J. Earth Syst. Sci. (2020)129 131
https://doi.org/10.1007/s12040-020-01401-4

Characteristics of convective/stratiform dominance on surface rainfall over a few tropical locations

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MS received 28 September 2019; revised 10 March 2020; accepted 12 March 2020

To understand rainfall dynamics, the characterization of convective and stratiform dominance needs a careful investigation. However, it remains a grey area to date. In this paper, the authors have attempted to differentiate between convective and stratiform events based on vertical profiles of a few upper-air meteorological elements, namely, cloud liquid water (CLW), precipitation water (PW), and latent heat (LH). The parameters have been obtained from the data product 2A12 of the Tropical Microwave Imager (TMI) onboard the Tropical Rainfall Measuring satellite (TRMM). The paper presents the demarcation technique between convective and stratiform dominance on surface rainfall without ambiguity.

Keywords. Convective; stratiform; cloud liquid water; precipitation water; latent heat.

1. Introduction

Rainfall is broadly classified into two categories – convective and stratiform. The knowledge of convective and stratiform precipitation is essential in understanding cloud microphysics and cloud dynamics. The convective/stratiform classification is a critical aspect of hydrological modelling (Steiner and Smith 1998). Knowledge of convective/stratiform classification characteristics is also essential in understanding the melting layer and its variability.

The differential heating between the tropical ocean and the landmass drives the atmospheric heat engine and induces global circulation. The vertical profile of latent heat (LH) associated with precipitating systems in the tropical region is linked with Walker circulation (Zuluaga *et al.* 2010). A study (Uppara *et al.* 2019) shows that positive anomaly over the foothills of central-eastern Himalayas (CEH), Indo-China, and negative anomaly over the Indian landmass induces poleward extending wave-train in the mid-troposphere. Studies (Choudhury and Krishnan 2011; Chattopadhyay *et al.* 2013) show that the latent heat profile associated with stratiform rain affects large-scale circulation during South Asian summer monsoon. Zuluaga *et al.* (2010) have pointed out that LH variability is high in the South Asian monsoon region, and the former influences global circulation (Webster 1994; Webster *et al.* 1998). Riehl and Malkus (1958) have shown that the latent heat released in the precipitating systems in the tropical region drives global circulation. Thus, it is essential to study the precipitating systems in the tropical region.

Several researchers all over the globe have been attempting to understand the difference between

Supplementary materials pertaining to this article are available on the Journal of Earth Science Website (http://www.ias.ac.in/Journals/Journal_of_Earth_System_Science).

Published online: 04 June 2020

the convective and stratiform rain events based on several parameters, viz., intensity of precipitation falling from the convective and stratiform cloud, origin of the event, growth mechanism of precipitation particles, raindrop size distribution, updrafts and downdrafts present in the cloud, the cloud height, reflectivity, and its vertical gradient, the fall velocity of hydrometeors, vertical latent heating profiles of the two precipitating systems, amount of cloud liquid water, and precipitation water in the cloud, etc.

A stratiform rain is considered to be of less intensity, while convective precipitation is associated with very heavy and extreme intensity (Emmanouil 2004; Shen *et al.* 2012).

Convective precipitation originates from convective clouds, viz., cumulus and cumulonimbus, while stratiform precipitation occurs in nimbostratus (Tokay and Short 1996). Schumacher and Houze (2003a) have opined that stratiform rainfall may occur in mesoscale convective systems (MCSs), and convective rainfall may be present within stratiform precipitation (Gregory *et al.* 1990; Houze 1993; Matthew *et al.* 2000). A study shows that convective precipitation dominates during the development stage of a convective cloud. However, the stratiform rainfall overtakes in the mature and final stage (Shen *et al.* 2012). A study (Schumacher and Houze 2003b) shows that convective precipitation falls from the region of active vertical motion, while stratiform rain falls from an area of weak vertical air motion.

The convective and stratiform precipitation has been differentiated based on growth mechanisms (Schumacher and Houze 2003b). Houze (1997) has shown that the raindrops grow by accretion in a convective cloud, while they grow by condensation/deposition in a stratiform cloud.

A more significant number of small to medium-sized drops are present in convective precipitation as compared to those in stratiform rainfall at the same rainfall intensity (Tokay and Short 1996).

Strong updraft exists throughout the troposphere in a convective cloud, while a weak updraft in the lower troposphere and a moderate updraft above, mark a stratiform cloud (Houze 1997). A convective cloud is found to exhibit stronger updraft than a stratiform cloud (Stenier and Smith 1998). A uniform horizontal distribution is seen in stratiform precipitation. Convective precipitation, on the other hand, is characterized by a more significant horizontal gradient of rainfall.

Steiner and Smith (1998) have reported that the horizontal reflectivity gradient is weaker in stratiform rain than that in convective rain. The vertical air motion in stratiform precipitation is smaller than the fall velocity of hydrometeors (Steiner and Smith 1998). The height of the convective cloud associated with thunderstorms may reach above 10.0 km (Battan 1973).

In stratiform precipitation, a prominent bright band is observed below the freezing level where snowflakes start melting (Battan 1973; Houze 1993), while the bright band signature is missing in a convective cloud (Battan 1973; Houze 1993). The absence of a bright band in a convective cloud is attributed to the large-scale mixing of different particle types (Battan 1973). Rao *et al.* (2008) have classified convective and stratiform clouds based on bright band signature and turbulence. A mixed stratiform/convective case is characterized by the presence of a bright band with turbulence above the melting layer. Stratiform precipitation is characterized by the presence of a bright band with no turbulence above the melting layer. If the precipitation does not show any bright band, and turbulence exists above the melting layer, then it is said to be a deep convective cloud, while precipitation without bright band signature with no turbulence above the melting layer, is said to be a shallow convective one.

It is universally accepted that a bright band is found only in a stratiform cloud (Battan 1973). However, Sen Jaiswal *et al.* (2010) have shown that a bright band may occur in a convective cloud also. In a convective cloud under severe updraft, there is a large-scale mixing of particle types. Under these circumstances, the water droplets and the snowflakes will be carried upward. This phenomenon will give a bright band signature.

Schumacher and Houze (2003b), and Houze (1989) have differentiated the convective and stratiform precipitation on the basis of the vertical profile of latent heat. It is found that the two types of precipitation show a difference in the vertical heating profiles (Steiner and James 1998). In convective precipitation, heat is distributed throughout the troposphere, while stratiform precipitation is found to cool the lower troposphere and heat the upper troposphere (Schumacher and Houze 2003b). In a convective cloud, the evolution peak of latent heat is found in the lower part of the cloud, while in a stratiform cloud, it occurs in the upper part (Tokay and Short 1996). It is opined that LH profiles associated with stratiform and convective precipitation may have different impacts on controlling large-scale circulation (Emanuel *et al.* 1994; Schumacher *et al.* 2004). Thus, the study of the LH profile under different types of precipitating systems is necessary for understanding atmospheric circulation.

The convective/stratiform discrimination scheme of the TMI onboard the TRMM is based on the brightness temperature at the orthogonal polarizations (Olson *et al.* 2001). Under stratiform precipitation, a differential brightness temperature is found at 85.5 GHz channel; however, in convective precipitation, no difference in brightness temperature is found between the two orthogonal polarizations.

The stratiform–convective precipitation demarcation scheme of the TRMM is also based on the variability of the liquid phase and ice phase precipitation in the horizontal direction (Churchill and Houze 1984). Convective clouds have more liquid water than those in stratiform clouds (Taylor and Ghan 1992). A large number of supercooled water drops are found in the convective cloud (Rosenfeld and Woodley 2000).

Ambiguity is found in the demarcation of convective and stratiform cases in the TRMM handbook (2007). The rain type flag '120', '130', '140', '152', and '160' of the data product 2A23 of the precipitation radar (PR) onboard the TRMM respectively mentions the ambiguous situations 'probably stratiform', 'maybe stratiform', 'maybe transition or maybe convective or something else', 'maybe stratiform' and 'maybe stratiform but rain hardly expected near the surface'.

Thus, it is realized that the convective/stratiform demarcation technique is a grey area that needs attention. In this paper, the authors have attempted to characterize stratiform and convective dominance based on vertical profiles of upper air meteorological elements. As the process of cloud formation depends on available moisture, the absorption and release of latent heat at different levels in the atmosphere; and understanding cloud microphysics requires the knowledge of cloud liquid water, the authors have chosen to investigate the vertical profiles of cloud liquid water (CLW), precipitation water (PW), and latent heat (LH) to characterize convective/stratiform dominance on surface rainfall.

Cloud liquid water (CLW) is the amount of liquid water per unit volume of air. It is expressed in g/m^3 or g/kg. Precipitation water is the actual amount of moisture that has precipitated as rain. Latent heat (LH) is released or absorbed due to phase change in water (Tao *et al.* 2006).

The knowledge of CLW is of immense importance in climatology and aviation. The PW at the peak CLW level is able to explain the peaks and troughs of rainfall time series (Sen Jaiswal *et al.* 2014). Cloud liquid water over the ocean is found to be correlated with precipitation (Bhattacharya *et al.* 2012). A large amount of supercooled CLW above the freezing level causes aviation hazards (Curry and Liu 1992). The attenuation caused by CLW in the microwave region is found to be proportional to CLW (Hogan *et al.* 2005; Sarkar and Kumar 2007).

Water vapour in the atmosphere provides information about the LH released and absorbed at different levels in the atmosphere during the formation and dissipation of clouds. As water absorbs radiations, it influences the emissivity of clouds (Taylor and Ghan 1992). Thus, PW and LH affect Earth's radiation budget and global circulation (Taylor and Ghan 1992) and needs careful analysis.

The authors have obtained CLW, PW, and LH values from version V6 of the data product 2A12 of the Tropical Microwave Imager (TMI) onboard the Tropical Rainfall Measuring satellite (TRMM). As the tropics play a significant role in atmospheric and oceanic circulation, the authors have chosen a few tropical locations in India, namely, Bangalore (12.97N, 77.59E), Bhubaneswar (20.29N, 85.82E), Calcutta (22.57N, 88.36E), and Gadanki (13.45N, 9.16E) for the investigation.

2. Data and methodology

The Tropical Microwave Imager (TMI) gives the values of CLW, PW, and LH on a pixel by pixel basis at 14 vertical levels starting from Earth's surface up to 18.0 km above. The values of CLW and PW have been multiplied by 1000 and stored. The values of LH are multiplied by 10 and stored (TRMM 2007). The daily CLW, PW, and LH values have been obtained from version V6 of the data product 2A12 onboard the TMI over the selected locations at 14 vertical levels, for the period 2002–2006, and 2008. Next, these values have been plotted against height. Thus, the vertical profiles of these elements have been obtained. The authors have investigated these profiles for all the days in each month of the year from 2002–2006, and 2008, when the TRMM had overpass. The results of the investigation are shown in section 3. The TRMM vertical profiling layers are shown in table 1.

It is noteworthy that over a location, the TRMM has overpass once, or rarely twice a day. Thus, it is realized that the TRMM has overlooked several rain events. Besides, the TRMM algorithm has a limitation. It gives CLW, PW, and LH only in rainy conditions (TRMM 2007). Nevertheless, the TRMM is undoubtedly a novel mission that helps to study rainfall and associated parameters from space.

The TMI provides surface rainfall and convective rainfall daily. The status flags of 2A23 (TRMM 2007) of the precipitation radar (PR) have been noted to identify stratiform and convective rain.

Next, the vertical profiles of CLW, PW, and LH for convective and stratiform dominance have been investigated in-depth, and the characteristics of stratiform and convective dominance have been identified based on the vertical profiles of these parameters. The characteristics of convective/stratiform dominance in the light of LH, CLW, and PW are respectively described in sections 3.1.1, 3.1.2, and 3.1.3. Section 3.2 presents a comprehensive analysis of individual events in the light of CLW, PW, and LH profiles, simultaneously. Section 3.3 describes the variability of the LH profile in different seasons.

3. Results

3.1 *Characterization of convective/stratiform dominance based on the vertical profile of latent heat, cloud liquid water, and precipitation water*

The investigation shows that convective/stratiform dominance on surface rainfall can be characterized based on the vertical profile of latent heat, cloud liquid water, and precipitation water.

3.1.1 *Identification of convective/stratiform dominance based on latent heat profile*

3.1.1.1 *Convective dominance:* A convective dominance is found to be associated with a single absorption peak close to the Earth's surface, and two prominent evolution peaks – one in the lower troposphere and the other in the mid-troposphere as shown in figure 1(a) over Gadanki on 20 September 2004; in figure 1(b) over Bangalore on 4 November 2006; in figure 1(c) over Kolkata on 4 September 2008, and in figure 1(d) over Bhubaneswar on 23 October 2003. At times, a convective dominance is marked by an extended plateau-shaped evolution region in the troposphere, as shown in figure 1(e) over Bangalore on 1 November 2002.

A convective dominance does not usually exhibit an extended absorption region in the lower troposphere. However, at times, even if an extended absorption region occurs in the lower troposphere, it may also represent a convective dominance provided a substantial amount of LH evolves throughout the troposphere (figure 2a). Figure 2(a) depicts a convective dominance over Kolkata on 15 August 2006, when an extended absorption region is located between the Earth's surface to 4.0 km. A substantial amount of LH of magnitude 4.12°C/hr evolved from Earth's surface up to 18.0 km above. The event is identified as a convective one based on the bright band height value '–1111' obtained from the data

Table 1. *TRMM vertical profiling layers.*

14 Vertical profiling layers		14 Vertical heating levels	
Layer index	Layer height (km)	Level index	Level height (km)
1	Surface–0.5	1	0
2	0.5–1.0	2	1.0
3	1.0–1.5	3	2.0
4	1.5–2.0	4	3.0
5	2.0–2.5	5	4.0
6	2.5–3.0	6	5.0
7	3.0–3.5	7	6.0
8	3.5–4.0	8	7.0
9	4.0–5.0	9	8.0
10	5.0–6.0	10	9.0
11	6.0–8.0	11	10.0
12	8.0–10.0	12	12.0
13	10.0–14.0	13	14.0
14	14.0–18.0	14	16.0

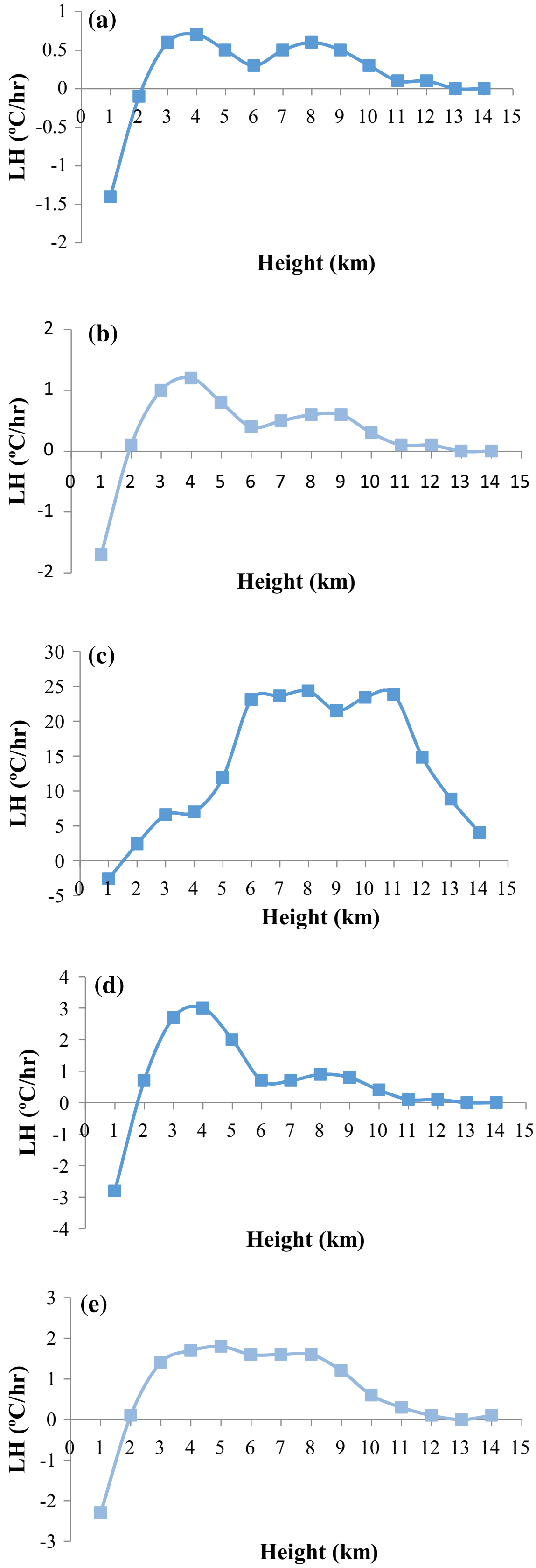

Figure 1. Variation of LH with height over (**a**) Gadanki on 20 September 2004, (**b**) Bangalore on 4 November 2006, (**c**) Kolkata on 4 September 2008, (**d**) Bhubaneswar on 23 October 2003, and (**e**) Bangalore on 1 November 2002.

product 2A23 of the PR onboard the TRMM, which represents 'no bright band' (TRMM 2007).

If the vertical profile of LH exhibits an extended absorption peak in the lower troposphere, then also it may be a convective dominance provided a very high evolution of LH that gradually increases with height occurs, else it is a stratiform dominance. Figure 2(b) shows a convective dominance over Bhubaneswar on 1 November 2003, when an extended absorption peak had occurred in the lower troposphere, and a very high evolution of LH of amount 6.63°C/hr is found throughout the vertical column from the surface up to 18.0 km above. It is found in figure 2(b) that the vertical profile shows a gradual increase in the evolution of LH in the troposphere. The event is identified as a convective one based on the rain type flag '272' (TRMM 2007) present in the data product 2A23 of the PR onboard the TRMM.

At times, a convective dominance may be found with a more or less pointed evolution peak, instead of usually found two peaks in the troposphere. Under these circumstances, if throughout the troposphere evolution of LH is found to be significantly more than absorption, then also it is a convective dominance (figure 3a), else it is a stratiform one (figure 3b). Figure 3(a) shows that over Kolkata on 18 October 2005, the convective dominance was associated with a sharp evolution peak, which is not usual for a convective

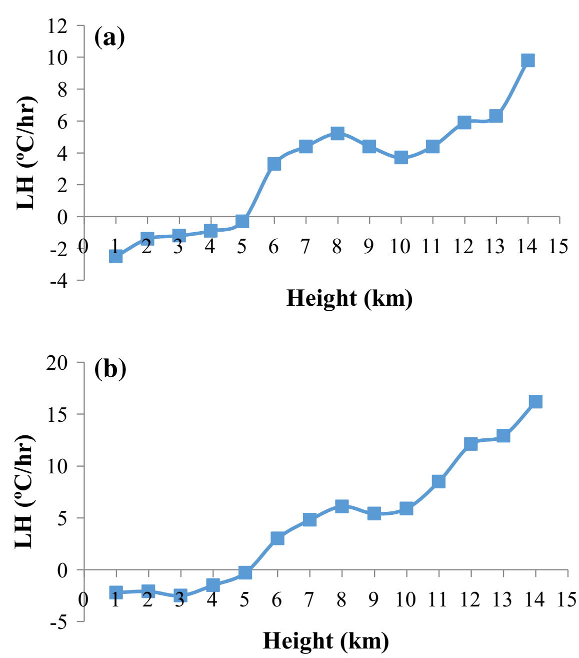

Figure 2. Variation of LH with height over (**a**) Kolkata on 15 August 2006 and (**b**) Bhubaneswar on 1 November 2003.

dominance. However, the case is identified as 'convective' as the amount of evolution of LH on 18 October 2005 was 2.3°C/hr, and the absorption of LH was of amount 3.2°C/hr, which was substantially less than the evolution of LH. The LH profile over Kolkata on 20 October 2005 (figure 3b), on the other hand, is identified as a stratiform one because the evolution of LH (0.73°C/hr) was not substantially more than absorption (0.24°C/hr) on the day.

A convective dominance is marked by a very high evolution of LH throughout the troposphere. It is noteworthy that a small +ve LH throughout the troposphere may or may not represent a convective case. If a little +ve LH is found to be associated with a single evolution peak in the mid-troposphere and an extended absorption in the lower troposphere, then it is a stratiform case (figure 4a), else it is a convective one (figure 4b). Figure 4(a) shows a stratiform dominance over Kolkata on 1 July 2002, when a small +ve LH of 0.49°C/hr was found in the entire vertical profile. Figure 4(a) further shows an extended absorption region close to the Earth's surface – from the surface to 4.0 km, and a sharp evolution peak at 6.0 km – a distinctive feature of stratiform dominance. Figure 4(b) shows a convective dominance over Bhubaneswar on 20 September 2002 with a resultant small +ve LH of amount 0.04°C/hr throughout the profile, which is marked by a single absorption peak on the surface and two evolution peaks in the troposphere.

3.1.1.2 *Characteristics of LH profile in stratiform dominance:* A stratiform dominance is found to be associated with an extended absorption region in the lower troposphere and a sharp evolution peak in the mid-troposphere, as shown in figure 5(a) over Bangalore on 25 May 2002. Figure 5(a) shows an extended absorption region from the Earth's surface to 3.0 km and a sharp evolution peak at 6.0 km.

However, at times, in a stratiform dominance, a single absorption peak is found in the lower troposphere like that of a convective dominance. Under these circumstances, if a single evolution peak is located in the mid-troposphere, then it is a stratiform case (figure 5b). Figure 5(b) shows a stratiform dominance over Bangalore on 30 July 2003, with a single absorption peak in the lower troposphere, which is unusual for a stratiform dominance. However, it is identified as a stratiform one as it is associated with a single evolution peak in the mid-troposphere.

It is further found out that if the total evolution of LH throughout the profile is –ve, then it is stratiform certain. Figure 5(c) shows the vertical profile of LH, which indicates a stratiform dominance over Kolkata on 20 April 2003. The vertical

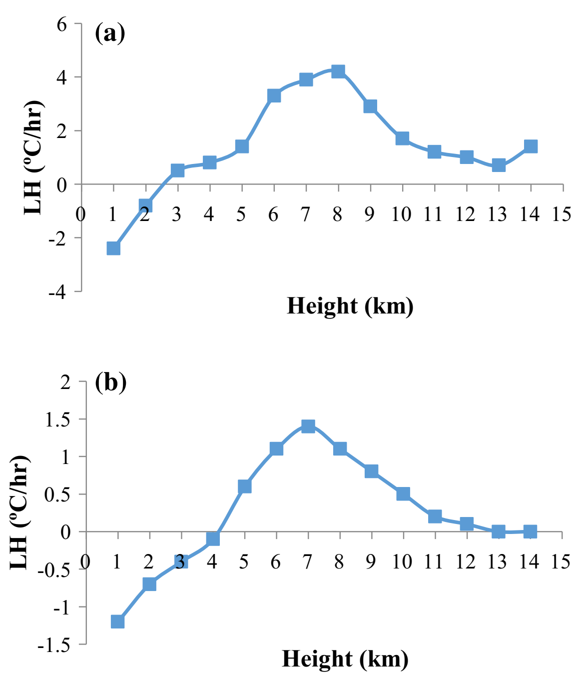

Figure 3. Variation of LH with height over Kolkata on (**a**) 18 October 2005 and (**b**) 20 October 2005.

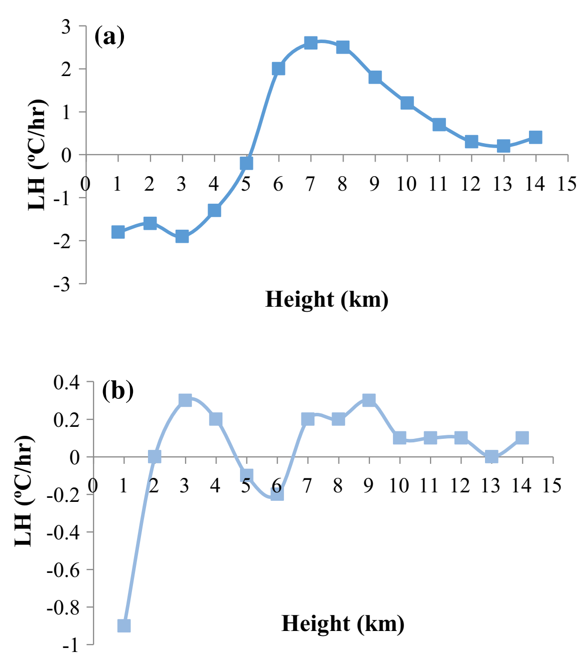

Figure 4. Variation of LH with height over (**a**) Kolkata on 1 July 2002 and (**b**) Bhubaneswar on 20 September 2002.

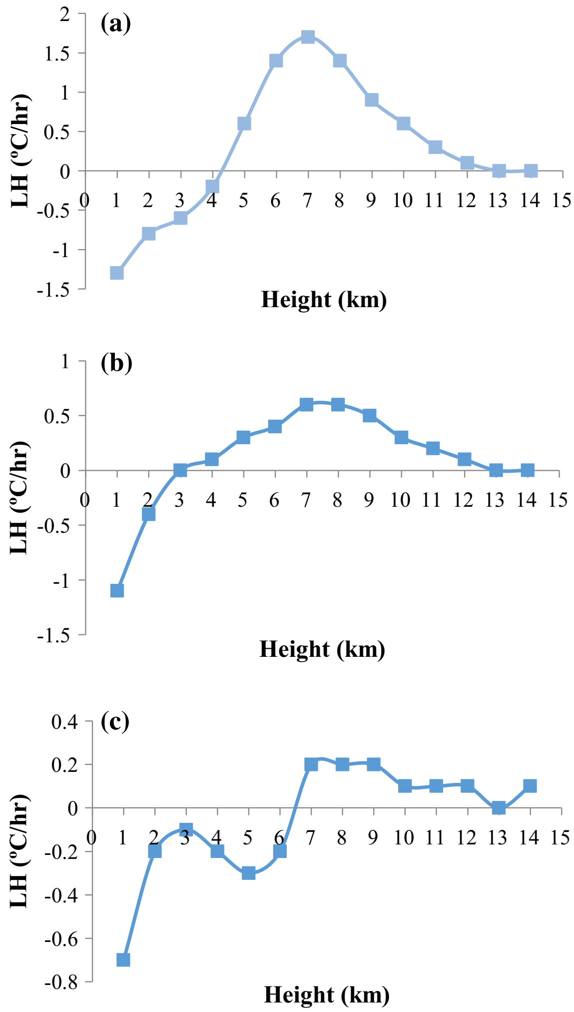

Figure 5. Variation of LH with height over (**a**) Bangalore on 25 May 2002, (**b**) Bangalore on 30 July 2003, and (**c**) Kolkata on 20 April 2003.

profile shows a net absorption of LH of the magnitude of 0.07°C/hr.

A small +ve value of LH throughout the vertical profile may also indicate a stratiform dominance if a sharp evolution peak in the middle-troposphere exists, irrespective of the presence of an extended absorption peak in the lower troposphere (figure 4a). Figure 4(a) shows that though a net evolution of LH of the magnitude of 0.49°C/hr was observed, the event as described in figure 4(a) was identified as a stratiform event since it was associated with an extended absorption region close to the Earth's surface, and a sharp evolution peak.

At times, a stratiform dominance is associated with the following characteristics of a convective dominance as follows:

(1) A single absorption peak close to the Earth's surface.
(2) A resultant positive LH in the vertical column.

Under these circumstances also, if a sharp evolution peak exists in the middle-troposphere, and zero or very less evolution of LH takes place between 10.0 and 16.0 km, then it is a stratiform case. It is noteworthy that under a stratiform dominance, LH is mostly zero or –ve in the 12.0–16.0 km.

3.1.2 *Identification of convective/stratiform dominance based on the vertical profile of cloud liquid water*

3.1.2.1 *Characteristics of convective dominance:* In a convective dominance, the vertical profile of CLW exhibits a bell-shaped curve, which implies a single, or two very closely-spaced peaks. The height where the CLW attains the peak value is termed as the peak cloud liquid water level (HPCL) by Sen Jaiswal *et al.* (2014). Figure 6(a) shows the vertical profile of CLW over Gadanki on 4 May 2004 under a convective dominance. Figure 6(a) shows two closely-spaced peaks at 2.5–3.5 km in the CLW profile. The same result is found over other locations (results not shown). At times, in the vertical profile of CLW, a secondary peak of smaller magnitude is observed (figure 6b). Figure 6(b) shows two peaks in the vertical profile of CLW over Gadanki on 20 May 2008.

3.1.2.2 *Characteristics of stratiform dominance:* Under a stratiform dominance, the vertical profile of CLW does not exhibit a bell-shaped curve like a convective one. At times, two CLW peaks are observed – one in the lower troposphere and the other in the mid-troposphere. The two peaks are separated by a prolonged dip, indicating that the peaks are far away from each other. Figure 6(c) shows the vertical profile of CLW over Gadanki on 19 August 2008 under stratiform dominance. The study further reveals that in a stratiform dominance, the vertical profile of CLW often shows two or multiple peaks, unlike convective dominance (results not shown). The same result is found over other locations (results not shown).

3.1.3 *Characterization of convective/stratiform dominance based on the vertical profile of precipitation water*

3.1.3.1 *Characteristics of convective dominance:* In a convective dominance, the peak PW is

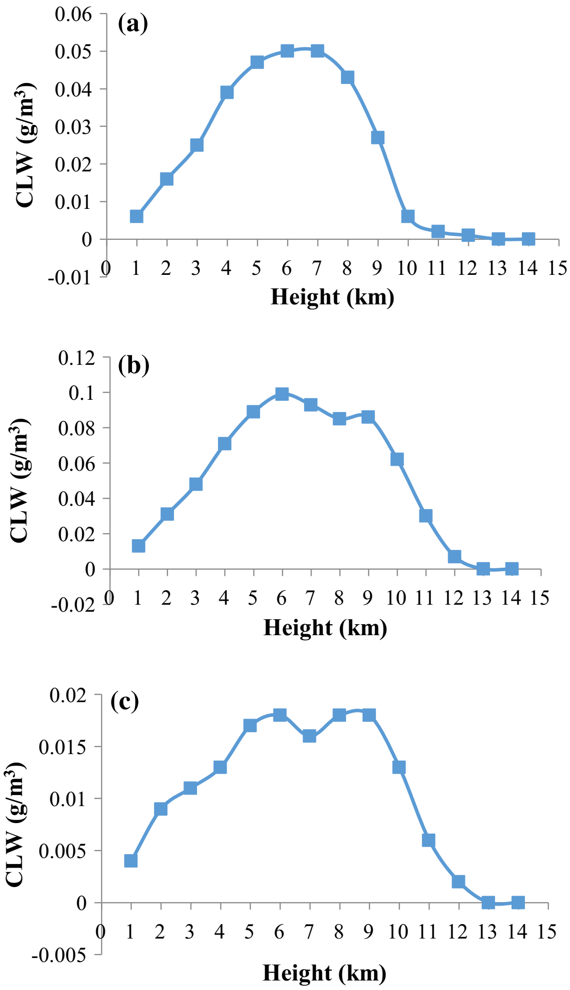

Figure 6. Variation of CLW with height over Gadanki on (**a**) 4 May 2004 under convective dominance, (**b**) 20 May 2008 under convective dominance, and (**c**) 19 August 2008 under stratiform dominance.

seen close to the Earth's surface, and then gradually decreases with an increase in height. Under a convective dominance, the PW profile is smooth. In the mid-troposphere, the PW profile takes a convex shape. Figure 7(a) shows the vertical profile of PW under convective dominance over Bhubaneswar on 26 April 2002. The same result is found over other locations (results not shown).

3.1.3.2 *Characteristics of stratiform dominance:* Unlike convective dominance, the vertical profile of PW shows a valley in the mid-troposphere. The curve looks concave in the mid-troposphere. Figure 7(b) shows the vertical profile of PW under stratiform dominance over Gadanki on 5 November 2004. The same result is found over other locations (results not shown).

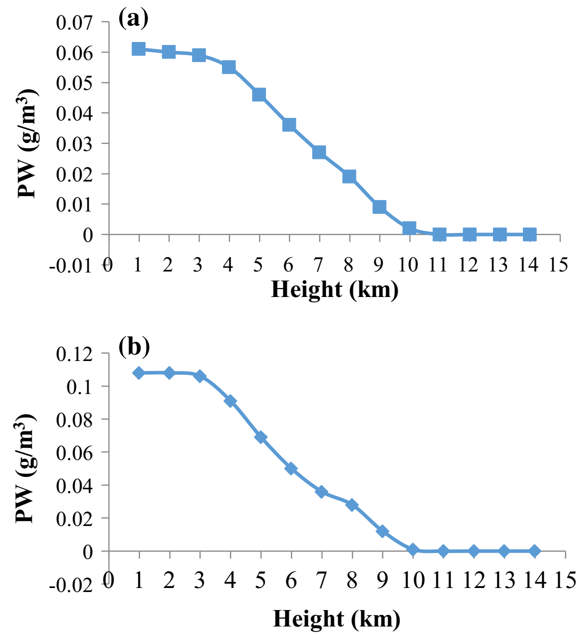

Figure 7. Variation of PW with height over (**a**) Bhubaneswar on 26 April 2002 under convective dominance and (**b**) Gadanki on 5 November 2004 under stratiform dominance.

3.2 *Comprehensive analysis of individual precipitation events*

3.2.1 *Identification of convective dominance*

This section gives an estimate of convective/stratiform characterization of individual events based on the vertical profiles of CLW, PW, and LH, simultaneously. The rain event on 20 September 2004 over Gadanki has been identified as a convective one with a single absorption peak close to the surface, and two evolution peaks – one in the lower troposphere and the other in the mid-troposphere on the basis of LH profile as described in section 3.1.1.1 (figure 1a). The vertical profile of CLW on the same day shows a bell-shaped curve (Supplementary figure S1), which has been identified as a characteristic of convective dominance, as mentioned in section 3.1.2.1.

The vertical profile of PW for the same event (S2) exhibits convexity in the mid-troposphere, which has been identified as a characteristic feature of convective dominance, as described in section 3.1.3.1.

The rain event over Bangalore on 1 November 2002 has been identified as a convective one (figure 1e) based on the LH profile in section 3.1.1.1. The LH profile shows an extended plateau-shaped region in the troposphere. The CLW profile of the same event (S3) shows a bell-shaped curve in the troposphere, which is a distinctive feature of convective dominance, as described in section 3.1.2.1. The PW profile of the same event (S4) shows convexity in the mid-troposphere, a distinctive feature of convective dominance, as described in section 3.1.3.1.

The precipitation event over Kolkata on 15 August 2006 has been identified as a convective one based on the vertical profile of LH (figure 2a) in section 3.1.1.1. Though the LH profile shows an extended absorption region, which is a characteristic feature of stratiform dominance, it is identified as a convective one as it is associated with a large evolution of LH of amount 4.12°C/hr. The rain type flag of the data product 2A23 of the precipitation radar (PR) onboard the TRMM on 15 August 2006 over Kolkata shows a value 120 which marks the event as 'maybe stratiform'. However, the event is identified as a convective one based on bright band height '–1111'. '–1111' represents 'no bright band' (TRMM 2007).

The same event is identified as a convective one based on the vertical profile of PW also (S5). The profile shows convexity in the mid-troposphere. The vertical profile of CLW on the same day identifies the event as a convective one with a bell-shaped curve (S6).

The rain event over Bhubaneswar on 1 November 2003 is identified as a convective one based on the LH profile (figure 2b), as described in section 3.1.1.1. It shows a gradually increasing LH with height and release of large latent heat of magnitude 6.63°C/hr. The evolution peak was observed at 16.0 km. The event is identified as a convective one based on the CLW profile also, as it is associated with a single peak (S7). The PW profile of the same event also identifies it as a convective one, with convexity in the mid-troposphere (S8). The rain type flag of the data product 2A23 of the precipitation radar (PR) onboard the TRMM on 1 November 2003 over Bhubaneswar is identified as convective based on the rain type flag '272'. The rain type flag '272' represents a convective case (TRMM 2007).

The rain event over Kolkata on 18 October 2005 is recognized as a convective one based on the LH profile, as described in section 3.1.1.1 (figure 3a). The PW profile of the same event identifies it as a convective one with convexity in the mid-troposphere (S9). The CLW profile (S10) of the same event identifies it as a convective one, with a bell-shaped nature.

3.2.2 *Identification of stratiform dominance*

The rain event over Kolkata on 20 October 2005 is identified as a stratiform one based on the LH profile (figure 3b), as described in section 3.1.1.1. The event is recognized as a stratiform one based on the CLW profile also, with two peaks – one in the lower troposphere and the other in mid-troposphere (S11), a distinctive feature of stratiform dominance as described in section 3.1.2.2. The event is identified as a stratiform one based on the PW profile also (S12) with a concavity in the mid-troposphere, a characteristic feature of stratiform dominance, as described in section 3.1.3.2.

The rain event over Bangalore on 25 May 2002 is identified as a stratiform one based on the LH profile, as described in section 3.1.1.2 (figure 5a). The CLW profile of the event (S13) identifies the event as a stratiform one with two peaks – one in the lower troposphere and the other in the mid-troposphere. The PW profile of the same event (S14) shows concavity in the mid-troposphere, a distinctive feature of stratiform dominance, as described in section 3.1.3.2.

The study identifies every single rain event very clearly either as convective or a stratiform one based on the vertical profile of CLW, PW, and LH (results for all events not shown).

3.3 *Latent heat profiles in monsoon seasons*

In this paper, an attempt has been made to find out if the vertical profile of latent heat exhibits any seasonal dependence. For this purpose, the absorption and evolution peaks of LH are noted on every day when the TRMM had overpass over the locations studied. It is found that the absorption peak always occurs at the surface over all the locations, irrespective of seasons, with some exceptions as mentioned below: over Bangalore on 11 February 2002, when the absorption peak had occurred at 1.0, 4.0, and 5.0 km. Over Bangalore, the absorption peak occurred at 1.0 km on 6 September 2006. Over Kolkata, the deviation occurs on 1 July 2002, and 23 April 2004, when the LH absorption peak had occurred at 2.0 km. On 3 June 2004, the LH absorption peak was found at 2.0 km and also on the Earth's surface. Over Bhubaneswar, the LH absorption peak had occurred at 1.0, 4.0, 2.0, 1.0, 2.0, and 2.0 km on 20 July 2002, 16 June 2003, 19 June 2003, 24 August 2004, 25 May 2008, and 7 June 2008, respectively.

Unlike the absorption peaks, the LH evolution peak shows variability. It appears to exhibit seasonal dependence.

Over Kolkata, in the NE monsoon, the LH evolution peak mostly occurs at 6.0 and 7.0 km. At times, it occurs at 3.0 and 8.0 km. Rarely it occurs at 5.0 km. In the SW monsoon, the LH evolution peak mostly occurs at 6.0 and 7.0 km. Several days it occurs at 4.0 and 5.0 km. On some days, it occurs at 8.0 and 16.0 km. In the pre-monsoon season, the LH evolution peak mostly occurs at 6.0, 7.0, and 8.0 km. At times, it occurs at 16.0 km. The LH evolution peak rarely occurs at 2.0–4.0 km.

Over Bangalore, in the pre-monsoon season, the LH evolution peak mostly occurs at 3.0 km. On several days it occurs at 2.0 km. At times, it occurs at 7.0 and 6.0 km. In the SW monsoon season, the LH evolution peak over Bangalore mostly occurs at 3.0 and 2.0 km. At times, it occurs at 7.0/6.0/8.0 km. It occurs at 5.0 km, rarely. Over Bangalore, in the NE monsoon, the LH absorption peak mostly occurs at 3.0 and 2.0 km. It occurs at 6.0 and 7.0 km, rarely.

Over Bhubaneswar, the LH evolution peak mostly occurs at 2.0, and 7.0–8.0 km, in the pre-monsoon. In the SW monsoon, it occurs mostly at 6.0 km. On several days it occurs at 3.0 and 7.0 km. Sometimes it occurs at 8.0, 16.0, and 4.0 km. In the NE monsoon, the LH evolution peak mostly occurs at 3.0 and 2.0 km. At times it occurs between 5.0 and 8.0 km. It occurs at 4.0 and 16.0 km, rarely.

Over Gadanki, in the pre-monsoon, the LH evolution peak mostly lies at 3.0 km. Sometimes it occurs at 2.0 km, and rarely 4.0, and 6.0–7.0 km. It rarely occurs at 8.0, 10.0, and 16.0 km. In the SW monsoon, the LH evolution peak mostly lies at 2.0, 3.0, 7.0, and 6.0 km. In the NE monsoon, it mostly occurs at 7.0, and 3.0 km. On several days, it occurs at 3.0 and 6.0 km.

It is noteworthy that over Bhubaneswar, only in May, June, and July, the LH evolution peak rarely occurred at 16.0 km. Over Kolkata, in July, September, and some times in May, the LH evolution peak was observed at 16.0 km. Over Bangalore, rarely in April, September, and October, it was found at such a high level. Over Gadanki, in March, May, June, and September, such a high-level LH evolution peak was seen only once a month. It was further found out that such a high-level evolution peak is always associated with a convective dominance.

Liu *et al.* (2015) have observed LH peak at 4.0–7.0 km over the continents in the tropical region, while over the ocean, two peaks were found out.

The LH profiles over the locations show the occurrence of binary and multiple peaks. Over Kolkata, multiple peaks are found on a few days in the pre-monsoon, SW, and NE monsoon season. The occurrence of multiple peaks is more in SW monsoon over Kolkata. Over Bhubaneswar, multiple peaks are found in the pre-monsoon, SW and, NE monsoon. However, the occurrence is more during SW monsoon. Over Bangalore, the multiple peaks are found in SW monsoon, and only once in pre-monsoon. In the NE monsoon, no multiple peaks were found over Bangalore. Over Gadanki, multiple evolution peaks mainly occur in the SW monsoon, and also in NE monsoon. No multiple peaks are seen in the pre-monsoon.

Thus, it appears that over the continental locations, the multiple peaks mostly occur in the SW monsoon. However, the coastal locations exhibit multiple peaks in all seasons. It is noteworthy that multiple peaks are associated with both stratiform and convective dominance.

It is found out from the study that over Gadanki and Bangalore (except in one case), always convective dominance was found to exist during the period of study. Liu *et al.* (2015) also found out that over continental locations in the tropics, the contribution to latent heating is mainly from convective precipitation. Over Kolkata and Bhubaneswar, in 27.94% and 27.48% cases, respectively, a stratiform dominance was observed. It is noteworthy that Kolkata and Bhubaneswar lie on the East coast of India, while Gadanki and Bangalore are far away from the sea. Liu *et al.* (2015) further reported that mesoscale convective systems contribute the most to latent heating over both land and ocean.

4. Conclusions

The article presents a clear and distinct characterization technique of stratiform and convective dominance based on the vertical profile of cloud liquid water, precipitation water, and latent heat. The investigation shows that a convective dominance is marked by a very high evolution of latent heat in the vertical column, starting from the Earth's surface up to 18.0 km above. A convective dominance is mostly associated with a single absorption peak close to the Earth's surface and an extended plateau-shaped evolution region in the mid-troposphere. Often, two evolution peaks in the troposphere mark a convective dominance. Besides, a convective dominance also shows some more typical characters at times. These specific characters, which appear to deviate from the usual pattern, have also been explained in section 3.1.1.

A stratiform dominance is associated with an extended absorption region in the lower troposphere and a sharp evolution peak in the mid-troposphere, with some deviations at times. These deviations also have been explained. A stratiform dominance is undoubtedly associated with net absorption or a minimal evolution of LH in the vertical column extending from Earth's surface up to 18.0 km above.

A bell-shaped curve marks the vertical profile of cloud liquid water in a convective dominance, i.e., a single peak or two closely-spaced peaks occurs. A stratiform dominance does not show a bell-shaped vertical profile of cloud liquid water. A stratiform dominance is characterized by two cloud liquid water peaks in the mid-troposphere. The cloud liquid water in the vertical column is less in a stratiform dominance than that in a convective dominance.

In a convective dominance, the vertical profile of precipitation water is smooth, gradually falling off from the maximum value at the Earth's surface. It shows little convexity in the mid-troposphere. A concavity in the vertical profile of precipitation water in the mid-troposphere marks a stratiform dominance.

The study also describes the variability of LH profile in the pre-monsoon, SW, and NE monsoon season.

Acknowledgements

The authors are grateful to the Tropical Rainfall Measuring Mission (TRMM) website team for providing the data for the study. The authors are thankful to Sona College of Technology, Salem, India, for providing the necessary infrastructure to carry out the work.

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Corresponding editor: C Gnanaseelan