THE POLAR WIND PRODUCT SUITE

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ABSTRACT

The polar wind product suite has expanded considerably in recent years. In addition to Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) winds being produced separately, a mixed-satellite product was developed in order to improve the timeliness of the winds and to extend the coverage equatorward somewhat. To take advantage of the additional temporal coverage provided by the NOAA satellites, polar wind products from the Advanced Very High Resolution Radiometer (AVHRR) on NOAA-15, -16, -17, -18 were implemented. The AVHRR winds will prepare us for the National Polar-orbiting Operational Environmental Satellite System (NPOESS) where, like the AVHRR, the Visible Infrared Imager Radiometer Suite (VIIRS) operational imager will not have a water vapor channel. Another AVHRR wind product, currently in an experimental stage, uses AVHRR data from the joint European-U.S. MetOp satellite. Because much of the MODIS and AVHRR wind information is not available soon enough for use in the principle numerical weather prediction data assimilation cycles, MODIS wind processing systems have been implemented at three direct broadcast sites to improve timeliness. Similar to the MODIS direct broadcast winds, winds are being generated from AVHRR data acquired at a High Resolution Picture Transmission (HRPT) site in Barrow, Alaska. Lastly, a polar wind data set spanning more than 20 years was processed using historical AVHRR data for potential use in climate reanalysis projects.

INTRODUCTION

Satellite-derived wind fields are most valuable for the oceanic regions where few observations exist and numerical weather prediction model forecasts are therefore less accurate. Like the oceans at lower latitudes, the polar regions also suffer from a lack of observational data. While there are land-based meteorological stations in the Arctic and a small number of stations around the coast of Antarctica, there are no routine observations of winds over the Arctic Ocean and most of the Antarctic continent. Unfortunately, geostationary satellites are of little use at high latitudes due to the large view angles and poor spatial resolution, resulting in significant uncertainties in the derived wind vectors at latitudes poleward of about 60 degrees.

In 2001, an experimental polar wind product was developed at the University of Wisconsin-Madison's Cooperative Institute for Meteorological Satellite Studies (CIMSS) using imagery from MODIS on NASA's Terra satellite. Early the next year, two numerical weather prediction centers demonstrated a positive impact of the MODIS winds on forecasts not only in the polar regions, but globally. Routine generation of the Terra MODIS winds began in 2002, with Aqua MODIS winds following soon thereafter. Today the MODIS winds are produced operationally at NOAA/NESDIS.

This paper describes the suite of satellite-derived polar wind products, in particular those based on the MODIS and the AVHRR. Over the last few years, model impact studies conducted at major numerical weather prediction (NWP) centers have shown that the MODIS winds have a positive impact on global weather forecasts. In fact, eleven NWP centers in seven countries now use the data in their operational forecast systems. It is therefore important to continue generating, improving, testing, and extending these products. In addition, new products should be explored to address product latency, spatial and temporal coverage, and future instruments.

MODIS WINDS

MODIS has a relatively high spatial resolution: IR bands are 1 km at nadir, though the winds are derived from data remapped at 2 km because the resolution drops off to several kilometers at the edge of a swath. The orbital period - also the time between subsequent overpasses of a given scene on the ground at high latitudes - is 100 minutes. With MODIS, wind retrievals can be done in both clear and cloudy conditions using water vapor and infrared window channels. This is not the case with AVHRR or the future NPOESS VIIRS instrument (as currently planned), as neither includes a thermal water vapor channel.

Cloud and water vapor tracking with MODIS data is based on the established procedure used for GOES, which is described in Nieman et al. (1997), and Velden et al. (1997, 1998, 2005). With MODIS, cloud features are tracked in the infrared (IR) window band at 11 μm and water vapor (WV) features are tracked in the 6.7 μm band. After remapping the orbital data to a polar stereographic projection, potential tracking features are identified. Water vapor targets are selected in both cloudy and cloud-free regions. Additional details are provided in Key et al. (2003). Improvements to wind vector height assignment are being investigated, as is the use of additional spectral channels, primarily in the near-infrared portion of the spectrum.

Single Satellite Winds

The first automated polar wind products were based on MODIS data from the Terra and Aqua satellites. Winds are generated from each satellite separately. With this approach, winds are derived in the area of overlap between successive orbits. Three orbits are used for quality control, so the time between the first and last orbits of the triplet is 200 minutes. The single-satellite MODIS polar winds procedure is currently running in real-time at CIMSS and in NESDIS operations. An example of the real-time winds is shown in Figure 1. Both water vapor and cloud-drift winds are combined in the figure, thinned for presentation (thousands of vectors are generated each day), and grouped into low, middle, and high altitude categories. Wind data are made available to the public via anonymous FTP as soon as they are generated. The NESDIS-generated winds are also broadcast in BUFR format to U.S. National Weather Service (NWS) offices through the NWS Telecommunications Gateway (NWSTG) and internationally on the Global Telecommunication System (GTS). Plots of MODIS winds are available on the Web at http://stratus.ssec.wisc.edu/products/rtpolarwinds.

Combined Terra and Aqua Winds

In theory, some improvements in wind quality and timeliness can be obtained by combining imagery from both Terra and Aqua into the same processing stream, primarily by reducing the time between images but also in providing coverage at somewhat lower latitudes (e.g., poleward of 60-65^{o} rather than 65-70^{o} latitude). Combining data from the two satellites requires that imagery be corrected for parallax, as the two satellites will view the same cloud or water vapor features from very different angles. Without a parallax correction, errors in location, and therefore wind speed and direction, can be significant.

Figure 2 shows the frequency with which MODIS on the two satellites views a particular location on the surface over the course of a 24-hour period, as a function of latitude. At very high latitudes, the surface location is viewed on every overpass. In practice, data at extreme sensor scan angles would not be used so that the actual viewing frequency would be somewhat less. Nevertheless, there are multiple times per day when Terra and Aqua MODIS view the same location within a few minutes of each other. Therefore, a mixed-satellite product was developed where both satellites are incorporated into the same data processing stream. Validation studies indicate that the mixed-satellite winds have similar error characteristics to the single-satellite winds.

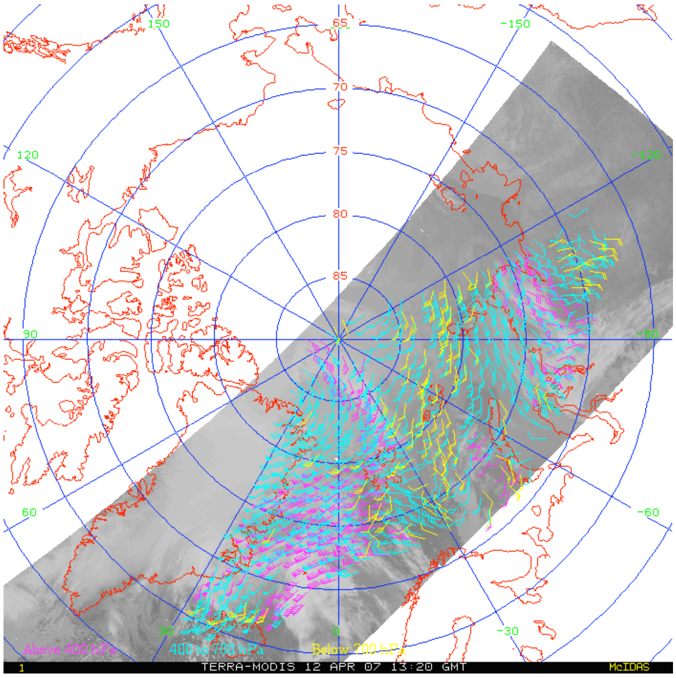

***Figure 1*. Winds from Terra MODIS over the Arctic for one 100-minute period on 12 April 2007 (thinned for clarity). Wind vector heights are categorized as low (yellow, below 700 hPa), middle (cyan, 400 to 700 hPa), and high (magenta, above 400 hPa).**

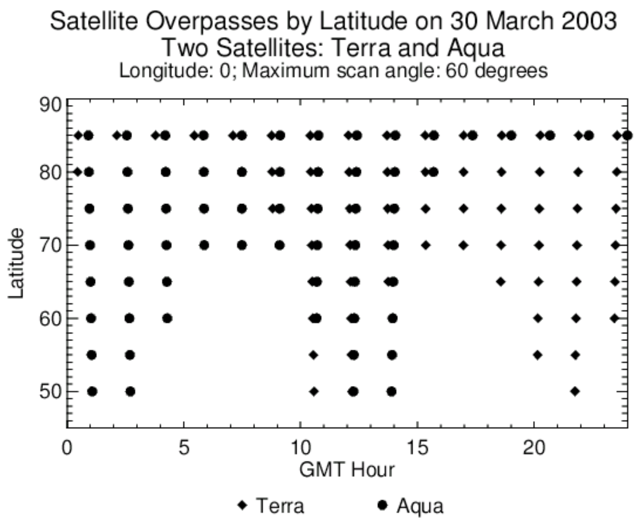

***Figure 2*. Frequency with which Terra and Aqua MODIS view a spot on the earth as a function of latitude over the course of a 24-hour period.**

Direct Broadcast Winds

For the standard MODIS wind products described above, MODIS data are acquired from the NOAA Real-Time System ("bent-pipe"), a computer system housed at the NASA Goddard Distributed Active Archive Center (DAAC). The level-1b data are typically available with a 1-2 hour delay. The final wind product lags the observing time (the time MODIS views an area) by about 3-5 hours. This includes a somewhat artificial delay of 100 minutes because the final wind vector time is assigned that of the middle image (orbit) of the triplet used in the wind retrieval. The 3-5 hour delay is too long for the data to be included in the principle data assimilation cycle at most NWP centers. Therefore, a system was developed to generate the MODIS winds using direct broadcast (DB) MODIS data in order to reduce the overall processing time. The system has been implemented at McMurdo, Antarctica, Tromsø, Norway, and Sodankylä, Finland. A similar system is being developed at Fairbanks, Alaska. All processing is done on site. Real-time results are available at http://stratus.ssec.wisc.edu/products/db/.

The Met Office demonstrated that the DB MODIS polar winds are similar in quality and number to the "bent-pipe" winds, but are available approximately 100 minutes faster. Figure 3 gives some statistics for Terra MODIS winds in the Northern Hemisphere generated at Tromsø in late 2006. Results are for mid-level, water vapor winds. The plots show the speed bias, the vector root-mean-square (RMS) difference, the lag time in receiving the data, and the number of wind vectors in the DB and bent-pipe data sets.

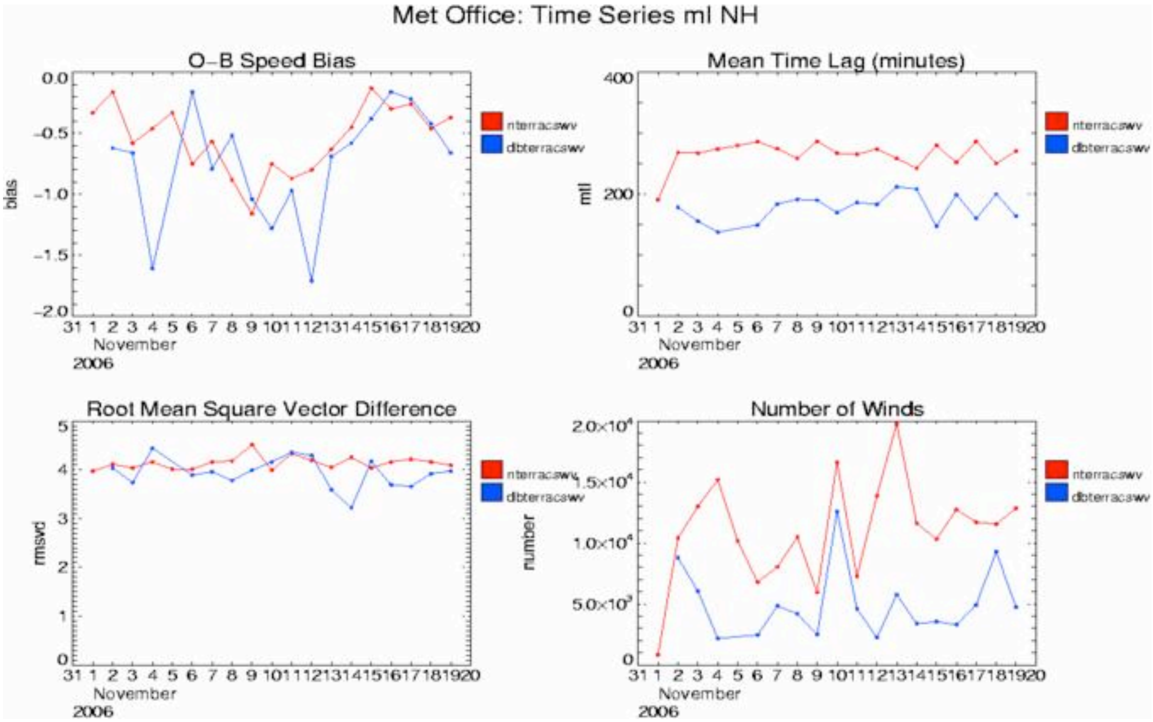

Figure 3. **Speed bias (satellite observation minus the background wind), vector RMS, lag time in receiving the data, and the number of wind vectors in the DB (blue) and bent-pipe (red) data sets. Results are for mid-level water vapor winds generated at Tromsø, Norway, with Terra MODIS data. (*Courtesy of M. Forsythe, Met Office)***

The DB winds from Tromsø and McMurdo are available via FTP and are also broadcast via EUMETCast.

AVHRR WINDS

Given the positive impact of MODIS winds on numerical weather forecasts, it is not unreasonable to expect that winds from AVHRR will also have an impact. Both MODIS instruments are aging, already operating beyond their life expectancies, so using the AVHRR for polar wind estimation will prepare us for a future without MODIS. But AVHRR can also be used now to supplement MODIS winds by providing additional temporal and spatial coverage, and can be generated back to the early 1980's for use in climate reanalyses.

Winds from NOAA Satellites

The procedure for estimating winds from AVHRR is similar to that for MODIS winds, though there are two important differences: spatial resolution and the absence of a water vapor channel. AVHRR Global Area Coverage (GAC) data, with a nominal 4 km resolution, are used because higher resolution data are not available globally. This has some implications for accuracy, as features for tracking are not as distinct. However, validation statistics show that the AVHRR winds are similar in quality to the MODIS winds. The lack of a water vapor channel limits the retrievals to cloudy areas, so the number of wind vectors produced is significantly lower than for MODIS. Furthermore, the vertical distribution of the winds changes, as most of the MODIS clear-sky water vapor wind vectors are in the middle and upper troposphere.

The AVHRR wind product is generated routinely in near real-time at CIMSS for four satellites separately: NOAA-15, -16, -17, and -18. It is scheduled for operational implementation in NESDIS in mid-2008. An example is given in Figure 4. Plots and more information are available at http://stratus.ssec.wisc.edu/products/rtpolarwinds.

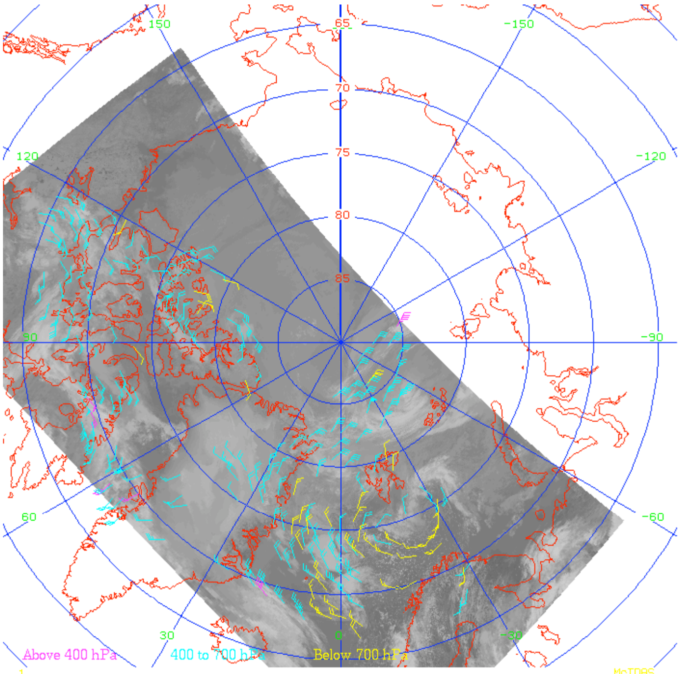

Figure 4. **Winds from NOAA-18 AVHRR at 10:43 UTC on 29 August 2007 over the Arctic. Wind vector heights are categorized as low (yellow, below 700 hPa), middle (cyan, 400 to 700 hPa), and high (magenta, above 400 hPa).**

Historical AVHRR Winds

If satellite-derived polar winds have a positive impact on weather forecasts, they should also have a positive impact on climate reanalyses (e.g., the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis and the European Center for Medium-Range Weather Forecasts (ECMWF) ERA-40 product). It has been shown that the major reanalysis products exhibit large errors in the wind field in areas void of radiosonde data (cf., Dworak and Key, 2008). Therefore, a polar wind data set spanning more than 20 years (1982-2002) was generated using AVHRR GAC data. Comparisons with winds from radiosondes show near-zero biases in the AVHRR-derived winds. In addition, AVHRR has lower speed root-mean-squared errors and speed biases than ERA-40 when compared to rawinsondes not assimilated into the reanalysis. It is recommended that the historical AVHRR polar winds be assimilated into future versions of the reanalysis products.

MetOp AVHRR Winds

The AVHRR instrument on MetOp-A, the first of three satellites of the EUMETSAT Polar System (EPS), has a distinct advantage over the AVHRR instruments on NOAA satellites with its global 1 km spatial resolution. CIMSS, NESDIS, and EUMETSAT are working together to implement MetOp AVHRR polar winds products, with operational products expected in the first half of 2009. An experimental product is currently being generated in near real time.

Direct Readout AVHRR Winds

As with the MODIS direct broadcast products, AVHRR data acquired at HRPT sites can also be used to reduce product latency. The first such system was implemented at the NESDIS facility in Fairbanks, Alaska, using real-time AVHRR data acquired at Barrow. Winds are available approximately 25 minutes after satellite flyover. At present, winds are being generated with data from NOAA-16, -17, and -18.

USE OF POLAR WINDS IN NWP

Model impact studies have been performed by NPW centers worldwide, and all have shown that the impact of the MODIS polar winds is positive. This is true not only in the polar regions where the data are obtained, but also for the Northern and Southern Hemisphere extratropics (poleward of 20 degrees latitude). The MODIS winds are used by the following NWP centers in their operational forecast systems:

- European Centre for Medium-Range Weather Forecasts (ECMWF)
- NASA Global Modeling and Assimilation Office (GMAO)
- Met Office (UK)
- Canadian Meteorological Centre (CMC)
- Japan Meteorological Agency (JMA)
- U.S. Navy’s, Fleet Numerical Meteorology and Oceanography Center (FNMOC)
- Deutscher Wetterdienst (DWD; Germany)
- National Centers for Environmental Prediction (NCEP)
- MeteoFrance
- Australian Bureau of Meteorology
- National Center for Atmospheric Research (NCAR)

The Met Office and FNMOC also use the MODIS direct broadcast winds in their operational forecast systems. To date, only a few impact studies have been done with AVHRR polar winds. As with the MODIS winds, the impact on forecasts is positive. The AVHRR GAC winds are used by FNMOC and the Met Office. Other NWP centers are testing both the DB and AVHRR winds.

SUMMARY AND CONCLUSIONS

The polar wind product suite has expanded considerably in recent years. In addition to Terra and Aqua MODIS winds being produced separately, a mixed-satellite product was developed in order to improve the timeliness of the winds and to extend the coverage equatorward. To take advantage of the additional temporal coverage provided by the NOAA satellites, polar wind products using data from the Advanced Very High Resolution Radiometer (AVHRR) on NOAA-15, -16, -17, -18 were implemented. The AVHRR winds will prepare us for a future without MODIS, where the NPOESS VIIRS imager will not have a water vapor channel. The latest wind product, currently in an experimental stage, uses AVHRR data from the joint European-US MetOp satellite.

To decrease product latency and increase the amount of wind information for NWP applications, MODIS wind processing systems have been implemented at a number of direct broadcast sites. At present, MODIS winds are generated on-site at McMurdo, Antarctica, Tromsø, Norway, and Sondankylä, Finland. Another system is under development at Fairbanks, Alaska. Similarly, winds are being produced with very low latency from AVHRR HRPT data acquired at Barrow, Alaska.

Lastly, in order to provide additional wind information for future reanalyses, a polar wind data set spanning more than 20 years was created using historical AVHRR data. All of these products are compared in Figure 5. The development timeline is shown in Figure 6.

Product/Feature	Spatial Coverage	Spatial Resolution	Latency (middle image)	Relative Accuracy	Operational NESDIS Product
MODIS, bent pipe, separate satellite	Entire Arctic and Antarctic	2 km	3-5 hrs	Similar to GOES	✔
MODIS, bent pipe, combined Terra & Aqua	Entire Arctic and Antarctic	2 km	2-4 hrs	Similar to GOES (additional tests needed)	✔ (mid-2008)
MODIS DB, single satellite	Part of Arctic or Antarctic	2 km	2.2 hrs	Same as bent pipe winds	Maybe never
AVHRR GAC	Entire Arctic and Antarctic	4 km	3-5 hrs	Good, but not as good as MODIS bent pipe	✔ (Apr 2008)
MetOp AVHRR	Entire Arctic and Antarctic	2 km	3-5 hrs	Same as bent pipe winds	✔ (Mar 2009)
HRPT AVHRR	Part of Arctic or Antarctic	2 km	2.0 hrs	Same as bent pipe winds	Maybe never
Historical AVHRR	Entire Arctic and Antarctic	5 km	N/A	Good, but not as good as bent pipe	Never

***Figure 5*. A comparison of polar wind products from MODIS and AVHRR. Spatial resolution is the pixel size used in the processing.**

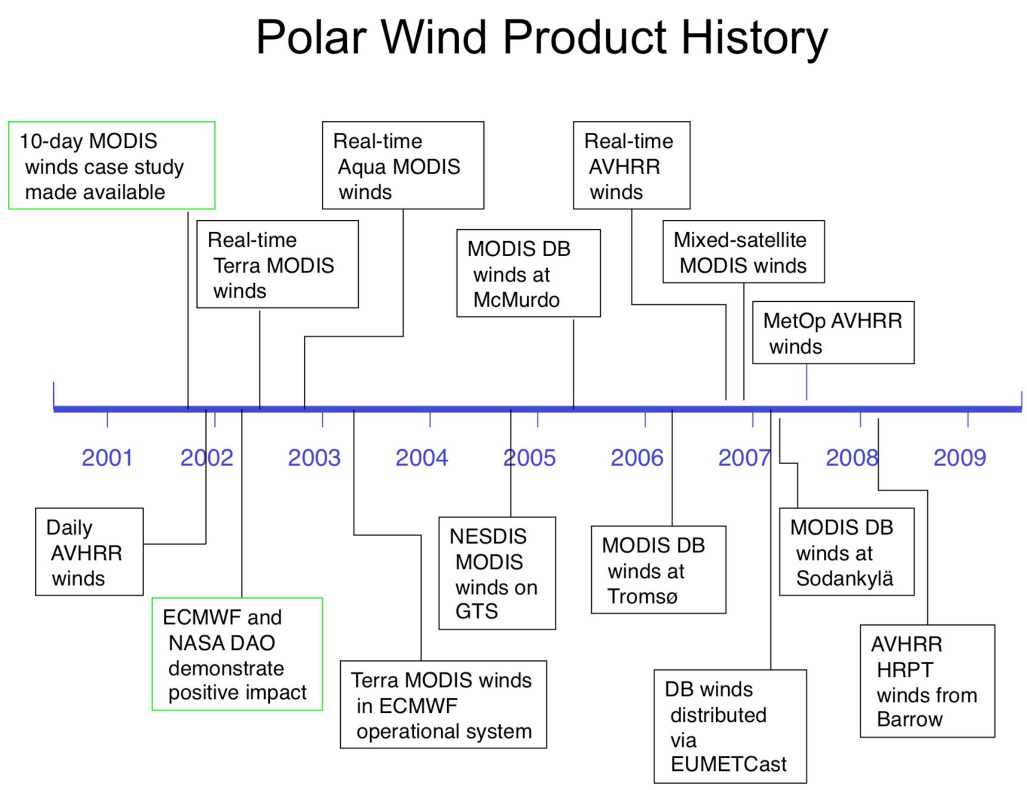

***Figure 6*. The polar wind product development timeline.**

Recommendations for improving polar wind products and their use include:

- Error characteristics of the MODIS and AVHRR winds need to be better quantified to improve their use in NWP models.
- MetOp AVHRR wind products should be further developed.
- Additional model impact studies with AVHRR winds must be done to assess the impact of IR-only winds on weather forecasts.
- Additional wind processing systems should be implemented at direct broadcast (MODIS) and HRPT (AVHRR) sites, particularly in Antarctica.
- More work is needed in wind vector height assignment. Case studies using cloud heights from MISR (Horvath and Davies, 2001) and CALIPSO are promising and should be expanded.
- Feature-track winds from hyperspectral sounders such as AIRS and IASI need to be investigated further. Case studies have demonstrated that winds derived in both radiance and retrieval space produce coherent wind fields. While the lower spatial resolution data produces fewer wind vectors in the horizontal, high vertical resolution retrievals are possible.

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