Operational Retrieval of Cloud-Top Heights Using MISR Data

Catherine Moroney, Roger Davies, and Jan-Peter Muller

***Abstract*—Due to its unique nine-angle configuration, the Multi-angle Imaging SpectroRadiometer (MISR) can retrieve cloud parameters such as cloud-motion vectors and cloud-top heights using a purely geometrical technique that involves locating the same cloud features at different viewing angles. The geometrical nature of this technique means that the retrievals are relatively insensitive to the absolute instrument calibration. Fast stereo-matching algorithms have been developed to perform this image matching automatically on an operational basis. Preliminary results are shown of the operational retrievals together with comparisons against other data. Cloud-top height is generally obtained on a 1.1-km grid with an accuracy of ±562 m, even over snow and ice. The limitations of the technique, resulting at times in height blunders, noisy retrievals, and discrete effects of wind correction, are discussed.**

***Index Terms*—Cloud-top heights, Multi-angle Imaging SpectroRadiometer (MISR), multiangle, pattern recognition, stereo-matching, winds.**

I. INTRODUCTION

ONE OF THE main research goals of the Multi-angle Imaging SpectroRadiometer (MISR) is to study the shortwave radiative forcing of clouds on a global basis, especially the determination of cloud albedo as a function of cloud properties [3]. This goal takes deliberate advantage of the vast amount of data acquired by MISR. It requires an operational approach that efficiently processes global data in order to obtain statistically reproducible results. However, since the analysis is statistical, it is broadly tolerant of local root mean square (rms) errors, so that the operational retrieval of some cloud properties such as heights need not reach the level of precision offered by lengthier approaches.

In the processing of multiangle data, cloud heights are needed to determine the reflecting layer reference altitude (RLRA), which is the dynamically varying reference plane to which the different angular measurements must be coregistered. More generally, knowledge about cloud heights has broad implications to our understanding of the earth's climate system, since cloud heights affect longwave cooling to space and total liquid- or ice-water content, to name but two examples.

Several other operational techniques for measuring cloud height from space already exist, though these tend to be indirect measurements of height based on cloud-top brightness temperature [1] or cloud-top pressure [2]. With the exception of lidar, which is not yet available operationally, MISR has the unique ability to determine cloud-top height (and also cloud-motion vectors) geometrically, without assuming a particular state of the atmosphere.

The operational retrieval of cloud-top heights is based on a stereophotogrammetric technique, which requires sufficient contrast in the cloud images to allow pattern matching. In the case of MISR, such pattern matching is aided by its 275-m spatial resolution and its 14-bit deep signal discrimination. Many decisions have to be made in the process of taking a pattern-matcher in isolation and transforming it to a fully automated, globally applicable processing algorithm. In a nonoperational context, for which processing time is not an issue, all of the nine measurement directions can be used to optimize the pattern matches. In an operational context, the number of measurement directions used must be minimized to reduce processing time. Consequently, a minimum of three cameras can be used to obtain the wind field at coarse resolution, and only two cameras are necessary to obtain the cloud height field at high resolution. In practice, the wind and height retrievals use data retrieved from both the forward and aft directions, so that brings the number of wind retrieval cameras used to five and the number of height retrieval cameras to three.

It takes about 7 min to make the entire set of nine angular measurements of a given cloud top, during which time the cloud may move substantially or not at all. Ignoring such motion would at times lead to significant errors in cloud height. However, this correction can generally be applied at coarse spatial resolution (70.4 km), due to the slowly varying nature of wind field.

The prelaunch operational procedure that was proposed for the retrieval of cloud-top heights and cloud-motion vectors (simply called wind in the following) is described in [4], and a prelaunch analysis of cloud-top height and wind errors is given in [5]. The first successful application of the proposed procedure was to aircraft data measured by AirMISR, with the cloud-top heights comparing well with independent lidar data, as described in [6]. Early results from MISR for cloud-top height and winds are given in [7], and they appear to be consistent with the prelaunch error analysis, suggesting an rms uncertainty of ±3 m/s in wind speed and ±400 m in the heights of such winds. This paper introduces additional examples of cases where the operational retrievals work well

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and cases where they appear to have their main difficulties. The current operational processing has evolved somewhat from its prelaunch version, and it is briefly described first, followed by examples of cloud height retrieval and comparison with other data sources. Since very few comparisons with surface and other data sources are as yet available, these cases are included simply as indicators of the technique and not as definitive comparisons.

II. OPERATIONAL PROCESSING

The MISR cloud-top height processing proceeds in two steps: first the wind vectors are retrieved at coarse horizontal resolution, and then the heights are retrieved at higher resolution. Both steps involve the use of stereo-matching algorithms, which are described in more detail in [8]. These stereo matchers measure the total disparity, or apparent distance, between similar features in a given image pair due to the combined effects of height above a common reference surface (the surface ellipsoid) and cloud motion due to advection during the elapsed time between the images. The first step separates these effects, providing a correction for wind that is then applied to the second stage.

The nine MISR cameras are labeled from the most forward looking (with respect to the orbital direction of Terra) camera to the most aftward looking camera as Df, Cf, Bf, Af, An, Aa, Ba, Ca, and Da. With the exception of the An camera, which is nadir looking, "A, B, C, and D" refer to viewing zenith angles, referenced to the earth's surface, of 26.1°, 45.6°, 60.0°, and 70.4° respectively, "a" to an aft camera, and "f" to a forward camera.

The entire pole-to-pole strip of orbital data is first broken up into 144 equal areas called blocks, each of which is 140.8 km long and 563.2 km wide and spans the entire swath width. Each block covers the same geographical location (as defined by a latitude and longitude range) for all cameras. However, the camera-to-camera shift of a given feature (terrain or cloud) may cause different cameras to view the same feature in different blocks. The blocks serve as a convenient way to break the orbital data into chunks of manageable size and do not vary with camera. The processing chain runs through the orbit on a block-by-block basis, keeping three blocks in memory at any one time. Each block is then subdivided into 16 mesoscale domains (70.4 km on a side), and the wind vectors are retrieved independently for each domain in the following manner.

A sparse and fast stereo-matching algorithm is run on the Bf–Df and Bf–An camera pairs. This yields a set of matched points between all three cameras which allows us to solve simultaneously for the cloud-motion and cloud-top height [4]. These results for the individual motion vectors are separated into north–south and east–west components and binned in a two–dimensional (2-D) histogram. The modal value of this histogram is then chosen as the best estimate of the mesoscale wind field for each domain. This completes the first step in the processing.

Once the winds have been retrieved, a higher resolution stereo matcher is then applied to each 1.1-km subregion in the domain. Search windows (range of possible disparities for a given camera pair) are set using the already calculated wind values, and the Af–An and Aa–An camera pairs are stereo-matched independently of each other. The stereo matchers for any pair of cameras may or may not find a valid match for each 1.1-km region within the allowable search window. The red-band data used as input to the stereo matchers are acquired and stored at 275-m resolution, but the height field is only retrieved for every fourth pixel due to time constraints in the processing. Featureless scenes containing an insufficient pattern of reflectivity routinely fail to yield matches. Similarly, it is difficult to obtain valid matches for scenes comprised of multilevel clouds with features simultaneously visible from different altitudes.

For each 1.1-km region with a valid stereo retrieval, the height is calculated using the previously determined wind value for this domain to correct the retrieved disparities for the cloud motion. For regions with a valid retrieval from only one camera pair, that height is accepted as is. If both the forward and aft camera pairs yield valid heights, the difference in the two heights is first compared against a domain-dependent threshold based on the variability of available heights in the current domain (see [4] for further details). If the heights agree well enough (they are within two standard deviations of the mean forward-aft height difference for that domain), the higher of the two is retained as the RLRA. Otherwise both heights are rejected as blunders.

A. Current Algorithms and Known Limitations

Three different stereo-matching algorithms, called NestedMax, M2, and M3, are used for the cloud-motion and height retrievals. As these are fully described in [4] and [8], only a summary description is provided here.

NestedMax is a very sparse and fast feature-matcher used for the operational wind retrievals. It uses inequality logic to find the sets of local maxima in one-dimensional (1-D) strings of radiances within a given mesoscale domain. Each set is similarly operated on iteratively, up to five times, becoming sparser and brighter with each iteration. Feature comparisons between camera pairs are then made, starting with the brightest set for each, discounting any ambiguous matches. M2 and M3 are traditional high-coverage area-matchers used in the cloud height retrievals. They work by shifting a small patch around a predetermined search window and choosing the pixel location that minimizes the difference between the patches.

Mandating that the stereo-matching proceed in a fast and hands-off manner imposes several constraints. Despite the use of forward and aft camera pairs, some blunders still occur, resulting in an occasionally noisy height field. Subpixel enhancements are prohibitively time consuming, so the height resolution of M2 and M3 is limited by pixel quantization to 562 m. Even though the algorithms are very fast compared to conventional pattern-matching techniques, computation time remains an issue due to the vast quantity of data being processed.

B. Enhancements

If not bound by the operational time constraints, several processing enhancements can be made, and these are helpful in evaluating the performance of the operational algorithms.

First, a matcher with better coverage (such as M2 or M3) can be used for the cloud-motion retrievals rather than NestedMax. This will provide for better-populated and better-shaped histograms, as well as fewer drop-outs in the wind values due to insufficient density in the stereo matcher results.

Second, more widely separated pairs of cameras can be used for the height retrieval. The operational code uses only the three A (near-nadir) cameras because the search windows are the smallest and because the patterns between these cameras tend to be the most similar. To first order, the height of a feature is determined by the horizontal disparity of the feature in the two images, divided by the sum (or difference) of the tangents of the viewing zenith angles of the two cameras. Since the operational stereo matchers do not have subpixel accuracy, the height retrieved by any pair of cameras is limited in resolution by the quantization of disparity values to the nearest pixel (± 275 m). Taking the default case of matching the An–Af cameras corresponds to a height resolution of ±562 m. If one uses the An–Bf cameras for height retrieval (where the B cameras have a 45.6° angle as compared to 26.1° for the A cameras), the height resolution increases to 275 m. This improvement in resolution continues with the use of the C and D cameras. However, pattern matching at oblique views becomes progressively harder. It is possible to use matches found more easily with the A cameras as starting locations for higher resolution matches by the more oblique cameras, without resorting to resampling and interpolation [8]. Matches can also be attempted for each 275-m pixel, rather than the operationally more efficient 1.1-km regions.

III. OPERATIONAL EXAMPLES

Fig. 1 illustrates an example of the first step in retrieving cloud heights: that of obtaining the winds and their heights for each 70.4-km domain. As previously described, the winds were calculated by simultaneously solving for the cloud motion and height from a triplet of points matched in three separate cameras. The default choice of the An, Bf, and Df cameras was used in this case. Note that the wind corresponds to the dominant cloud layer in a meteorologically consistent manner. Also shown (at the top of the figure) are the apparent "wind" vectors over land. As expected, these have values less than 3 m/s at a height of about 0 km.

Examples of results from the second step, which yields cloud-top heights corrected for wind, at a spatial resolution of 1.1 km, are given in Figs. 2–5. These represent results from the standard operational processing, without any changes or enhancements that might be appropriate for more detailed studies.

Fig. 2 shows deep convective clouds over a tropical ocean surface, including a mixture of cumulus, cumulus congestus, cumulonimbus, and cirrus. The retrieved heights appear realistic and span the depth of the tropical troposphere, depending on cloud type. Unretrieved cloud heights are given in black, and these typically correspond to uniform cloud or ocean reflectivity where the lack of features prevents the operational algorithm from finding a pattern to match. The winds in this scene were fairly light, so the correction to the heights was small.

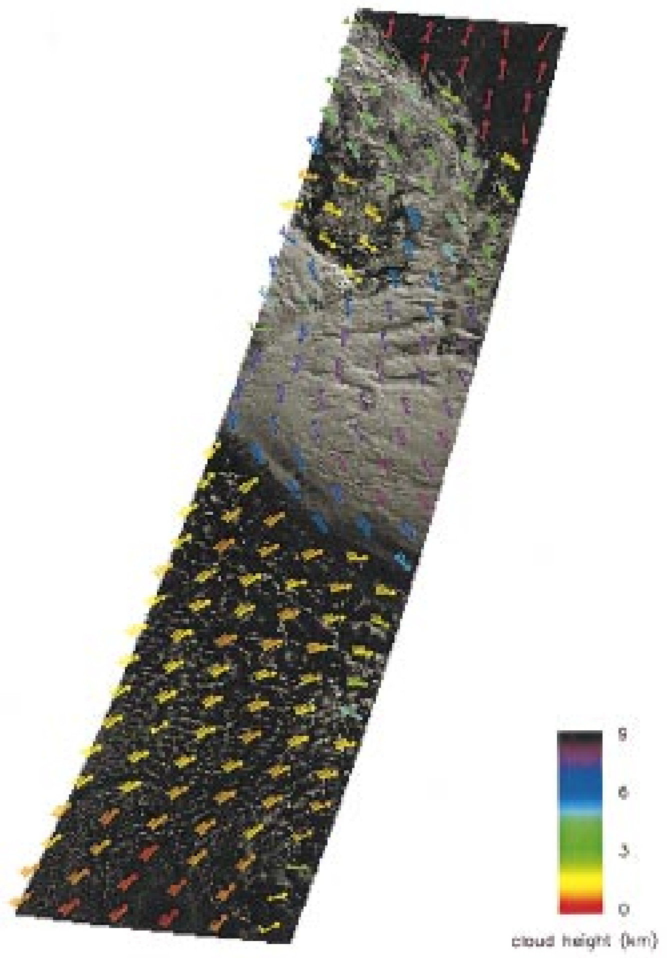
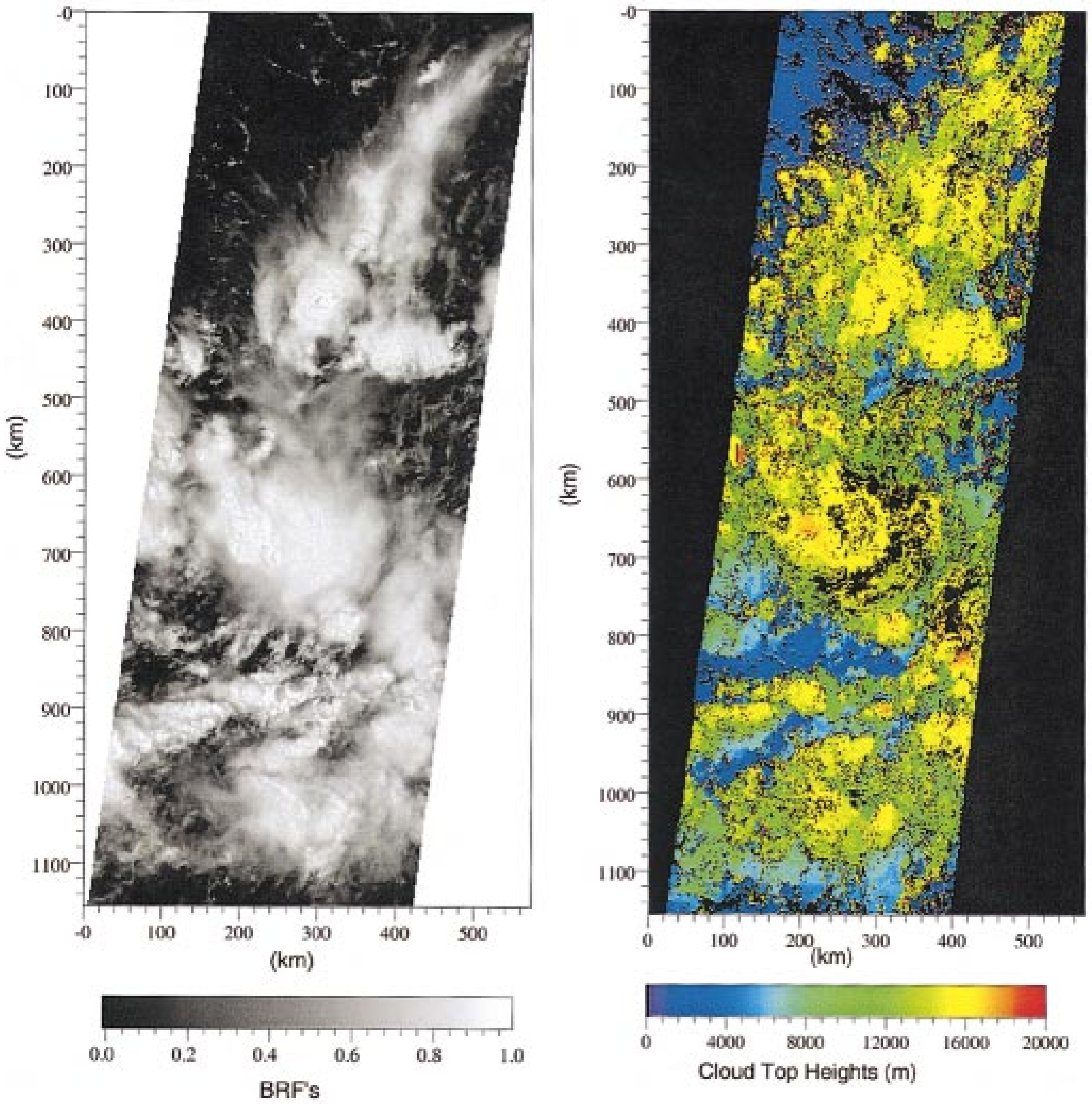


Fig. 1. Example of MISR cloud-motion wind retrievals (path 109, orbit 3316, blocks 116–130). Speed is given in meters per second (full barb = meters per second). The vectors are color-coded according to their height.

Fig. 3 shows an example with higher winds, that of Hurricane Alberto over the Atlantic Ocean. The heights again appear to be realistic and consistent with a meteorological interpretation of the image. The wind correction prevents the heights from showing any observable bias with location around the hurricane. The discrete nature of the wind correction on the 70.4-km grid is faintly observable as a square blockiness in some portions of the height image.

Traditional radiance-based measurements of cloud heights have difficulty in detecting the presence of clouds over snow and ice because the brightness of the surface is similar to that of the cloud. However, good success with a geometrically based method was recently obtained by [9], who used the M2 stereo matcher on the Along Track Scanning Radiometer 2 (ATSR2) data to demonstrate improved cloud classification over the Greenland ice sheet compared to traditional radiometric methods. Since the MISR retrieval algorithms only care about the patterns in the radiance values, they are also well suited to this problem. Fig. 4 shows an example of clouds over snow and ice in the Arctic. Here, the operationally retrieved heights are a little noisy, but generally appear to be very useful in correctly distinguishing a cloud from snow or ice, even when the cloud is fairly close to the surface.

Finally, in this sequence, Fig. 5 shows an example of a difficult mid-latitude scene containing a variety of stratiform and cumuliform cloud types with differing heights. Here, the radiance patterns can be noticeably different from different viewing angles, especially from the most oblique directions. This creates



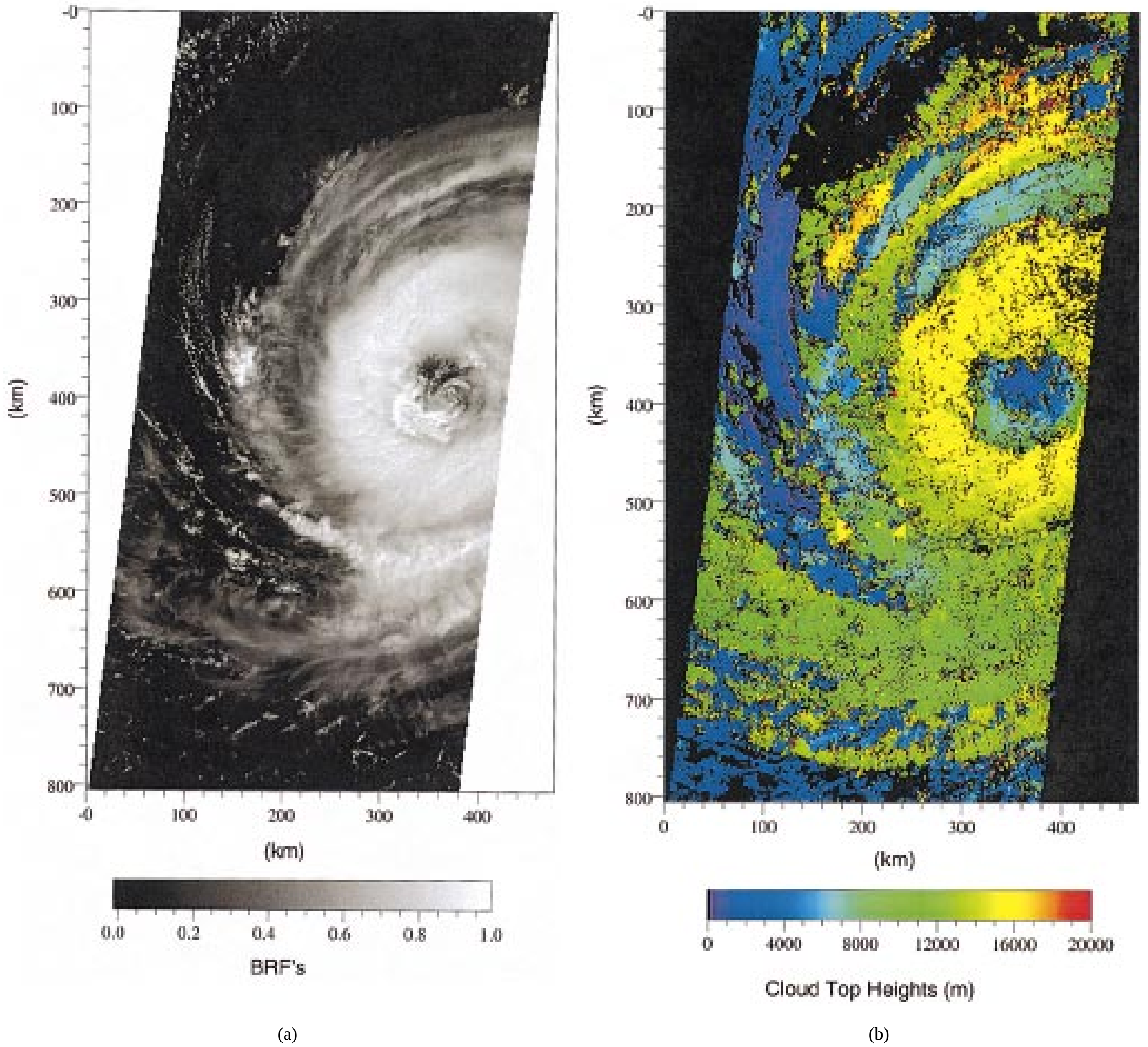
(a) (b)

Fig. 2. A deep convective scene over West Pacific tropical ocean (MISR path 090, orbit 3708, blocks 79–89). (a) Nadir radiances (red band). (b) Operational cloud-top heights.

more uncertainty in the wind retrievals leading to a mesoscale quilting or blockiness in the retrieved heights, which is discussed further below.

IV. PRELIMINARY COMPARISONS OF MISR RETRIEVALS WITH OTHER DATA SOURCES

A favorable preliminary comparison of MISR-derived cloud-motion winds and heights with those from the Geosynchronous Operational Environmental Satellites (GOES) has already been reported [7]. Additional validation of the MISR cloud-top heights and cloud-motion vectors is proceeding in several ways. Cloud-top heights are being compared on a pixel-by-pixel basis with those generated by the Moderate Resolution Imaging Spectroradiometer (MODIS) (using a CO_2 slicing method) and against ground-based radar and lidar measurements on a local basis. Also, the MISR stereo-matching algorithms are being evaluated against P-Gotcha, which is a more computationally intensive “superstereo” algorithm from University College London, London, U.K. [8].



(a) (b)

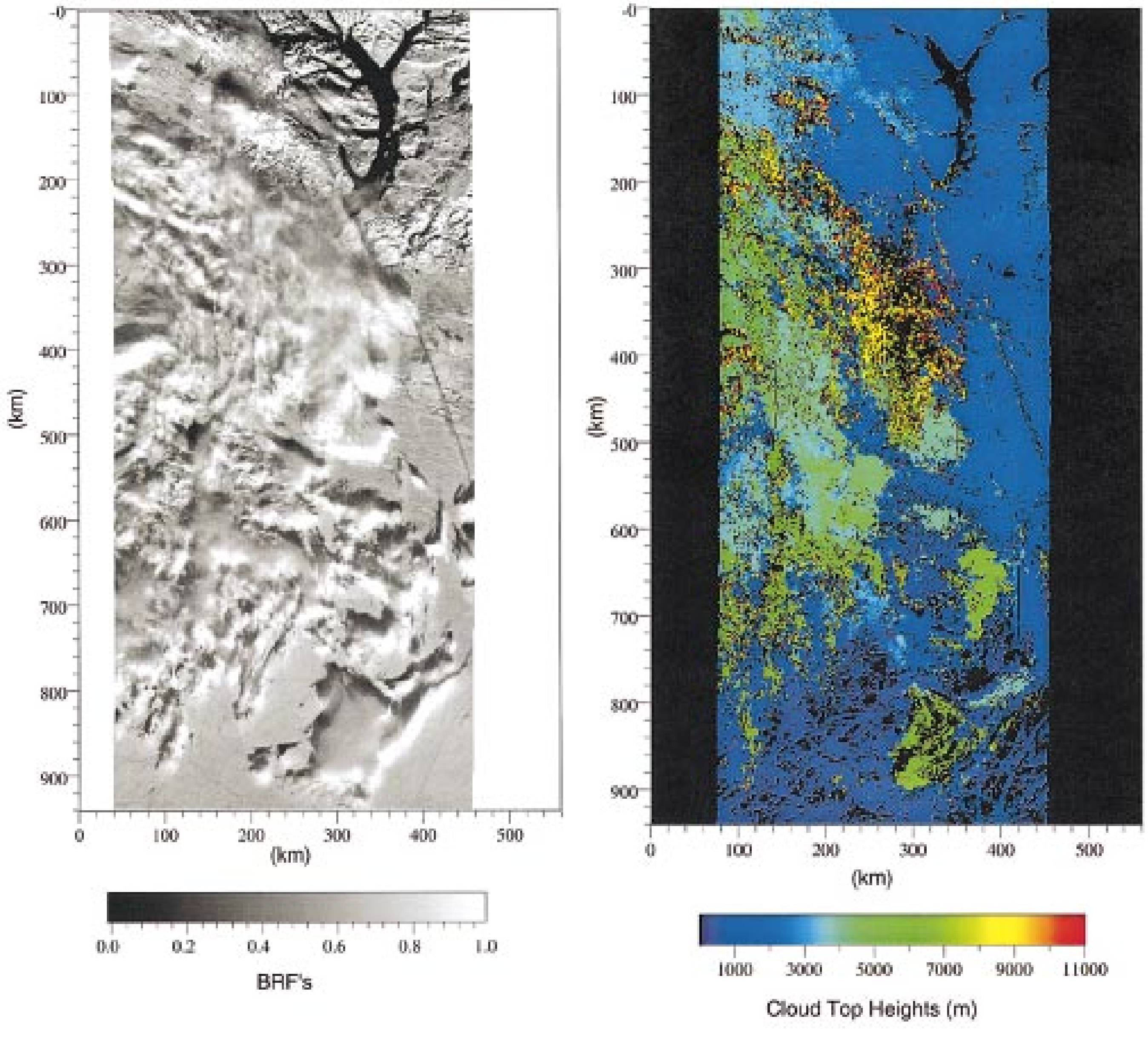
Fig. 3. Hurricane Alberto over the Atlantic Ocean (MISR path 003, orbit 3455, blocks 60–70). (a) Nadir radiances (red band). (b) Operational cloud-top heights.

Fig. 6 shows MISR- and MODIS-derived cloud heights for a scene over the North Sea on September 11, 2000. In order to perform this intercomparison, it was necessary to transform MODIS cloud-top pressures (hPa) into heights (m) using in this case the European Centre for Medium-Range Weather Forecasts (ECMWF) objective analysis data. Here, the MISR and MODIS heights are in general agreement, but some differences appear that warrant deeper study to be reported later.

Fig. 7 provides one example of a comparison with the reflectivities from a 94-GHz ground-based radar station at the Chilbolton site in England. Here, the overpass of Terra is colocated in time and space with the Chilbolton measurement, and consequently it provides only a single point of comparison. Clearly, more comparisons are required for a definitive study, which is a goal for the future, but this initial comparison at least shows a promising height agreement with the radar to within about 1.5 km for MODIS and about 500 m for MISR.

V. QUALITY ASSESSMENT

Based on the internal consistency of the results obtained thus far, and the limited comparison with other data sources, the operational retrieval of cloud-motion winds and cloud-top heights by MISR appears to be working reasonably well overall. When the scene has sufficient texture and moderately well organized cloud layers, the images obtained from operational processing are visually consistent. For scenes with complex cloud layers, or insufficient contrast, the intermittency of height retrievals and mesoscale blockiness is evident in the appearance of the operational images. However, these are largely cosmetic



(a) (b)

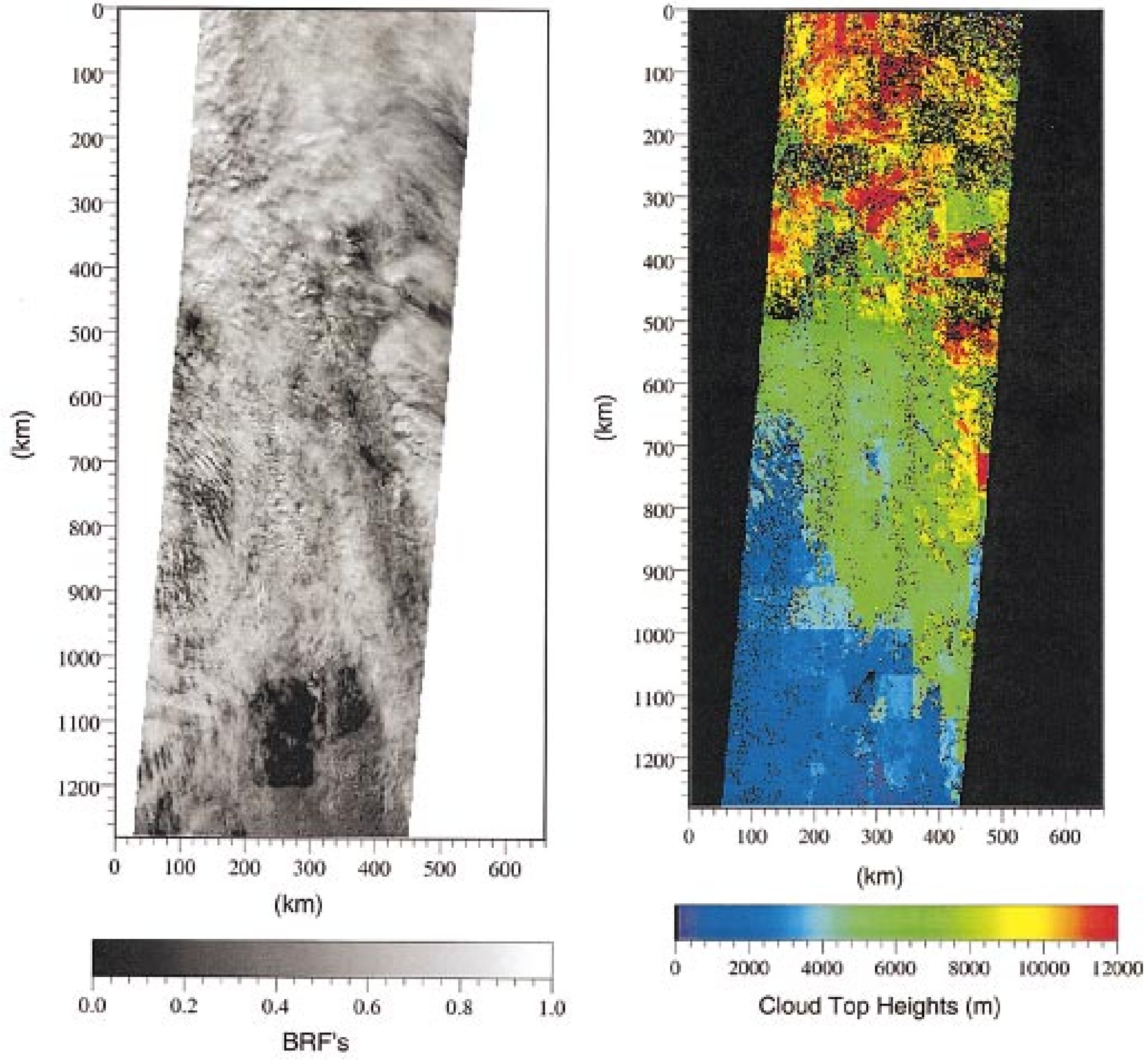
Fig. 4. Clouds over snow and ice, Arctic Ocean (MISR path 090, orbit 3708, blocks 14–23). (a) Nadir radiances (red band). (b) Operational cloud-top heights.

in nature, and provided that they are not symptomatic of sustained biases in cloud heights, they are not expected to be an issue when the data are examined statistically for global studies.

Most of the cosmetic difficulties with the MISR height retrievals fall into two main categories: "blocky" heights on 70.4-km domain boundaries and "noisy" areas where the heights show little continuity from one pixel to the next. This is illustrated in Fig. 8(a), which is an example of the operational product, showing cloud-top heights calculated at 1.1-km resolution using the sparse stereo matcher (NestedMax) for the wind retrievals and Af/Aa–An for the second step, resulting in a height retrieval resolution of 562 m.

By applying additional processing, some of these difficulties can be removed, as can be seen in Fig. 8(b) for the same scene. Here, the enhanced image was generated by using M2/M3 for the motion retrieval, matching every 275-m pixel rather than every 1.1-km pixel and using the Af/Aa–An disparities as seed points for the Cf/Ca–An matching, yielding a better height resolution of 160 m.

The blockiness in the heights is caused by discontinuities in the retrieval of the cloud-motion vectors at 70.4-km resolution. The wind retrievals are particularly challenging because of operational constraints (processing time) and the wide variations in view angles. The most oblique images can look very different from the nadir ones, especially when thin high clouds are present, making pattern matching from the D to the B to the An cameras quite difficult, and the much larger search window (set to accommodate the entire range of possible values in both wind and height) also makes the choice of the best match much more difficult. Multilayer scenes prove to be a particular challenge for the wind retrieval because



(a) (b)

Fig. 5. A mixed layer, mid-latitude cloud example (MISR path 201, orbit 3846, blocks 43–51). (a) Nadir radiances (red band). (b) Operational cloud-top heights.

a layer can be practically transparent in the nadir view and quite opaque in the more oblique ones. The magnitude of the blockiness is difficult to quantify because it is directly related to the wind measurements in those domains where the quality of the winds is poor to begin with. Jumps in cloud-top heights from one domain to the next of up to 3000 m have been observed. This is much greater than the per-pixel height resolution of 550 m.

The currently employed stereo matchers (M2 and M3) also lack a completely satisfactory blunder detection capability, which leads to areas of noisy retrievals on occasion. A prescreen for areas of low contrast is performed prior to beginning height retrieval, but it is difficult to accurately set a contrast threshold that will work for all cases. In addition, no postprocessing is done on the height values once they are retrieved other than comparing the heights retrieved from Af–An and Aa–An matching on a pixel-by-pixel basis. While running M2 and M3, a threshold cut is applied to the magnitude of differences in the patches surrounding prospective matches. Research has shown that this threshold removes a lot of obvious blunders, but it is difficult to assign a global threshold that works for all scene types [8].

VI. SUMMARY

The preliminary examples presented here demonstrate that a purely geometrical technique of stereo-matching images measured at different viewing angles and times can be applied oper-

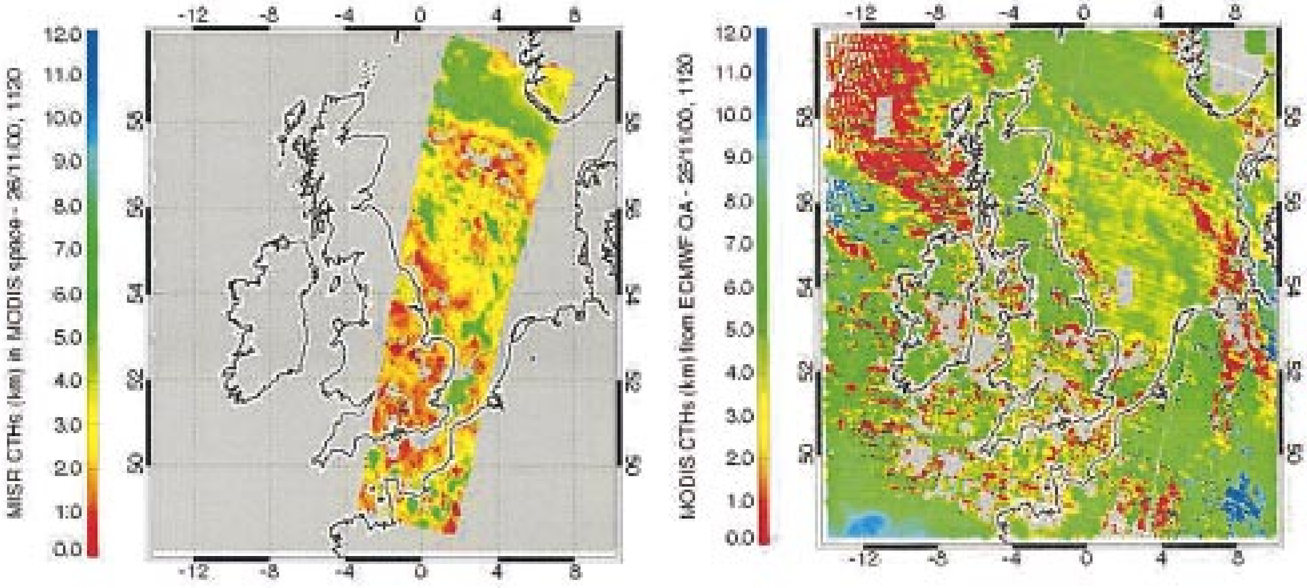


Fig. 6. A comparison of MISR and MODIS cloud-top heights for November 26, 2000. Note that a different color bar has been used in this figure.

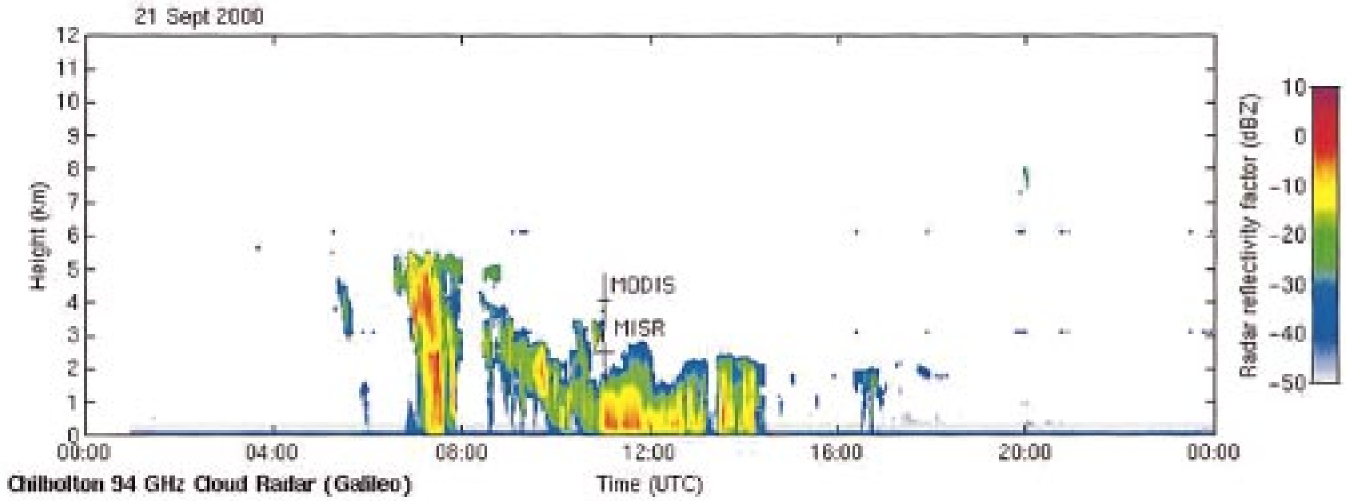


Fig. 7. Time-height cross-section of radar reflectivity at Chilbolton, September 21, 2000, showing the heights obtained from MISR and MODIS at the time of the Terra overpass.

ationally (i.e., fully automatically, with no manual intervention, and applied to the entire data set) to retrieve cloud-top heights with generally good results. Unlike conventional retrievals, this technique does not rely on the absolute value of the measured radiances, but only their relative patterns, and is thus relatively insensitive to the absolute instrument calibration. It is also able to retrieve cloud heights over snow and ice, which is a traditional problem area.

Cloud-motion winds are retrieved on a 70.4-km grid with typical accuracies of ±3 m/s, with an assigned height accuracy of ±400 m (this is the accuracy of the heights corresponding to the individual wind-vectors, not the overall height field.) Cloud-top heights, corrected for the effects of motion, are obtained operationally at a higher spatial resolution on a 1.1-km grid with a typical accuracy of ±562 m.

While the operational products generally produce very useful images, especially for thick, heterogeneous cloud scenes, and excellent orbital statistics, they also contain some blunders and can be noisy for some complex cloud scenes. Such effects are difficult to remove operationally, due to computational time constraints. However, improved images can be obtained for specific images using algorithm enhancements already developed.

As additional comparisons of MISR cloud-top heights with other satellite and ground-based measurements, as well as against "superstereo" algorithms, become available, it is anticipated that new enhancements will be added, and a probability distribution of cloud-top height errors will be established. Initial emphasis will be on trying to improve the wind retrievals to alleviate some of the height blockiness and on implementing a more robust blunder detection algorithm.

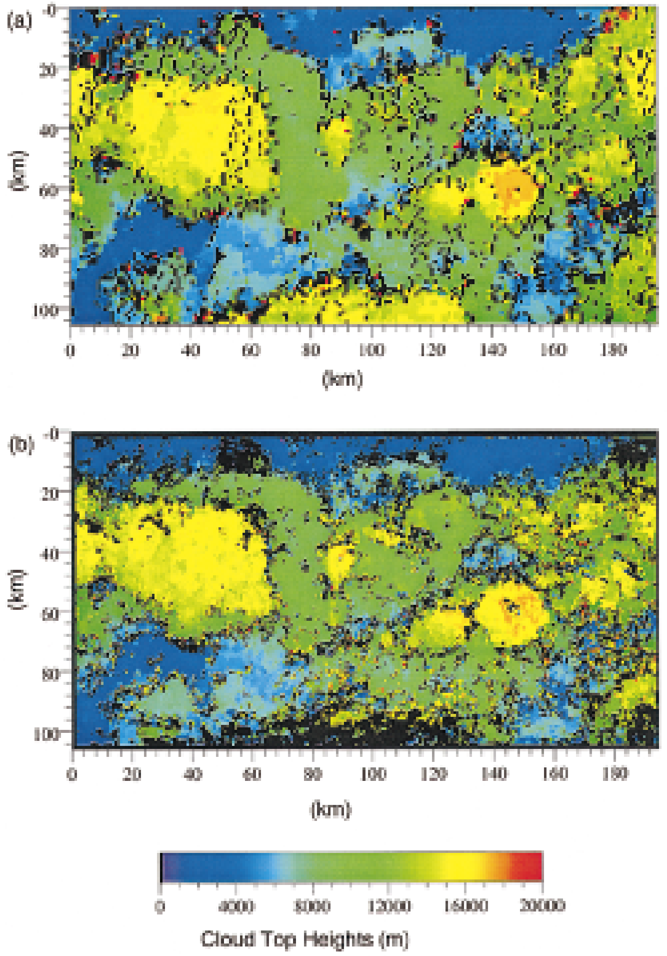


Fig. 8. Example of (a) standard and (b) enhanced processing results for cloud-top height retrievals. MISR path 090, orbit 3708, block 85.

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