winds; Bottom: Low-level vectors

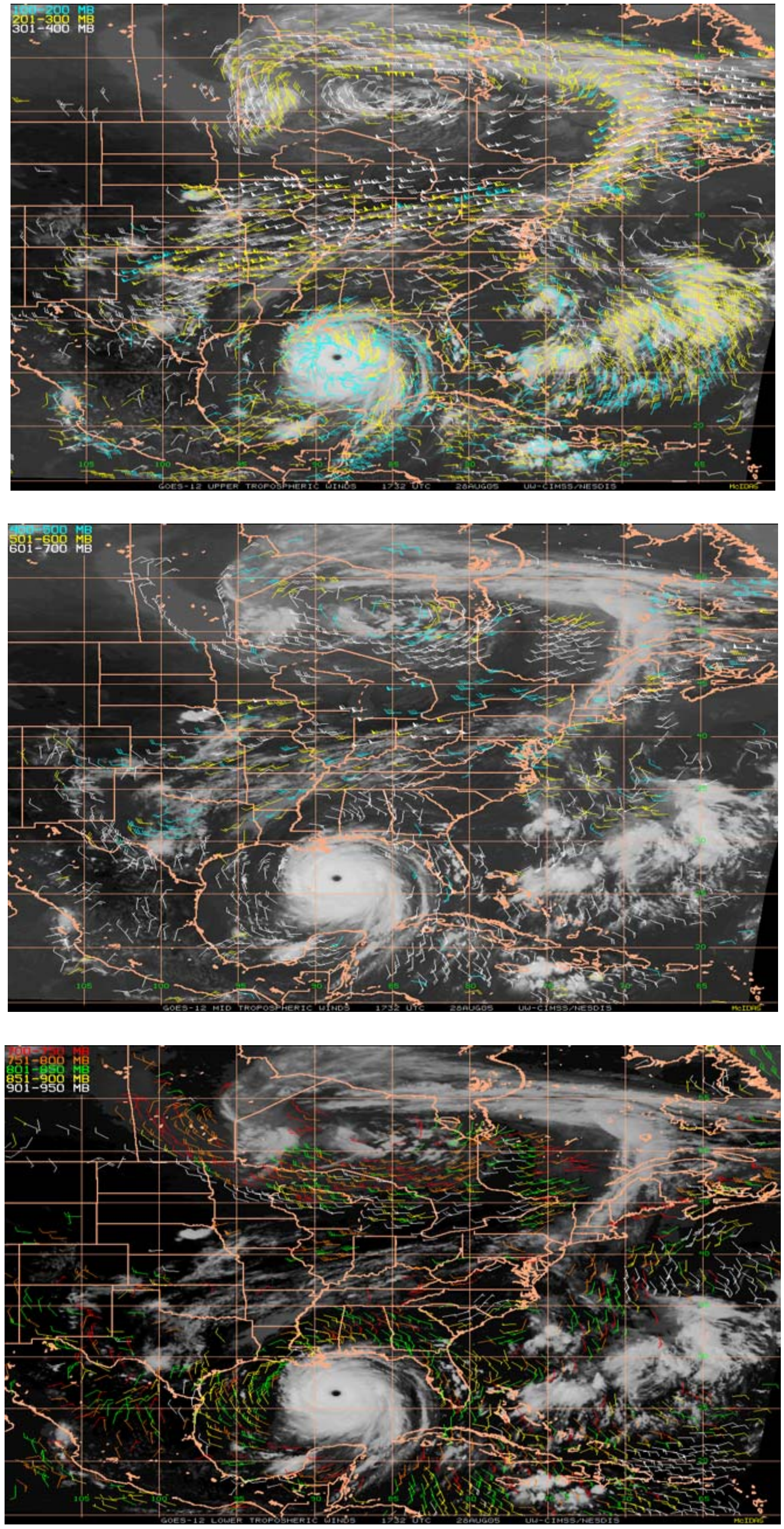


Figure 8. GOES-12 rapid-scan winds during TROPEX, 28 August, 2005 during Hurricane Katrina. Top: Upper-level winds; Middle: Mid-level winds; Bottom: Low-level winds.

Acknowledgments

John LeMarshall, Megan Dunn, and Chris Redder are thanked for their efforts with formulating the EE coefficients for GOES and MODIS AMVs and for contributing Figure 3. This work is being done through the Joint Center for Satellite Data Assimilation (JCSDA) at NOAA.

References

Barron, J.l, D.J Fleet, and S.S. Beauchemin, 1994: Systems and Experiments; Performance of Optical Flow Techniques. *International Journal of Computer Vision*, 12:1, 43-77.

Holmlund, K., 1998: The utilization of statistical properties of satellite-derived atmospheric motion vectors to derive quality indicators. *Weather and Forecasting*, 13, 1093-1104.

Holmlund, K., Velden C., and M. Rohn, 2001: Enhanced automatic quality control applied to high-density satellite-derived winds. *Mon. Wea. Rev.*, 129, 517-529.

LeMarshall, J. A., A. Rea, L. Leslie, R. Seecamp, and M. Dunn, 2004: Error characterization of atmospheric motion vectors. *Aust. Meteor. Mag.*, 53, 123-131.

Lucas, B. and T. Kanade, 1981: An iterative registration technique with an application to stereo vision. *Proc. 7th Int. Joint Conf on Artificial Intelligence*, Aug 24-28, Vancouver, British Columbia, 674-679.

Santek, D., J. Key, C. Velden, and N. Bornemann, 2002: Deriving winds from polar orbiting satellite data. *Proc. Sixth Int. Winds Workshop*, Madison, Wisconsin, EUMETSAT, 251-261.

Sonka, M., Hlavac, V. and R. Boyle, 1993: *Image Processing, Analysis and Computer Vision*, Chapman and Hall Computing.

Velden, C., et al., 2005: Recent innovations in deriving tropospheric winds from meteorological satellites. *Bull. Amer. Meteor. Soc*., 86, 205-221.