9th International Winds Workshop, Annapolis, Maryland, USA, 14-18 April 2008

THE IMPACT OF MODIS-DERIVED POLAR WINDS ON GLOBAL FORECASTS

David Santek

Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin-Madison
1225 West Dayton Street, Madison, WI, 53706, USA

Abstract

The use of Atmospheric Motion Vectors (AMVs) in NWP (Numerical Weather Prediction) models continues to be an important source of information in data sparse regions. These AMVs are derived from a time-sequence of images from geostationary and polar orbiting satellites. NWP centers have documented positive impact on model forecasts not only in regions where the AMVs are measured, but elsewhere as well. One example is the effect of the Moderate Resolution Imaging Spectroradiometer (MODIS) polar winds on forecasts in the middle and lower latitudes.

Using a pre-operational version of the National Centers for Environmental Prediction's (NCEP) Global Forecast System (GFS), an experiment was run during August and September 2004, with and without the MODIS polar winds. Several cases within this period were analyzed to determine how winds poleward of 65 degrees latitude affect the height and wind fields into lower latitudes.

From the five cases examined, it was determined that the addition of the polar winds modifies the mass balance in synoptic-scale waves near the polar jet streams, more consistently in data void regions. This change in mass balance is evident in differences in the ageostrophic wind, which has an effect on the speed and amplitude of baroclinic waves that extends from the jet stream into lower latitudes in later forecast times. These results reveal the substantial impact that polar-only observations may have on the predictability of global weather systems.

INTRODUCTION

While the polar regions comprise only one-eighth of the earth's total surface area, the importance of observations in those regions is becoming increasingly more evident. There are many examples on the influence of the polar regions on lower latitude atmospheric conditions on time scales from synoptic to climatic, space scales from meso to global, and extending through the depth of the troposphere (Gallimore and Johnson 1981; Pyle et al. 2004). However, Francis (2002) found that the existing upper-air observation network in high latitudes is insufficient for the accurate depiction of the tropospheric wind field. The influence that the polar regions have on lower latitude circulation systems coupled with an inaccurate knowledge of the polar atmospheric state may result in an erroneous picture of global weather systems and subsequent forecasts.

Near the turn of this century, the National Aeronautics and Space Administration (NASA) launched two research weather satellites (Terra and Aqua). The infrared and water vapor channels on the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery were chosen to investigate the feasibility of tracking clouds and clear-sky water vapor features over the polar regions. The first experiment of assimilating satellite-derived winds from MODIS proved successful, with a positive impact in forecasts being reported (Key et al. 2003). A somewhat startling result was that the positive impact was not restricted to the polar regions where the winds were measured, but it extended to lower latitudes.

The question was asked by members of the Numerical Weather Prediction (NWP) community: “Why do MODIS winds measured near the poles have a significant impact on global forecasts?” This study investigates the hypothesis that the assimilation of polar winds modifies the flow in high latitudes near the polar jet stream and that this effect propagates to lower latitudes in extended forecasts. This hypothesis will be tested by investigating the impact that the MODIS winds have on model analyses and forecasts versus a control run, and how these differences can be explained in terms of data assimilation and atmospheric dynamics.

WINDS FROM MODIS

Unlike geostationary satellites at lower latitudes, it is not be possible to obtain complete polar coverage at a snapshot in time with one or two polar-orbiters. Instead, winds must be derived for areas that are covered by two or three successive orbits (Figure 1). The gray area is the overlap between three orbits.

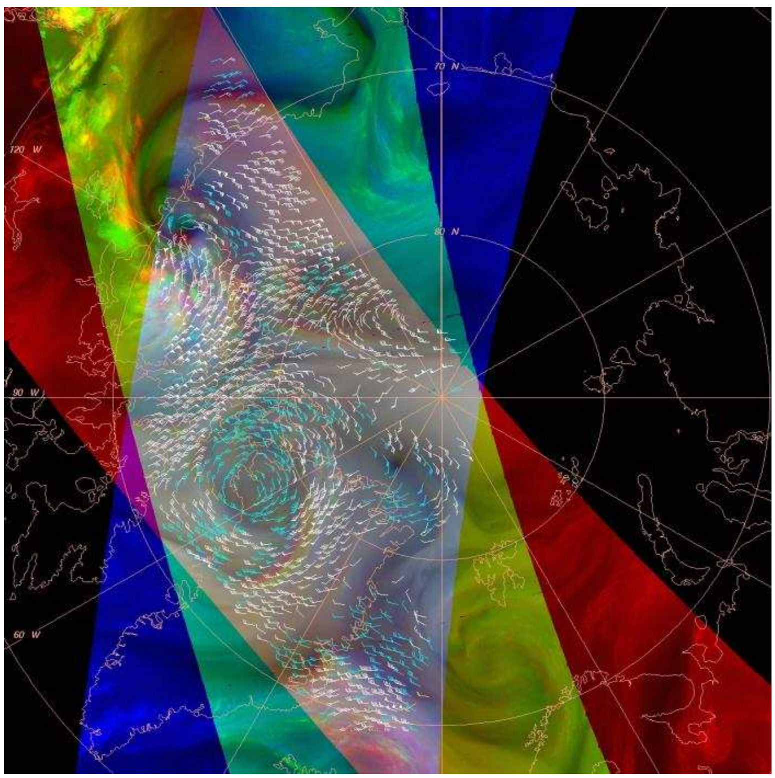

***Figure 1*: Coverage from three successive Arctic passes, 100 minutes apart, are depicted as red, green, and blue. The gray area is the region where the three passes overlap and winds are derived (shown as wind barbs).**

Cloud and water vapor features are tracked from successive triplets of Terra and Aqua MODIS passes over the polar regions. Because the overlap region of the successive passes is small, it takes an entire day to get complete polar coverage from a single satellite.

MODEL IMPACT

The satellite-derived winds from MODIS have been input to many global numerical models for several years. Positive impact in the forecasts has been reported from these NWP centers (Key et al. 2003). The typical method used to determine the quality of a forecast is the calculation of the anomaly correlation. The anomaly correlation is defined as the correlation between the predicted and analyzed anomalies of the variables. These anomalies are deviations from the mean climatological values (Krishnamurti et al. 2003). Figure 2 is an example how the MODIS winds impact the 60-hour northern hemisphere forecast, evaluated using the ACC, for a one-month time period in 2003. Generally, the impact is neutral, except for the two cases when there is a very poor forecast in the control, the model run with the MODIS winds improved those forecasts significantly.

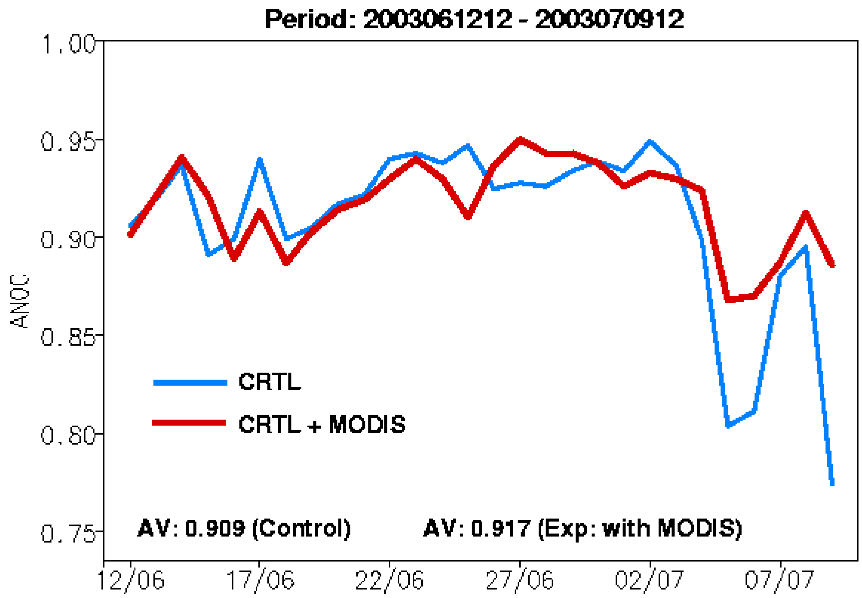

***Figure 2*: 60-hour ACC for the northern hemisphere 500 hPa geopotential heights from the Deutscher Wetterdienst (DWD) global model. Time period is from 12 June to 9 July 2003 (from Cress 2004).**

EVALUATING THE EFFECT OF POLAR WINDS ON LOWER LATITUDE FLOW

Using the operational version of the NCEP's Global Data Assimilation System (GDAS) and the pre-operational model Global Forecast System (GFS), a side-by-side experiment was run for a six-week period from 10 August to 18 September 2004, with and without the MODIS polar winds. This model has a resolution of T254 with 64 layers (Jung et al. 2007). T254 corresponds to a horizontal grid point spacing of approximately 0.5 degrees. Cases were chosen well into the experiment so that any 'data shock' adjustments are not an issue in interpreting the differences in the model runs.

Two areas were investigated as candidate mechanisms that propagate information near the poles to lower latitudes: Data assimilation and dynamics near the jet stream.

Data assimilation

The effect of the MODIS winds on the GFS analyses may be due, in part, to factors inherent in the assimilation system (GDAS) such as, a dynamic bias correction for the satellite radiances and spectral assimilation. These two factors are discussed, although it is not known how large the effects are.

A bias correction is a statistical technique to account for systematic errors in the observations, which is important since the assimilation system assumes only random errors are present. A dynamic bias correction for satellite radiances is built into the GDAS, which is unlike other observations (such as, rawinsondes) where the bias correction is applied outside the assimilation. This correction accounts for the combined biases in the radiative forward model, instrument, number of vertical levels, airmass, etc. which can not be determined independently. However, this dynamic bias correction may result in changes to the analysis in regions far away from the observed radiance data or from the inclusion of other types of data. The addition of the MODIS winds may affect the radiance bias correction as when satellite winds are added, an adjustment takes place in the height field (conservation of momentum), which in turns affects the temperature field (thermal wind balance constraint), which alters the radiance bias correction, which propagates globally. Therefore, adding MODIS winds has a direct effect on the satellite radiance bias correction.

The Spectral Statistical Interpolation (SSI) used in the GDAS has two characteristics that may make it difficult to interpret how the addition of data affects the forecast (Parrish and Derber, 1992):

1. All the data are interpolated globally. The weighting is less for observations farther from the grid point, but it is evident in poorly observed regions.
2. The analyses are initialized as an independent step resulting in adjustments away from the data. This initialization is necessary to correct for any imbalance in the mass and temperature fields that could result in amplifying gravity waves.

These result in changes in regions away from the observed data, which will undoubtedly affect the forecasts. These can spread throughout the entire domain very quickly; faster than atmospheric dynamics can explain.

Dynamics near the jet stream

The MODIS are winds are derived in an area generally poleward of the polar jet streams, where conventional weather observations are relatively scarce. Tracking cloud and water vapor features provides predominantly upper-troposphere wind information that is a measure of the true winds (including the ageostrophic component). This is unlike satellite sounder winds which are in thermal, geostrophic balance.

When the MODIS winds are assimilated, a mass adjustment takes place which results in changes in the height and wind field in the model atmosphere. This results in changes to the geostrophic and ageostrophic wind. An interesting relationship can be derived that relates the divergence of the ageostrophic wind to vorticity advection, shown in Equation 1 (Martin 2006).

$$\nabla \bullet \vec{V}_a = -\frac{1}{f_0}\vec{V}_g \bullet \nabla \zeta_g \qquad (1)$$

According to quasi-geostrophic theory, “advection of relative vorticity tends to move the vorticity pattern and hence the troughs and ridges” downstream (Holton 1992), therefore a change in the ageostrophic wind will affect the speed of the baroclinic waves.

Differences in the divergence of the ageostrophic wind at 500 hPa between the MODIS winds and control model runs were computed. The largest differences in the analyses occurred in the jet stream region. In subsequent forecasts, it was observed in several cases that the speed of the jet stream waves was altered. An example is presented in the next section.

Wave propagation speed

The phase shift of the 500 hPa waves for the 120-hour forecast between the MODIS winds and control is measured at 50°N and 35°N. This is done by extracting the 500 hPa heights at the latitude band and fitting a 2nd order polynomial to the correlation coefficient evaluated with differing lag distances between the two curves. Figure 3, an example at 35°N, shows the wave shift between the two models changes sign along the latitude band. Sometimes the MODIS winds slow the waves (longitude 320 to 340) or increase the wave speed (longitude 250 to 280).

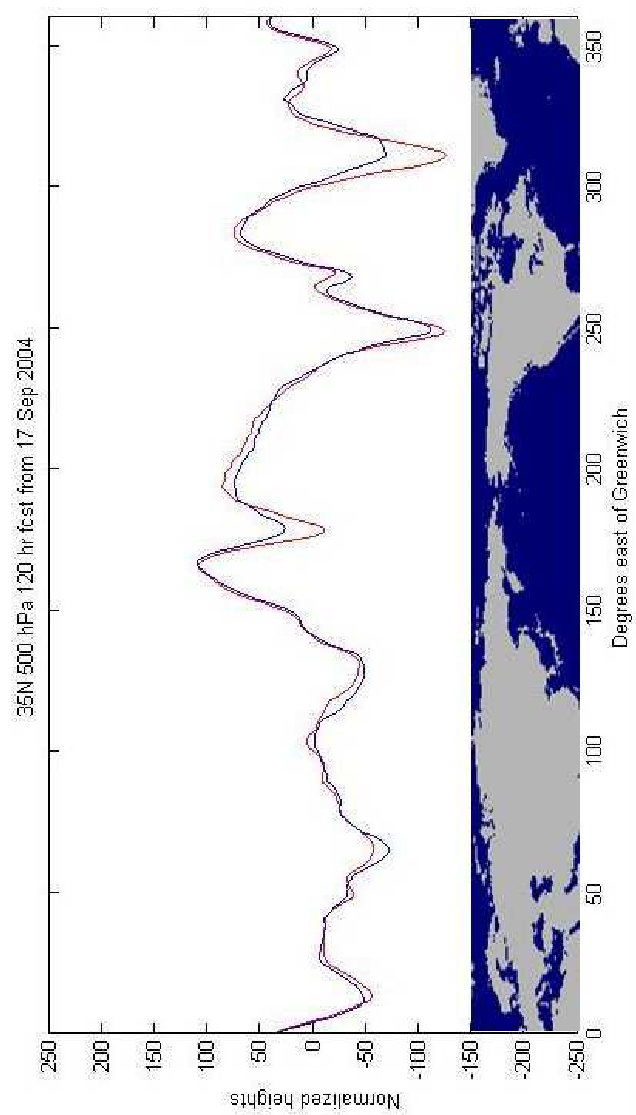

***Figure 3*: Latitude slice at 35°N of 500 hPa heights for the 120 hour forecast from 17 September 2004 for the control (blue) and the MODIS winds (red).**

The average shift for this case is 85 km westward, which means the addition of the MODIS winds slowed the eastward propagation of the waves in the 120-hour forecast. The largest the shift for this time and latitude is 200 km for the wave south of Greenland over the mid-Atlantic.

Tropical cyclone forecast impact

The addition of satellite-derived geostationary data improves the forecast tracks of tropical cyclones (Velden et al. 1998). These are cases where the satellite data is in the tropical regions. Surprisingly, the MODIS winds also have a positive impact on hurricane track forecasts, specifically for the 2004 season (Jung et al. 2007).

NCEP's tropical cyclone track verification was done for the two model runs: with and without the MODIS winds for the 2004 hurricane season. The addition of the MODIS winds resulted in an average improvement of 50 nmi in the forecast track of tropical cyclones. Moreover, this better forecast occurred 70% of the time, which indicates that this was an overall improvement and not the result of large track differences in a few isolated cases. The impact of the MODIS winds is insignificant in the early forecast times, with the best impact in the five-day forecast which suggests that time is needed for information propagation. These statistics are based on tropical (or subtropical) cyclones that were present at both the forecast time and verification time. The verification stops at the last time the system was either a tropical depression or a subtropical depression. This means these statistics cover the cyclones that have moved into mid-latitudes but are still tropical in nature (Santek 2007).

The example shown in Figure 4 depicts a trough that affected the forecast position of Hurricane Karl. Karl remained in the mid-Atlantic Ocean throughout its lifetime, moving generally northwestward for several days "until 22 September when it turned northeastward in response to a deep-layer baroclinic trough developing north of the hurricane." (Beven 2004) The model containing the MODIS winds held back the advancement of this trough which permitted the forecast position of Karl to track farther west than the control. This resulted in an improved forecast track for Hurricane Karl in the 96-hour forecast, although it was still too far east (MODIS: 19.3°N 45.4°W; Control: 18.7°N 43.0°W) instead of at 18.7°N 47.0°W. This is an error of 184 km and 424 km, respectively. This agrees with the 200 km shift in the wave at 35°N shown in Figure 3.

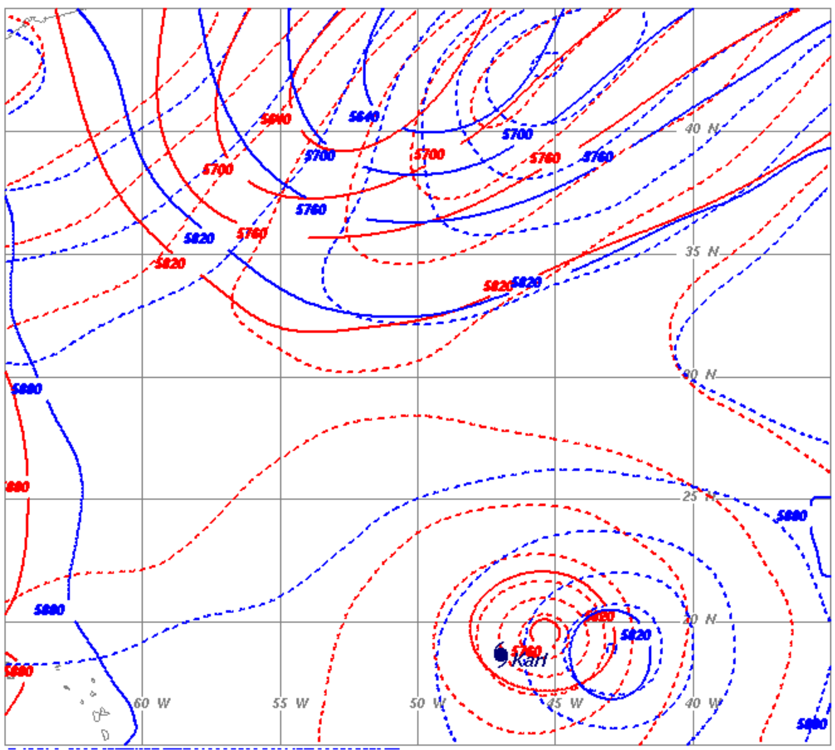

***Figure 4*: Hurricane Karl over the Atlantic Ocean in the 96-hour forecast from 0000 GMT 17 September 2004. Solid red contours are the 500 hPa heights with MODIS winds; dashed red are 1000 hPa heights. Solid blue are 500 hPa heights of the control; dashed blue are 1000 hPa heights. Actual position at the forecast time of hurricane Karl is shown with the hurricane symbol.**

SUMMARY

This example shows that the addition of polar winds may affect the dynamics of the waves near the jet stream, resulting in slowing the overall wave propagation. This effect is then evident in later forecast times extending to lower latitudes, resulting in modifying hurricane tracks that are steered by mid-latitude flow.

This may be the first case of assimilating high resolution data that is only available in the polar regions and highlights the importance of polar observations for improving global forecasts.

REFERENCES

Beven, J., 2004. Tropical Cyclone Report: Hurricane Karl. Retrieved 27 April 2007 from http://www.nhc.noaa.gov/2004karl.shtml.

Cress, A., 2004. Impact of MODIS winds on the global NWP system of the German weather Service. Proc. Of the Seventh Int. Winds Workshop, Helsinki, Finland, WMO (Available online at www.eumetsat.int/).

Francis, J. A., 2002. Validation of reanalysis upper-level winds in the Arctic with independent rawinsonde data. Geophys. Res. Lett., 29, No. 9.

Gallimore, R. and D. Johnson, 1981. The forcing of the meridional circulation of the isentropic zonally averaged circumpolar vortex. J. Atmos. Sci., 38, 583-599.

Holton, J. R., 1992. An introduction to dynamic meteorology. Academic Press, San Diego.

Jung, James A., T. Zapotocny, R. Treadon, and J. LeMarshall, 2007. A two season impact study of satellite and in-situ data in the NCEP Global Data Assimilation System. Weather and Forecasting, Accepted.

Key, J. R., D. Santek, C. S. Velden, N. Bormann, J.-N.l Thépaut, 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, 482-492.

Krishnamurti, T. N., K. Rajendran, T.S.V. V. Kumar, S. Lord, Z. Thoth, X. Zou, S. Cocke, J. Ahlquist, I.M. Navon, 2003. Improved skill for the anomaly correlation of geopotential heights at 500 hPa. Mon. Wea. Rev., 131, 1082-1102.

Martin, J.E., 2006. Mid-latitude atmospheric dynamics: a first course. Wiley, Hoboken.

Parrish, D. and J. Derber, 1992. The National Meteorological Center's spectral statistical interpolation analysis system. Mon. Wea. Rev., 120, 1747-1763.

Pyle, M., D. Keyser, L. Bosart, 2004. A diagnostic study of jet streaks: kinematic signatures and relationship to coherent tropopause disturbances. Mon. Wea. Rev., 132, 297-319.

Santek, D., 2007: The global impact of satellite-derived polar winds on model forecasts. Ph. D. dissertation. University of Wisconsin-Madison. 147 pp.

Velden, C., T. Olander, and S. Wanzong, 1998. The impact of multispectral GOES-8 wind information on Atlantic tropical cyclone track forecasts in 1995. Part I: Dataset methodology, description, and case analysis. Mon. Wea. Rev., 126, 1202-1218.