Simultaneous retrieval of cloud motion and height from polar-orbiter multiangle measurements

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Abstract. For the first time, the fully automated retrieval of cloud motion from a polar orbiter is possible using a unique technique based on multiangle imagery. The main advantages of the method are the ability to simultaneously determine cloud height along with the wind and the capability of obtaining retrievals at high latitudes (up to 82°). The first results are consistent with the prelaunch error estimates of ±3 ms⁻¹ for wind and ±400 m for height.

1. Introduction

The Multi-angle Imaging Spectroradiometer (MISR) was successfully launched on the Terra satellite on 19 December 1999 and has been continuously providing data since February 2000. The instrument’s high spatial resolution and unique multiangle capability allow the simultaneous retrieval of cloud height and motion using a purely geometric stereoscopic technique [Horváth and Davies, 2001]. Approximate knowledge of the mesoscale horizontal cloud motion field is required in order to accurately compute high-level MISR products, such as small-scale, cloud-top height variations. Cloud motion retrievals, however, have performed better than expected and thus may find broader applications.

In the past, cloud heights have been estimated from satellite observations by a variety of geometric and non-geometric techniques [Hasler et al., 1983; Nieman et al., 1997]. Cloud motions have also been routinely estimated, but only from geostationary satellites [Nieman et al., 1997]. The MISR technique offers the novelty of detecting cloud motion from a polar orbiter, as well as the ability to assign geometric heights to the retrieved motion. Here we report the first results obtained using MISR’s fully automated cloud motion wind algorithm and compare these with similar results from geostationary measurements. Note that the term “cloud motion wind,” or more simply “wind,” in the following is shorthand for the cloud displacement vector per unit time. For boundary layer clouds, this approximately corresponds to the true wind vector at cloud-base altitude.

2. Retrieval Method

2.1. Instrument Overview

MISR is a pushbroom scanner that measures spectral radiances reflected in nine different directions and four spectral bands (446, 558, 672, and 866 nm). The nine different directions (0, ±26.1°, ±45.6°, ±60°, and ±70.5°) are labeled by their cameras, An, Af/Aa, Bf/Ba, Cf/Ca, and Df/Da, respectively. The combination of instrument geometry and orbital characteristics (sun-synchronous, 705-km altitude, near-polar orbit) allows each point within a 360-km-wide orbital swath to be observed from all nine directions within an interval of approximately 7 min. In the red spectral band, which is used for wind retrieval, the cross-track, ground-projected field-of-view and sample spacing are 275 m for the off-nadir cameras and 250 m for the nadir camera. The along-track field-of-view ranges from 214 m at nadir to 707 m at the most oblique angle (±70.5°). The along-track sampling remains at 275 m for all cameras.

2.2. Algorithm Description

The algorithm used for operational retrieval is described in detail, together with an error analysis, by Horváth and Davies [2001]. In summary, it uses a fast stereo matcher to match solar reflectivity patterns within a 70.4-km² mesoscale domain for three appropriate view angles (typically An, B and D cameras). These measurements are then solved for the wind and height of each match. The individual results can be noisy, so about 100 samples are taken within each domain to reduce the uncertainty. Prelaunch error estimates based on simulated images yielded an accuracy of about 3 ms⁻¹ for wind and 400 m for height [Horváth and Davies, 2001].

3. Retrieval Example: MISR Cloud Motion Winds for a Mature Extratropical Cyclone

The capabilities of the wind retrieval algorithm are demonstrated in Figure 1. Results are shown for an MISR overpass of a mature extratropical cyclone off the west coast of North America. The data corresponding to blocks 50 to 70 of path 54, orbit 1900, were obtained at approximately 2015Z on 26 April 2000. The winds (Figure 1a) and heights (Figure 1b) calculated using the default Da-Ba-An aft camera triplet are overlaid on the nadir image. For high-quality wind retrievals, accurate coregistration of the cameras is crucial. The automatic coregistration of MISR images is able to provide the necessary accuracy (down to a pixel) in the vast majority of cases. Occasionally, however, manual correction of the image registration may be required, which can be achieved by identifying coastlines and land features in the multiangle views.
Figure 1. Cloud motion wind retrievals: a) MISR winds, b) MISR heights, and c) GOES-W winds. Winds are given in m s$^{-1}$, heights are in km. Yellow, white, and red, respectively, refer to low-, medium-, and high-level clouds with corresponding pressure (height) intervals of $>700$ mb ($<3$ km), 700–400 mb (3–7 km), and $<400$ mb ($>7$ km).
Each block of data contains two rows with eight mesoscale domains in each row. The retrieval failed for some domains due to lack of data, low contrast, or an ambiguous (flat) distribution of cloud motion within the domain. The above factors resulted in, on average, 10/11 wind vectors per block.

4. Comparison with GOES-W Cloud Motion Winds

The corresponding GOES-W cloud motion winds valid at 2000Z were obtained from NOAA/NESDIS and are shown in Figure 1c. These motion vectors were determined by tracking visible, infrared, and water vapor features in consecutive images. Infrared images yield winds at all levels; water vapor winds are representative for medium and high levels, while the visible channel generally provides only low-level winds. Cloud heights and/or pressures are assigned to these vectors by the infrared-window brightness temperature method, the carbon-dioxide slicing method, or the water-vapor intercept method [Nieman et al., 1993]. In Figure 1c, for ease of visual interpretation, only 25% of the visible winds and 50% of the infrared and water vapor winds are plotted, and the data are classified into low-, medium-, and high-level bins with respective pressure (height) intervals of >700 mb (< 3 km), 700-400 mb (3-7 km), and < 400 mb (< 7 km).

Both MISR and GOES tend to determine the average cloud motion and height for mesoscale regions. The MISR domain size is 70.4 x 70.4 km², while the GOES tracking procedure uses cross-correlation templates corresponding to areas of 50 to 100 km on a side, depending on the channel. In general, MISR and GOES are in good agreement in terms of both wind speed and direction. Particularly, in the open-cell convection region in the cold sector of the cyclone (blocks 57-62), winds are characteristically westerly to northwesterly, with speeds ranging from 20-25 ms⁻¹ to 15-20 ms⁻¹ from the northern edge to the southern tip of this region. Both MISR and GOES yield low-level winds except for the bright east-west cloud band (block 60) in the middle of the region, which features middle-level cloud tops between 3 and 5.5 km. North of this cloud band the cells are somewhat lower than to the south, with tops at around 1 km as opposed to 1.5 km.

The jet stream running just east of the open cell region is picked up nicely in both data sets. This area features transverse cirrus, normal to the mostly southerly to southwesterly flow. Wind speeds range from 40 to 60 ms⁻¹, while cloud top heights vary between 8 and 10 km.

The frontal band south of the open-cell convection (blocks 62-65) has strong southwesterly flow with wind speeds ranging from 30 to 60 ms⁻¹. MISR indicates middle- and low-level clouds between 2.5 and 6 km, while GOES yields predominantly high clouds in this region. The strong lower-level flow is completely missing from the GOES analysis. This discrepancy between the two data sets is most likely due to different target selection (contrast, cloud detection) and the shorter time interval of MISR (low-level, cumulus-type clouds are easier tracked with shorter time intervals between images). Agreement is also good in the closed-cell marine stratocumulus field in blocks 67-70. The winds are very weak in this region, typically 5 ms⁻¹, and cloud tops are ~1 km.

The striking difference between the MISR and GOES analyses is the lack of retrievals in the latter over the comma cirrus in blocks 50-53. The GOES retrieval fails to pick up the strong (35-50 ms⁻¹) upper-level (9.5-11 km) flow in this region. MISR also outperforms GOES in blocks 53-55, where it indicates the closed circulation associated with the surface low. The better performance of MISR may stem from its finer resolution (275 m vs. 1 km) and larger bit depth (14 bits vs. 10 bits). These factors are probably responsible for the appearance of cirrus striations in the MISR imagery and for the lack of contrast in the GOES images, which, in turn, strongly influence the efficiency of cloud tracking.

The comparison of MISR and GOES pressure heights is shown in Figure 2. The GOES pressure heights are obtained by fitting the measured brightness temperatures to forecast temperature profiles. Due to lack of these forecast profiles, MISR geometric heights were converted to pressure heights using a standard atmosphere valid for mid-latitude spring conditions [NOAA, 1976]. The data show a few mid-level winds and two main clusters: one at around 300 mb (~9 km), which corresponds to high (jet-stream) cirrus close to the tropopause, and one at around 900 mb (~1 km), corresponding to the open-cell and closed-cell convection regions. In the low-level cluster, GOES pressures (geometric heights) are biased low (high) by ~65 mb (645 m) with respect to MISR. The high-level cluster has a much smaller positive (negative) bias of ~9 mb (~235 m) for pressure (geometric height). Considering that the uncertainty of MISR height retrievals is about 400 m, the bias in the low-level data seems to be real, while that in the

Figure 2. MISR pressure heights vs. GOES-W pressure heights. The solid line indicates a one-to-one relationship.
high-level data appears insignificant. The rms difference between the two data sets is \(\sim 100 \text{ mb} \) and \(\sim 45 \text{ mb} \) for the low and high clusters, respectively, which corresponds to approximately 1 km in both cases. For low-level winds, the negative GOES pressure bias is most likely due to a reduced brightness temperature caused by thin cirrus. At high levels, GOES assigns most winds to a single layer (around 300 mb), while MISR pressures show a larger scatter.

5. Summary

The first results obtained with a novel technique allowing the simultaneous retrieval of mesoscale cloud motion and height have been presented. Provided the coregistration of different views is accurate enough (down to a pixel), MISR’s multiangle enhanced stereo algorithm yields reasonable wind and height fields that are consistent with the general synoptic situation. The retrievals are also in good agreement with standard cloud motion vectors derived from GOES-W imagery.

The absolute accuracy of the retrieved winds and heights is yet to be evaluated. The stereoscopic height calculation, however, is expected to improve on the traditional brightness temperature technique, which can introduce errors of several kilometers. The prelaunch uncertainty estimate was 3 ms\(^{-1}\) for wind and 400 m for height. When applied to clear-sky surface data, the algorithm was able to retrieve the zero wind and height of topography with at least the above accuracy. This performance, however, might not carry over for cloud-motion retrievals, and future studies have to validate MISR winds in a systematic, quantitative manner against radiosonde observations, numerical model predictions, and/or geostationary satellite winds.

Compared to existing geostationary measurements, the higher bit depth and spatial resolution of MISR, together with the near simultaneity of its multiangle views, provide it with the main advantage of concurrently obtaining geometrically based heights and winds. The polar orbit also permits the retrieval of winds by such techniques for the first time from high latitudes. However, this comes with the usual tradeoff of poor temporal sampling associated with a single sun-synchronous orbit. Both the polar-orbiter and the geostationary techniques tend to retrieve winds on a mesoscale average, rather than on a pixel or point basis. MISR outperforms GOES for certain conditions (e.g., over thick cirrus), but it generally provides fewer motion vectors for a given area than does the geostationary method. It is noted, however, that the redundancy in the retrieval density of the latter technique is typically high.

The limitations of the MISR instrument, such as the narrow swath width and long repeat cycle, render the current wind retrievals unsuitable for operational purposes. The success of the presented stereoscopic cloud motion algorithm, however, may indicate the potential for a dedicated wide-field-of-view, polar-orbiter, wind-retrieval system. Such an instrument would require only a single spectral band and no radiometric calibration, and could provide cloud motion vectors for the forecasting community in a cost-effective manner.

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