THE POLAR WIND PRODUCT SUITE

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ABSTRACT

In 2001, an experimental polar wind product was developed using imagery from the Moderate Resolution Imaging Spectroradiometer (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, and eleven NWP centers in seven countries use the data in their operational forecast systems. 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. To take advantage of the additional temporal coverage provided by the NOAA satellites, polar wind products were developed using data from the Advanced Very High Resolution Radiometer (AVHRR) on NOAA-15, -16, -17, -18, -19, and Metop were developed. MODIS and AVHRR wind processing systems have been implemented at direct readout sites in the Arctic and Antarctic, providing wind information in minutes rather than hours. At present, MODIS or AVHRR winds are generated on-site at McMurdo, Antarctica, Rothera, Antarctica, Tromsø, Norway, Sondankylä, Finland, Fairbanks, Alaska, and Barrow, Alaska. This paper provides an overview of the polar wind product suite and describes new research products, operational product transitions, and additional direct readout sites.

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 and AVHRR 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 AND AVHRR 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 - 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 and AVHRR 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.

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.

The procedure for estimating winds from AVHRR is similar to that for MODIS, 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 for five satellites separately: NOAA-15, -16, -17, -18, and -19. An example is given in Figure 1. 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. Metop winds are being generated routinely at CIMSS and in NESDIS operations. A EUMETSAT product is currently being tested.

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 at http://stratus.ssec.wisc.edu/products/rtpolarwinds.

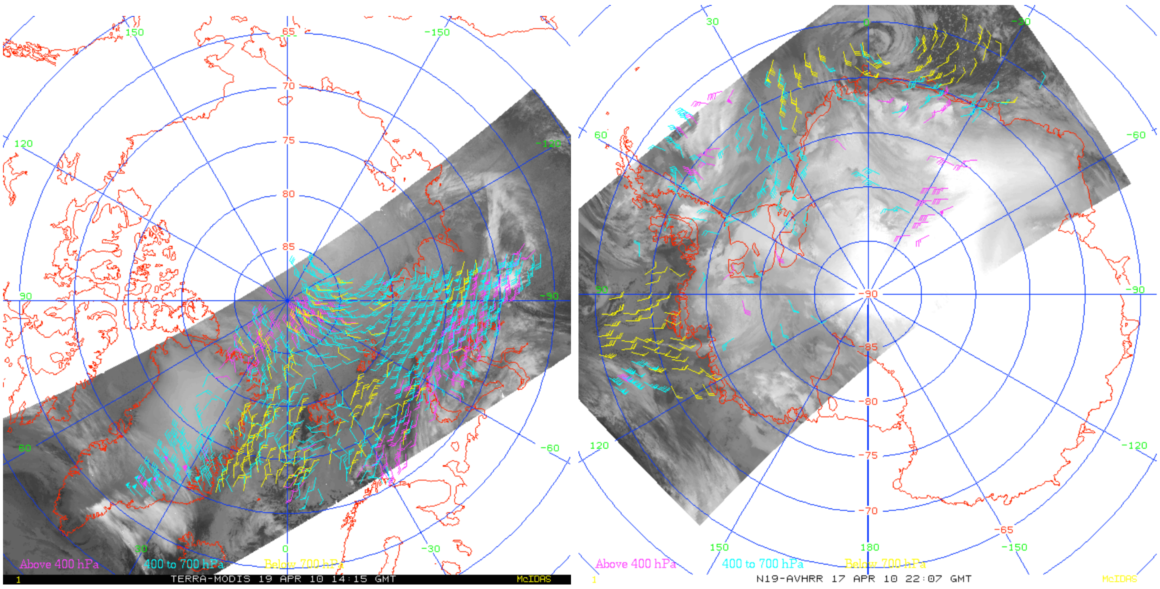

***Figure 1*. Left: Winds from Terra MODIS over the Arctic for one 100-minute period on 19 April 2010 (thinned for clarity). Right: Winds from NOAA-19 AVHRR over the Antarctic on 17 April 2010. Wind vector heights are categorized as low (yellow, below 700 hPa), middle (cyan, 400 to 700 hPa), and high (magenta, above 400 hPa).**

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). In fact, the time between the first and third images of a triplet from an alternating satellite sequence (e.g., Terra-Aqua-Terra or Aqua-Terra-Aqua) is 100 minutes, or half the time span for a triplet based on a single satellite. However, combining imagery from multiple satellites introduces two issues: parallax and time stamps.

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. Parallax corrections can and should be done with single-satellite wind generation as well, but the impact is relatively small because the viewing angle change is smaller from one orbit to the next.

In the wind derivation process, a fixed time is typically assigned to each image in a triplet. With mixed-satellite winds this becomes a significant problem because the two satellites of an alternating pair cross the pole from different, more or less opposite, directions. The range of time differences in the two images can be large, up to half of the nominal time difference. Therefore, using a fixed time for each image can result in significant errors in wind speeds, up to a factor of two. To alleviate this problem, per-pixel time stamping is currently being implemented and tested.

In spite of issues with time stamping and parallax, validation studies indicate that the mixed-satellite winds have similar error characteristics to the single-satellite winds. The "bad" vectors are, fortunately, rejected by the quality control procedures, but the result is significantly fewer winds. The mixed satellite MODIS wind product is routinely generated at CIMSS and will be operational in NESDIS in 2010.

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 28 years (1982-2009) has been generated using AVHRR GAC data. Generally, two satellites are used throughout the time series. 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.

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 1-3 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, Sodankylä, Finland, and – most recently – Fairbanks, Alaska. All processing is done on site. Real-time results are available at http://stratus.ssec.wisc.edu/products/db/.

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. Another system was implemented at Rothera, Antarctica, hosted by the British Antarctic Survey. Winds are available approximately 25 minutes after satellite flyover. At present, winds are being generated with data from NOAA-16, -17, -18, and -19, depending on the site. AVHRR HRPT data have the added advantage of being higher resolution than GAC data, 1 km (remapped to 2 km) versus 4 km for GAC. Figure 2 shows the station masks for the MODIS and AVHRR direct readout/broadcast sites. (Note: "Direct broadcast" is a term typically applied to MODIS; "direct readout" is commonly used for AVHRR HRPT acquisitions.) Figure 3 gives an example of AVHRR winds from Rothera.

The Met Office demonstrated that the DB MODIS polar winds are similar in quality and number to the conventional winds, but are available approximately 100 minutes faster. In fact, 91% of the direct broadcast winds are available within three hours of the observation time, with more than 80% available within two hrs. In contrast, only 2% of the operational MODIS winds were available in less than three hours. Figure 4 compares AVHRR and MODIS winds from direct broadcast sites and conventional data sources. The plots show the vector root-mean-square (RMS) differences and the number of winds. The vector RMS of the direct broadcast winds similar to, or lower than, the operational winds.

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

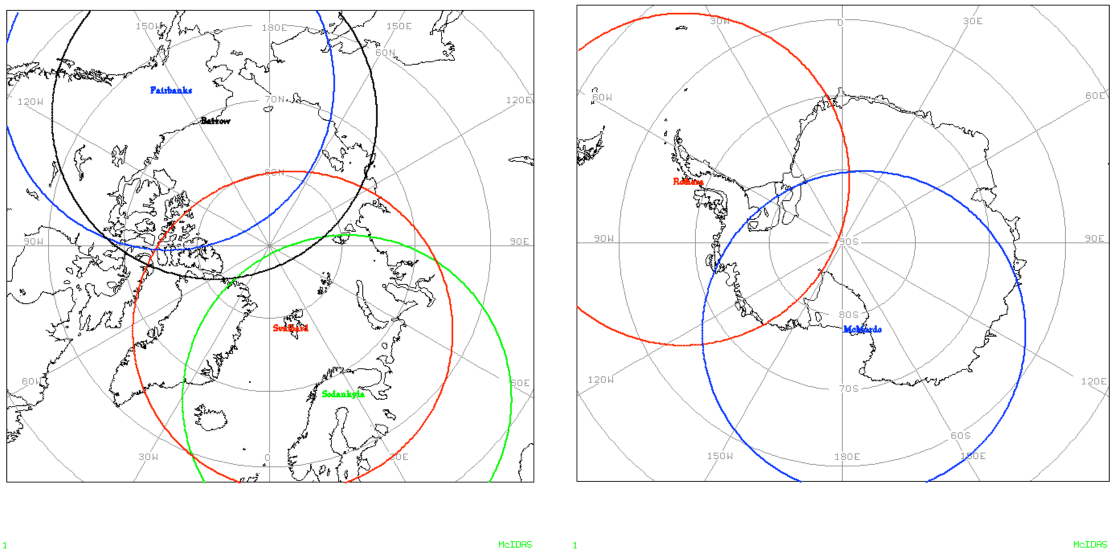

Figure 2. **Station masks for direct broadcast sites in the Arctic (left) and Antarctic (right).**

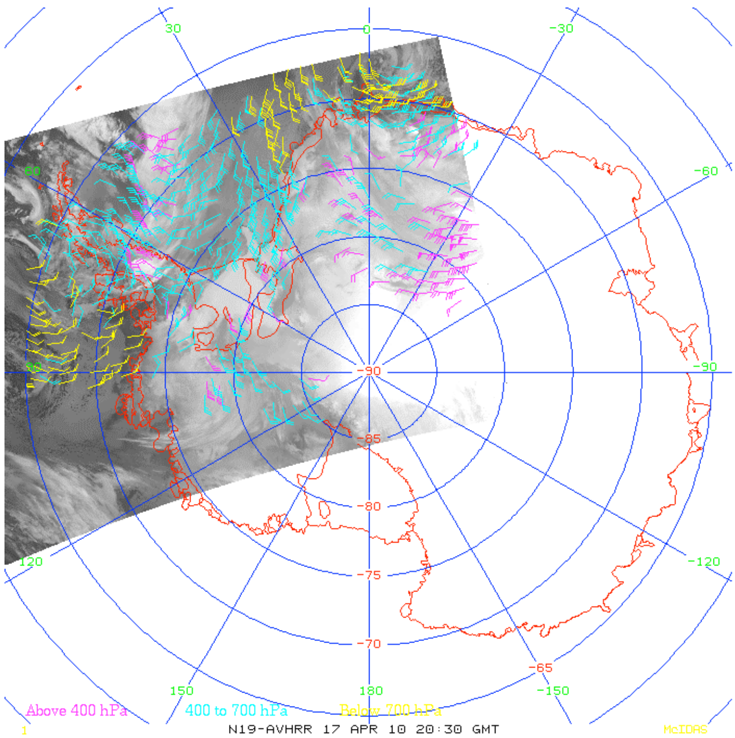

Figure 3. **Winds from NOAA-19 AVHRR on 17 April 2010. Data were received and processed at Rothera, Antarctica. Wind vector heights are categorized as low (yellow, below 700 hPa), middle (cyan, 400 to 700 hPa), and high (magenta, above 400 hPa).**

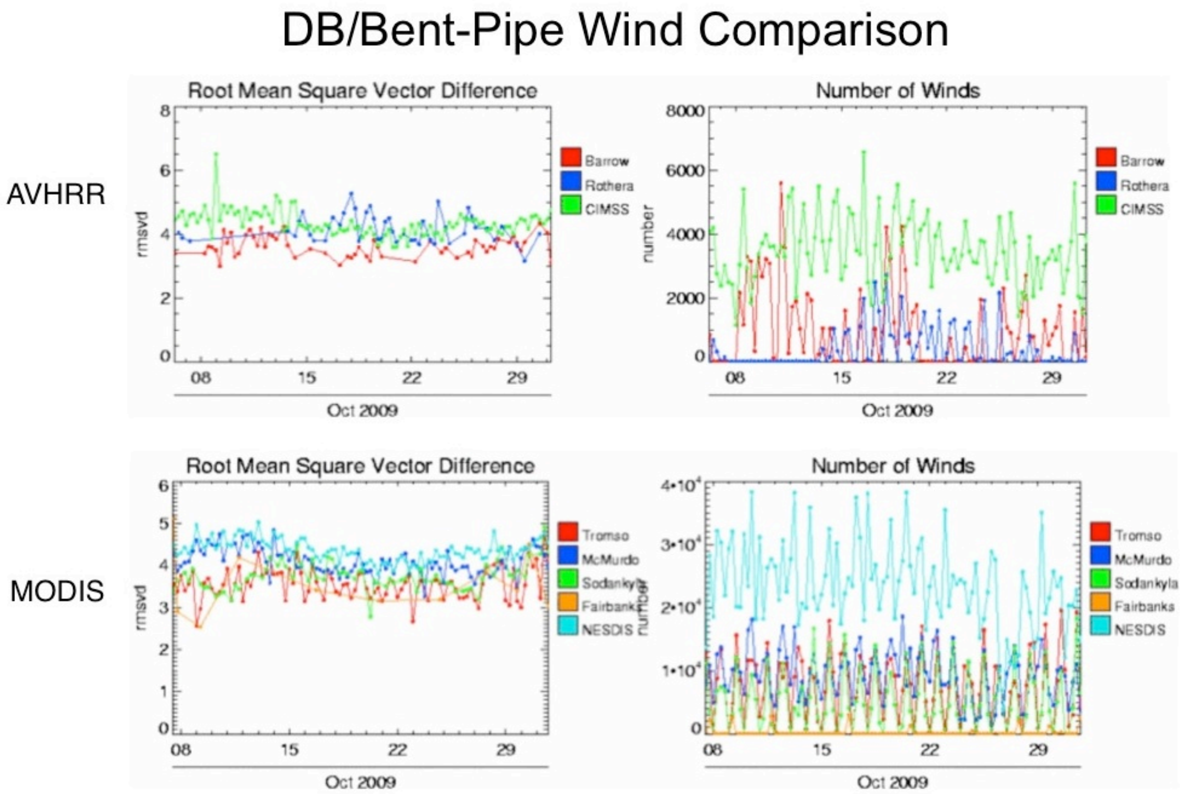

***Figure 4*. Time series plots showing the root mean square vector difference and number of winds for (top) AVHRR winds and (bottom) MODIS winds from different sites. "CIMSS" refers to the AVHRR GAC winds routinely generated at CIMSS; "NESDIS" refers to operational MODIS winds from NESDIS. (*Courtesy of M. Forsythe, Met Office*)**

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 in operational forecast systems at 11 NWP centers in seven countries:

- 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, FNMOC, CMC, and NCAR also use MODIS and/or AVHRR direct broadcast winds in their operational forecast systems. As with the MODIS winds, the impact of AVHRR winds 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, and -19 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 (Terra and Aqua MODIS), Rothera, Antarctica (AVHRR), Tromsø, Norway (Terra MODIS), Sondankylä, Finland (Terra MODIS), and Fairbanks, Alaska (Terra MODIS and AVHRR from Barrow).

Lastly, in order to provide additional wind information for future reanalyses, a polar wind data set spanning 28 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 Comparison

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-2010)
MODIS DB, single satellite	Portions of Arctic and Antarctic	2 km	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	✔
Metop AVHRR	Entire Arctic and Antarctic	2 km	3-5 hrs	Same as bent pipe winds	✔
HRPT AVHRR	Portions of Arctic and Antarctic	2 km	2 hrs	Same as bent pipe winds	Maybe never
Historical AVHRR	Entire Arctic and Antarctic	5 km	N/A 1982-2009	Good, but not as good as bent pipe	Not applicable

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

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.
- 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.

- Winds from two images rather than three should be investigated as they would allow for a broader latitudinal range and lower latency.

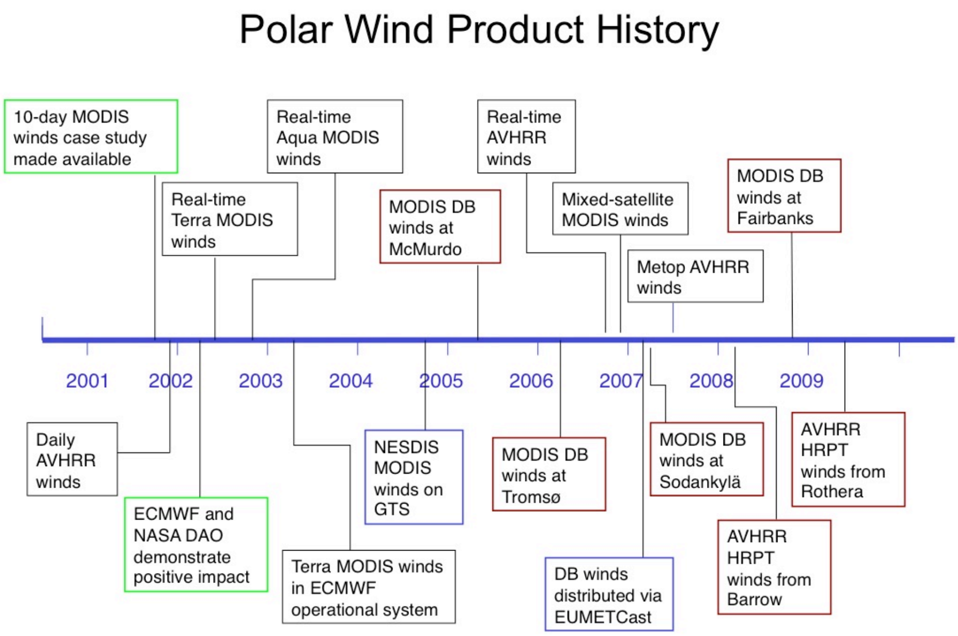

***Figure 6*. The polar wind product development timeline.**

Acknowledgements: The success of the polar winds project is largely a result of work done at the NWP centers. In particular, we thank Mary Forsythe, Randy Pauley, Niels Bormann, Lars Peter Riishojgaard, John LeMarshall, Jim Jung, Real Sarrazin, Alexander Cress, Koji Yamashita, Masahiro Kazumori, Christophe Payan, Yan-Qiu Zhu, Claire Delsol, Lueder von Bremen, Iliana Genkova, Antonio Irving, and Hongming Qi. Paul Menzel suggested exploring MODIS polar winds in 2000. Product development was funded by NOAA and NASA.

REFERENCES

Dworak, R. and J. Key, (2007) 20 Years of Polar Winds from AVHRR: Validation and Comparison to the ERA-40. *J. Atmos. Ocean. Tech*., accepted (May 2008).

Horvath, A., and R. Davies, (2001) Simultaneous retrieval of cloud motion and height from polar-orbiter multiangle measurements. *Geophysical Research Letters*, 28, 2915-2918.

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.

Velden, C., J. Daniels, D. Stettner, 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.

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.

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), 173-196.

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.