Convective thundercloud development over the Western Ghats mountain slope in Kerala

R. Vishnu[1,*], V. Anil Kumar[2], Hamza Varikoden[2], K. Sarath Krishnan[1], T. S. Sreekanth[1], V. N. Subi Symon[1], S. Murali Das[1] and G. Mohan Kumar[1]

[1]Centre for Earth Science Studies, Thiruvananthapuram 695 031, India
[2]Indian Institute of Tropical Meteorology, Pashan, Pune 411 008, India

Studies were carried out on the data from Braemore mountain observatory (lat. 8°45′N, long. 77°5′E) using a single-lens ceilometer (LIDAR), an electric field mill and a portable automatic weather station throughout the year 2010. The simultaneous data collected using the above instruments indicate the existence of strong updrafts followed by the formation of thunderclouds, a characteristic of the mountain slopes, during the thunderstorm months. Changes in atmosphere related to condensation and formation of water droplets during updraft events on the mountain slope could be detected from the ceilometer scattering data. Results of the study point to the cause of relatively more thunderstorm activity in that zone. This seems to be due to excessive updraft, which is strongly related to lightning activity in the region.

Keywords: Convective Cbs, disaster, lightning, mountain weather, updraft.

LIGHTNING is a transient, high-current electrical discharge observed in nature. It occurs when some region of the atmosphere attains an electric charge sufficiently large that the electric fields associated with the charge cause electrical breakdown of the air. Lightning is caused by cumulonimbus clouds (Cb) and the cause of lightning is linked to cause of Cb formation. In India, Kerala is known to have relatively high rate of lightning flashes[1,2]. Ranalkar and Chaudhari[3] also observed that the spatial distribution of lightning flash density is high over southern peninsular India, especially over Kerala during pre-monsoon periods.

Diurnal variations of lightning activity over the Indian region were studied by Kandalgaongar *et al.*[4]. They found two peaks – the first at 10:00 UTC and the second at 16:00 UTC. Several other studies have been conducted in the rest of the world, e.g. Oladipo and Mornu[5] over Nigeria, Maier *et al.*[6] over Florida, Williams and Heckman[7] over Australia and Finke and Hauf[8] over southern Germany. All these studies reveal that the diurnal peaks in different regions were different and this was due to the mesoscale circulation over the region and the influence of topography[9,10]. However, the spatial and temporal distribution of lightning incidence in Kerala is different during different seasons. From the analysis of 17 years of lightning incidents over Kerala, it was found that 83% of the total lightning incidents are in the evening hours[11] between 15:00 and 19:00 h. This is supported by the observations of Hamza *et al.*[12] that the cloud frequency in the region during pre-monsoon season is more between 15:00 and 19:00 h. These observations are significant in that the clouds which form in the afternoon hours are mostly convective clouds[13–17].

Kerala has a maximum width of 120 km and lies in the northwest southeast direction. It is bounded on the western side by the Arabian Sea and on the eastern side by the Western Ghats mountain range. The Indian Ocean is on the southern side of the state. Murali Das *et al.*[11] observed that in Kerala, lightning incidences are more in the midlands and less in the mountain and coastal regions. Also, incidences are less in the region west of Palakkad gap, where there are hardly any mountains. Based on these characteristics, they deduced the possible role of the Western Ghats in aiding convective Cb formation causing high lightning occurrence in the state. Studies by Vishnu *et al.*[18] point to the possibility of the Western Ghats mountain weather being instrumental in the formation of thunderclouds. With this background, a study to understand the possible convective thundercloud formation and its characteristics over the location was carried out using a ceilometer, an electric field mill (EFM) and an automatic weather station (AWS). Results of the study are presented and discussed here.

Materials and methods

A high-altitude field station was set up at Braemore (lat. 8°45′N, long. 77°5′E) in Thiruvananthapuram district, Kerala. Figure 1 shows the location map of the field station. The station is at an altitude of about 400 m amsl at a radial distance of about 40 km from the coast. Physiography map of Kerala and location of the state in South India are also shown separately in the figure. It has been reported that the terrain slope will influence convective thundercloud formation over mountain slopes with the

*For correspondence. (e-mail: vishnuplr@gmail.com)

arrival of sea breeze[19,20]. Braemore is on the western slope of the Western Ghats mountains, where the possibility of orographic lifting exists. This is because the slope increases gradually in the direction of sea breeze from 5° to the horizontal at 20 km inside the coast, to 30° to the horizontal at 45 km (*Resource Atlas of Kerala*[21]). At 45 km inside the coast, the altitude increases to 300 m.

The field station had three types of equipments – an AWS, a laser ceilometer and an EFM. AWS had sensors for measuring air temperature (AT), relative humidity (RH), pressure (P), wind speed (WS), wind direction (WD) and rainfall (RF). The AWS was programmed for collecting data every 10 min as the phenomenon to be studied has a timescale of the order of 1 h (ref. 14). Table 1 gives sensitivity/resolution, range and accuracy of the weather elements monitored. An EFM was designed and fabricated to measure the electric field due to charged Cb. It was calibrated for fields up to ± 2778 V/m and the average sensitivity was 0.75 V/1000 V/m. The sampling interval of data acquisition was 1 min. In addition, a ceilometer which provides cloud base height (CBH) information and sky condition was deployed to understand the behaviour of atmosphere during the updraft events leading to cloud formation. It employs the LIDAR technique for measurement. The operating principle is based on the measurement of the time needed for a short pulse of light to traverse the atmosphere from the transmitter of the ceilometer to a backscattering cloud base and back to the receiver of the ceilometer. For the present study, ceilometer was configured to measure CBH every 2 sec. In its normal full-range operation, the ceilometer digitally samples the return signal and provides a vertical resolution of 5 m from ground to a maximum distance of 7.5 km. Specifications of the transmitter and receiver of the ceilometer used are shown in Table 2.

As more than 60% of lightning in the state is reported during the pre-monsoon period[11], data were collected from the high-altitude station during March–May. AWS

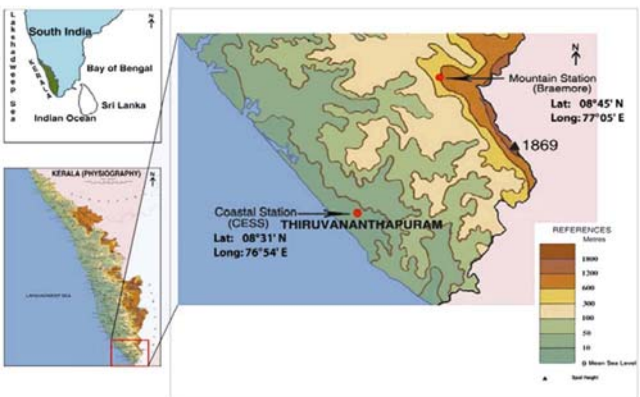

Figure 1. Map showing the location of the mountain station at Braemore and the coastal station at Thiruvananthapuram (Cetnre for Earth Science Studies).

and ceilometer data were also collected simultaneously from a coastal station, namely Centre for Earth Science Studies (CESS), Thiruvananthapuram. The location of CESS is also shown in Figure 1.

Results and discussion

As mentioned above, simultaneous data collected from AWS, ceilometer and EFM on several thunderstorm and normal days were analysed. Personal observations were also made to get a better understanding of the weather prevailing over the location during the thunderstorm days. Simultaneous measurements taken on a typical thunderstorm day are discussed in the following subsections.

Measurements made on 9 May 2010, a typical thunderstorm day

From personal observations, it was found that the sky was clear till around 11:00 h on 9 May 2010. Sky condition shown by the ceilometer also indicated ‘clear sky’ during this time. Figure 2 shows the AWS data recorded on 9 May 2010. As described by Vishnu *et al.*[18], an updraft event with concurrent increase in RH and decrease in AT is seen to occur between 13:50 and 15:00 h local time. The updraft event with simultaneous increase in RH is marked between the left and right edges of the rectangular box. During this time, RH registered a peak value of 92% at 14:40 h. Corresponding changes were reflected in AT and P also. For this time, WS recorded was zero. This is an indication that the vertical updraft was much stronger than the speed of horizontal wind. The speed of updraft can be 1–10 m s^{-1}, according to Houze Jr[22] and according to Moore and Vonnegut[23], it can be 4–6 m s^{-1} with a maximum greater than 10 m s^{-1}. In fact, the change in P is not a localized phenomenon. For example, heating by solar radiation in the morning every day is not detected in a P record. Therefore, the quantity of water vapour that gets lifted by this change in P as seen in the weather data is quite significant and involves several square kilometres of area. Summing up, as illustrated by Vishnu *et al.*[18], the phenomenon as seen from the variations of AT, RH, P and WS can be deduced to indicate the arrival of cold humid air over the location from below the station. Figure 3 is the wind rose diagram for April and May during the morning hours (07:00 to 12:00 h) at Braemore. It indicates that WD is perpendicular to the mountain range, i.e. the source of moisture is mainly from sea breeze originating from the Arabian Sea or the Indian Ocean. The increase in WS after 09:00 h and WD during the morning hours is coherent with the sea breeze. The angle of normal to the coastline to the azimuth is 230°. WD is between 210° and 270°, and at this period of time, WS is also high. Moreover, WS data from the coastal

Table 1. Weather elements monitored, sensitivity/resolution, range and accuracy

Weather elements	Sensitivity/resolution	Range	Accuracy
Air temperature	0.1°C	–40–+ 65°C	± 5ºC
Wind speed	0.1 m/s, 0.3 m/s at threshold	1–64 m/s	± 5%
Wind direction	1°	0–360°	± 4%
Relative humidity	1% RH	0–100%	± 5%
Rain	0.2 mm	0–9999 mm	± 4%
Pressure	0.1 hPa	880–1080 hPa	± 3 hPa
Solar radiation	–	–	–

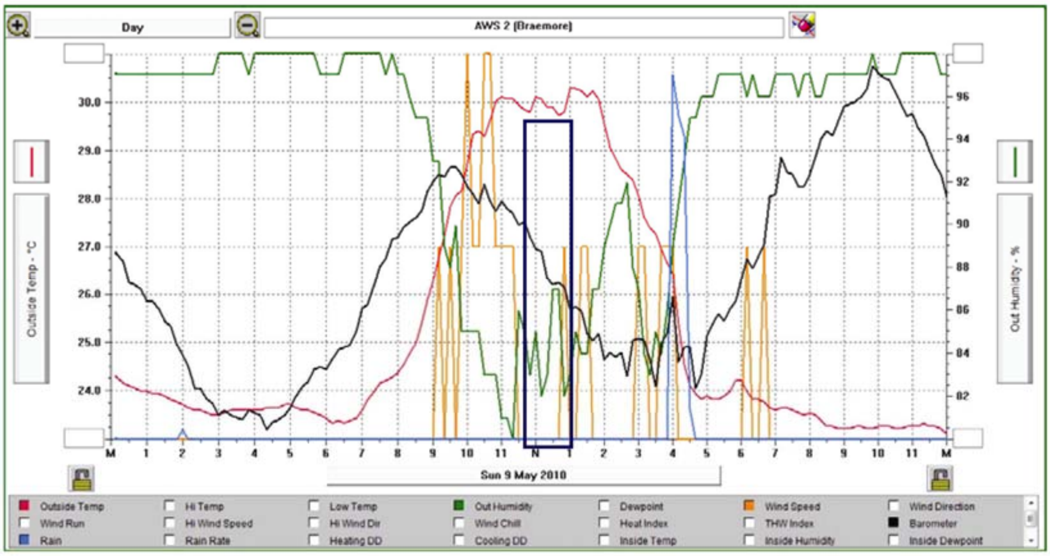

Figure 2. Screen shot of automatic weather station (AWS) data recorded on 9 May 2010 showing updraft events with simultaneous increase in relative humidity.

Table 2. Specifications of the transmitter and receiver of the ceilometer

Property	Description/value
Transmitter specifications	
Laser source	InGaAs diode laser
Centre wavelength	910 ± 10 nm at 25°C (77°F)
Receiver specifications	
Detector	Silicon avalanche photodiode (APD)
Surface diameter	0.5 mm
Receiver bandwidth	3 MHz (–3 db)
Interference filter	Centre wavelength 915 nm typical
50% pass band	36 nm
Transmissivity at 913 nm	80% typical
Field-of-view divergence	± 0.83 mrad

station on the day were also examined. As the coast is at a distance of about 40 km from Braemore, the sea breeze which sets in at about 08:00 h can reach the mountain station in about an hour. This is evident from the comparison of simultaneous WS data depicted in Figure 4. Therefore, it can be deduced that the wind at the location during daytime as indicated by the WD and WS data is the sea breeze from the Indian Ocean and the Arabian Sea. This probably is the main source of water vapour that can supply the quantity of moisture required for a Cb. As RH had already recorded values in the range 80–85%, this fast rising air can be expected to reach saturation and condense to form a cumulus cloud in the lower layers of the troposphere over Braemore.

In fact, personal observations made at the location on 9 May 2010 confirmed the formation of cumulus clouds over the station. The cumulus clouds seem to have grown into a Cb and possibly because of this, electric field variations were recorded around 16:15 h. Figure 5 depicts the electric field data recorded on 9 May 2010. The transient type of signal shown inside the circle could be due to charge build-up in the Cb formed over the station. It was noticed from personal observation that the electric field variation was accompanied by rumbles of thunder at a frequency of about 1 at an interval of 10 min. The electrical activity of clouds, followed by thunder indicates the presence of charged Cb over the nearby location. Figure 6 (detection of CBH on 9 May 2010) shows the presence of low-level clouds over the station from 11:00 h onwards. This information should be noted in conjunction with the updraft events and simultaneous changes in RH recorded by AWS. Summing up, as indicated by the data from AWS, EFM and ceilometer, the Cb seem to have formed at low heights on the mountain range location. Similar simultaneous data which indicate formation of thunderclouds at low heights over the location were obtained for almost all thunderstorm days examined during the thunderstorm months.

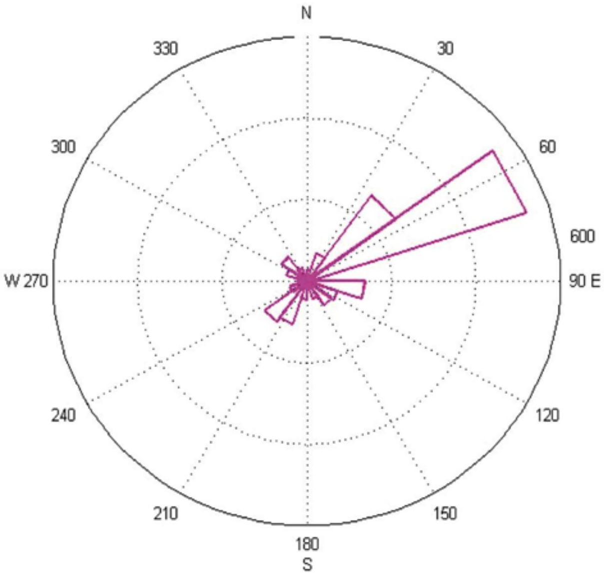

Figure 3. Wind rose diagram indicating wind direction from the coast during morning hours.

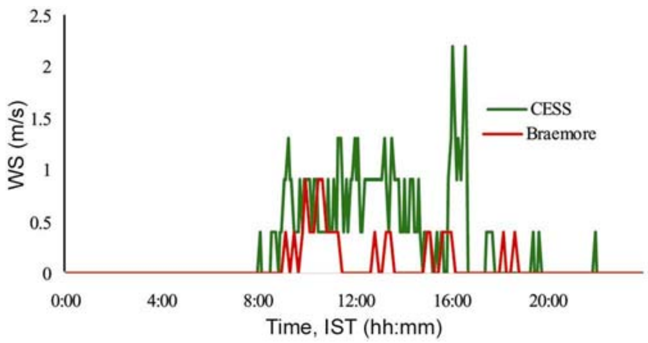

Figure 4. Wind speed (WS) data recorded at CESS and Braemore on 9 May 2010.

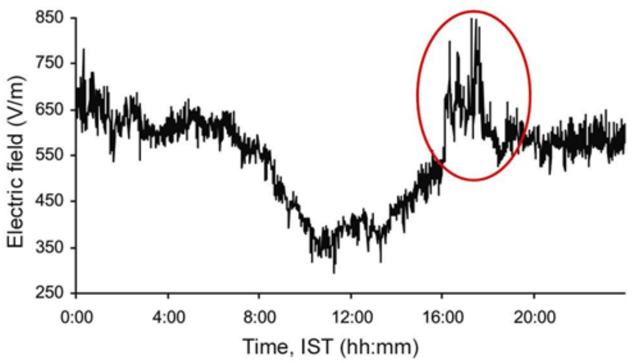

Figure 5. Electric field recorded at Braemore on 9 May 2010. Thunderstorm activity with thunder was present over the location by 16:15 h.

Analyses of ceilometer scattering data recorded on 9 May 2010

The condition of the atmosphere over Braemore as detected by the ceilometer on 9 May 2010 before and after an updraft event which led to cloud formation was studied in detail. The backscattering data were analysed by taking the mean and standard deviation (SD) of scattered signal strength to understand the changes in the atmosphere. As the scattered signal strength depends on the size of the particles in the atmosphere, the SD of the scattered values will show how much the particles are diversified. A low SD will indicate that the particles tend to be very close to the mean, whereas high SD will indicate that the particles are diversified or spread out over a large range of values. However, this exercise is valid for a given altitude only. By 12:30 h, the condition of the atmosphere changed, indicating the possibility of instability setting in. Figure 7 shows the condition of the atmosphere between 12:40 and 12:51 h as seen in the ceilometer graphical display. On the right-hand side of the display, a vertical band-like structure extending up to 7.5 km is seen. Essentially, the deep blue colour indicates stronger backscatter signal and relatively large water droplets. It was observed from many rain episodes that the deep blue colour in the ceilometer backscatter diagram indicates strong scatter signal from high-density water. Therefore, the band-like structure seen on the right-hand side of Figure 7 seems to be a vertical column of condensed water in liquid or ice phase. It is to be noted that during the time when this band-like structure was observed, WS was zero and RH reached 87%. In fact, the absence of wind is an indication that the updraft was rather heavier. Moreover, it was found that the particle size distribution changed, which is indicated by increase in SD values at that time. The SD and mean plots for two time intervals are shown in Figure 8. From 12:51 h onwards the mean

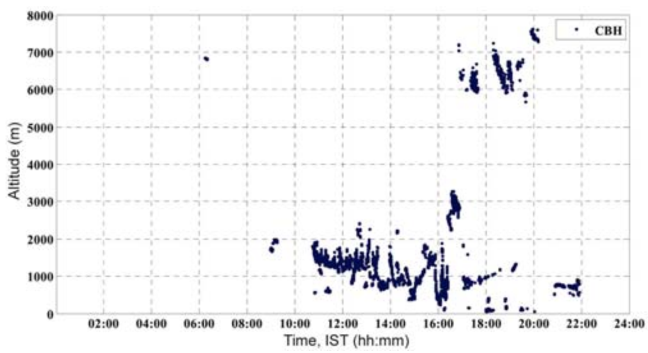

Figure 6. Ceilometer data recorded at Braemore on 9 May 2010 showing the presence of low-level clouds during noon hours. CBH, Cloud Base Height.

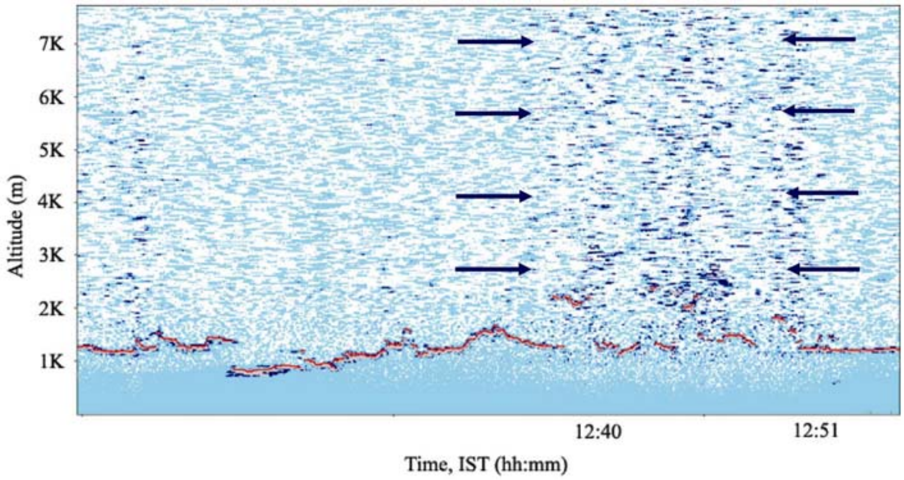

Figure 7. Ceilometer display showing particle distribution between 12:40 and 12:51 h. The vertical band-like structure between the arrows indicates the presence of water droplets.

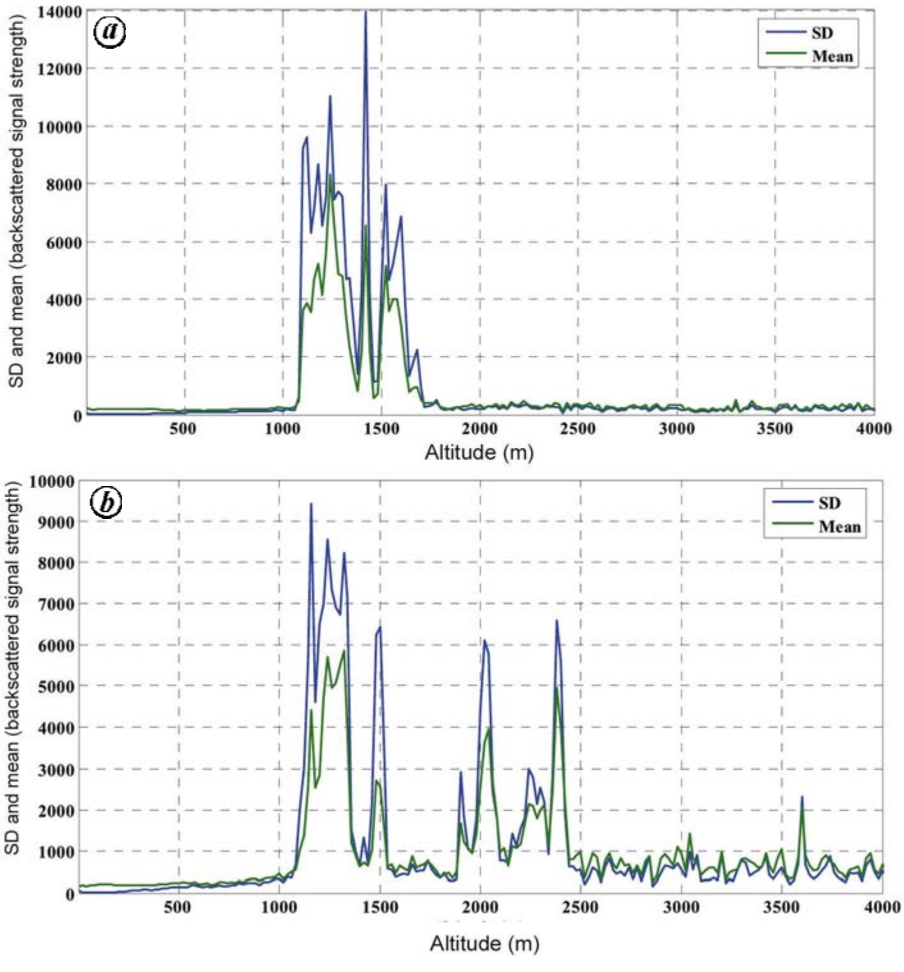

Figure 8. Mean and SD of scattering data at Braemore between 12:30 and 12:35 h (***a***) and 12:40 and 12:45 h (***b***).

value started rising and by 12:57 h it reached a magnitude of 30,000 units (Figure 9). The ceilometer display corresponding to 12:57 h is shown in Figure 10. The increase in occurrence of band-like structure can be noticed in the ceilometer display.

Summing up, the analyses of scattering data justify the argument that the updraft event with concurrent increase in RH leads to condensation and formation of clouds a few hundred metres above the Braemore station.

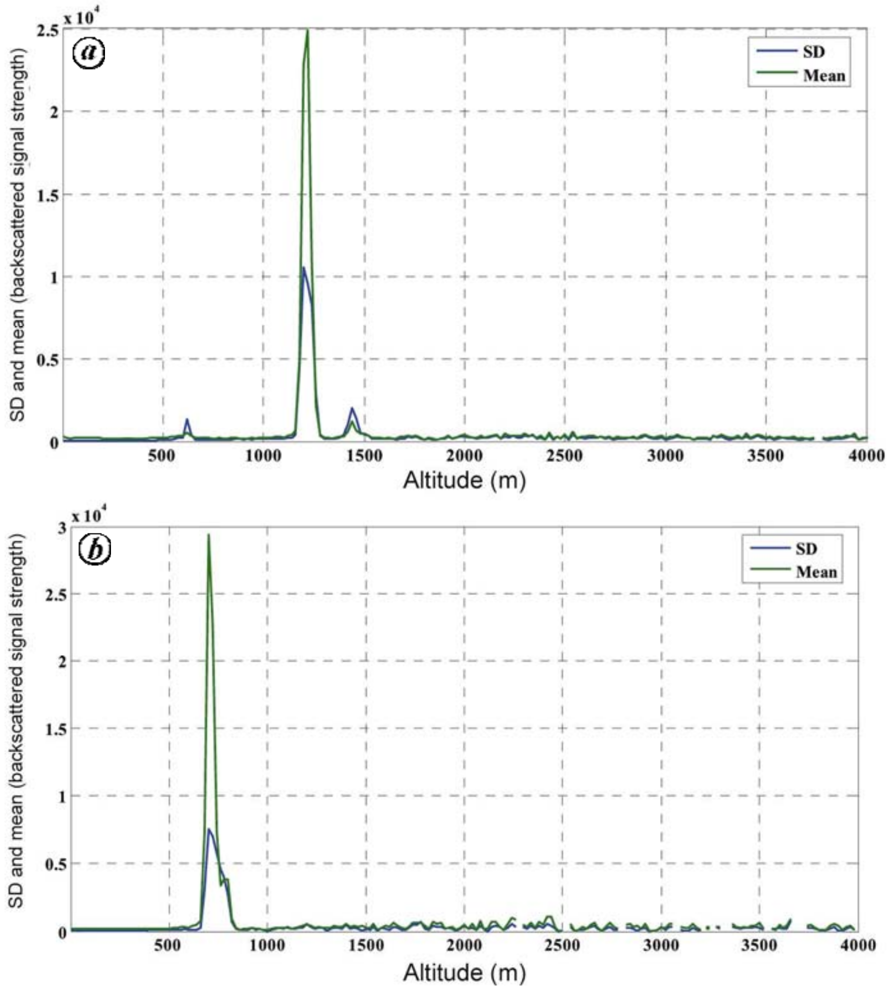

Figure 9. Mean and SD changes at Braemore between 12:51 and 12:55 h (***a***) and 12:57 and 12:58 h (***b***).

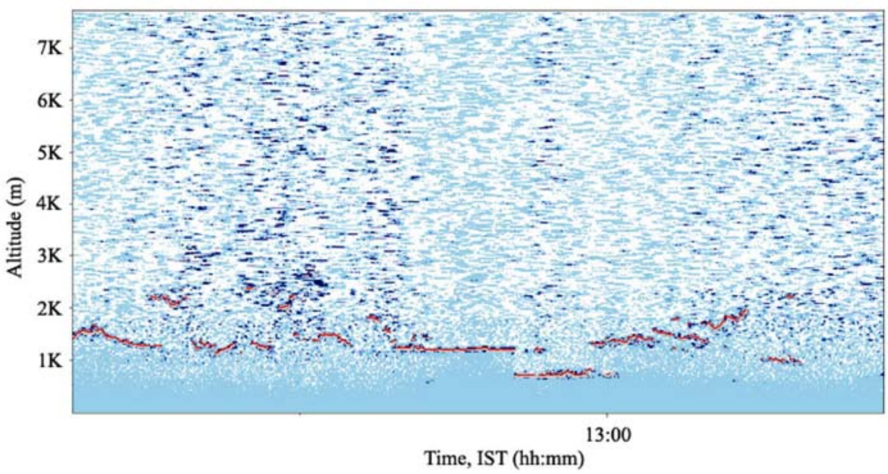

Figure 10. Band-like vertical columns corresponding to SD and mean plots of Figure 9.

Electric field measurements at Braemore

While examining the electric field data recorded at Braemore, it was noted that contrary to the expected high electric field during the evening hours of thunderstorm days, the electric field recorded was relatively less in magnitude. Figure 11 depicts the electric field measured on two thunderstorm days. On both days, the transients

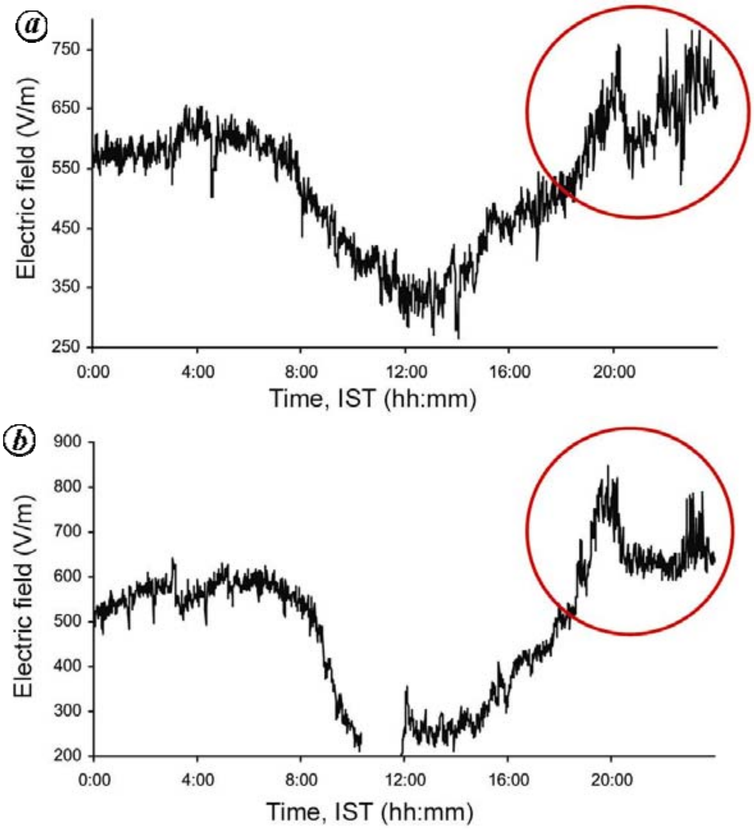

Figure 11. Electric field measured at Braemore on 7 May 2010 (***a***) and 5 May 2010 (***b***). Shown inside the circles are the transients associated with thunderstorm activity over the location.

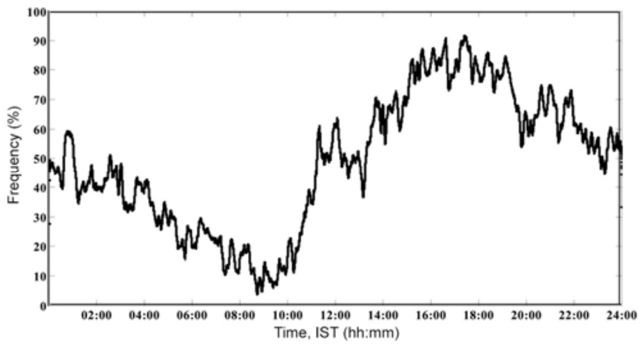

Figure 12. Diurnal variation of frequency of cloud occurrence at Braemore during the pre-monsoon season of 2010.

touched a maximum of only about 800 V/m in the evening, when high thunderstorm activity was supposed to occur due to the formation of Cb over the location. Therefore, it can be inferred that at Braemore, Cb are being formed over the location and not yet fully charged or mature at the time of measurement. During this period of measurements, the predominant upper level wind direction is northeast (i.e. towards southwest). Therefore, it seems that as the clouds form and the charging mechanism just begins, they move over to the midlands and cause more thunderstorm activities there. Indeed, this inference corroborates the observation by Murali Das *et al.*[11] that the incidence is relatively less in mountainous and coastal regions and more in the midlands.

Diurnal variation of CBH observed at Braemore

Figure 12 shows the diurnal variation of CBH at Braemore during March–May. While examining the diurnal variation during the season, it was found that the cloud occurrence increases by 10:00 h and reaches a maximum of about 90% between 16:00 and 18:00 h. Moreover, it was found that cloud occurrence was high at Braemore during the afternoon hours. This is taken as an indication of convective Cb formation over the mountain slopes. During the pre-monsoon period of 2011, CBH at Braemore and CESS was simultaneously measured. As mentioned earlier, CESS is a coastal station which is about 40 km away from the mountain station. The diurnal variation of CBH from the two stations is shown in Figure 13. As in the case of 2010, the cloud occurrence at Braemore increases after 10:00 h and reaches a maximum of 70% in the afternoon. When compared to Braemore, during the noon and afternoon hours, the frequency of maximum cloud occurrence was only about 30% at the coastal station, CESS. Therefore, from the simultaneous measurements it can be

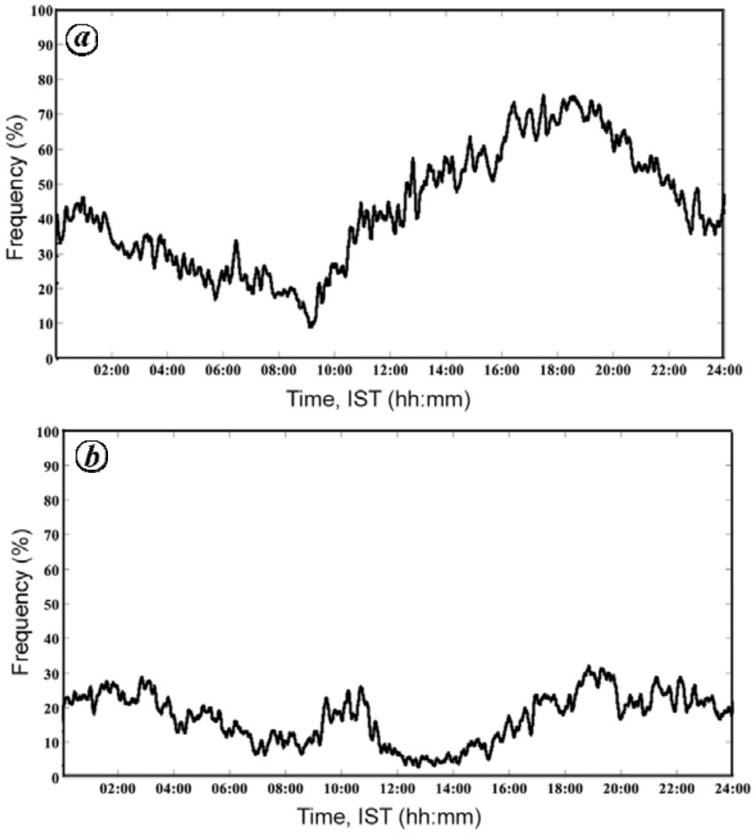

Figure 13. Diurnal variation of frequency of cloud occurrence at (***a***) Braemore and (***b***) Thiruvananthapuram (CESS) during the pre-monsoon season of 2011.

inferred that cloud formation occurs over Braemore and it might be getting dissipated by the time it reaches over the coastal station.

Conclusions

The primary aim of this article is to detect and confirm the initiation of convective Cb over a mountain slope. Changes in atmosphere during updraft events were investigated using an AWS and a ceilometer. EFM was used to detect the presence of charged Cb over the location. Transformation of water vapour into liquid phase during updrafts on thunderstorm days could be detected. By comparing the SD and mean of backscattered signal strengths, changes in the particle size during growth and different stages of a cloud could be identified. The CBH measurement indicated that during the thunderstorm days, cloud formation starts by about 10:00 h and reaches a maximum of about 70–90% in the afternoon hours. Simultaneous measurements indicate that the thunderclouds formed over the mountain slopes are of the convective-type and the frequency of cloud occurrence during thunderstorm days is much higher than that at a coastal station. The simultaneous measurements presented here possibly indicate the development of a convective thundercloud. In other words, the data can be used for monitoring development of convective Cb and thereby, for a relatively early thunderstorm warning.

1. GHCC, NASA, Global distribution of lightning April 1995–February 2003 from the observations of NASA instruments; www.nasa.gov/centers/goddard/news/topstory/2003/0619lightning.html; Accessed on 26 December 2005.
2. Rakov, V. A. and Uman, M., *Lightning Physics and Effects*, Cambridge University Press, UK, 2003.
3. Ranalkar, M. R. and Chaudhari, H. S., Seasonal variation of lightning activity over the Indian subcontinent. *Meteorol. Atmos. Phys*., 2009, **104**, 125–134.
4. Kandalgaonkar, S. S., Tinmaker, M. I. R., Kulkarni, J. R. and Nath, A., Diurnal variation of lightning activity over the Indian region. *Geophys. Res. Lett.*, 2003, **30**, 2022; doi: 10.1029/2003GL018005.
5. Oladipo, E. O. and Mornu, M. E., Characteristics of thunderstorms in Zaria, Nigeria. *Weather*, 1985, **40**, 316–322.
6. Maier, L. M., Krider, E. P. and Maier, M. W., Average diurnal variation of summer lightning over the Florida peninsula. *Mon. Weather Rev*., 1984, **112**, 1134–1140.
7. Williams, E. R. and Heckman, S., The local diurnal variation of cloud electrification and local diurnal variation of negative charge on the earth. *J. Geophys. Res.*, 1993, **98**, 5221–5234.
8. Finke, U. and Hauf, T., Characteristics of lightning distribution in southern Germany. In Proceedings of the 10th International Conference on Atmospheric Electricity, Osaka, Japan, 1996, pp. 380–383.

9. Lopez, R. E. and Holle, R. L., Diurnal and spatial variability of lightning activity in northeastern Colorado and Central Florida during the summer. *Mon. Weather Rev*., 1986, **114**, 1288–1312.
10. Pinto, I. R. C. A., Pinto Jr, O., Rocha, R. M. L., Diniz, J. H., Carvalho, A. M. and Cazetta Filho, A. C., Cloud to ground lightning in southeastern Brazil in 1993. 2. Time variations and flash characteristics, *J. Geophys. Res.*, 1999, **104**, 31381–31387.
11. Murali Das, S., Mohan Kumar, G. and Sampath, S., *Understanding Lightning Accidents to Alleviate the Hazard*, Project Report, Centre for Earth Science Studies, Thiruvananthapuram, 2004.
12. Hamza, V., Harikumar, R., Vishnu, R., Sasi Kumar, V., Sampath, S., Murali Das, S. and Mohan Kumar, G., Observational study of cloud base height and its frequency over a tropical station, Thiruvananthapuram, using a ceilometer. *Int. J. Remote Sensing*, 2011, **32**, 8505–8518.
13. Ruhnke, L. H. and Latham, J. (eds), Proceedings in Atmospheric Electricity, A Deepak Publishing, Virginia, USA, 1983.
14. McGorman, D. R. and Rust, W. D., *The Electrical Nature of Storms*, Oxford University Press, New York, 1998, p. 422.
15. Uman, M. A., *Lightning*, McGraw-Hill, New York, 1969.
16. Golde, R. H., *Lightning*, Academic Press, London, 1977, two vols.
17. Magono, C., *Thunderstorms, Developments in Atmospheric Science*, Elsevier, New York, 1980.
18. Vishnu, R., Murali Das, S., Sampath, S. and Mohan Kumar, G., Detection of possible thunderstorm formation inferred from weather element changes at ground level on a mountain slope. *J. Lightning Res*., 2010, **2**, 12–24.
19. Bourscheidt, V., Juniora, O. P., Naccarato, K. P. and Pintoa, I. R. C. A., The influence of topography on the cloud-to-ground lightning density in South Brazil. *Atmos. Res*., 2009, **91**, 508–513.
20. Sano, T. and Tsuboki, K., Structure and evolution of a cumulonimbus cloud developed over a mountain slope with the arrival of sea breeze in summer. *J. Meteorol. Soc. Jpn.*, 2006, **84**, 613–640.
21. *Resource Atlas of Kerala*, Centre for Earth Science Studies, Thiruvananthapuram, 1984.
22. Houze Jr, R. A., *Cloud Dynamics*, Academic Press, California, USA, 1993.
23. Moore, C. B. and Vonnegut, B., The thundercloud. In *Lightning, Vol. 1, Physics of Lightning* (ed. Golde, R. H.), New York, Academic Press, 1977, pp. 51–98.

ACKNOWLEDGEMENTS. We thank CESS for financial support, and the Director, CESS for his encouragement and support. H.V. and V.A.K. thank Prof. B. N. Goswami, Director, Indian Institute of Tropical Meteorology, Pune for support. We also thank M/s Braemore Estates for allowing operation of our field station in their premises.

Received 19 October 2012; revised accepted 18 March 2013