Cloud-Drift and Water Vapor Winds in the Polar Regions from MODIS

SUMMARY AND PURPOSE OF DOCUMENT

This paper summarizes the new research wind product derived from the MODIS IRW and water vapor images. Model impact assessments are also discussed.

ACTION REQUESTED: NONE

CLOUD-DRIFT AND WATER VAPOR WINDS IN THE POLAR REGIONS FROM MODIS

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ABSTRACT

Wind products from geostationary satellites have been generated for over 20 years, and are used in numerical weather prediction systems. However, because geostationary satellites do not provide useful wind information poleward of the midlatitudes, and because the high-latitude rawinsonde network is sparse, the polar regions remain data poor. This study demonstrates the feasibility of deriving tropospheric wind information at high latitudes from polar-orbiting satellites. The methodology employed is based on the algorithms currently used with geostationary satellites, modified for use with the Moderate Resolution Imaging Spectroradiometer (MODIS). The project presents some unique challenges, including the irregularity of temporal sampling, different viewing geometries in successive orbits, uncertainties in wind vector height assignment as a result of low atmospheric water vapor amounts and thin clouds typical of the Arctic and Antarctic, and the complexity of surface features. A 30-day case study dataset has been produced and is being used in model impact studies. Preliminary results are encouraging: when the MODIS winds are assimilated in the European Centre for Medium Range Weather Forecast (ECMWF) system and the NASA Data Assimilation Office system, forecasts of the geopotential height for the Arctic, Northern Hemisphere extratropics, and Antarctica are improved significantly.

1. Introduction

In the early 1960s, Tetsuya Fujita developed analysis techniques to use cloud pictures from the first TIROS polar orbiting satellite for estimating the velocity of tropospheric winds (Menzel, 2001). Throughout the 1970s and early 1980s, cloud motion winds were produced from geostationary satellite data using a combination of automated and manual techniques. In 1992, the National Oceanic and Atmospheric Administration (NOAA) began using an experimental automated winds software package developed at the University of Wisconsin Space Science and Engineering Center that made it possible to produce a full-disk wind set without manual intervention. Fully automated cloud-drift and water vapor motion vector production from the Geostationary Operational Environmental Satellites (GOES) became operational in 1996, and now wind vectors are routinely used in operational numerical models of the National Centers for Environmental Prediction (NCEP) (Nieman et al., 1997).

In this paper we present an overview of a fully automated methodology for estimating tropospheric motion vectors (wind speed, direction, and height) using the Moderate Resolution Imaging Spectroradiometer (MODIS) on-board the National Aeronautics and Space Administration's (NASA) polar orbiting Terra and Aqua satellites. The retrieval methodology is discussed and case study results are presented. The case study dataset is used in numerical weather prediction (NWP) model impact studies, where the effect of the MODIS winds on forecasts is assessed. Also, the status of the real-time production of MODIS winds is presented. Additional details are given in Key et al. (2002).

2. Wind Retrieval Methods

Cloud and water vapor tracking with MODIS data is based on the established procedure used for GOES, which is essentially that described in Merrill (1989), Nieman et al. (1997), and Velden et al. (1997, 1998). 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. The lowest (coldest) brightness temperature in the infrared window band, generally indicating cloud, within a target box is isolated and local gradients are computed. Gradients that exceed a specified threshold are classified as targets for tracking. For water vapor target selection, local gradients are computed for the area surrounding every pixel rather than the single pixel with the minimum brightness temperature in a box. Water vapor targets are selected in both cloudy and cloud-free regions.

Wind vector heights are currently assigned by one of two methods. The infrared window method assumes that the mean of the lowest (coldest) brightness temperature values in the target sample is the temperature at the cloud top. This temperature is compared to a numerical forecast of the vertical temperature profile to determine the cloud height. The method is reasonably accurate for opaque clouds, but inaccurate for semitransparent clouds. In our case study, the U.S. Navy Operational Global Atmospheric Prediction System (NOGAPS) model with 1.0 degree spatial resolution and 13 vertical levels was used.

The H_2O-intercept method of height determination is also used for height assignment. This method examines the linear trend between clusters of clear and cloudy pixel values in water vapor-infrared window brightness temperature space, predicated on the fact that radiances from a single cloud deck for two spectral bands vary linearly with cloud fraction within a pixel. The line connecting the clusters is compared to theoretical calculations of the radiances for different cloud pressures. The intersection of the two gives the cloud height (Szjewach, 1982; Schmetz et al., 1993).

After wind vectors are determined and heights are assigned, the resulting data set is subjected to a rigorous post-processing, quality-control step. A 3-dimensional objective recursive filter is employed to re-evaluate the tropospheric level that best represents the motion vector being traced, to edit out vectors that are in obvious error, and to provide end users with vector quality information (Velden et al., 1998).

3. Application

A 30-day case study has been completed. The study period is 05 March - 03 April 2001. MODIS Level 1B data from the Terra satellite were acquired from NASA's Goddard Distributed Active Archive Center (DAAC). The 1 km image data were normalized and de-striped to reduce the effect of detector noise and variability. Two to four 5-minute granules from each orbit were remapped into a polar stereographic projection at 2 km resolution and composited with the Man computer Interactive Data Access System (McIDAS). The resulting images are 2800 x 2800 pixels in size. Winds were derived from successive image triplets of the water vapor (band 27) and IR window (band 31) channels. Approximately 25,000 quality-controlled vectors, on average, were produced per day at each pole for the 30-day study period.

There are two approaches to quantitatively assessing the quality of the wind vectors: comparing the satellite-derived winds with collocated rawinsonde observations, and evaluating their impact on numerical weather prediction. NWP studies are described in the next section. Statistics from comparisons with rawinsondes can provide a measure of product quality over time and can aid in the determination of observation weights used in objective data assimilation. In the 30-day case study, the root-mean-square (RMS) difference between the satellite winds and rawinsonde observations, averaged over all vertical levels, is 8.11 m/s with a speed bias of –0.58 m/s (satellite wind speed less than rawinsonde) for approximately 27,000 collocations. The RMS differences include errors in rawinsonde measurement and reporting, which are on the order of 3 m/s (Hoehne, 1980). The RMS and bias values are similar to, but slightly larger than, those for geostationary satellite winds. This is expected from the larger temporal sampling intervals. The best results are obtained for the middle and upper troposphere. Low-level RMS differences are larger relative to the mean wind speed. The verifying observational network is sparse in the polar regions so that these statistics do not necessarily apply uniformly to the entire Arctic and Antarctic.

4. Impact of MODIS Winds on NWP Forecasts

Given the sparse rawinsonde observation network in the polar regions and the relative importance of high-latitude wind observations in NWP forecasts noted by Francis (2002), satellite-derived polar wind information has the potential to improve forecasts in polar and sub-polar areas. Model impact studies using the 30-day case study dataset were performed at ECMWF and the NASA Data Assimilation Office (DAO). The goal for both was to determine if forecasts are improved when MODIS winds are assimilated.

ECMWF Impact Study

An initial model impact study was performed at the ECMWF with the 30-day case study dataset. All experiments employed a 3D variational analysis assimilation scheme (3DVAR) with 6-hourly analyses that used the model first guess (FG) at the appropriate observation time. The model and analysis resolutions were T159 (approximately 125 km) with 60 levels in the vertical. Ten-day forecasts were run from each 12 UTC analysis.

Two experiments were conducted: the control experiment with routine observational data used as in operations, and the MODIS experiment with everything as in the control experiment plus the assimilation of MODIS winds. Over land, the IR and WV winds above 400 hPa were used. Over the ocean, IR winds above 700 hPa and WV winds above 550 hPa were used. These restrictions were chosen after trial experiments indicated a somewhat poorer quality of lower level winds, possibly due to height assignment problems over orography and ice and the use of relatively coarse resolution model data for the height assignment. As with operational wind vectors from geostationary satellite data, the MODIS winds were thinned to a 140 km resolution, and quality control in the assimilation was based on an asymmetric check against the first guess (Rohn et al. 2001).

Table 1 gives the first guess statistics from a passive comparison of the MODIS water vapor cloud winds against the first guess used in the assimilation. The table gives the normalized RMS vector difference (NRMSVD), the wind speed bias, the mean wind speed, and the number of cases that were used in the statistics. The NRMSVD is defined as the RMS vector difference divided by the mean wind speed. As with the rawinsonde comparisons, for most levels and regions the NRMSVD and the speed bias are similar to or slightly poorer than other extra-tropical satellite-derived winds currently assimilated by ECMWF. This highlights the acceptable quality of the MODIS winds. The current exception is at lower levels in the Antarctic region where the monitoring statistics reveal large RMS vector errors and relatively strong, fast speed biases (reaching 1.3 m/s). These poorer statistics motivated the cautious use of the MODIS winds at lower levels. The statistics are similar for the MODIS IR cloud winds.

The mean polar wind analysis is considerably altered in the experiment with MODIS winds. The differences for the Arctic are largest over the sea ice, with differences up to 3 m/s at all levels. Here, the MODIS winds act to strengthen the circulation at upper levels, whereas at lower levels the difference field suggests a weakening of the local circulation. There are some indications that MODIS winds correct deficiencies in the Arctic flow field in the model in this case: the u-component bias between the Canadian Arctic profiler data and the first guess is slightly improved, and the fit of other observations against the first guess is unaltered in the MODIS experiment.

Table 1. First guess statistics for all WV cloud MODIS winds from the control experiment.

	Southern Hemisphere	Northern Hemisphere
Mid-level (400-700 hPa)		
NRMSVD	0.60	0.37
Speed bias (observation-FG) (m/s)	1.39	-0.36
Mean model speed (m/s)	12.55	15.06
Number of cases	282,527	207,324
High-level (above 400 hPa)		
NRMSVD	0.41	0.34
Speed bias (observation-FG) (m/s)	-0.51	0.70
Mean model speed (m/s)	21.29	20.86
Number of cases	80,083	23,196

There is a significant positive impact on forecasts of the geopotential heights when MODIS winds are assimilated, particularly over the Northern Hemisphere. Figure 1 shows the improvement in forecasts of the 1000 and 500 hPa geopotential heights over the Arctic (north of 65° latitude) when the MODIS winds are assimilated. The figure shows the correlation between the forecast geopotential height anomaly and the verifying analysis with the forecasts from the MODIS and the control experiments each validated against their own verifying analyses. The forecast improvements are significant at the 98% confidence level or better (t-test) at most vertical levels for a forecast range of 2-5 days.

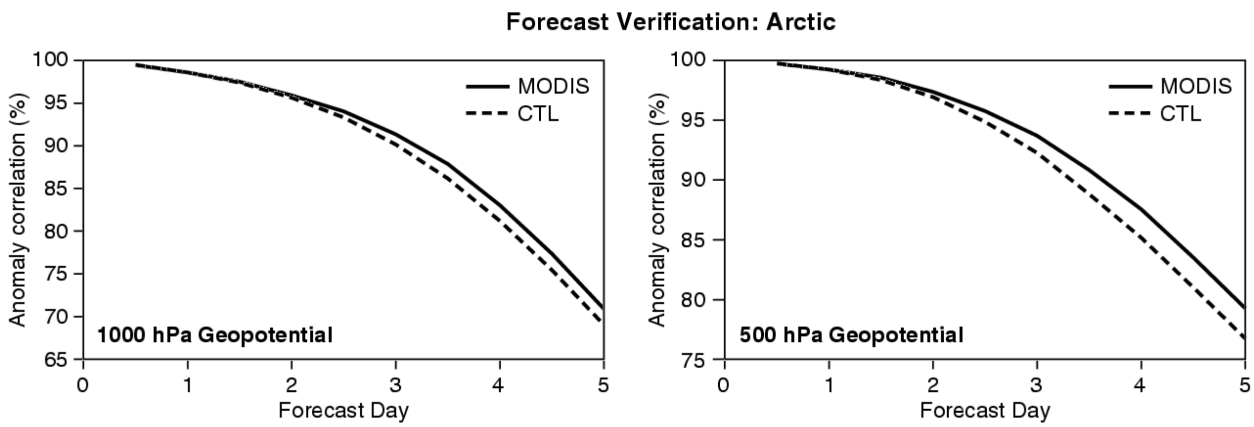

Figure 1. Anomaly correlation as a function of forecast range for the 1000 hPa (left) and 500 hPa (right) geopotential height forecast in the Arctic region for the ECMWF MODIS winds impact experiments. The MODIS experiment (solid) and the control experiment (dashed) have each been verified against their own analyses. The study period is March 5-29, 2001. The Arctic region is defined as the area north of 65° latitude.

DAO Impact Study

The MODIS winds were also tested in the next-generation assimilation system of the NASA Data Assimilation Office. This a global three-dimensional system based on the flux-form semi-Lagrangian general circulation model of Lin and Rood (1998), coupled with the Physical-space Statistical Analysis System (PSAS; Cohn et al., 1998). The PSAS algorithm solves the Kalman Filter analysis equation globally, in the same way that a 3D variational algorithm does, but calculations are carried out in observation space rather than in spectral space. The model resolution is 1.0 x 1.25 degrees latitude/longitude with 55 vertical levels. Analysis increments are calculated at 2.0 x 2.5 degrees for 25 levels. The MODIS winds were thinned to a 0.5 by 0.5 degree resolution; winds were not otherwise excluded from the experiments.

First, a control experiment was performed for the MODIS test period including all the standard observations available for operational NWP purposes, but excluding the MODIS winds. At each analysis time and observation location the observation-minus-6-hour forecast residuals (OMF) were calculated. Next, an assimilation that included the MODIS winds was performed and the OMF residual was again calculated. This residual is calculated before the analysis is performed, so it is essentially a diagnostic of the consistency between the analysis background (the 6-hour forecast) and the observations. The OMF residual for the assimilation that includes the MODIS winds was significantly smaller than in the control assimilation, especially at 500 hPa. This demonstrates that the observations are consistent with the dynamics of the model, and that the MODIS winds contain information that can be ingested and retained by the assimilation system. As a result, the short-range forecast becomes more consistent with the observations at the new analysis time.

Five-day forecasts were then run from the 0Z analyses on every other day of both the MODIS assimilation and the control assimilation. This was done for water vapor winds, IR winds, and for all MODIS winds together. The combined IR and water vapor winds experiment is discussed here. In the ECMWF study, both sets of forecasts were compared to their own verifying analyses. In the DAO study they are instead verified against operational ECMWF analyses.

Figure 2 shows the 500 hPa forecast score (anomaly correlation) as a function of forecast day for the Arctic and Antarctic, both defined as the area poleward of 60^o latitude. Forecasts from the MODIS winds assimilation scored significantly higher than the control experiment in the Arctic, and marginally higher in the Antarctic. Due to the lack of observations over Antarctica, the Southern Hemisphere result may therefore be less meaningful than the Northern Hemisphere result. For the extratropics of each hemisphere (not shown), the MODIS winds improved the forecast skill in the Northern Hemisphere while the Southern Hemisphere impact was neutral to slightly positive.

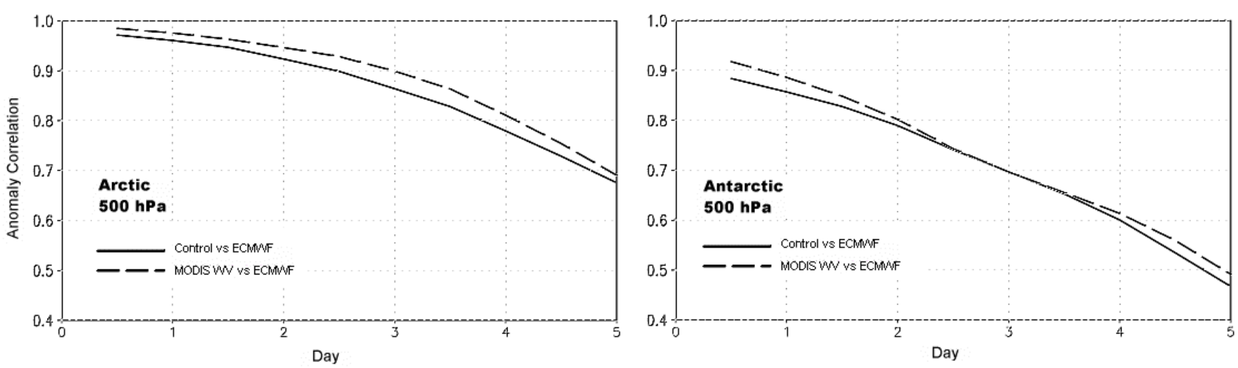

Figure 2. Anomaly correlation as a function of forecast range for 500 hPa geopotential height forecast over the Arctic (left) and Antarctic (right) from the DAO model impact study. The MODIS experiment (dashed) and the control experiment (solid) have each been verified against ECMWF analyses for the study period of 5-29 March 2001. Arctic and Antarctic are defined as poleward of 60^o latitude.

5. Real-time Processing

On 2 July 2002 we began routinely generating MODIS-derived winds in near real-time. These winds are being used by ECMWF, NASA/DAO, Navy, and the Canadian Meteorological Centre. Generally, the winds lag real-time by about 8 hours. This lag is due to:

- 2 to 5 hour delay before MODIS data is available
- 1/2 hour to transfer data from NASA Goddard
- 1 hour to process winds
- 1-1/2 hour offset due to assigning vector to middle image time

This gives a delay of 5 to 8 hours from real-time. Even at 8 hours, the ECMWF is able to use approximately 70% of the total winds generated.

6. Conclusions

This study has demonstrated the feasibility of deriving tropospheric wind information at high latitudes from polar-orbiting satellites. The cloud and water vapor feature tracking methodology is based on the algorithms currently used with geostationary satellites, modified for use with the polar-orbiting MODIS instrument on the Terra and Aqua satellites. Orbital characteristics, low water vapor amounts, a relatively high frequency of thin, low clouds, and complex surface features create some unique challenges for the retrieval of high-latitude winds.

Nevertheless, model impact studies with the MODIS polar winds conducted at ECMWF and the NASA Data Assimilation Office are very encouraging. A 30-day case study dataset was produced and assimilated in the ECMWF model and the DAO assimilation system to assess forecast impact. When the MODIS winds are assimilated, forecasts of the geopotential height for the Arctic and Northern Hemisphere extratropics are improved significantly in both impact studies. The impact is also positive for the Antarctic.

The vast majority of the MODIS polar wind vectors come from tracking features in the water vapor imagery. This fact reduces the utility of imagers without water vapor channels for wind retrieval, such as the current operational NOAA polar-orbiting satellite AVHRR instrument. It also provides strong support for a water vapor channel on the Visible Infrared Imager/Radiometer Suite (VIIRS) that will be flown on the National Polar-Orbiting Operational Environmental Satellite System (NPOESS).

Improvements in height assignment, parallax corrections, and the use of additional spectral channels are under investigation. Progress in any of these areas can be expected to increase the impact of the MODIS polar winds on model forecasts. The impact of these wind data sets should be further enhanced with the use of 4D variational data assimilation techniques. Near real-time processing of MODIS data has begun and with the addition of Aqua MODIS data expected soon, we will have even better coverage of the polar regions on a daily basis.

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