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Impact of MODIS Polar Winds in ECMWF's 4DVAR Data Assimilation System

Niels Bormann and
Jean-Noël Thépaut

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European Centre for Medium Range Weather Forecasts
Shinfield Park, Reading, Berkshire RG2 9AX, England

Abstract

This report characterises the impact of a new satellite derived wind product over the polar regions on ECMWF’s global 4-dimensional variational assimilation system. The winds are derived at the University of Wisconsin (Madison) by tracking structures in successive swaths from the polar-orbiting Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra satellite. The new wind product provides unprecedented coverage of the polar wind field. The data are assimilated subject to cautious quality control at lower levels and over land.

The MODIS winds have a positive impact on medium-range global weather forecasts, particularly over the polar regions, but also elsewhere over the Northern Hemisphere. The mean polar wind analysis can be considerably altered as a result of the MODIS winds assimilation. Sensitivity calculations highlight the importance of polar regions for forecasts in the midlatitudes and indicate how MODIS winds can reduce key analysis errors in this region. The MODIS winds are now assimilated operationally at ECMWF.

1 Introduction

Polar wind analyses for numerical weather prediction have long been hampered by a lack of wind observations in polar regions (e.g., Fig. 1). Radiosonde, pilot balloons or profiler data do not cover the Arctic Ocean, aircraft reports rarely reach latitudes north of 70N or south of 60S, and Atmospheric Motion Vectors (AMVs) derived from geostationary satellite data are not available north of 60N or south of 60S. Infrared or microwave radiances from polar-orbiting satellites provide some indirect information on the polar wind field, but they remain difficult to use in polar regions because of poor discrimination between clouds and ice or poor representation of the surface emissivity. It is thus not surprising that independent rawinsonde data from Arctic field experiments, for instance, indicate biases in the polar wind fields of reanalyses from the National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) or ECMWF (e.g., Francis 2002).

Recently, a new satellite-derived wind product has become available which is capable of providing unprecedented coverage of the polar wind fields (e.g., Key et al. 2003, hereinafter KEY). These winds are derived by tracking structures in three successive 100-min swaths from the Moderate Resolution Imaging Spectrora-

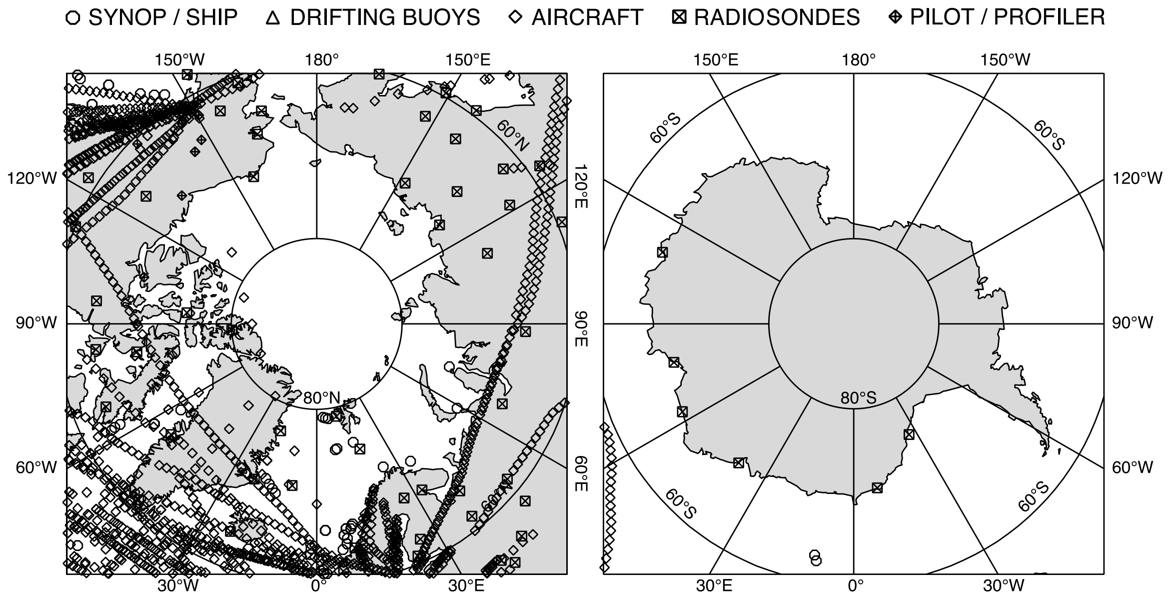

Figure 1: Example of the locations of conventional polar wind observations used in the operational ECMWF assimilation for the 12-h period 3–15 UTC on 4 August 2002. See the legend for an explanation of the symbols.

diometer (MODIS) instrument flown on the polar-orbiting Terra and Aqua satellites. The method is based on the established procedures used to derive wind observations from image sequences from geostationary satellites (e.g., Nieman et al. 1997; Velden et al. 1997). The quality of these wind observations is similar to or slightly lower than that of AMVs from geostationary satellite data, except at lower levels where the MODIS winds appear somewhat poorer (KEY).

Initial assimilation studies at ECMWF and the National Aeronautics and Space Administration (NASA)/Data Assimilation Office (DAO) indicated substantial gains in forecast skill when these winds are assimilated within 3-dimensional variational (3DVAR) data assimilation systems (KEY, Bormann et al. 2002). Assimilation of these winds also had a notable impact on the mean polar wind analysis. In the present study we report on the first 4-dimensional variational (4DVAR) assimilation trials with the new MODIS winds over an extended period.

The structure of the report is as follows. First we give an overview of the MODIS winds and the assimilation experiments. We then provide results from our assimilation trial in terms of the analysis impact, the forecast impact, and an illustrative forecast example. Conclusions and a discussion are provided in the last section.

2 Data and experiments

The derivation of MODIS winds is described in detail in KEY. Feature tracking is possible with MODIS data in an area north of 60N and south of 60S. Cloud features are tracked in the infrared (IR) window band at 11 μm and water vapour (WV) features are tracked in the 6.7 μm band. Wind vector heights are assigned by first determining a representative temperature of the feature using either the IR or the WV-intercept method (e.g., Schmetz et al. 1993), using forecast data from the U.S. Navy Operational Global Atmospheric Prediction System (NOGAPS) model at 1.0° spatial resolution and 19 vertical levels. A test dataset of Terra-MODIS winds has been prepared by the Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the University of Wisconsin-Madison for the period 5 March – 3 April 2001. Near realtime Terra-MODIS winds are available since June 2002, and Aqua-MODIS winds are available in near realtime since December 2002. Due to a combination of occasional late availability of the raw MODIS data and the processing requirements at CIMSS, realtime MODIS winds are currently available only with a highly variable delay (5–15 h), so that only about 60 % of the winds arrive within the operational data cut-off times at ECMWF[1]. At the time of writing, the operational cut-off times for ECMWF are: 8:30 UTC for observations between 15 and 21 UTC the previous day, 9 UTC for 21-3 UTC observations, 19 UTC for 3-9 UTC observations, and 19:15 UTC for 9-15 UTC observations.

The impact experiments described herein employ ECMWF's 4DVAR data assimilation system similar to the operational configuration (Rabier et al. 2000, Klinker et al. 2000). The model resolution for these experiments is T511 ($\approx$ 40 km) with 60 levels in the vertical. 12-hourly incremental 4DVAR analyses are performed at T159 ($\approx$ 125 km). Two study periods are considered: 5 March – 3 April 2001 and 13 July – 29 August 2002. Ten day forecasts were run from each 12 UTC analysis.

Two experiments were run for each period. In the control experiment (CTL), the operational set of observations was assimilated, comprising a variety of conventional and satellite data. This included radiosonde, pilot, profiler, and aircraft data, observations from synop/ship stations and buoys, scatterometer wind estimates, AMVs from geostationary satellites, Special Sensor Microwave/Imager (SSM/I) data, and selected radiances (microwave and infrared) from two National Oceanic and Atmospheric Administration (NOAA) satellites as well as clear-sky water-vapour radiances from Meteosat-7. In the MODIS experiment, Terra-MODIS winds were assimilated in addition to the operational set of observations. Over land we used MODIS IR and WV

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[1] This situation has been improved since our experiments have been performed. Now, about 80 % of the MODIS winds arrive within the operational data cut-off times at ECMWF.

winds above 400 hPa only. Over sea, we used IR winds above 700 hPa and WV winds above 550 hPa. These restrictions for lower level winds were as in KEY, and they were chosen after earlier trial experiments indicated poorer quality of the lower level winds, most likely a result of height assignment problems over high orography and ice. All other settings for the MODIS winds were as for operational AMVs from geostationary satellites (Rohn et al. 2001): the winds were thinned to 140 km resolution, and quality control was based on an asymmetric check against the First Guess (FG; Järvinen and Undén 1997). While all winds of the offline test dataset were considered in the assimilation for the March/April 2001 period, ECMWF's operational cut-off times applied during the July/August 2002 period for which the realtime Terra-MODIS winds were used. This resulted in a loss of available data as described above.

3 4DVAR assimilation results

3.1 Analysis impact

The assimilation of the MODIS winds has a notable impact on the mean polar wind analysis. For the March/April 2001 study period the differences for the Arctic are largest over the Arctic Ocean, with differences up to 2.5–3 m/s at most levels. Here, the MODIS winds act to strengthen the cyclonic circulation (e.g., Fig. 2). The

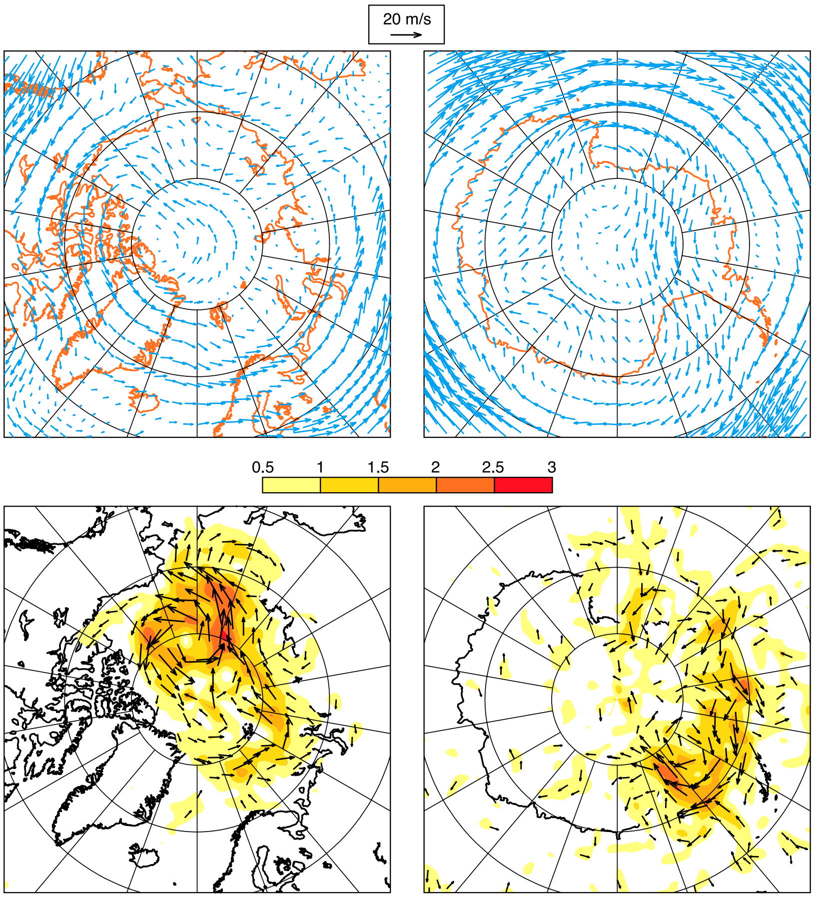

Figure 2: Mean polar wind analyses at 400 hPa for the CTL experiment for 5 March - 3 April 2001 (upper row). The difference between the mean wind analysis for the MODIS and the CTL experiment for the same period is shown in the lower panels. Shading indicates the length of the difference vector [m/s].

changes to the mean wind analysis appear to be supported by the rest of the observing network: the u-component bias between the FG and Canadian pilot reports is marginally improved in the MODIS experiment (not shown). The differences in the mean polar wind analysis also agree well with the ones reported for the 3DVAR experiments over the same study period (Bormann et al. 2002), with the peak differences shifted slightly eastward. For the July/August 2002 experiment, differences in the mean wind analyses are much smaller (less than 1.5 m/s vector difference at all levels, not shown). The reason for smaller differences may be seasonal variations in the bias pattern between the MODIS winds and the model data. Also, changes in the ECMWF model or the data usage between the two periods may have reduced the discrepancies. The variability of the analyses of the upper level geopotential tends to be slightly decreased in the MODIS experiment.

Globally, the fit of other observations against the FG or the analysis is not significantly altered when MODIS winds are assimilated (not shown). This indicates a good overall consistency between the assimilation of MODIS winds and the assimilation of other observations. Locally, we could identify some changes, most notably for the US profiler network for which the analysis fit is considerably improved and more observations

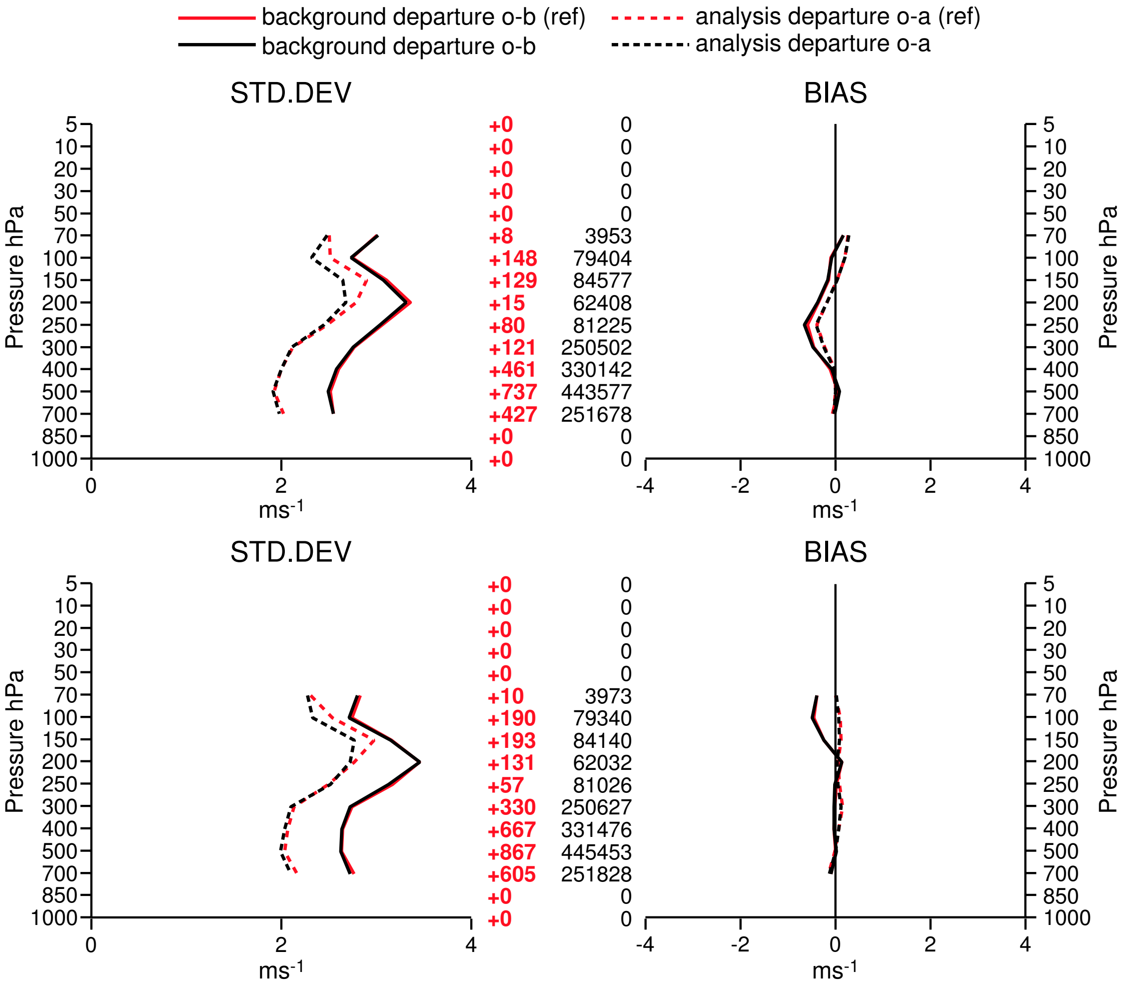

Figure 3: Statistics for the First Guess (solid) and the analysis departures (dashed) for used US profiler data for the MODIS (black) and the CTL (red) experiment. The left row shows standard deviations [m/s] versus pressure, whereas the right row shows biases [m/s] versus pressure level, with statistics for the u-component in the upper row and statistics for the v-component in the lower row. The number of winds used is also shown between the columns, with the difference MODIS-CTL given in red. Statistics for the two study periods have been pooled together.

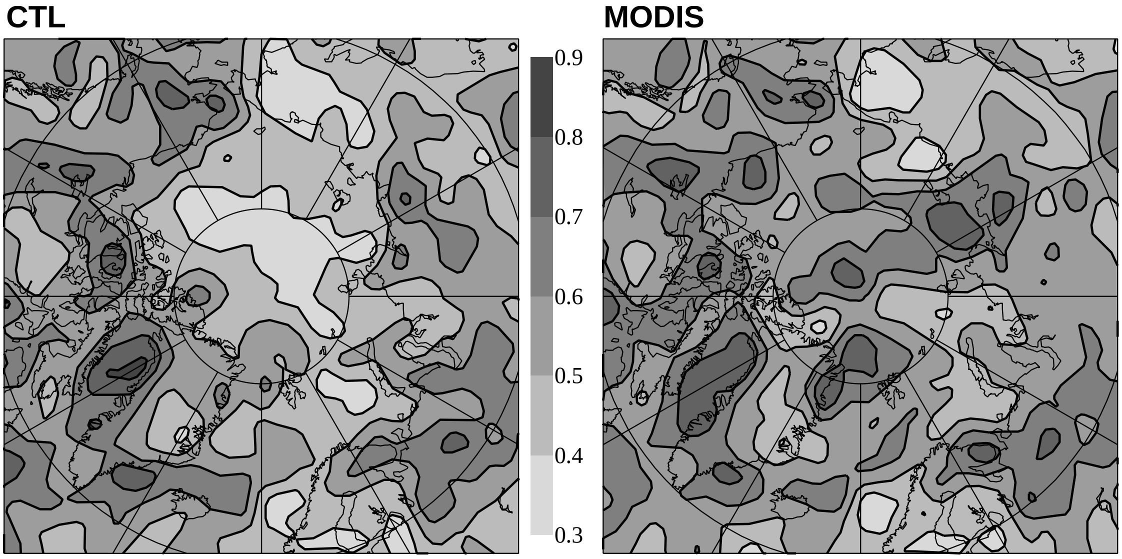

Figure 4: Root mean square of the analysis increments of the 500 hPa geopotential height [gpdm] for the CTL (left panel) and the MODIS experiment (right panel) for the July/August 2002 period.

are used in the MODIS experiment (Fig. 3). This suggests a better model wind field in this region. As MODIS winds do not cover this area, the improvement is likely due to downstream developments, possibly as a result of a better positioning of the jet stream in the MODIS winds analyses thanks to the nature of the 4DVAR assimilation system. A marginal degradation can be reported locally for some conventional wind observations in the Arctic region covered by the MODIS winds (north of 60N). Here, the standard deviation of the FG departures for radiosonde or pilot observations is very slightly increased around 300 hPa, whereas the fit to aircraft wind observations is mainly unaltered (not shown). The marginal degradation may be due to altered variability in the FG as a result of the MODIS winds assimilation, and it may well be compensated by better FG quality over the Arctic Ocean where no other wind observations are available. Nevertheless, the differences suggest some small local discrepancy in the use of the MODIS winds compared to other observations, possibly as a result of misspecified error or bias characteristics. For instance, MODIS winds may be prone to similar spatial error correlations as AMVs from geostationary satellites (non-zero error correlation on scales of about 800 km and thus larger than the thinning scales used, Bormann et al. 2003), and these error correlations are not accounted for in our assimilation.

The assimilation of MODIS winds significantly increases the upper level analysis increments in the polar areas covered by the MODIS winds (e.g., Fig. 4). Increments are the adjustments made to the FG in the assimilation to produce an analysis which incorporates new observational information. The increased increments in the polar region are not surprising, as they occur in an area with few other observations (e.g., Fig. 1). Without the MODIS winds, the analyses in this region will be largely determined by the forecast model, whereas with MODIS winds previously undetected FG errors can be corrected. Supporting this, the increased increments over the Arctic Ocean occur in a region where the increments in the CTL experiment tend to be much smaller than over the well-observed surrounding areas (Fig. 4). In contrast, in the MODIS experiment the analysis increments have a much more consistent size over the entire higher midlatitudes. We therefore consider the increased increments over the poorly observed polar region a positive sign of the MODIS assimilation. It should be noted, however, that in well-observed regions smaller or unaltered increments are usually preferred, as they indicate smaller FG errors and a good consistency of the assimilation. Indeed, such consistency can also be reported for our experiments over better-observed regions such as Northern Europe, the North Atlantic or North America where the analysis increments are overall not similarly increased.

3.2 Forecast impact

There is a significant positive impact on forecasts of the geopotential height when MODIS winds are assimilated, particularly over Europe and also over the entire Northern Hemisphere extra-tropics. Figure 5 shows the improvement in forecasts of the 500 hPa geopotential height when the MODIS winds are assimilated. The Figure shows the correlation between the geopotential height anomalies of the forecasts and the verifying analyses with the forecasts each validated against their own verifying analyses (resulting in a total of 58 cases). The forecast improvements over Europe are significant at the 90% confidence level or better (t-test) for a forecast range beyond 5 days. Wind forecast errors over the Northern Hemisphere are also reduced, including over the Arctic region (Fig. 6).

For the Southern Hemisphere, wind forecast errors over Antarctica are also improved considerably (Fig. 6), whereas the impact over the entire Southern Hemisphere extra-tropics is neutral overall, with a marginal improvement for the forecasts of the geopotential in the day 5 to 6 range (Fig. 5). The interpretation of forecast scores against analyses over the Southern Hemisphere is more difficult as fewer available observations lead to smoother verifying analyses, whereas the addition of MODIS winds alters the variability of these analyses. However, the more neutral impact is also confirmed by a verification against observations which avoids the above problems, although it is meaningful only over limited areas. The more neutral impact is in agreement with findings in KEY, and there are a number of possible reasons for the somewhat weaker impact of the MODIS winds over the Southern Hemisphere. Fewer MODIS winds are used due to the strict blacklisting

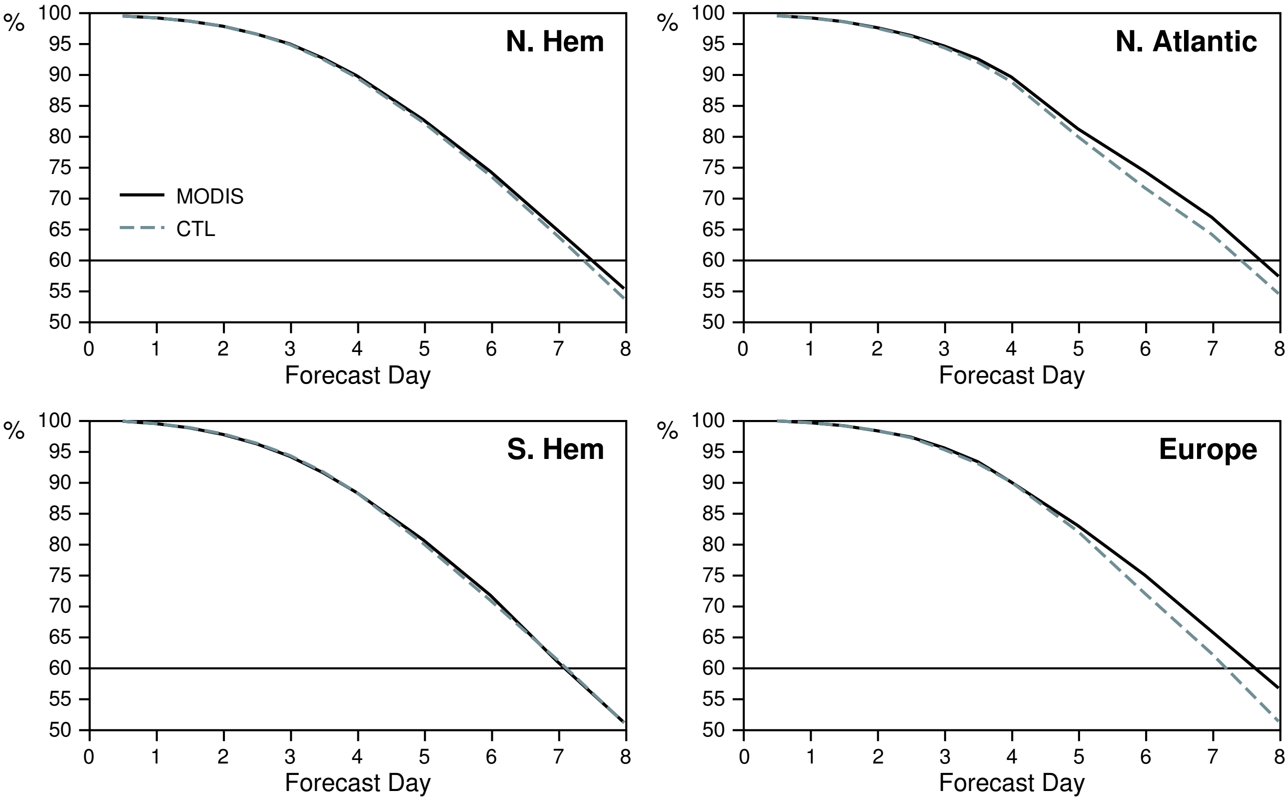

Figure 5: Anomaly correlations for the 500 hPa geopotential height forecast against the verifying analysis as a function of forecast range. The forecasts for the MODIS experiment (solid black) and the CTL (dashed grey) have each been verified against their own analyses, and scores for both periods have been pooled together (58 forecasts). The four plots show anomaly correlations over the Northern Hemisphere extra-tropics, the Southern Hemisphere extra-tropics, the North Atlantic, and Europe respectively.

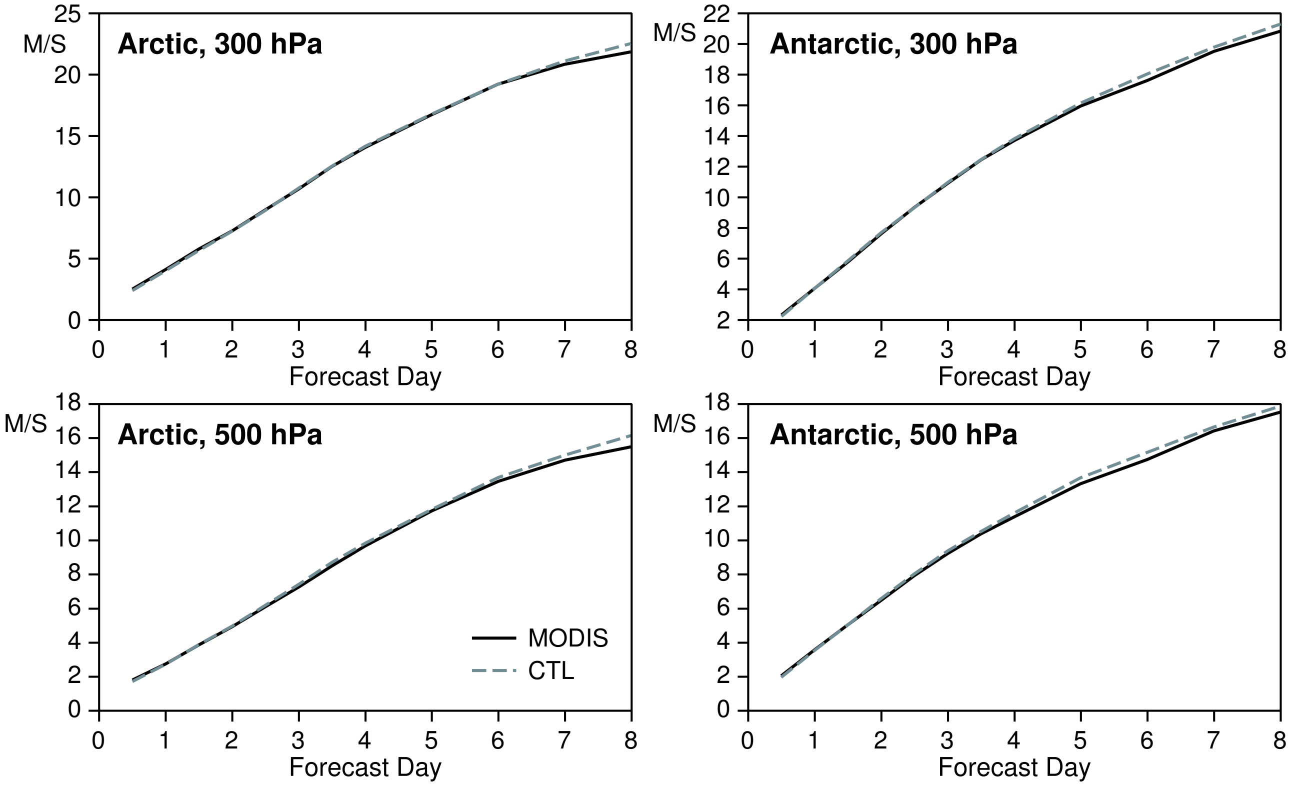

Figure 6: Root mean square errors for the 300 hPa and the 500 hPa wind forecast for the MODIS experiment (solid black) and the CTL (grey dashed), with each experiment verified against the own analyses. Scores for the two study periods have been pooled together (58 forecasts). The panels show values for the Arctic (north of 65N) and the Antarctic region (south of 65S), respectively.

of lower level winds over land. Also, height assignment for the MODIS winds is more difficult over the high and steep orography of the Antarctic continent, possibly limiting the quality of the MODIS winds. Moreover, the more zonal flow over the Southern Hemisphere may limit the interaction between polar regions and the midlatitudes.

It is worth mentioning that the impact of the MODIS winds appears to vary over time, suggesting that the impact depends on the synoptic situation. Our experiments indicate the strongest positive impact over the Northern Hemisphere for the first half of the July/August 2002 experiment, while for other times the impact is more neutral. It appears that during July and beginning of August 2002 the polar analysis played a more important role for the subsequent forecast. Daily examinations of ECMWF's numerical forecasts indeed tend to indicate greater sensitivity to the polar regions in May-July compared to other times of the year (F. Grazzini, pers. communication).

3.3 Forecast example

We will now discuss a sample forecast initialised on 4 August 2002 12 UTC to illustrate how the assimilation of MODIS winds can improve subsequent forecasts. The coverage of the MODIS winds for the corresponding 12-h assimilation cycle is illustrated in Fig. 8; for comparison, the coverage of conventional wind observations over the same period is indicated in Fig. 1. Figure 7 shows the initial analysis for this forecast together with the analysis differences between the MODIS and the CTL experiment. Differences between the two analyses are

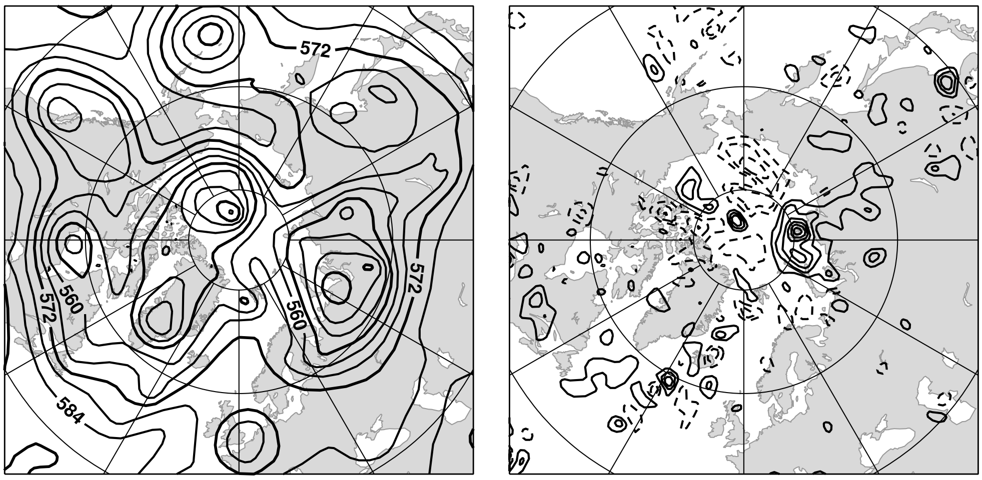

Figure 7: Analysis of the 500 hPa geopotential height [gpdm] for the MODIS experiment for 4 August 2002 12 UTC (left panel). Differences MODIS-CTL between the 500 hPa geopotential height analyses for the same day are shown in the right panel. Solid contours indicate positive differences, dashed contours indicate negative differences (0.4 gpdm contour interval).

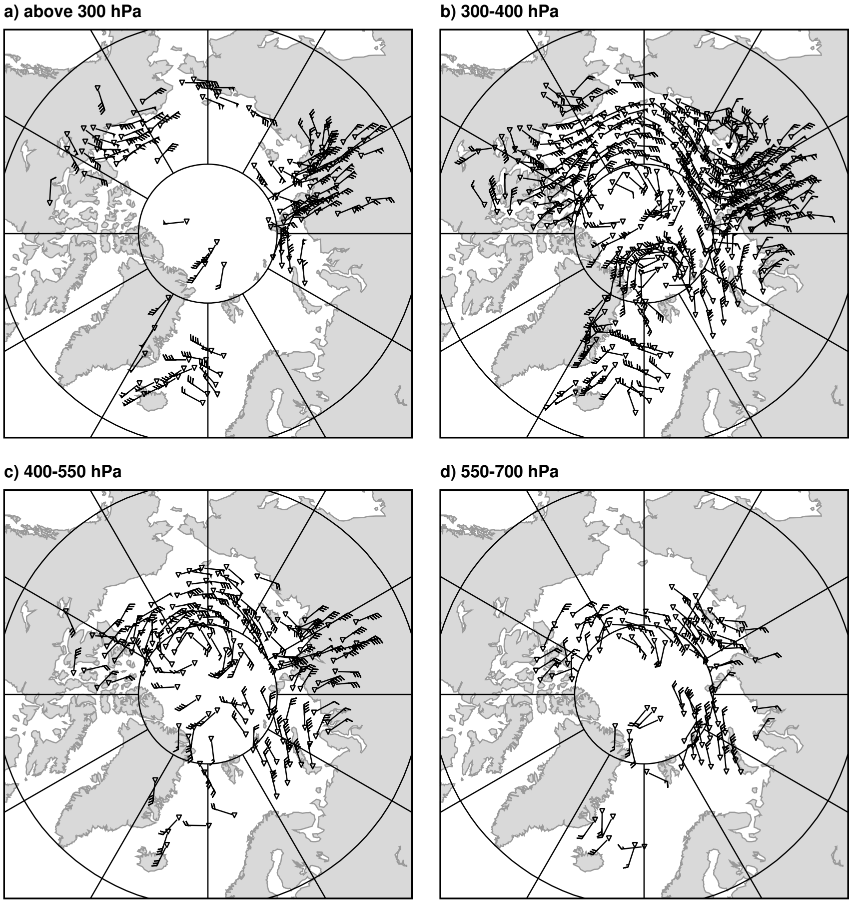

Figure 8: Coverage of the used MODIS winds for the 3-15 UTC assimilation cycle on 4 August 2002, stratified by pressure level as indicated. The winds have been slightly thinned for display purposes.

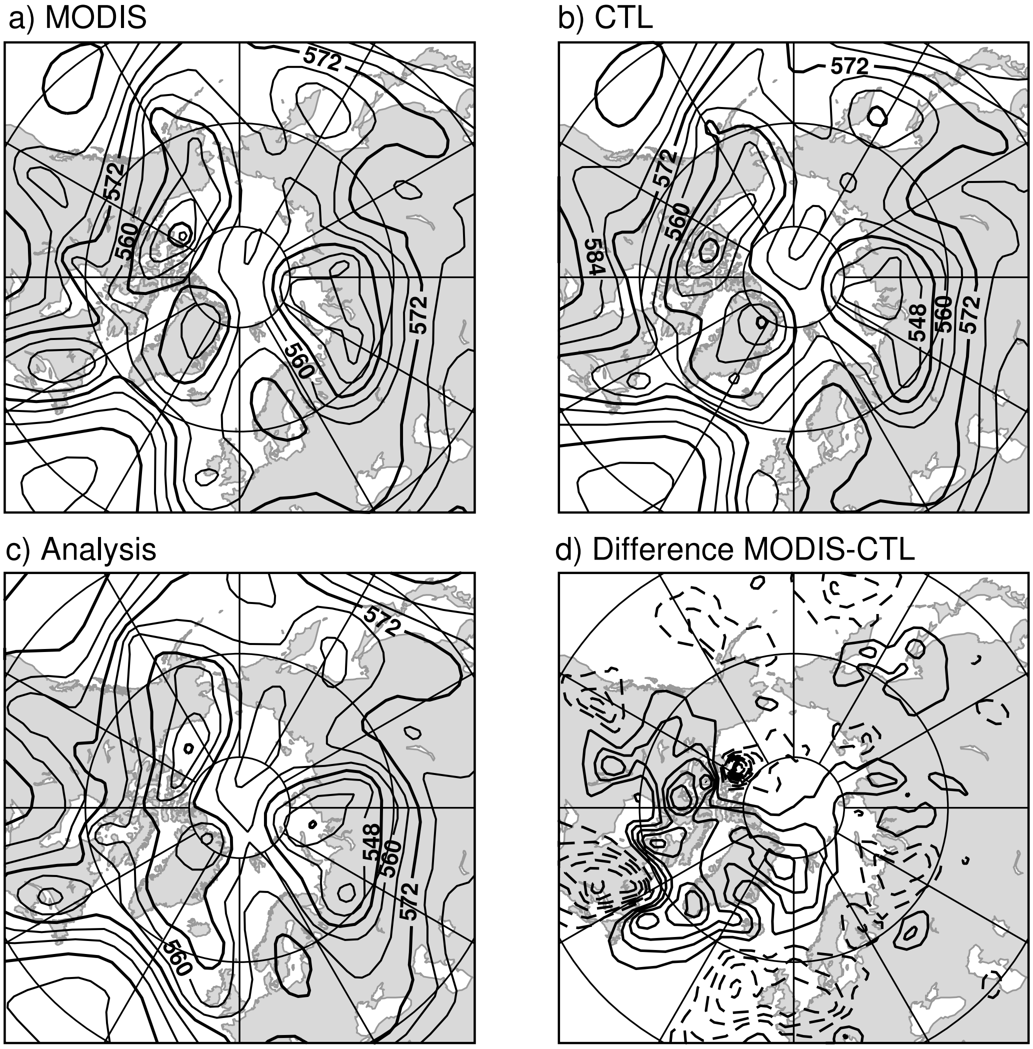

Figure 9: Four day forecasts of the 500 hPa geopotential height for (a) the MODIS and (b) the CTL experiment, valid on 8 August 2002 12 UTC. c) Verifying analysis for 8 August 2002 12 UTC from the CTL experiment. d) Differences between the MODIS and the CTL forecast shown in a) and b). Solid contours indicate positive differences, dashed contours indicate negative differences (2.0 gpdm contour interval).

noticeable north of the Bering Strait and Siberia, regions well covered by MODIS winds over this assimilation cycle. Other differences are also present, for instance, south-east of Greenland and near Newfoundland. Peak differences are of the order of 1-3 gpm for the 500 hPa geopotential. These differences propagate downstream in the subsequent forecast, grow and interact, leading to large forecast differences over North America and the Northern Atlantic already at day 4 (Fig. 9). A comparison with the verifying analysis reveals, for instance, a better location and orientation of the trough north of Alaska, and a much improved forecast of the ridge over the North Atlantic.

To investigate which regions in the analysis played a particularly important role for the subsequent forecast we estimated so-called "key analysis errors" highlighting the sensitivity to initial conditions for the sample forecast (e.g., Klinker et al. 1998). These sensitivity calculations estimate analysis perturbations required to minimise the subsequent 2-day Northern Hemisphere forecast error under the total energy norm, using the adjoint method. In other words, these calculations estimate "key analysis errors" by using the analysis two days after the initial time and mapping the forecast errors against this verifying analysis back to the initial analysis.

The model used to evaluate the error propagation is based on the linear approximation and has a somewhat lower resolution (T63, approximately 320 km). Such sensitivity calculations provide a powerful tool to identify particularly sensitive regions in the initial analysis.

The calculations indicate considerable sensitivity of the 2-day forecast to the polar regions. Figure 10 shows the absolute value of the sensitivity perturbations for the streamfunction on model level 39 (approximately 500 hPa) for the CTL experiment, with maxima in the polar region around the Bering Strait, north of Siberia, over Scandinavia, and over Quebec. For the MODIS experiment, the sensitivity perturbations over most of these very sensitive areas are noticeably reduced by about 0.1-0.2 m^2s^{-1} (10-30 %), except north of Quebec and over the Northern Atlantic (Fig. 10). The reduction of the sensitivity perturbations suggests a reduction of analysis errors in these areas, introduced either through the MODIS winds assimilated in this assimilation cycle or through earlier improvements already present in the FG. The improvements north of Siberia and north-west of the Bering Strait coincide with areas well covered by the MODIS winds used in the 12 UTC analysis on 4 August 2002 (Fig. 8), whereas no MODIS winds were present in the region around Quebec where a slight degradation is present. While it is difficult to directly relate the changes in the sensitivity pattern to the MODIS winds for only one cycle the findings highlight the ability of MODIS winds to reduce key analysis errors over the polar regions.

Forecast improvements linked with a reduction of key analysis errors in the polar regions have been observed in a number of other forecast cases in the MODIS experiment. While the reduction is not necessarily systematic, the assimilation of MODIS winds tends to reduce extreme values in the sensitivity perturbations, as highlighted in the above example.

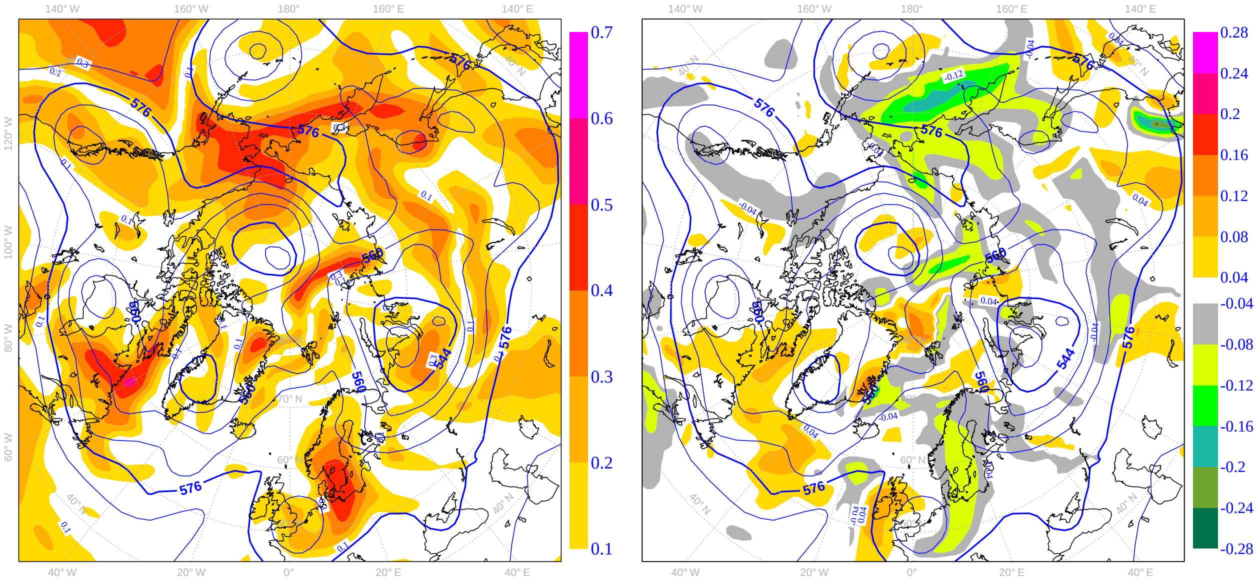

Figure 10: Left panel: Shading shows absolute values of the sensitivity perturbations for the streamfunction [m^2s^{-1}] at model level 39 (approximately 500 hPa) for the analysis valid 4 August 2002 12 UTC. Contours show the 500 hPa geopotential [gpdm]. Right panel: Shading shows the differences between the MODIS and the CTL experiment in terms of the absolute value of the sensitivity perturbations for the streamfunction shown on the left. Contours indicate the 500 hPa geopotential [gpdm].

4 Discussion and conclusions

This paper reported on the first impact experiments with polar winds from MODIS within a 4DVAR framework. The main findings are:

- The MODIS polar winds have a positive forecast impact, particularly over the polar regions and Europe, but also over the Northern Hemisphere as a whole.
- The assimilation of the MODIS winds can considerably alter the mean polar wind analysis for some periods, suggesting that the MODIS winds can correct systematic deficiencies in model analyses.
- A forecast example highlights how Northern Hemisphere forecasts are sensitive to analysis perturbations over the polar regions and how the assimilation of MODIS winds can reduce key analysis errors in these areas, subsequently leading to improved forecasts.

The above findings confirm earlier results of positive forecast impact with the MODIS winds in a coarser resolution 3DVAR configuration over a shorter time period (KEY, Bormann et al. 2002). Within the current observing network, the MODIS winds are capable of adding wind information in an otherwise poorly observed and sensitive region also in a 4DVAR framework. As a result of these findings, the Terra-MODIS winds are assimilated operationally at ECMWF since 14 January 2003.

The positive forecast impact demonstrated in 3DVAR and 4DVAR experiments is particularly encouraging as it has been obtained by merely adopting the assimilation approach from geostationary AMVs with few specific adjustments for the MODIS winds. As a consequence there is scope for refinements in the assimilation of the MODIS winds. Quality control decisions for instance have been fairly cautious with no assimilation of low-level winds. In addition, quality indicators for the derived winds are provided with the data (e.g., Holmlund et al. 2001), and this information has not been used in our experiments. Use of such information in the quality control or the thinning step of the assimilation can be beneficial (e.g., Rohn et al. 2001). More generally, fine tuning of the observation error characteristics remains to be done, since at present values corresponding to geostationary AMVs have been used. This fine tuning includes a revision of the thinning scales to suppress spatially correlated errors in light of recent findings on spatial error correlations for winds derived from geostationary satellite data (Bormann et al. 2003). Also, bias characteristics for the MODIS winds should receive further attention to assure that these are treated appropriately in the assimilation (e.g., Bormann et al. 2001). Progress in these areas is expected to lead to improvements over our present "day-1" system.

In addition, further improvements are also possible on the data side. For instance, this study investigated only the impact of the Terra MODIS winds. In the meantime, MODIS winds have also become available from the Aqua satellite, providing even better coverage of the polar wind field. On top of this, combined use of Terra and Aqua data in the winds processing allows the shortening of the time interval between swaths (currently 100 min) and could therefore lead to improved tracking. It has also been suggested that the use of relatively coarse resolution forecast data in the winds processing negatively affects the height assignment for lower level MODIS winds, and this aspect will be investigated further by using higher-resolution ECMWF fields. A further challenge would be to provide and assimilate a clear-sky radiance product from MODIS data, similar to that used from some geostationary satellites (e.g., Köpken et al. 2002, Munro et al. 2000).

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