

Abstract

The paper explores the possibility of implementing an advanced photogrammetric technique, generally employed for satellite measurements, on airglow imager, a ground-based remote sensing instrument primarily used for upper atmospheric studies, measurements of clouds for the extraction of cloud motion vectors (CMVs). The major steps involved in the algorithm remain the same, including image processing for better visualization of target elements and noise removal, identification of target cloud, setting a proper search window for target cloud tracking, estimation of cloud height, and employing 2-D cross-correlation to estimate the CMVs. Nevertheless, the implementation strategy at each step differs from that of satellite, mainly to suit airglow imager measurements. For instance, climatology of horizontal winds at the measured site has been used to fix the search window for target cloud tracking. The cloud height is estimated very accurately, as required by the algorithm, using simultaneous collocated Lidar measurements. High-resolution, both in space and time (4 min), cloud imageries are employed to minimize the errors in retrieved CMVs. The derived winds are evaluated against MST radar-derived winds by considering it as a reference. A very good correspondence is seen between these two wind measurements, both showing similar wind variation. The agreement is also found to be good in the both zonal and meridional wind velocities with RMSEs $< 2.4 \text{ ms}^{-1}$. At the end, the strengths and limitations of the algorithm are discussed, with possible solutions, wherever required.

1 Introduction

Clouds play a vital role in the Earth's hydrological cycle and also as "atmospheric blankets" because of their shortwave scattering and longwave absorption of radiation. It is, therefore, highly essential to monitor the clouds and their motion on a continuous basis, which is being done primarily by geostationary meteorological satellites (Leese et al., 1971; Hutchison et al., 1995; Jolivet and Feijt, 2003; Glantz, 2010; Escrig et al.,

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2013). The capability of continuous monitoring of clouds by these satellites has been utilized to retrieve the cloud motion vectors (CMVs), by considering clouds as tracers of wind. Satellite-derived CMVs are extremely helpful in understanding synoptic-scale atmospheric dynamics and circulations and now have become potential input parameters to numerical weather prediction models (Menzel, 2001; Thies and Bendix, 2011, and references therein).

There is a tremendous progress in retrieval techniques for CMVs and their utilization for operational usage in the last few decades. The retrieval techniques advanced from a simple cross-correlation analysis in the beginning (Fujita, 1968; Izawa and Fujita, 1969; Leese et al., 1971; Hubert and Whitney, 1971) to those involving very advanced photogrammetry and satellite imagery analysis in recent times for obtaining CMVs with higher precision (Schmetz et al., 1993; Velden et al., 1997; Kishtawal et al., 2009; Deb et al., 2013; Kaur et al., 2015, and references therein). First level unrefined knowledge about a cloud element can be obtained from the cloud top temperatures, retrieved by Thermal infrared (IR) channel. This is the most commonly used means for CMV estimation, even to this day. However, tracking of low clouds (> 700 hPa) will be difficult with IR measurements, because the low cloud top apparent temperature becomes so close to the surface temperature that the images lack contrast between the cloud and ground levels. Also, the geostationary satellites observe only cloud tops and, therefore, may not be able to detect the multilayered clouds, i.e., for instance a low-level cloud located beneath a high-level cloud.

In this regard, ground-based instrumentation with a large field of view would augment satellite cloud observations (Seiz et al., 2002; Pfister et al., 2003; Souza-Echer et al., 2006; Smith and Toumi, 2008; Liu et al., 2013; Klebe et al., 2014). Such augmentation improves vertical distribution of clouds, albeit at the measurement locations. These sky-imaging devices (eg., Whole-sky imager, Total-sky imager, All-sky imager, etc.) are automatized to achieve real-time hemispheric sky images and cloud fraction (Long et al., 2006; Yang et al., 2012; Kazantzidis et al., 2012).

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Among these imagers, the airglow imager is designed primarily for monitoring emissions from the Mesosphere and Lower Thermosphere (MLT) with good spatial and temporal resolutions. The invent of commercial solid state imaging arrays in the eighties revolutionized airglow imaging observations and in resolving many technical issues in the image processing, such as long-lasting bands, transient short scale ripples, superimposed transversely propagating waves, airglow depletions (Taylor et al., 1995; Batista et al., 2000) and MLT dynamics, such as mesospheric wave signatures and gravity wave seeding of equatorial plasma bubbles (Taori et al., 2013, and references therein). Since, it is an optical device; the measurements are confined only to clear-sky and new moon periods. Nevertheless, its capability to observe clouds on a continuous basis provides an opportunity to derive the CMVs.

The main aim of the present article is to demonstrate the capability of an air-glow imager, developed recently at National Atmospheric Research Laboratory, Gadanki (13.45° N, 79.18° E), for deriving the CMVs, thereby extending its utilization to the lower atmosphere. In this article, an attempt has been made to adopt the advanced photogrammetry, image processing techniques and satellite CMV retrieval algorithms and implement on ground-based optical imager measurements to obtain the CMVs. The paper includes 6 sections, describing the instrumentation and database (Sect. 2), study region (Sect. 3), the algorithm and its implementation on a case study (Sect. 4) and validation of the technique (Sect. 5). The strengths and limitations of the technique employed here are also discussed in Sect. 5. The results are summarized in Sect. 6.

2 Instrumentation and database

The cloud imageries used in the present study are obtained from an airglow imager located at Gadanki. The imager uses a circular medium format F/4 Mamiya fish eye lens having a focal length of 24 mm. At peak wavelengths of 558 and 630 nm, it measures mesospheric O(¹S) and thermospheric O(¹D) emissions, respectively, while a wide-band 800–900 nm filter for mesospheric OH emission. For observing clouds, OH fil-

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have been done on the data to remove spurious outliers, if any exist, following Tsuda et al. (2006). First, the median and standard deviation (SD) of winds for each season are generated. Each profile in this season is then checked for seasonal consistency, i.e., whether or not it falls within 1 SD of median profile. Profiles that are consistent with the seasonal pattern (i.e., those satisfy the above condition) are only considered further for developing the climatology of zonal and meridional winds.

The MST radar at Gadanki is a highly sensitive pulse-coded coherent VHF phased array radar, operating at 53 MHz with an average power aperture product of $3 \times 10^{10} \text{ W m}^2$. Complete technical and system specifications of the MST radar are given in Rao et al. (1995). The routine operation of MST radar for troposphere employs 6 beams for obtaining winds and turbulence parameters at 4 min and 150 m temporal and vertical resolutions, respectively. Important specifications of MST radar and different types of Lidars are given in Table 1.

Though the above remote sensing instruments are in operation for more than a year, but simultaneous measurements of all instruments are available only for few days (7 days) for the following reasons. During the rain, it is not possible to operate both airglow imager and Lidar. The laser beam cannot penetrate the low-level thick clouds and therefore is generally switched off whenever the low cloud persists. On many days, these instruments are in operation for some other experiment in a different mode. For instance, the airglow imager is in operation for MLT studies or MST radar is in operation for ionosphere or convection studies. Since the present article mainly aims to demonstrate the applicability of a satellite technique to a ground-based remote sensing device for deriving CMVs, the number of existing cases (7 days) is sufficient.

3 Study region and background meteorology

Gadanki (~ 375 m above the mean sea level) is located in a remote tropical environment in southern peninsular India, at about 90 km away from the East Coast (Fig. 1). It is located in a complex hilly terrain with hill heights varying in the range of 300–1000 m.

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This region receives rainfall from two major monsoon seasons, namely southwest monsoon (June–September) and northeast monsoon (October–December), besides pre-monsoon/summer (March–May) thunderstorms (Rao et al., 2009). Nevertheless, it receives an annual rainfall of only ~ 750 mm, as it is in the rain shadow region (east of Western Ghats). But different types of clouds, originated from a variety of processes, pass over this location frequently (Gadanki is covered with clouds for about 60–70 % of time) (Fig. 1).

Since a priori climatological wind information minimizes the error in retrieved CMVs, wind climatology is built from 6 years of GPS radiosonde observations. Figure 2 shows vertical profiles of mean zonal and meridional winds (solid line) along with SD (error bars) and maximum and minimum (dash-dot lines) winds within the season. Clearly, strongest winds (predominantly easterlies) are observed during the main rainy season for this region, southwest monsoon, in the upper troposphere. These strong winds, popularly known as Tropical Easterly Jet (TEJ), with a peak at 16 km are an integral part of monsoon circulation. The predominant occurrence of cirrus during the monsoon season is ascribed partly to TEJ, which sweeps the cirrus from neighbouring deepest convective regions and spreads over the entire peninsular India (Das et al., 2011). Although the mean zonal wind is small in other seasons, often it exceeds 15 ms^{-1} during the winter and early summer, mainly due to the intensification of upper tropospheric subtropical troughs. The meridional winds are generally weak with monthly mean values $< 5 \text{ ms}^{-1}$. The monthly mean meridional velocities show southerlies in the middle and upper troposphere in all seasons, except for the monsoon. From the range of wind variation (minimum to maximum winds) and the SD, it is clear that the winds are steady and strong during the monsoon season. On the other hand, the winds vary considerably in other seasons, even they change the direction.

4 Description of the algorithm and its application on a case study (17 April 2012)

This section describes the method adopted for the retrieval of cloud motion with the help of airglow imager data collected on 17 April 2012. In fact, a variety of retrieval techniques for CMVs using satellite brightness temperatures (from thermal satellite imagery) are now available (Kishtawal et al., 2009; Deb et al., 2013; Kaur et al., 2015, and references therein). The present algorithm adopts one such retrieval technique for the estimation of CMVs and modifies it to suit airglow imager observations. In the following subsections, the major processing steps involved in the algorithm are discussed in detail.

1. Image processing to remove the noise, enhancing the image and identifying the target cloud.
2. Estimation of cloud height and pixel width.
3. Estimation of cloud movement using a cross-correlation technique and CMVs.

Figures 3–5 show the output of each of the above processing steps.

4.1 Image processing and target cloud identification

The first and most important step of the algorithm is to process the image for better identification of the target cloud. The image processing involves correction of coordinates, removal of noisy structures (like stars), improving the image contrast for better visualization of target elements (clouds in our case) (Fig. 3). The original 512×512 pixel images are cropped to 256×256 pixels to remove the pixels that are affected by the housing of the airglow imager (Taori et al., 2013) (Fig. 3b). The cropped image corresponds to 90° circular field of view. During the measurements, the boundaries of the instrument roof were marked by the directions identified by the magnetic compass, which

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appears to be reversed along N–S directions in the raw images. Hence the cropped images are flipped vertically so as to correct for geographical coordinates. We enhanced the image contrast by using Gray-Level Histogram method (Otsu, 1979). This involves mapping the intensity values on gray scale image to new values such that 1 % of data is saturated at low and high intensities of the image. This increases the contrast of the output image (Fig. 3c). The appearance of stars and other galactic objects in the image caps the cloud structures and decreases the image SNR. These “noisy” structures need to be removed before identifying the target cloud(s) in the image. These bright objects (stars and clouds) are detected using an edge detection technique.

Edge detection is one of the very basic concepts used for image processing to identify the target elements. The edge detection techniques are basically of two types; gradient-based and Laplacian-based techniques (Argyle, 1971; Grimson and Hildreth, 1985; Torre and Poggio, 1986; Canny, 1986). While the former detects the edges from the gradient (first derivative) of pixel intensities, the later detects edges from zero crossings in the second-order derivative of pixel intensities. Canny edge-detection method (Canny, 1986), which follows the gradient method with the following optimization criteria, has been used in the present study.

1. Minimizing the incorrect marking of non-existing edge points and missing the real edge points, i.e., good detection or low error rate.
2. The distance between the detected and the actual edge pixels should be minimized, i.e., good localization.

To avoid small statistical fluctuations in pixel intensities being detected as target elements or noisy structures, the image is smoothed using the Gaussian smoothing filter. The algorithm then estimates the spatial derivative of pixel intensities and this gradient matrix is subjected to hysteresis analysis to identify the edges. Hysteresis uses two thresholds, a high and a low. Any pixel in the gradient matrix that has a value greater (lower) than high (low) threshold is identified as (not) an edge pixel. The pixel is also treated as an edge pixel, if it has a value between the two thresholds and is connected

are examined for their continuity. In other words, the successive CBH measurements should not vary by more than 300 m. Figure 4a shows the temporal variation of CBH retrieved from the photon counts of boundary layer Lidar during 21:40–22:04 IST. Once the height of cloud is known, the estimation of pixel width is simple. Since the angle subtended by the cropped image at the location of measurement is 90° , the pixel width at different altitudes can be estimated by a simple mathematical relation,

$$\text{Pixel width} = R \cdot \tan(45)/128,$$

where R is the height of cloud base. The vertical variation of pixel width estimated from the above relation is shown in Fig. 4b.

4.3 Tracking the target cloud and the estimation of CMV

Tracking the target cloud is very essential for the estimation of CMV. Three factors are crucial in tracking the target cloud and dictate the accuracy of CMV: search window, temporal resolution between the images and identification of the same cloud in successive images. To reduce the computational load and to avoid other clouds or noisy structures, if any remain, entering into the area of interest; it is a common practice to track the target cloud in a smaller search domain in successive images. While the large target window allows other unwanted noisy structures enter into the search domain, too small window increases false alarms (Bresky et al., 2012). Conventionally, wind guess (WG) information supplements this exercise and to set the coordinates of smaller windows in the later image before matching (Velden et al., 1997; Bedka and Mecikalski, 2005; Bresky et al., 2012). In the present study, the horizontal wind climatology discussed in Sect. 3 is used to set the search window. The time interval between successive images has a significant impact on the quality of the derived CMVs. Though satellites generally use 30 min intervals to derive the CMVs, earlier studies have shown that a temporal gap of 5 min for 1 km pixel size would produce largest number of valid motion vectors (Garcia-Pereda and Borde, 2014). The time interval between the successive images in the present study is 4 min, which is nearly equal to the optimum

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5 Discussion

It is important and necessary to evaluate the performance of any new algorithm or technique or instrument as it gives credibility to the final product. A similar exercise has been done, in which CMVs derived from all the cases were compared against a reference. In the present study, MST radar-derived winds measured simultaneously are taken as a standard reference for comparison. Figure 7 shows the comparison of zonal and meridional winds as derived by both air-glow imager (CMVs) and MST radar. Clearly, the airglow imager-derived winds show good correspondence with radar-derived winds in both zonal and meridional components with similar variations. Even the wind magnitude matches well between the two datasets with root mean square error (RMSE) values $< 2.25 \text{ m s}^{-1}$. The agreement is much better in the zonal component (RMSE is 1.60) than in meridional (RMSE is 2.24). It appears from Fig. 7 that there is no bias in airglow imager-derived winds and the difference between the wind estimates is due to statistical error.

Although the performance of the algorithm is fairly good and the technique is having several advantages (like better temporal resolution, pixel resolution, etc.), but it also suffers with the following drawbacks. (i) Since the airglow imager is an optical instrument, observations are limited to non-rainy days. (ii) Though the imager detects the target cloud and tracks it, but it will not be able to estimate the height of the target cloud. As discussed above, CBH information is crucial not only for assigning the derived winds to that height, but also to estimate the pixel width (Fig. 4b) and thereby the cloud displacement for CMV estimation. Though we used a Lidar for obtaining CBH as those measurements are readily available, it is a costly proposition. A ceilometer would suffice the purpose. (iii) The limited field of view imposes a limit on the applicability of the algorithm to certain clouds. Since the algorithm needs isolated clouds for tracking, the clouds with dimensions much less than the field of view of the imager can only be used as target clouds. (iv) As the cloud is not a frozen body but an evolving system, the cloud boundaries do change with time. Since the time interval between two successive

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images is only 4 min, the changes may not be significant and ignored. But during a period of few 10's of minutes, the periods typically used in satellite retrievals of CMVs, the cloud appearance can change significantly (Fig. 5). It reiterates the requirement of small interval between the successive images and proper selection of target cloud (rapidly evolving clouds should not be considered as target clouds) for better extraction of CMVs.

6 Summary

The present study utilizes the 865 nm channel of the airglow imager to take high-resolution images of clouds. These bi-products of airglow imager have been used to estimate CMVs by adopting advanced satellite retrieval algorithms and implementing them, after suitable modifications, on airglow imager-derived cloud imageries. The present article describes the algorithm and implementation steps adopted while deriving the CMVs. The images are first processed with advanced image processing tools and later detected the target cloud within the image. Climatological wind profiles developed from GPS radiosonde data have been utilized for fixing a proper search window to minimize the errors. The tracking of target cloud from sequential images has been done by subjecting 2-D cross-correlation on the successive images. The displacement of cloud due to the horizontal wind in both east–west and north–south planes is identified from the lead/lag position of maximum correlation. To convert the cloud displacement from number of pixels to distance and to assign the derived winds to a height, accurate estimation of cloud height is essential. High-resolution measurements of collocated Lidar were used for this purpose. The derived winds are then evaluated against a reference (MST radar-derived winds in the present study). Good correspondence is seen between the two measurements of wind (airglow imager and MST radar), as both of them show similar variation. The magnitude of wind also matches well with the reference wind (obtained by the MST radar) with a small RMSE ($< 2.4 \text{ m s}^{-1}$). The

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strengths and limitations of the algorithm are highlighted with possible solutions, whenever required.

Acknowledgements. The ISCCP D2 image (Fig. 1) is generated from the International Satellite Cloud Climatology Project (web site <http://isccp.giss.nasa.gov>), maintained by the ISCCP research group at the NASA Goddard Institute for Space Studies, New York.

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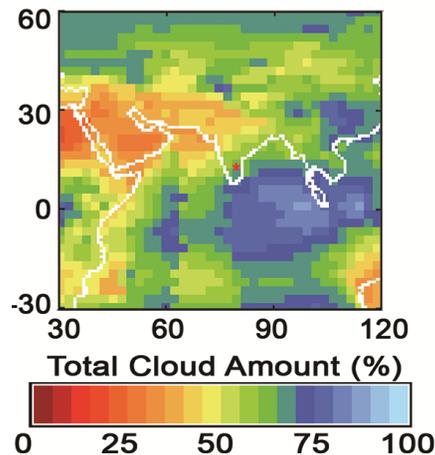


Figure 1. Average cloud cover (in terms of % of occurrence) over India. The cloud cover data are generated by International Satellite Cloud Climatology Project (ISCCP) from the day and night measurements of polar orbiting satellites made during 1983–2009. The star denotes the location of Gadanki (13.45° N, 79.18° E). (Courtesy: <http://isccp.giss.nasa.gov>; Reference for ISCCP data product descriptions: Rassow and Schiffer, 1999.)

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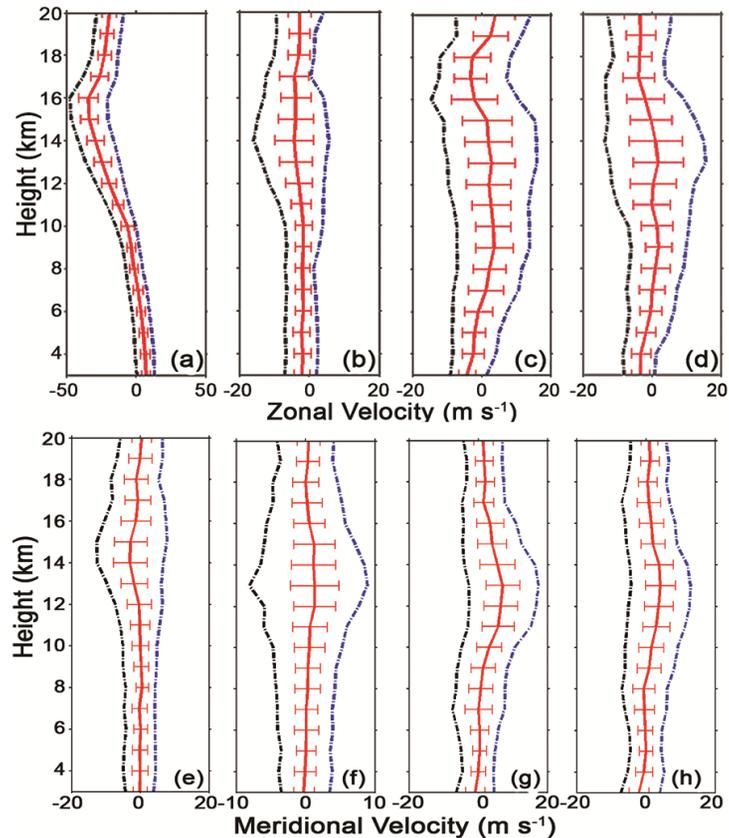


Figure 2. The seasonal mean (a–d) zonal and (e–h) meridional winds (solid line) for southwest monsoon, northeast monsoon, winter and summer seasons, respectively. Also shown are the SD as error bars and the range of wind velocities (minimum and maximum winds as dash dot lines) within the season.

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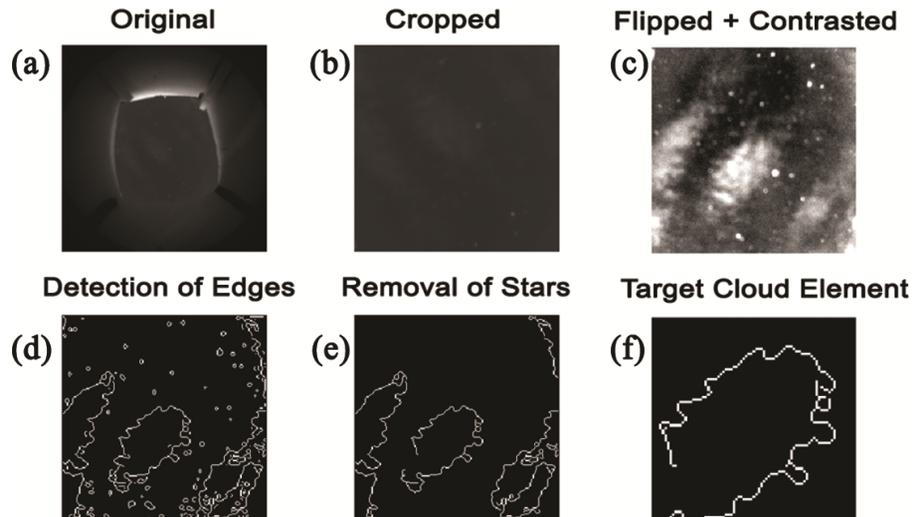


Figure 3. Various processing steps involved in identifying the target cloud. **(a)** The original image having 512×512 pixels, **(b)** the cropped image having 256×256 pixels, **(c)** the image corrected for geometric coordinates and later enhanced using gray-level histogram method, **(d)** the contours of high intensity identified by using Canny method of edge detection, **(e)** the cleaned cloud image after the removal of stars and noisy structures and **(f)** the target cloud.

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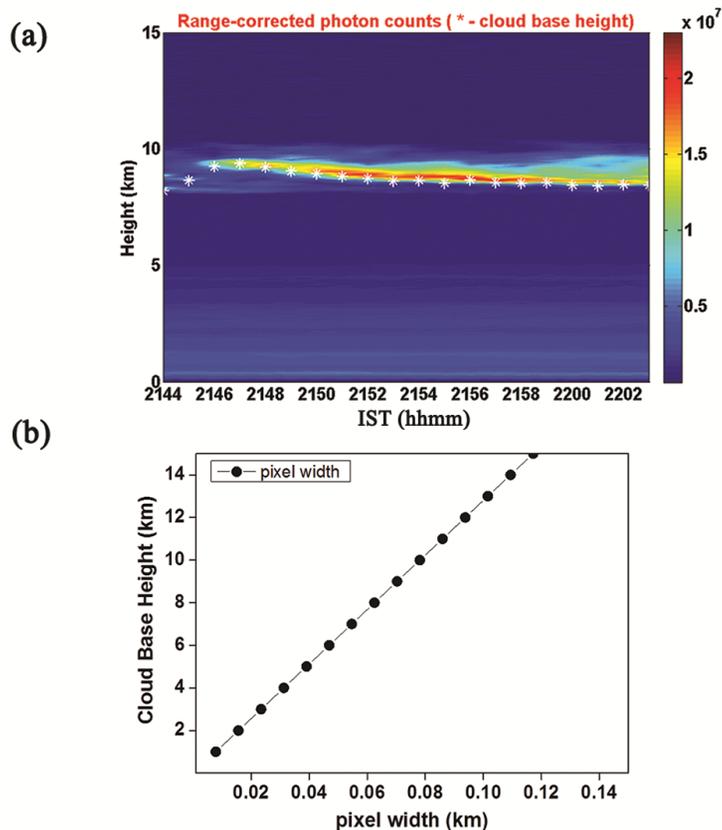


Figure 4. (a) Height–time variation of range corrected photon count (shading) showing the CBH variation (white stars) on 17 April 2012. (b) Vertical profile of pixel width calculated using the CBH.

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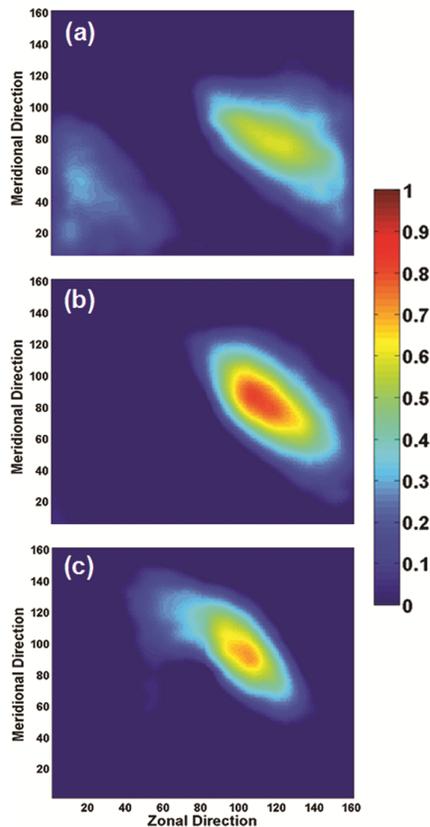


Figure 6. Images showing the output of 2-D cross-correlation between the sequential images **(a)** 21:44–21:48 IST **(b)** 21:48–21:52 IST and **(c)** 21:52–21:56 IST.

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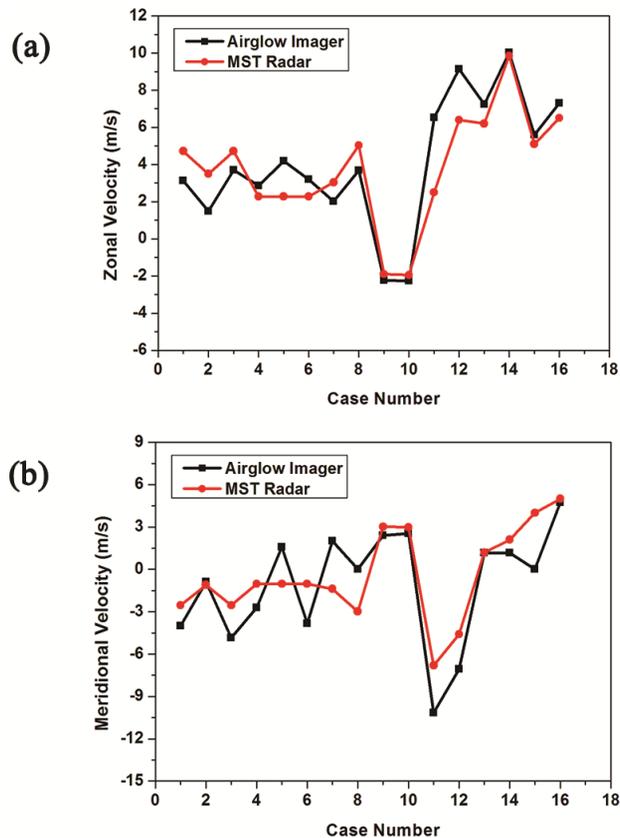


Figure 7. Comparison of (a) zonal and (b) meridional wind velocities derived by airglow imager and MST radar.