THE IMPACT ON FORECAST SKILL OF WATER VAPOR AND WINDOW CHANNEL WINDS FROM MODIS

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Abstract

The feature-tracking winds from NASA's MODIS instruments have been successfully implemented in operational data assimilation systems at a number of different forecast centers worldwide. This has led to a community-wide push for access to timely high-latitude satellite winds for those regions that are not covered by the geostationary satellites. Currently, wind measurements are derived from two MODIS channels, the 6.7 micron water vapor channel and the 11 micron window channel. An important open question with direct implications for future space programs is the respective contribution to skill that can be attributed to each of these two channels. Another important question is the potential impact on forecast skill of obtaining polar winds in time for the operational cut-off of the main forecast runs at the operational centers, something which is not possible under the current MODIS scenario. A series of assimilation and forecast experiments designed to shed light on these issues has been carried out with a preoperational version of GEOS-5, the next-generation global data assimilation system developed by the Global Modeling and Assimilation Office at the Goddard Space Flight Center.

INTRODUCTION

Polar winds from MODIS are now used operationally for numerical weather prediction by a growing number of meteorological services. The successful assimilation of these data has led to a concerted effort toward ensuring continued access to feature-tracking winds from the high-latitude regions once NASA's two MODIS missions will have come to an end. This can be accomplished either via one or more dedicated missions or via implementing a set of changes to some of the satellite systems already under development. In order to identify the best way of proceeding, a number of open issues related to the required capabilities of a polar winds producing system will have to be addressed. Two of the most important questions are addressed here, namely the channel configuration and the timeliness requirement on the winds.

Channel selection

Polar winds from MODIS are currently processed using imagery from two different channels, the 11 micron window channel and the 6.7 micron water vapor channel. The 11 micron channel is used for tracking cloud features, whereas the 6.7 micron channel is used for tracking both cloud structures and features in the clear-sky water vapor field. Since the water vapor winds are processed for both cloudy and clear portions of the images, these winds constitute the majority of the total wind vectors processed, and their horizontal distribution is more homogeneous than that of the 11 micron winds. Initial tests from a number of forecast centers have indicated that a substantial portion of the total skill can be attributed to the 6.7 micron winds. This is an important point for two reasons. First, even though water vapor channel winds have been generated from GOES and METEOSAT imagery for a number of years, these winds have typically been

considered of inferior quality compared to the cloud track winds and have been shown to have a negligible impact on forecast skill. It is therefore of scientific interest to establish why and how the MODIS winds are different in this respect. Second, neither of the currently planned primary imagers for the future operational polar systems – AVHRR/3 for the European METOP satellite series, and VIIRS for the US NPOESS program – will include a water vapor channel. A strongly supported user requirement for such a channel will therefore have important ramifications for future mission planning.

Timeliness

At the present time (May 2006) NASA maintains two MODIS sensors in orbit on the Terra and Aqua research platforms respectively. The winds processing algorithms rely on image triplets, and currently only single-satellite winds are generated. The orbital period of Terra and Aqua are both of the order of 100 minutes, so the total data acquisition period for a given set of winds is therefore upward of 200 minutes (two full orbits plus the additional time required to complete the third image of the scene). The nominal observation time for a given wind vector is set to the nominal time of the central of the three images on which the retrieval of that wind is based. This means that the spacecraft will not complete the image acquisition until nearly two hours after the nominal observation time. Once the data has been downlinked, processed and disseminated to the users, the MODIS wind observations are typically between 3 and 5 hours old.

The data cut-off for the global operational forecast runs of the main meteorological services is generally shorter than that – e.g. at NOAA's National Centers for Environmental Prediction (NCEP) the cut-off for the main global forecast run is 2h 45min. Similar to operational practice in most other main forecast centers, NCEP maintains a data assimilation stream with a longer cut-off in order to accommodate late arriving observational data. However, data that do not meet the cut-off criterion do not directly influence the initial conditions for the forecast model. Their influence is indirect, via their contribution to a better background state for the analysis that generates the model initial conditions

Because of this timeliness issue, it is of interest to establish how much – if any - additional skill the MODIS winds could have contributed to the forecasts, had they been available in time for the forecast run. This may help substantiate the timeliness requirement for future systems aiming to provide high-latitude wind observations. For reference, the currently recommended WMO requirement concerning the timeliness of polar winds is "60 minutes or better".

DATA ASSIMILATION SYSTEM AND EXPERIMENTAL DESIGN

The data assimilation system used for the experiments discussed here is a test version of the next-generation GEOS-5 system developed in the Global Modeling and Assimilation Office.   The forecast model is based on the dynamical core of Lin and Rood, also used in currently operational GEOS-4 system, but in the new system coupled with a newly developed physics package. The analysis algorithm is the so-called Grid-point Statistical Interpolation method (GSI), developed jointly by NCEP and GMAO. It is a 3D-VAR like algorithm, but in contrast to several other such methods, the analysis variable is here formulated in the physical space of the model.

In order to obtain a representative set of samples of different meteorological situations, two sets of experiments were performed. The first set extended over the months of August and September of 2004, and a five-day forecast was issued every other day at 12 Z. The second set covered the months of January and February 2005, with five-day forecasts issued every other day at 00 Z. For both sets of experiments, the statistics are therefore based on 30 semi-independent individual forecasts. In order to test the robustness of the results, two independent verifications were used for each experiment: verification against analyses from the experiment itself, and verification against the corresponding analysis from the operational NCEP run. The results were generally in good agreement, and only results from the NCEP verification are shown here.

In all MODIS experiments, the BUFR winds routinely produced by NESDIS were used. No thinning was performed on the data, and a relatively coarse screening procedure was implemented: No winds were admitted at pressure elevation higher than 50 hPa above the background tropopause level, and no winds were admitted over land within 200 hPa above the background surface pressure. A simple online quality control procedure was used to eliminate all winds for which the magnitude of the vector observation-minus-forecast residual exceeded 7 m/s. No filtering based on Recursive Filter Flag (RFF) or Quality Indicator (QI) values was implemented.

For each of the two experimental periods, the following set of experiments was carried out:

1. A control experiment in which no MODIS winds were assimilated. A full complement of operational observations was used, including surface pressure observations, radiosonde winds and temperatures, scatterometer surface winds, geostationary satellite winds, aircraft winds, infrared and microwave satellite radiances and SBUV ozone retrievals
2. Control + MODIS IR winds
3. Control + MODIS water vapor winds
4. Control + all MODIS winds
5. Control + all MODIS winds, except for the initial conditions for the forecast that were generated as for exp 1.

In experiments 2 through 4, all MODIS winds were assimilated as if they had been available within the operational data cut-off, i.e. all the observations valid for a given analysis time were assimilated irrespective of their actual arrival time. In order to explore the issue of timeliness, experiment 5 was designed to include the MODIS winds in the background assimilation, but added a separate analysis that excluded these observations to generate the initial conditions for the forecast. This was intended to mimic as closely as possible the situation in operations where the MODIS winds can be included only in the background run as explained above.

EXPERIMENTAL RESULTS

All experiments were evaluated using anomaly correlation coefficients and RMS errors. Only a few samples are shown here, and it is important to point out that the results are obtained with a development version of a new system and that they may therefore not be representative of the scores of the final version.
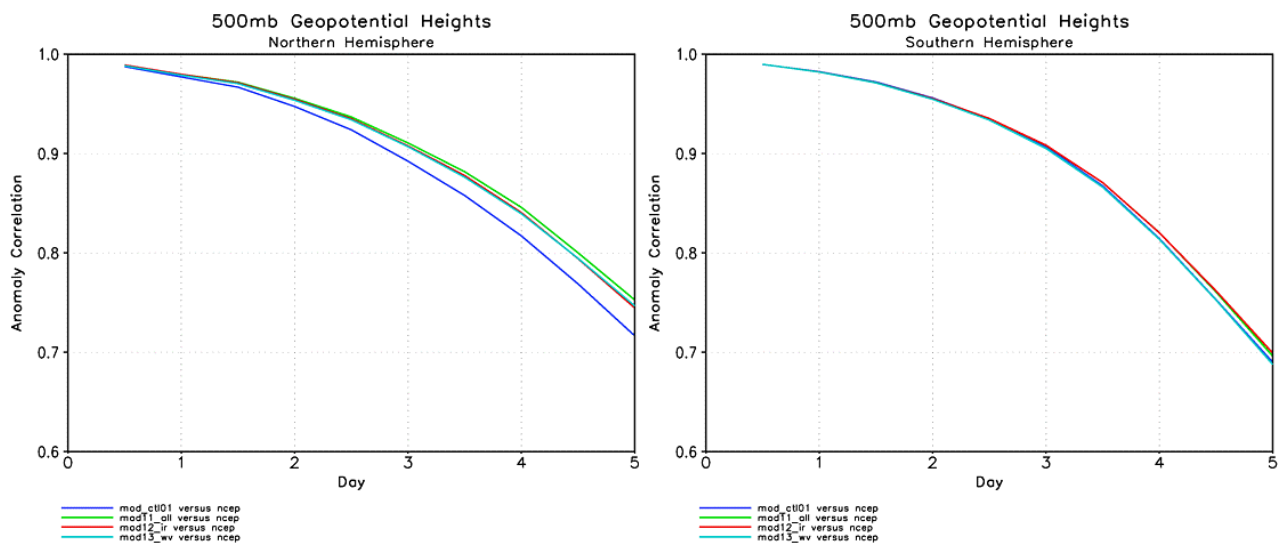

Fig. 1. 500 hPa anomaly correlation coefficients as a function of time for the summer 2004 experiment, Northern hemisphere (20 to 80 deg lat, left panel), and for the Southern hemisphere (right panel). Control (no MODIS winds) in blue, Control + MODIS WV winds in aqua, Control + MODIS IR winds in red, Control + all MODIS winds in green.

In Figure 1, anomaly correlation correlation coefficients for the 500 hPa height field in the Nothern and Southern hemispheres are shown for the summer 2004 run. Figure 2 shows similar curves for the winter 2005 run. The figures show a large impact of the MODIS winds in the Northern Hemisphere in general and for the summer 2004 period in particular.
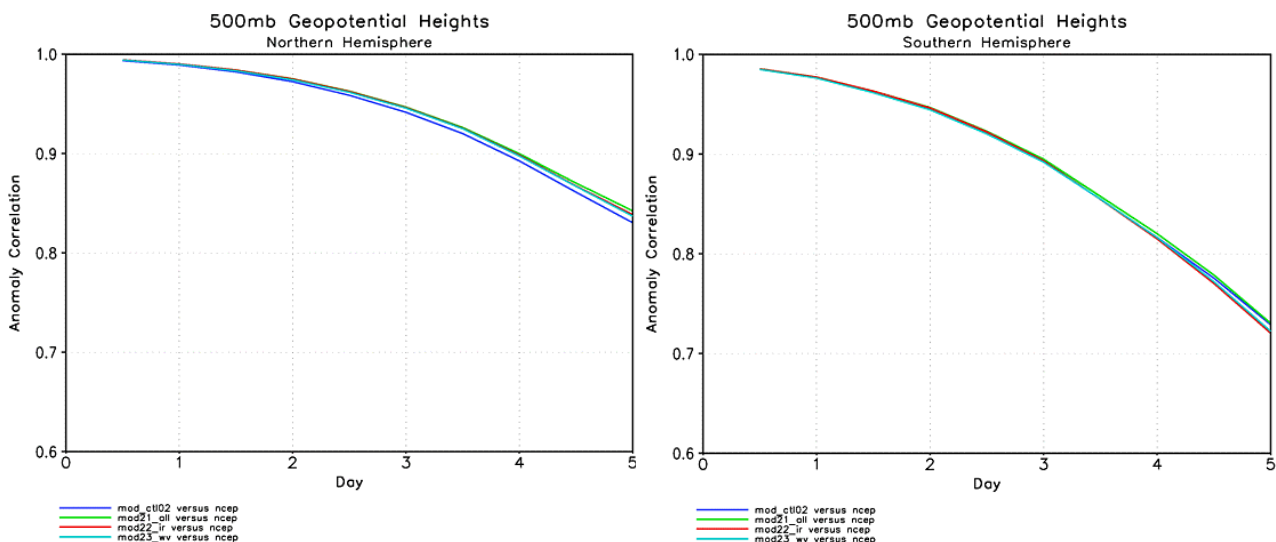
Fig. 2 Anomaly correlation coefficients as in Figure 1, but for the winter 2005 experiments

The impact of the MODIS winds is neutral to positive for both periods and in both hemispheres, but it is somewhat surprising to see that the impact is so much larger in the Northern hemisphere. The impact tends to be generally larger in the summer period where the overall skill is generally at a lower level. In the light of previous experience with the MODIS winds, this result is not unexpected, but the large difference in skill between the winter and summer run is a concern and our results should therefore be used with caution.

Concerning the relative ranking of the importance of the IR vs. water vapor winds, the experiments are somewhat inconclusive. In Figure 1 (left panel), it is seen that adding the infrared MODIS winds to the system leads to a substantial improvement in skill. Adding instead the water vapor winds leads to a very slight further improvement, whereas including both types of MODIS winds in the assimilation leads to skills that are clearly above what either one type of winds can accomplish alone.
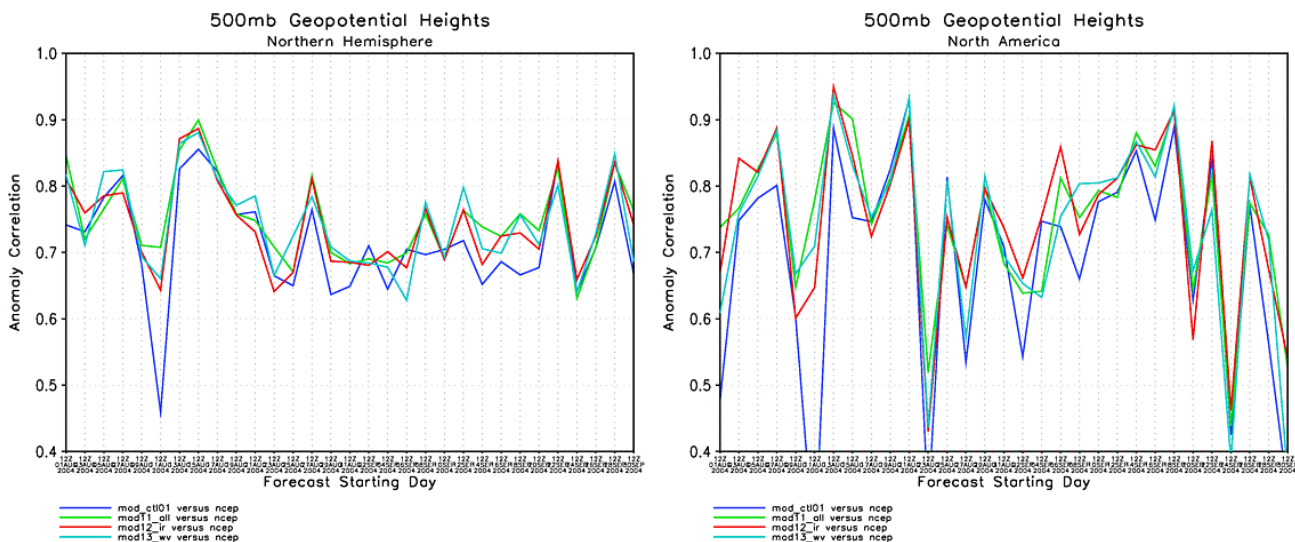

Figure 3. Day-5 anomaly correlation coefficients, summer 2004, NH (left), North America (right).

Figure ... which ... the ... of the anomaly correlation coefficients ... Day-5 forecast range - illustra ... ... 2), while t ... of the MODIS experiments, and the MODIS contribution to skill thus seems to be fairly robust. Much of the time, the water vapor experiment shows better skill than the IR experiment, but in a couple of high-skill cases this picture is reversed. A very substantial "bust" occurred in the control run for the forecast launched at 00 Z on August 11 (forecast initial time). This bust was largely absent in the experiments including the MODIS

winds. The water vapor experiment is marginally better than its IR counterpart, and the experiment in which both types of winds were used clearly outperforms them both. The 5-day skill over North America (right panel) exhibits an even larger day-to-day variability due to the smaller verification region. Also the relative ranking of the three MODIS winds experiments is highly variable on these spatial scales. At times the water vapor experiment has the best skill, at times the IR wind is better, and at other times the experiment using all of the MODIS winds shows the best performance. The August 11 bust is even more pronounced here, and the relative impact of the water vapor winds toward mitigating the bust is larger.

The evolution of the August 11 case is typical of the way in which the MODIS winds tend to correct many of the forecast busts that might otherwise have occurred over North America. In figure 4, the 500 hPa height field over North America in the control analysis at the initial time of the forecast run is shown. It is easy to imagine why this particular flow configuration – a ridge over the western part of the continent and a trough over the east – might render the subsequent forecast vulnerable to a lack of information in the upper left area of the plot, since this is where the flow will be coming from over much of the subsequent forecast period.

This point can be illustrated by the temporal evolution of the forecast error. Figure 5 shows the forecast errors (verifying analysis minus forecast) from experiments 1 through 4 at 12 hours (first write-out), while figure 6 shows the forecast error at 120 hours (end of the forecast run). The color scale is identical for the two plots, and all errors are calculated with respect to the NCEP verifying analyses.
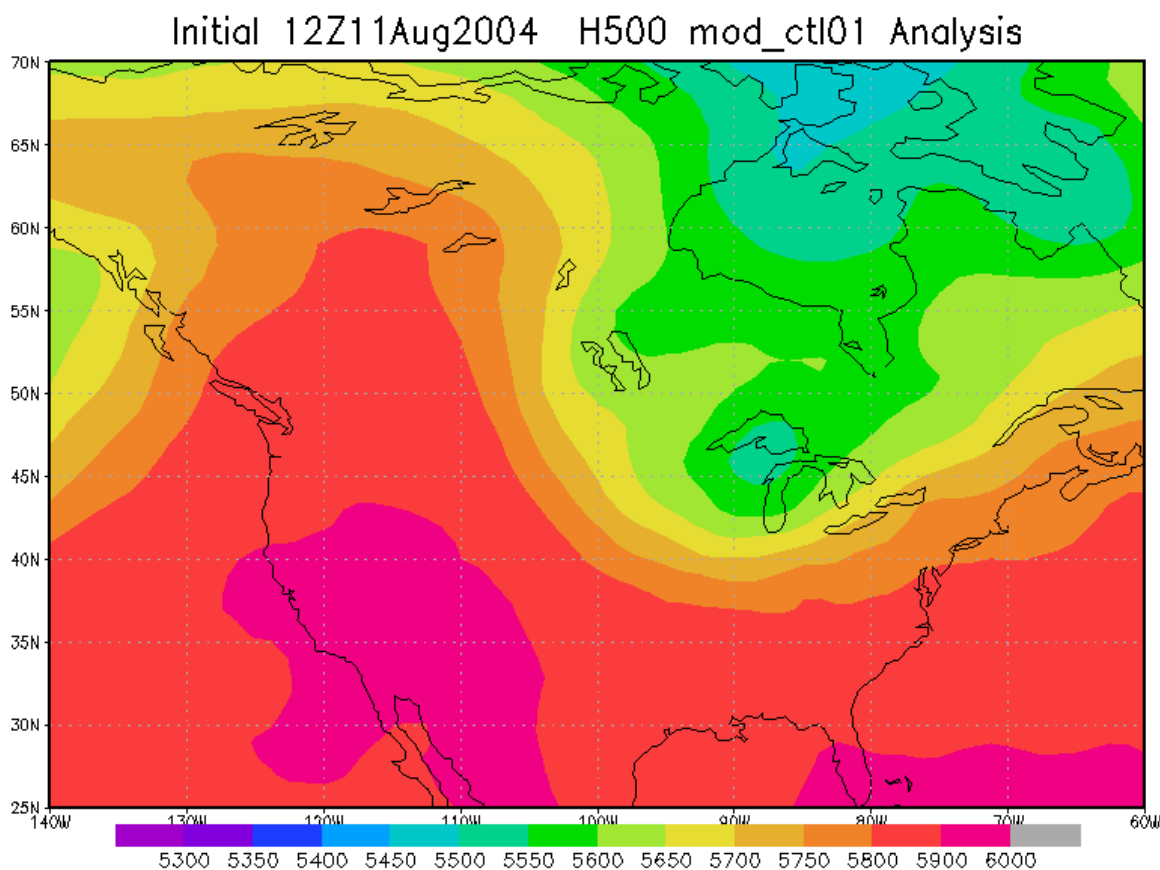

Fig. 4. Control analysis, 500 hPa heights over North America, Aug 11, 2004, 12 Z
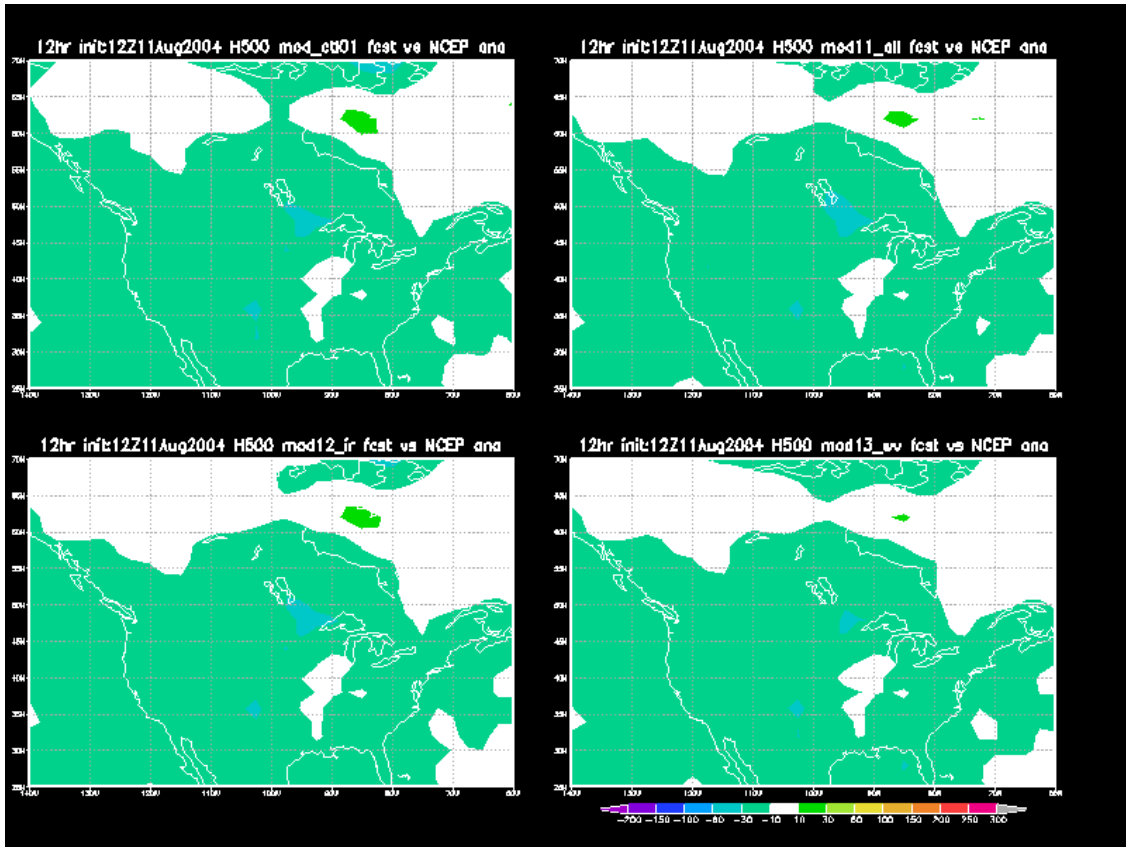
Figure 5. Forecast errors (verification minus forecast) for experiments 1 through 4 at the 12 hour range. Control (upper left), Control + all MODIS (upper right), Control + MODIS IR (lower left), Control + MODIS water vapor (lower right.
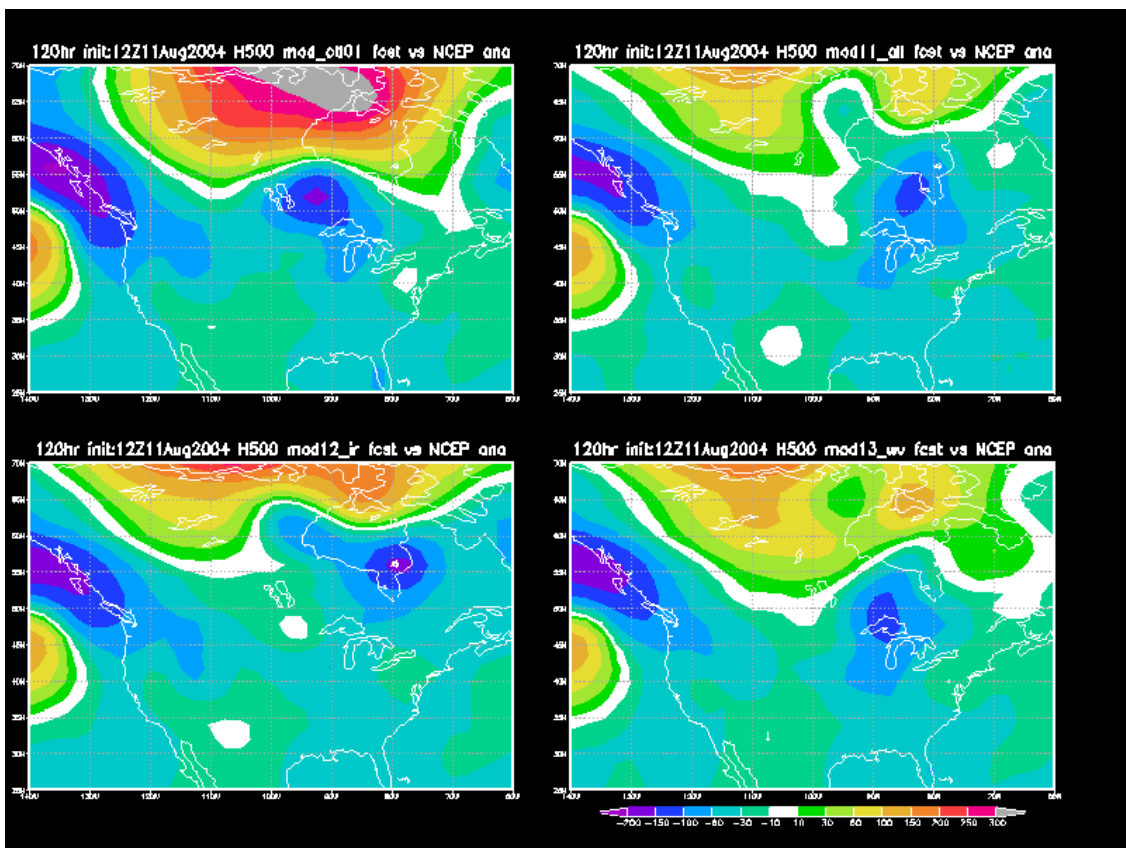

Figure 6. Forecast errors as in figure 5, but at a forecast range of 120 hours.

At the beginning of the forecast range, the error structure and magnitude are both very similar between the different experiments. Close inspection reveals slightly larger errors in the control run, but the differences are mostly minute. However, toward the end of the forecast range, the differences have become dramatic. As one would expect, the all MODIS winds experiment shows the smallest errors, whereas the control experiment exhibits the largest error overall. The difference is most pronounced over the Arctic region, but note that there is a marked improvement in the error (Fig. 6 top left vs. top right) all the way down to the edge of the region plotted here (at 26 deg N). This is consistent with the improvement in hurricane track forecasting attributed to the MODIS winds in experiments using the NCEP operational data assimilation system by J. LeMarshall et al. (personal communication).

In addition to the plausibility argument given above, the recent development of the adjoint of the GEOS-5 model with simplified physics can be used to provide a more rigorous demonstration of low-latitude sensitivity to high-latitude observations. In figure 7, the sensitivity to the 48-hour forecast error in the Northern Hemisphere is plotted as diagnosed by the model adjoint. The cost function to which the sensitivity is calculated is a vertically integrated measure of the magnitude of the 48-hour forecast error, and the plot shows the vertically integrated sensitivity to this measure at the initial time – in other words the colored areas are those in which a given change of initial conditions would have had the largest impact on the forecast error. The most striking feature of the plot is found over a well-defined region from stretching from Alaska across the Bering Strait down toward Japan. For the particular case shown here, almost half of the visible sensitivity structure for the hemispheric forecast error is located of 60 deg N, which is also where the MODIS wind observations are found.
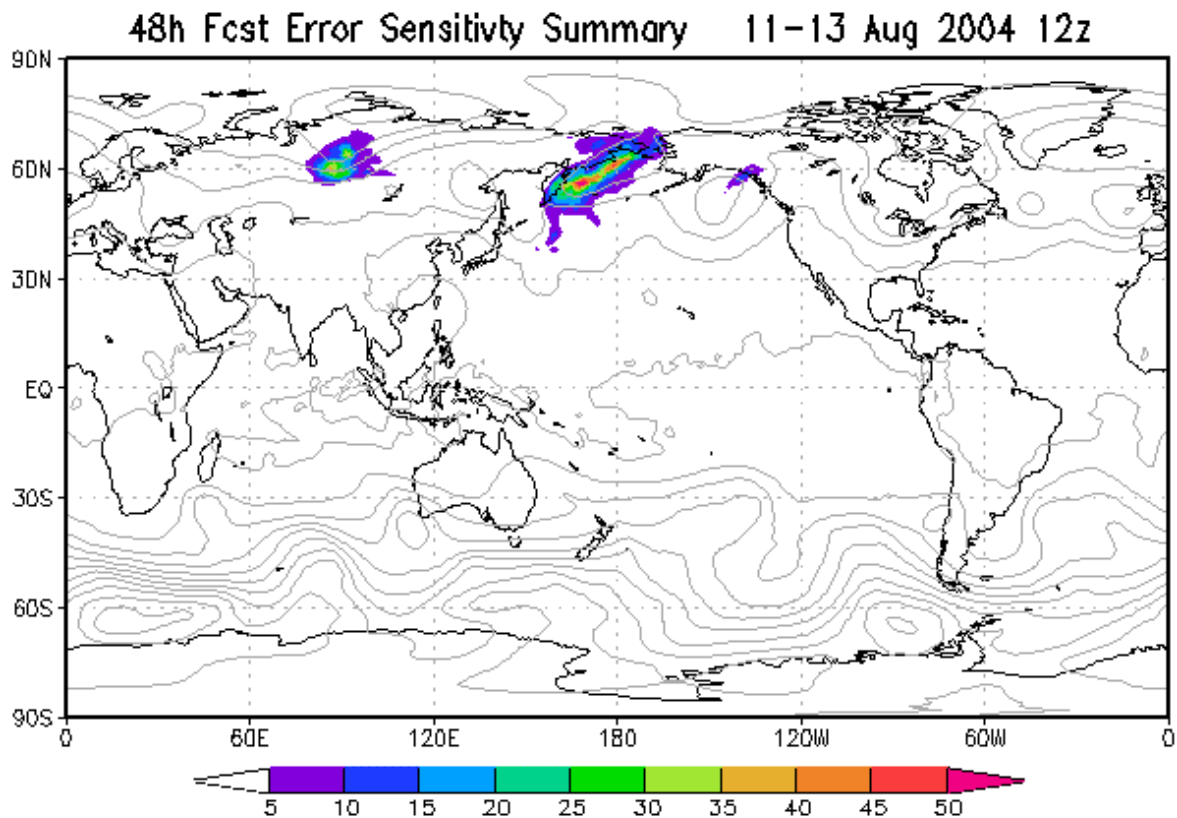

Figure 7. Vertical integral of initial condition sensitivity to a vertically integrated measure of the 48-h forecast error for the northern hemisphere (*plot courtesy of Ron Gelaro, GMAO).*

The link between the sensitivity structure shown in Figure 7 and the error evolution shown in Figs 5 and 6 and the times in between (not shown) makes for a visually compelling argument for the importance of the high-latitude wind measurements such as those provided by MODIS. However, it is important to point out that the plot in Figure 7 represents a vertically integrated measure of sensitivity across all variables and it is

therefore conceivable that observations of some other quantity - or observations of the wind at a different set of levels than those obtained here – might be even more successful than the MODIS winds in reducing the forecast error.

Further experimentation is planned with using the adjoint of both the GEOS-5 model an the GSI analysis algorithm in order to explore the relative sensitivity to wind vs. other types of observations over high-latitude regions as well as identifying the vertical distribution of the sensitivity.

SUMMARY AND CONCLUSION

We have tested the impact of the MODIS winds in a test version of the GEOS-5 assimilation system soon to be implemented in the GMAO. The impact is neutral to positive in all regions and for both periods studied. The largest impact is found in the summer 2004 period in the northern hemisphere. In the mid-latitudes, the main contribution of the MODIS wind observations is to reduce the severity of the forecast busts. The impact of the water vapor winds and the IR winds was tested separately. At times the IR winds contribute most to the added skill, at other times the water vapor winds seem to be more important. On average, the impacts are similar in magnitude. An important point is that the impact is substantially larger on average when both types of winds are included. The potential impact of having real-time access to these observations was also tested. As expected, a tangible positive contribution to skill was found.

ACKNOWLEDGEMENTS: