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NOAA CONSIDERATION OF PRODUCING AMV WIND PRODUCTS OVER THE POLES

In response to CGMS Action 34.21

This paper summarizes current wind products from polar orbiting imagers. Products generated in real-time are cloud drift and water vapor winds from MODIS on NASA's Terra and Aqua satellites, and cloud drift winds from AVHRR on NOAA satellites. Plans for new products are also discussed.

NOAA CONSIDERATION OF PRODUCING AMV WIND PRODUCTS OVER THE POLES

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1 INTRODUCTION

Satellite-derived wind fields are most valuable for the oceanic regions where few observations exist and numerical weather prediction model forecasts are less accurate as a result. 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 (Figure 1). 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.

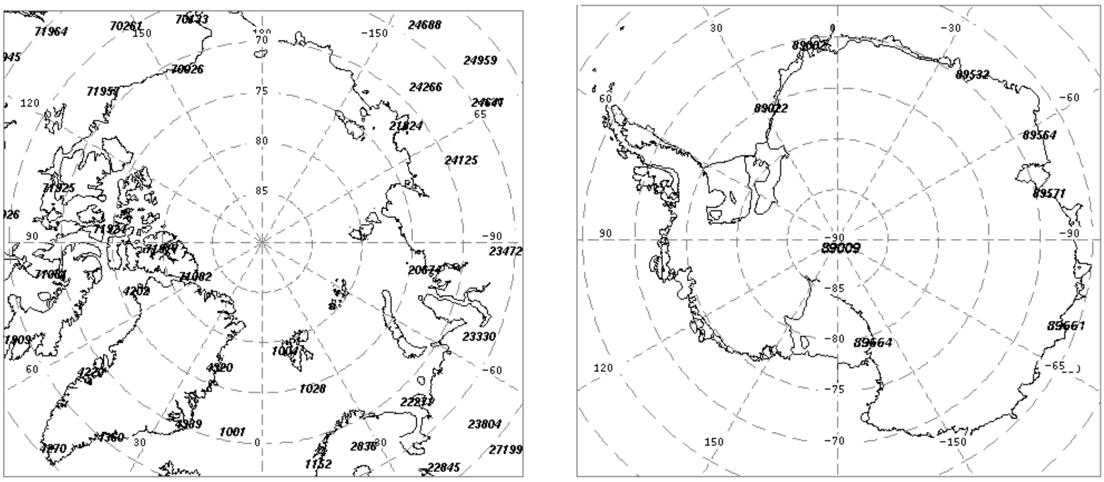

Fig. 1. WMO stations across the Arctic (left) and Antarctic (right). Only those stations that provide regular daily wind data are shown.

This paper reports on the status of efforts to estimate tropospheric winds at high latitudes from polar-orbiting satellite imagers, in particular the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Advanced Very High Resolution Radiometer (AVHRR). Over the last few years, model impact studies conducted at major numerical weather prediction (NWP) centers in six countries have shown that the MODIS winds have a positive impact on global weather forecasts. It is therefore important to continue generating, improving, testing, and extending these products. In addition, new products should be explored, such as winds from hyperspectral sounders. For example, the Atmospheric InfraRed Sounder (AIRS) and the Infrared Atmospheric Sounding Interferometer (IASI) may offer an improvement in height assignment, albeit at a lower spatial resolution. Product latency is also an important issue, in that a large proportion of the MODIS and AVHRR winds are not generated soon enough for early model runs. Experiments with direct broadcast sites demonstrate that the delay in obtaining MODIS data can be reduced substantially. Only feature-tracked wind derivation is discussed in this paper. Thermal winds calculated from sounder-derived temperature profiles (cf, Zheng and Zou, 2006; Francis and Zou, 2006) are not addressed.

2 MODIS WINDS

Methodology

Cloud and water vapor tracking with MODIS data is based on the established procedure used for GOES, which is described in Merrill (1989), 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). No significant changes to the methodology have been made over the past year, though a number are planned. 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. The impact of different first guess model fields on wind retrievals is being examined.

Single Satellite

In 2001 the Cooperative Institute for Meteorological Satellite Studies (CIMSS) and NOAA/NESDIS collaborators developed a methodology for generating wind vectors in the polar regions using MODIS on-board NASA's Terra and Aqua satellites. The methodology employed is based on the algorithms used with geostationary satellites, modified for use with polar-orbiting imagers. MODIS has a relatively high spatial resolution: IR bands are 1 km, though the CIMSS and NESDIS winds are derived from regridded data at 2 km since the 1 km resolution is at nadir and drops off to several kilometres 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 National Polar-orbiting Operational Environmental Satellite System (NPOESS) Visible/Infrared Imager/Radiometer Suite (VIIRS) instrument (as currently planned), since neither of these sensors includes a thermal water vapor channel.

The 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 2. Both water vapor and cloud-drift winds are combined in the figure, thinned significantly 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 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

Until recently, winds from the Terra and Aqua satellites were generated separately. In theory, some improvements in wind quality and timeliness can be obtained by combining imagery from the two satellites 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 65^{o} rather than 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 different angles. Without a parallax correction, errors in location, and therefore wind speed and direction, can be significant.

Figure 3 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.

Both satellites are now incorporated into the same data processing stream, in addition to the continuing production of winds from each satellite individually. Validation studies indicate that the mixed-satellite winds have similar error characteristics to the single-satellite winds.

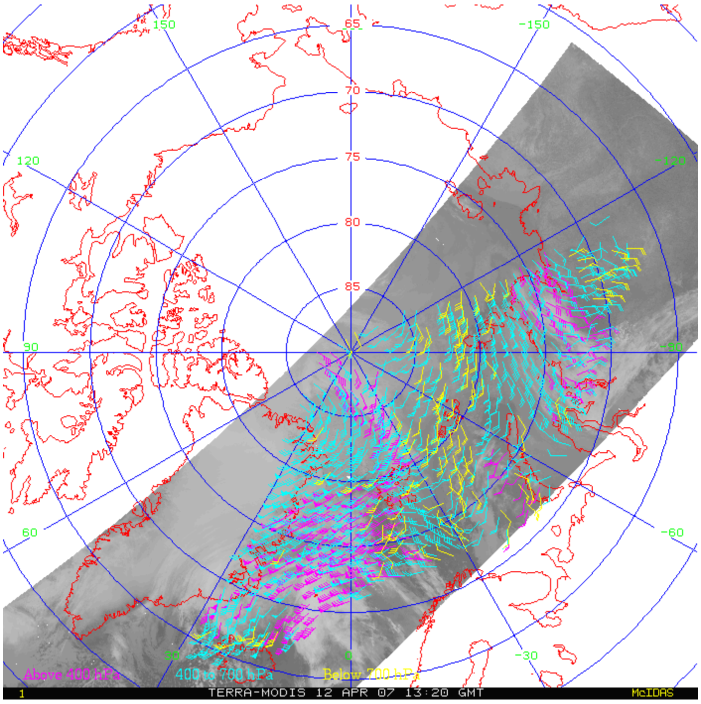

Fig. 2. Winds from Terra MODIS over the Arctic for one 100-minute period on 12 April 2007 (thinned for clarity). Wind vector heights are categorized as low (yellow, below 700 hPa), middle (cyan, 400 to 700 hPa), and high (magenta, above 400 hPa).

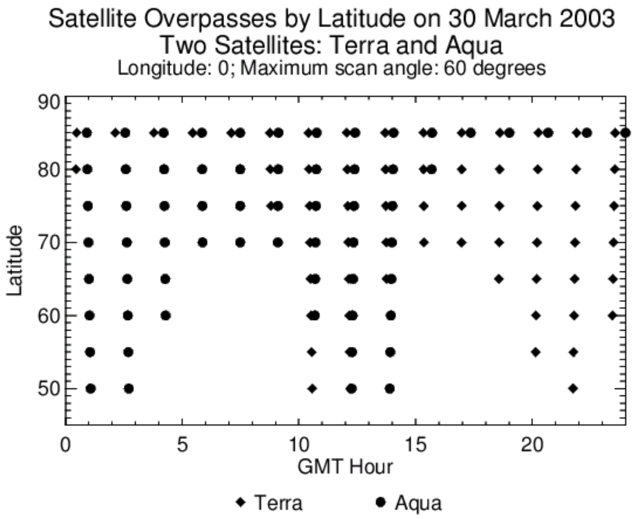

Fig. 3. Frequency with which Terra and Aqua MODIS view a spot on the earth as a function of latitude over the course of a 24-hour period.

Direct Broadcast

For the winds generated routinely at CIMSS and in NESDIS operations, 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 a triplet of three consecutive orbits is used, and the final wind vector 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. We have therefore developed a system 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. All processing is done on site. Real-time results are available at http://stratus.ssec.wisc.edu/products/db/.

The (UK) Met Office (M. Forsythe) has demonstrated that the DB MODIS polar winds are similar in quality and number to the "bent-pipe" winds, but are available significantly faster, approximately 100 minutes faster. Figure 4 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.

Fig. 4. 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)*

3 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, even though they can only be derived for cloudy areas. (This is discussed further in section 5.) Additionally, both MODIS instruments are aging, with Terra already operating beyond its life expectancy. 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 coverage, and can be generated with data back to the early 1980's for use in climate reanalysis projects.

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 around the 500 hPa level.

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 2008. An example is given in Figure 5. Plots and more information are available at http://stratus.ssec.wisc.edu/products/rtpolarwinds.

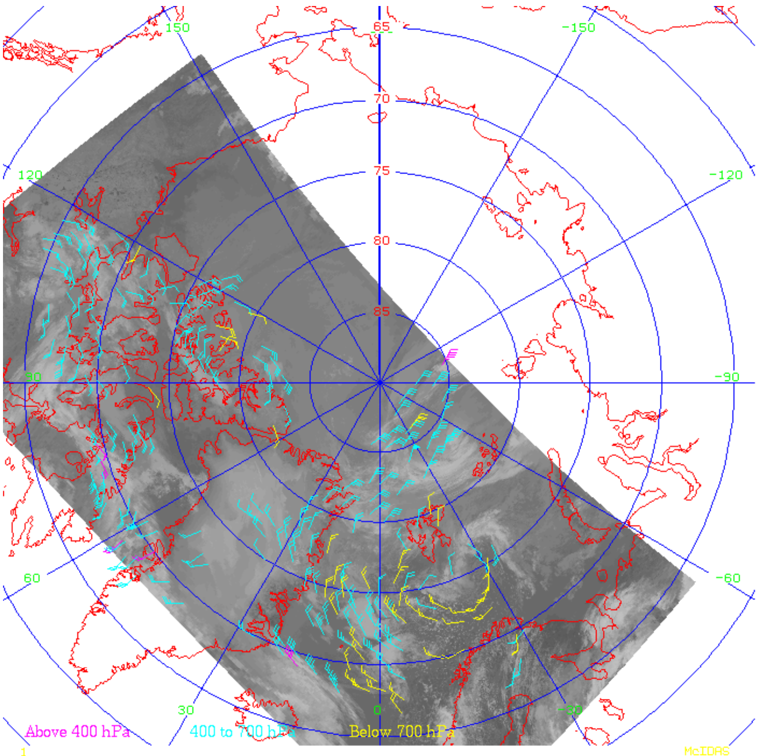

Fig. 5. Winds from NOAA-18 AVHRR at 10:43 UTC on 29 August 2007 over the Arctic. Wind vector heights are categorized as low (yellow, below 700 hPa), middle (cyan, 400 to 700 hPa), and high (magenta, above 400 hPa).

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). 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

There is significant interest in generating polar winds from the AVHRR instrument on MetOp-A, the first of three satellites of the EUMETSAT Polar System (EPS). The advantage of the MetOp AVHRR is its global 1 km spatial resolution. EUMETSAT, CIMSS, and NESDIS all have plans for a MetOp AVHRR polar winds product in the near future and are engaged in product development at the time of this writing.

4 Feature-Track Winds from AIRS

Using the same concept as for deriving MODIS winds, is it possible to track features with Atmospheric Infrared Sounder (AIRS) single-field-of view (SFOV) radiances? Since the AIRS field of view is much larger (13.5x13.5 km, reduced to 16 km for tracking) than that of MODIS (1x1 km, reduced to 2 km for tracking), the number of successfully tracked features and spatial coverage of AIRS-derived winds is much lower when compared with MODIS winds coverage (Figure 6).

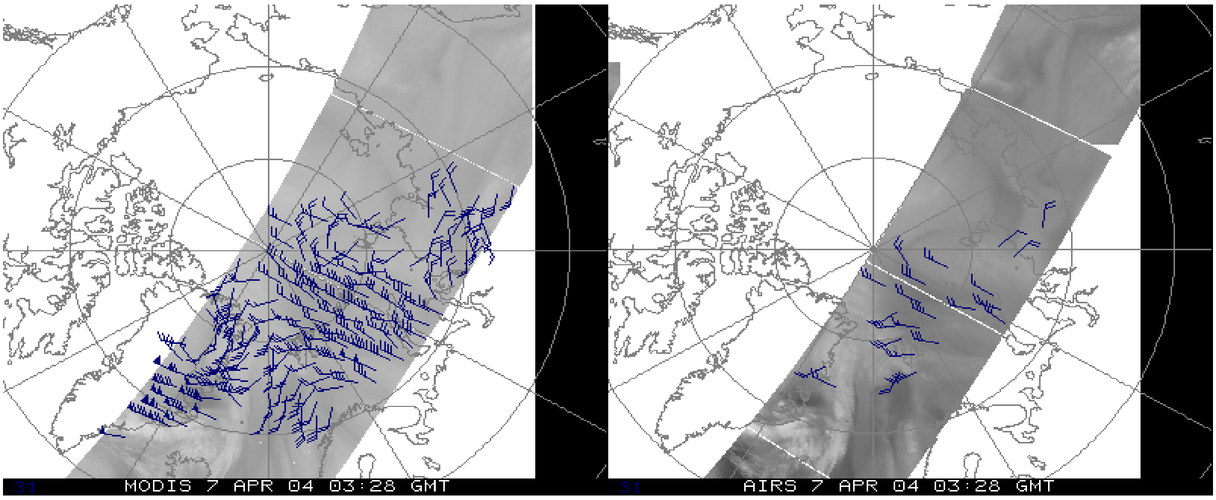

Fig. 6. Comparison of MODIS (left) and AIRS (right) water vapor imagery winds over the same arctic region on 7 April 2004.

Given that the spectral and vertical resolution of AIRS is much higher than that of MODIS, another approach is to employ retrieved moisture fields for the winds tracking rather than radiances, thereby avoiding the ambiguity of the vector height. Additionally, winds from many distinct vertical levels can be resolved. As a test of this approach, AIRS cloud-cleared soundings are derived using 3x3 pixel cells (40x40 km, horizontal resolution). With about 100 minutes of refresh time, the spatial resolution is too large for any practical and reliable wind derivation. The need for higher spatial resolution cloud-cleared soundings for this application prompted the use of not yet completely validated but published pseudo-single AIRS pixel (14x14 km at nadir) cloud-clearing retrieval approach under development as CIMSS. To test this approach, retrieved constant-level moisture fields were then derived from three successive arctic overpasses on 6 September 2002 and employed as input to the tracking algorithm. The results for one level (400 hPa, others were similar) are shown in Figure 7. As can be seen, coverage is marginal, but coherent vector fields are achievable. Additional case studies are needed.

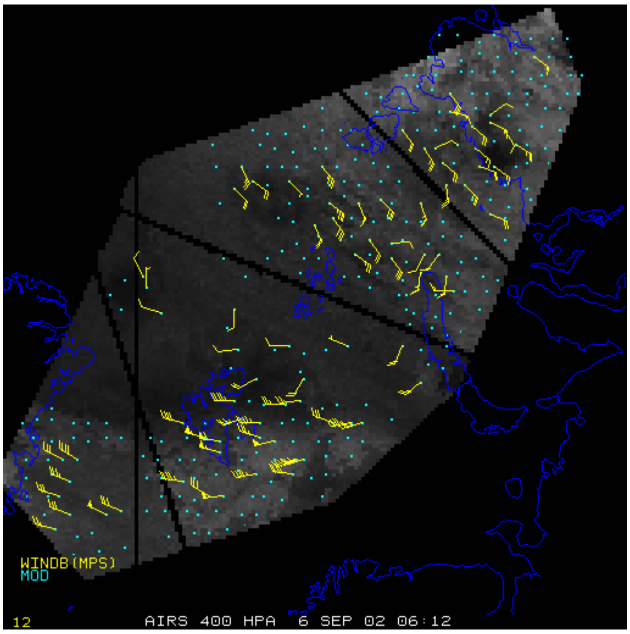

Fig. 7. AIRS moisture retrieval targets (cyan) and wind vectors (yellow barbs) at 400hPa.

5 MISR and CALIPSO for Height Validation

Heights assigned to winds derived from NASA's Multi-angle Imaging SpectroRadiometer (MISR) on the Terra satellite are derived geometrically by taking advantage of the unique instrument configuration that involves nine cameras imaging the same earth scene under different viewing angles fore and aft during the flyover (Horvath et al, 2001a, 2001b). Due to the narrow swath, the MISR winds are unlikely to have a large impact on numerical weather prediction skill on their own. However, they do represent one of the few independent verification datasets for the MODIS winds, in particular since the two instruments are flying on the same platform. The temporal and spatial collocation issues that often limit the conclusions that can be drawn from cross-validation efforts are therefore all but absent for these two data sources. Another attractive characteristic of the MISR winds is the geometric height assignment method that in theory is much more accurate and robust than the methods used for MODIS. Errors in height assignment are widely believed to be the most important factor limiting the impact on forecast skill of the feature tracking satellite winds obtained from MODIS and the geostationary satellites.

As with MISR, data from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite can help assess the quality of satellite-derived cloud motion vector (CMV) height assignments. CALIPSO combines an active lidar instrument with passive infrared and visible imagers to probe the vertical structure and properties of thin clouds and aerosols over the globe. Comparison of collocated CALIPSO cloud altitudes and operational height assignments are expected to yield improvements in both cloud height algorithms and CMV error characteristics that should increase their exploitation by NWP forecast models.

Procedures have been developed to compare the CO_2 slicing heights from MODIS with the CALIPSO-derived altitude. Figure 8 is a histogram of the differences for all cloud tops, CALIPSO cloud tops less than 4 km, and tops greater than 6 km. The skew to larger biases in the case of high clouds is associated with the optical thickness of the cloud. For thin clouds, the upwelling radiance comes from the cloud top as well as the surface, lower cloud layers, and atmosphere below and within the cloud, which is typically warmer than the cloud top. Therefore, the passive IR method will tend to underestimate the cloud top height.

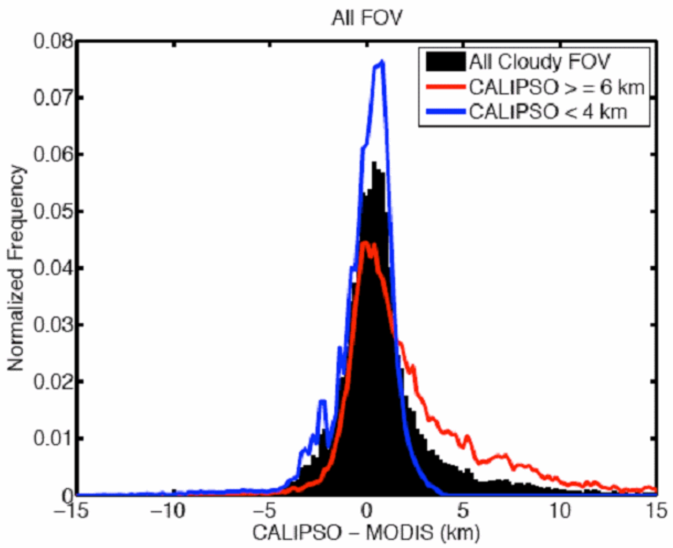

Fig. 8. Cloud altitude biases between CALIPSO and MODIS for August 2006.

6 MODEL IMPACT STUDIES

Can the polar wind data improve weather forecasts? Model impact studies have been performed by at least ten numerical weather prediction centers in six countries:

- the European Centre for Medium-Range Weather Forecasts (ECMWF),
- the NASA Global Modeling and Assimilation Office (GMAO),
- the (U.K.) Met Office,
- the Canadian Meteorological Centre (CMC),
- the Japan Meteorological Agency (JMA),
- the U.S. Navy's, Fleet Numerical Meteorology and Oceanography Center (FNMOC),
- the Joint Center for Satellite Data Assimilation (JCSDA),
- Deutscher Wetterdienst (DWD; Germany),
- MeteoFrance, and
- the National Center for Atmospheric Research (NCAR).

All of these centers use the MODIS winds in their operational forecast systems.

Overall, the impact of the MODIS polar winds on numerical weather forecasts is positive (Figure 9). 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 fill a significant gap in the global observing system.

To date, no impact studies have been done with AVHRR polar winds. While the quality of the cloud drift winds is similar for AVHRR and MODIS, AVHRR does not have a water vapor channel and hence no clear sky winds are produced. How will this impact weather forecasts? The relative contribution to forecast skill of winds processed from the 6.7 micron water vapor channel imagery versus those derived from the 11 micron window channel was explored at the NASA GMAO. The average forecast skill curves in Figure 10 show that the MODIS winds have a strong positive impact in the high latitudes (left panel), and the impact extends to the lower latitude regions (right panel). In all cases, the impact is larger if both types of winds (IR and water vapor) are used.

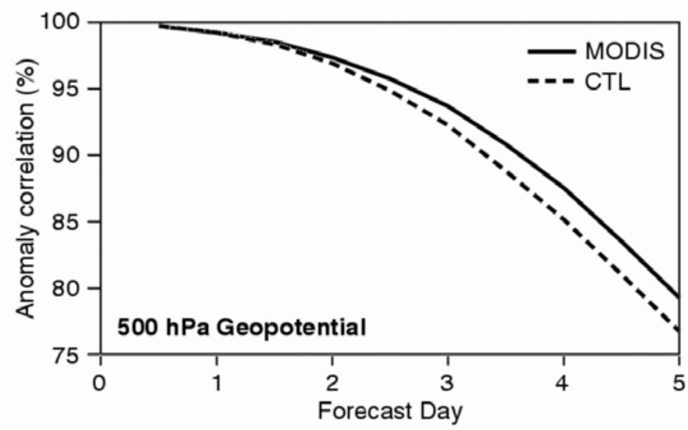

Fig. 9. Forecast scores, or 'anomaly correlation' for a 30-day Arctic case study done by ECMWF. The figure shows the forecast skill for model runs with (MODIS) and without (CTL) the polar winds data. Anomaly correlation expresses the agreement between a forecast and the actual state of the atmosphere, where the higher the percent, the better the agreement. Starting with the second day, the forecasts that used the MODIS winds were in better agreement with the analysis ("truth") than the forecasts without the MODIS winds.

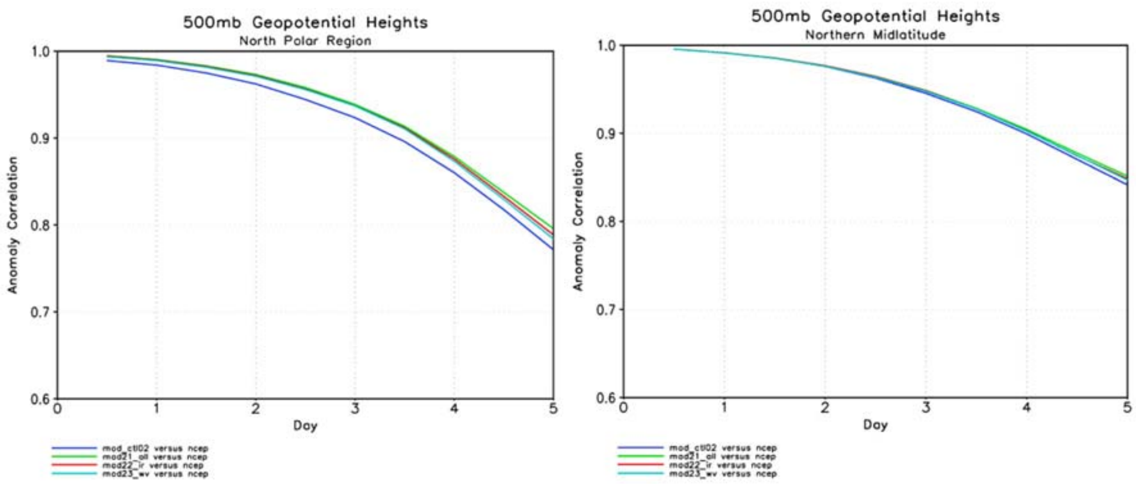

Fig. 10. 500 hPa height anomaly correlation coefficients for January and February 2005 as function of forecast range (GEOS-5 verified against NCEP) for the Arctic region (left panel) and for the Northern mid-latitudes (right panel). Control experiment (No MODIS winds) shown in blue, control+MODIS water vapor winds in turquoise, control+MODIS IR winds in red, control+all (IR and water vapor) MODIS winds in green.

Another impact study was done to address the expected additional impact of the MODIS winds under a hypothetical scenario in which the winds would be available to the operational users within the data cut-off for the main forecast runs. Due to the late arrival of the MODIS winds (3-5 hours after real-time for the bent-pipe winds), these observations are not used to correct the initial conditions for the model forecast. They are used to keep the overall assimilation trajectory on track, and they therefore have the indirect effect of helping to provide better initial conditions due to a better analysis background. The skill curves in Figure 11 show that the forecast impact is larger if the winds are used to correct the forecast initial conditions than when they are used only to keep the background assimilation on track. This has important implications for the generation of MODIS winds at direct broadcast sites. Due to this data latency problem, the positive impact demonstrated by forecast impact studies that used only the bent-pipe MODIS winds should be considered conservative estimates of the potential operational value of high-latitude wind observations.

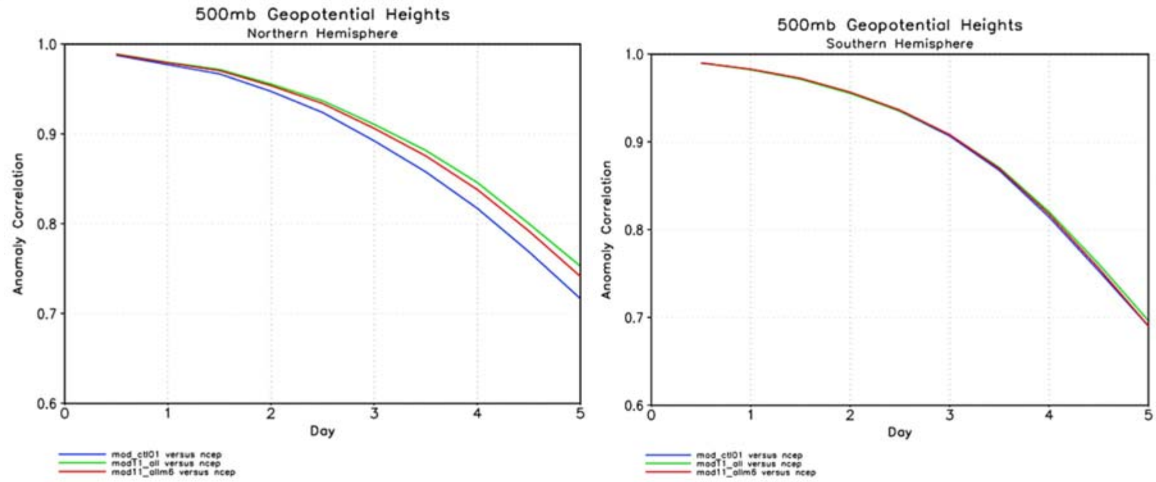

Fig. 11. 500 hPa height anomaly correlation coefficients for July and August 2004 as function of forecast range (GEOS-5 verified against NCEP) for the Northern hemisphere (left panel) and Southern hemisphere (right panel). Control experiment (no MODIS winds) is shown in blue; control+MODIS winds in the forecast initial conditions in green, control+MODIS winds in background run only shown in red.

7 CONCLUSIONS

MODIS polar winds continue to be produced in real-time with a 2-5 hour delay. They are used operationally by at least ten numerical weather prediction (NWP) centers in six countries. All have demonstrated that the MODIS winds have a positive impact on global weather forecasts. Systems to generate MODIS winds with direct broadcast (DB) data have been implemented at McMurdo, Antarctica, Tromsø, Norway, and Sodankylä, Finland. The DB MODIS winds are available on average well over an hour sooner than the conventional MODIS winds. A model impact study demonstrated that having the DB data available early enough to correct forecast initial conditions provides additional improvement in forecasts. MODIS winds are generated from Terra and Aqua separately, and also in a combined data stream.

Polar winds are also generated in near real-time from the AVHRR instrument on four NOAA satellites. Model impact studies are in progress. AVHRR data have also been used to generate an historical wind product covering the period 1982-2002.

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.
- MODIS wind processing systems at additional direct broadcast sites in the Arctic and Antarctic should be implemented. Direct broadcast AVHRR (HRPT) systems should be considered.
- Additional work is needed in wind vector height assignment. Case studies using cloud heights from MISR and CALIPSO are promising and should be expanded.
- The potential of polar winds from hyperspectral sounders, with retrievals done in retrieval rather than radiance space, should be further explored.

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