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ORIGINAL PAPER

Land-sea contrasts for climatic lightning activity over Indian region

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Abstract

The land-ocean convective contrasts observed by the satellite-driven data from the Tropical Rainfall Measuring Mission for the year 1998 to 2014 (17 years) are analysed to examine the role of static land surface relative to the dynamic ocean surface for the lightning flash counts (FC). We present the relationship between the lightning flash counts per convective available potential energy (CAPE) (FC/CAPE), the product of CAPE and rainfall (CAPE × RF) and Bowen ratio, FC (land/ocean) and AOD (land/ocean) and FC (land/ocean) and maximum updraft speed (land/ocean) to examine the land-ocean contrasts over the Indian region. The results show that FC/CAPE over Indian land increases by up to 520% with respect to FC/CAPE over Indian oceanic regions. The land-ocean contrast seems to be a result of increase of Bowen ratio and FC over land by up to 800% as compared with Bowen ratio and FC over ocean surface. The increase of CAPE over land is by up to 47% relative to CAPE over ocean with corresponding increase of maximum updraft speed over land by up to 117% with respect to maximum updraft speed over ocean. The temperature profiles over the land and ocean show the same temperature in the lower troposphere, followed by a temperature difference of 8 °C between land and ocean at about 16000 m during pre-monsoon and post-monsoon periods. The product of CAPE with RF over land is higher by 66% to that of oceanic region with aerosol load (AOD) of about 49% more over land as compared with that of ocean. The results demonstrate the warming contrasts of land-ocean in a comparative analysis of FC, CAPE, RF and AOD in the tropics.

1 Introduction

Global lightning observations report 40–100 lightning flashes per second worldwide (Orville and Henderson 1986; Christian et al. 1999) with an order of magnitude in land-ocean contrast. The dominance of continental lightning activity could be due to land-ocean contrast in surface properties. The land surface (rock, soil, vegetation, tall trees, urbanised high-rise structures, etc.) heats more readily with its low heat capacity than the fluid ocean surface. Additionally, aridity in tropics may be important for the land-ocean warming contrast of the region. The ratio of sensible heat–to–latent heat (Bowen ratio) ranges from 0.1 over ocean to 10 over landmass (Williams and Renno 1993, Williams and Stanfill 2002). In addition, the sensitivity of near-surface air temperatures over land is greater than over ocean, with land surfaces warming of about 50% stronger than ocean surfaces (Sutton et al. 2007; Boer 2011; Byrne and O'Gorman 2013). As a result, continental storm produces more lightning activity than the oceanic storms (Orville and Henderson 1986). Most of the lightning activity takes place over land regions (Turman and Edgar 1982; Orville and Henderson 1986; Christian et al. 1999; Williams et al. 1999; Williams and Stanfill 2002; Williams et al. 2002; Williams and Satori 2004; Williams and Chan 2004; Pal et al. 2016; Chate et al. 2017). Further, these previous studies showed monthly ratio of continental to oceanic flash rate from about 2.2 to 4.2. Christian et al. (1999) found about 82% more lightning activity over the landmass to that over the ocean from Optical Transient Detector (OTD) data for the year 1995–1996. From the lightning imaging sensor (LIS) and OTD data, Boccippio et al. (2000) found a difference of factor two for the mean flash rates between land and ocean. Nevertheless, a quantitative theory to explain the magnitude of lightning activity with the land-ocean warming contrast is yet to emerge. Observed convective available potential energy (CAPE) over land and ocean region shows warming contrast (Williams and Renno 1993; Lucas et al. 1994). The land-ocean contrast is a ratio of maximum updraft speeds over land and ocean surfaces $\left(\frac{W_{(\mathrm{Land})}}{W_{(\mathrm{Ocean})}}=\sqrt{\frac{\mathrm{CAPE}_{(\mathrm{Land})}}{\mathrm{CAPE}_{(\mathrm{Ocean})}}}\right)$ as shown by Williams and Stanfill (2002), where maximum updraft speed is computed as $W_{\max} = \sqrt{2\mathrm{CAPE}}$ for the efficient transformation of CAPE into

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kinetic energy of updraft. The strong incoming and outgoing radiations on tropical landmass lead to high Bowen ratio to trigger the buoyant parcel to ascend through the boundary layer to upper troposphere where lapse rate is much less than 2 K/km that ceases the entrainment (Williams et al. 2005; Chen et al. 2013). On the other hand, parcels in Tropical Ocean with weak thermal buoyancy in the lower and middle troposphere undergo significant entrainment from smaller parcel widths through a shallower boundary layer.

Indian landmass of 3.28 million km^2 is the largest subcontinent in South-Asia with boundaries of 15,200 km including its coastline of 6100 km with western and eastern coastal plains of 10–20 km and 120 km across Arabian Sea and Bay of Bengal, respectively, with triangular tableland of 0.5 million km^2. The distributions of lightning activities over the Indian landmass and the oceanic region (Chate et al. 2017) is as a function of bulk feature of land-ocean warming contrast to be hypothesised with the scale analysis of CAPE, flash counts (FC), rainfall (RF), Bowen ratio, aerosol optical depths and maximum updraft speed. These parameters to be scaled in this work are governed by the warming contrast between static rough surface of Indian landmass and thermohaline circulations involving temperature and salinity in the Arabian Sea, Bay of Bengal and Indian Ocean. Therefore, unique bulk properties of Indian landmass–oceanic warming contrast are proposed to be flash count per CAPE (FC/CAPE), the product of CAPE and rainfall (CAPE × RF), FC/CAPE and Bowen ratio, FC (land/ocean) and AOD (land/ocean) and FC (land/ocean) and maximum updraft speed (land/ocean).

2 Data

The datasets are retrieved from the Tropical Rainfall Measuring Mission (TRMM) satellite-based total lightning flash counts derived from the lightning imaging sensor (LIS). LIS system and TRMM satellite instrumentations are described elsewhere (Christian et al. 1999; Boccippio et al. 2000, 2002; Bond et al. 2002; Kandalgaonkar et al. 2003; Kandalgaonkar et al. 2005; Kandalgaonkar et al. 2010; Cecil et al. 2014; Tinmaker et al. 2015; Kumar and Kamra 2013; Tinmaker et al. 2017; Chate et al. 2017). The lightning flash count data for the 0.5° × 0.5° grid spacing are retrieved from the NASA GHRC website (http://thunderstorm.msfc.nasa.gov/data/data_lis.html) (Tinmaker et al. 2014, 2015; Chate et al. 2017; Tinmaker et al. 2017) for the period of 17 years (1998–2014). In this study, we have considered oceanic region of Arabian Sea (5°N–20°N, 50°E–80°E) and Bay of Bengal (5°N–20°N, 80°E–100°E) for the analysis, while for the landmass area, we have considered the region between 8°N–36°N and 66°E–98°E, as shown in Fig. 1. The data for hourly rainfall, AOD, temperature profile, sensible and latent heat fluxes

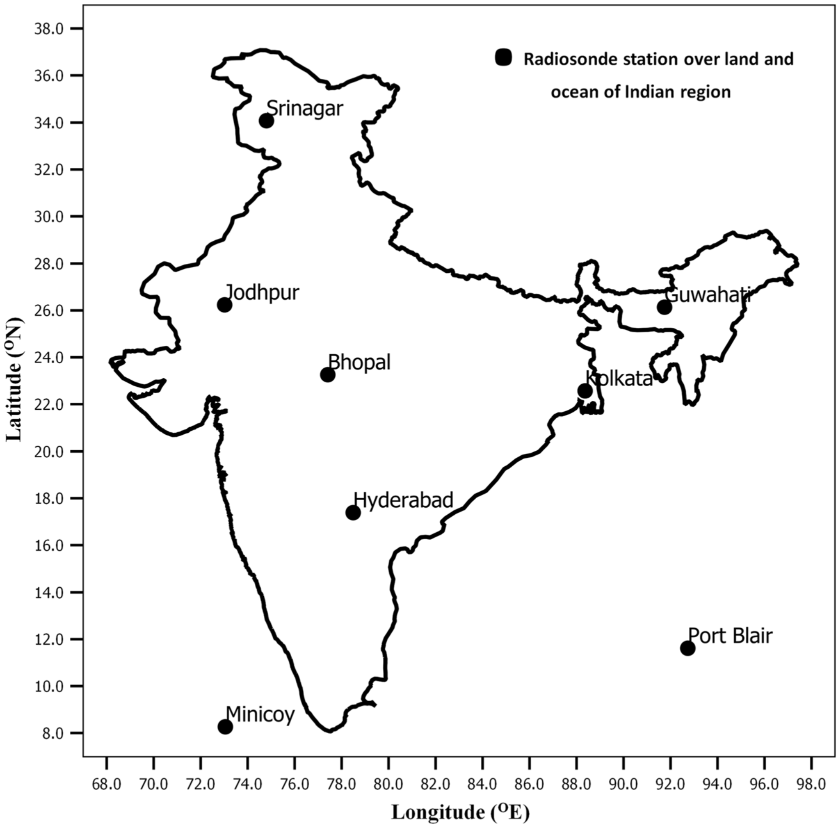


Fig. 1 Map showing land and oceanic (AS + BOB) regions over India

have been used to calculate the Bowen ratio (sensible heat flux/latent heat flux), which was retrieved for the same study period from the NASA GHRC website (http://disc.sci.gsfc.nasa.gov/giovanni/). For the same study period, the data of CAPE for Indian land and oceanic region are retrieved from the University of Wyoming website (http://weather.uwyo.edu/upperair/sounding.html).

In the present work, the variables such as flash count/CAPE (FC/CAPE) can determine the impact of CAPE on lightning activity and vice-versa. The product of CAPE × rainfall is indicative of the proportionality of the CAPE times the rainfall. The relationship of FC (land/ocean) with AOD suggests the role of aerosol in the occurrence of strong mixed-phase development and warm precipitating cloud over land relative to ocean which enhances the lightning activity over land as compared with the oceanic region. Furthermore, relationship of FC (land/ocean) with maximum updraft suggests that the land-ocean contrast energises the cloud microphysical processes for the development of thunderstorms. The results presented illustrate the land-ocean warming contrast in a comparative analysis of FC, CAPE, RF and AOD in the tropics.

3 Results and discussions

Figure 2 a and b show the annual variations of the monthly mean flash count per CAPE (FC/CAPE) and the product of CAPE and rainfall (CAPE × RF) over the land and oceanic regions of India for the period of 17 years (1998–2014). The annual variation of FC/CAPE and CAPE × RF shows first peak during the month of May and second peak in September, although it is lower than that of the May peak. It is seen from the

Fig. 2 Annual variation of monthly mean FC/CAPE and CAPE × rainfall over land (**a**) and ocean (**b**) of India

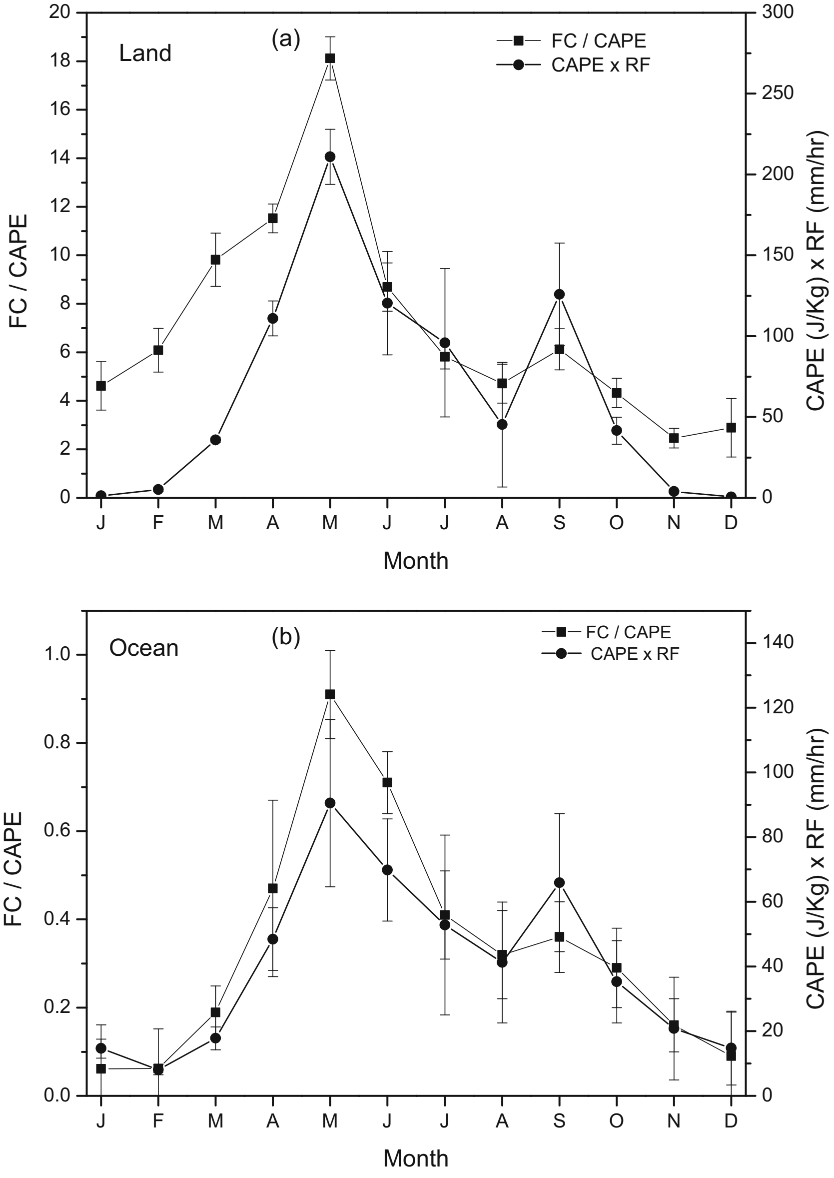


Fig. 3 Correlation coefficient of FC/CAPE and CAPE × RF over land (**a**) and ocean (**b**) regions of India

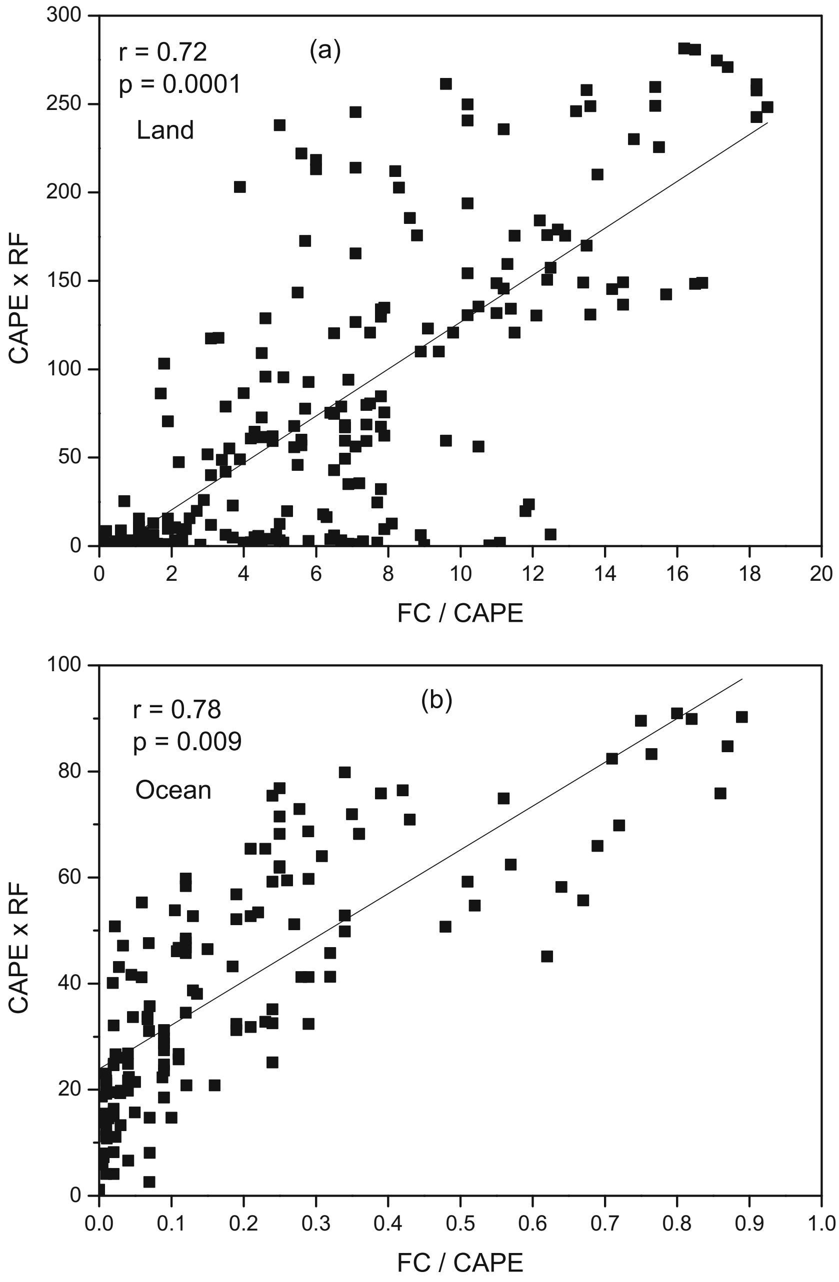


figure that FC/CAPE is found to be higher by two orders of magnitude over land and CAPE × RF is found to be double over the land to that over the oceanic region of India. Since lightning is proportional to the precipitation times CAPE, the most charging mechanism is consistent with the idea that higher CAPE and moisture contents should yield higher lightning activity. CAPE is a measure of vertical velocity responsible for initiating deep convection. The thunderstorm clouds developed owing to deep convection (higher CAPE) are highly electrified over land than over the ocean. The larger values of FC/CAPE during pre-monsoon period suggest that the energy is transformed from CAPE to kinetic energy, which drives deep convection with the availability of moisture in the lower troposphere. Because of the development of strong conditional instability over land, the precipitation particles lifted above the freezing level in developing cloud initiate the ice nucleation processes for the formation of thundercloud with higher lightning activity during pre-monsoon period (Manohar et al. 1999; Kandalgaonkar et al. 2010; Tinmaker et al. 2017; Chate et al. 2017). Furthermore, the relatively higher peak for CAPE × RF during pre-monsoon period confirms the formation of convective clouds with heavy rainfall and lightning activity over land area (Kodama et al. 2005). Upon the onset of monsoon, large-scale rainfall over the ocean limits the deep convection for thunderstorm formation and lightning activities over land (Manohar et al. 1999 and Kandalgaonkar et al. 2008;

Kandalgaonkar et al. 2010) as seen in Fig. 2 a and b. The second relatively smaller peaks of FC/CAPE and CAPE × rainfall in September are indicative of latent heat release with enough moisture contents for the formation of thunderstorm with lightning activity over land and oceanic regions of India (Tinmaker et al. 2010). The correlation coefficient between FC/CAPE and CAPE × RF over the land is found to be of 0.72 significant at 0.0001, while over ocean, it is found to be 0.78 significant at 0.009 (Fig. 3a, b). The FC and CAPE show higher values over land relative to RF, while FC and CAPE over oceanic region show smaller values with corresponding higher RF over ocean as compared with land.

Figure 4 a and b show the annual variations of FC/CAPE and Bowen ratio (the ratio of sensible heat to latent heat) over the Indian land and oceanic regions. In this figure, the FC/CAPE and Bowen ratio are highest during May and lower in September over land and oceanic regions of India. Bowen ratio is a measure of intensity of the thermal eddies that is an indicator of base and width of convective cloud (Williams and Stanfill 2002). The higher FC/CAPE and Bowen ratio over land as compared with that of oceanic region during pre-monsoon season could be due to increased sensible heat relative to that of latent heat. The sensible and latent heats are likely to play quite different roles. The primary role of sensible heat is to modify the efficiency of producing deep convection. Though latent heat can be an indicator of high moisture, on its own, it cannot withstand the deep convection (Chate et al. 2017). The higher values of FC/CAPE and Bowen ratios over land relative to those over oceanic region during May and September indicate the formation of continental mixed-phase thunderclouds with high cloud bases and cloud tops (Williams and Stanfill 2002). The heavy rainfall from such deep

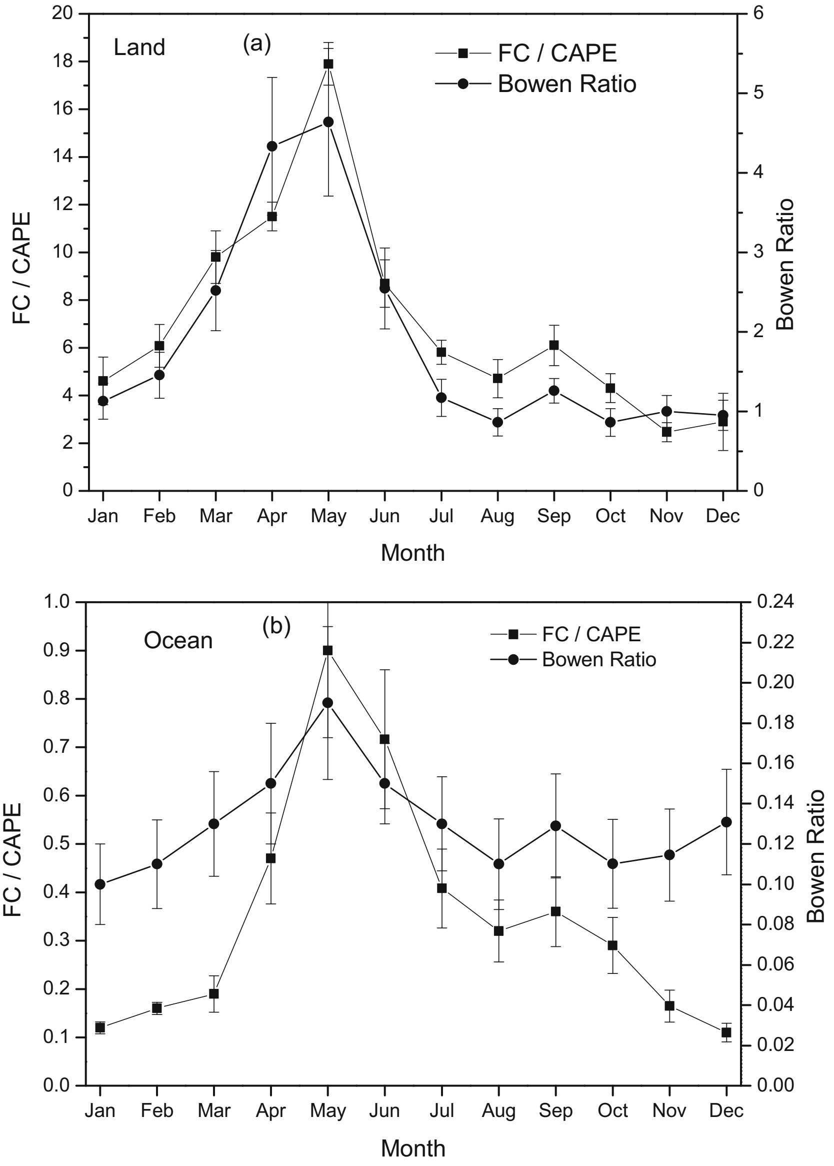


Fig. 4 Annual variation of monthly mean FC/CAPE and Bowen ratio over land (**a**) and ocean (**b**) of India

convective thunderclouds is associated with higher lightning activity. The second peak in September is due to the release of latent heat from the convective air parcel with the corresponding decrease in sensible heat that increases Bowen ratio. The Bowen ratio over land is found to be about 800% higher than that of oceanic region (Tinmaker et al. 2015). Over oceanic region, shallow convection affects the mean updraft speed that limits the formation of supercooled water droplets, graupel and ice particles (Williams and Satori 2004; Albrecht et al. 2011). As a result, the correlation coefficient of FC/CAPE with Bowen ratio over land is found to be 0.79 at significant level 0.0004, whereas over the oceanic region, it is 0.68 at significant level 0.001 (Fig. 5a, b).

Figures 6 a and b show the temperature profiles over land and ocean during May to June (pre-monsoon) and September to October (post-monsoon) over the Indian region. It is seen from the figure that the temperature is the same over land and ocean in the lower troposphere followed by a temperature difference of about 8 °C between land and ocean at about 16000 m during pre-monsoon and post-monsoon periods. There is a greater rate of increase of surface temperature over land than the ocean; in turn, the land-ocean difference in the rate of heating is considered the primary cause for the observations of enhanced lightening activity over land than ocean during pre-monsoon and post-monsoon. Nevertheless, observations and model simulations show increase of surface

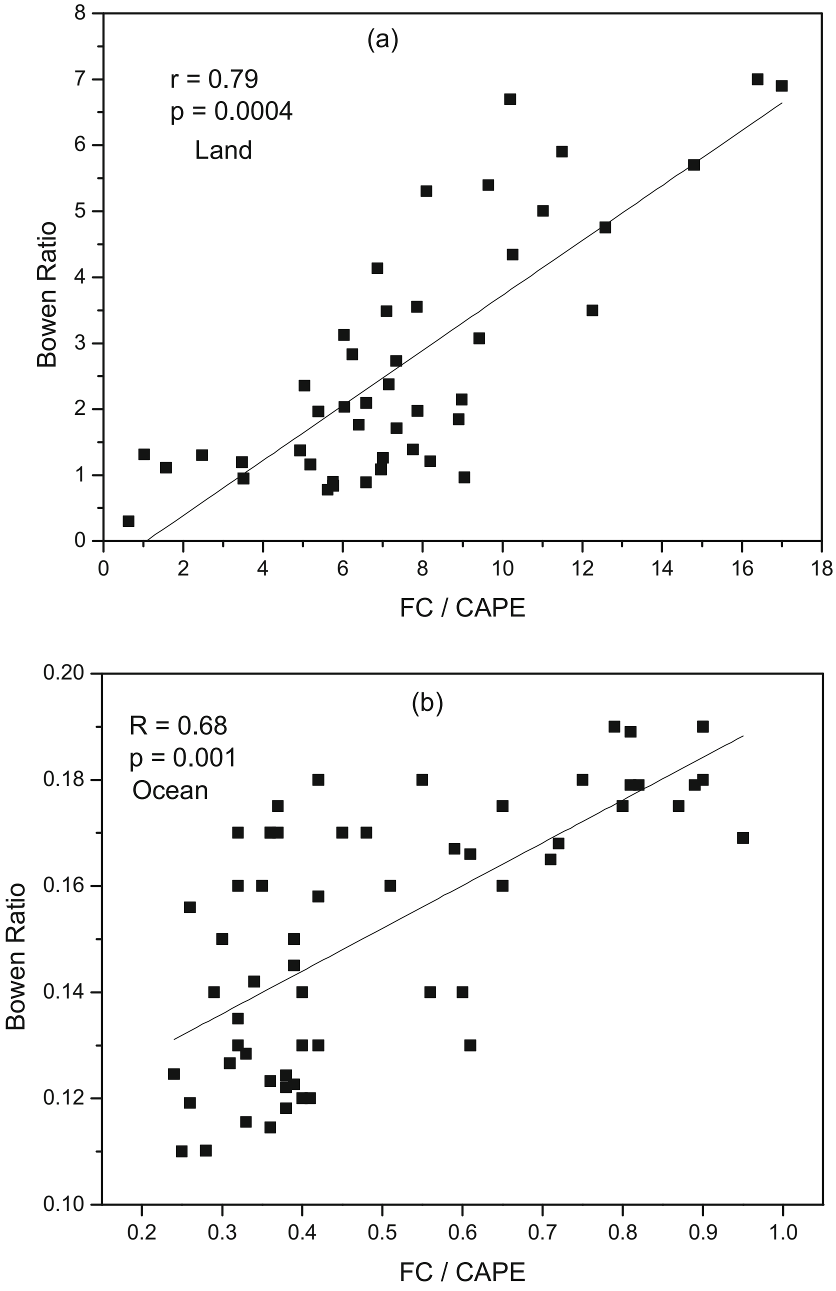


Fig. 5 Correlation coefficient of FC/CAPE and Bowen ratio (**a**) land (**b**) ocean region of India

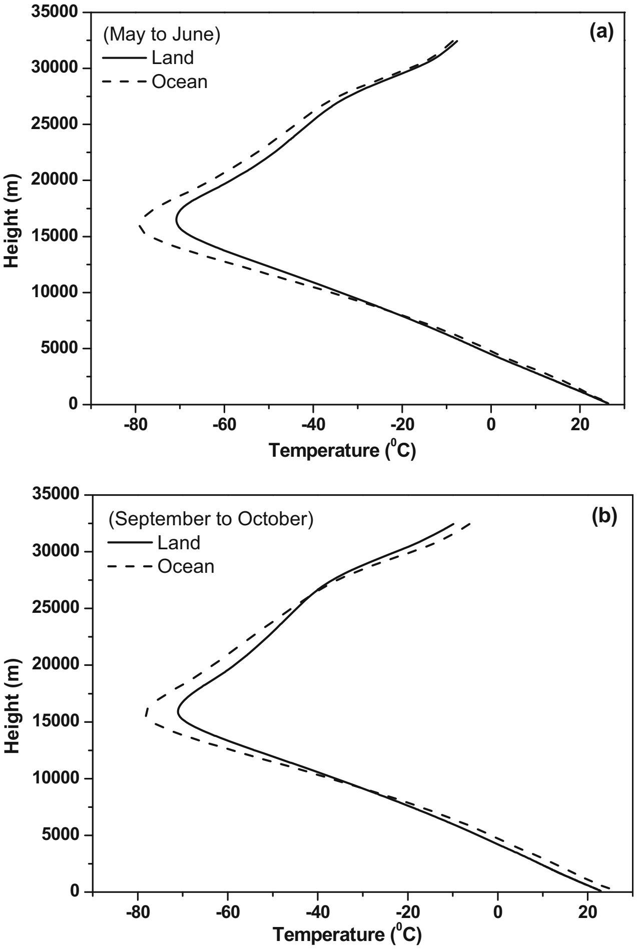


Fig. 6 Temperature profile during **a** pre-monsoon and **b** post-monsoon over land and ocean regions of India

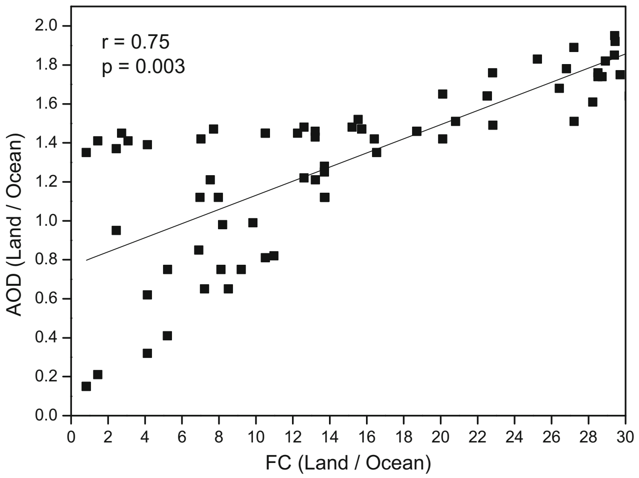


Fig. 8 Correlation coefficient of FC (land/ocean) and AOD (land/ocean) over India

temperature at a greater rate over land than ocean (Manabe et al. 1991; Sutton et al. 2007; Lambert and Chiang 2007; Fasullo 2010; Boer 2011). This land-ocean warming contrast could be due to differences in the lapse rates over static landmass and dynamic oceanic water surface with limited availability of moisture over inland. Therefore, land-ocean warming contrast is in general larger for arid regions. Nevertheless, changes in aridity and cloud cover are also effective even in moist regions (Joshi et al. 2008; Doutriaux-Boucher et al. 2009; Fasullo 2010). Because of weak temperature gradients in the tropical free troposphere, land and ocean temperatures are equal at sufficiently high levels in the

Fig. 7 Annual variation of FC (land/ocean) and AOD (land/ocean) over India

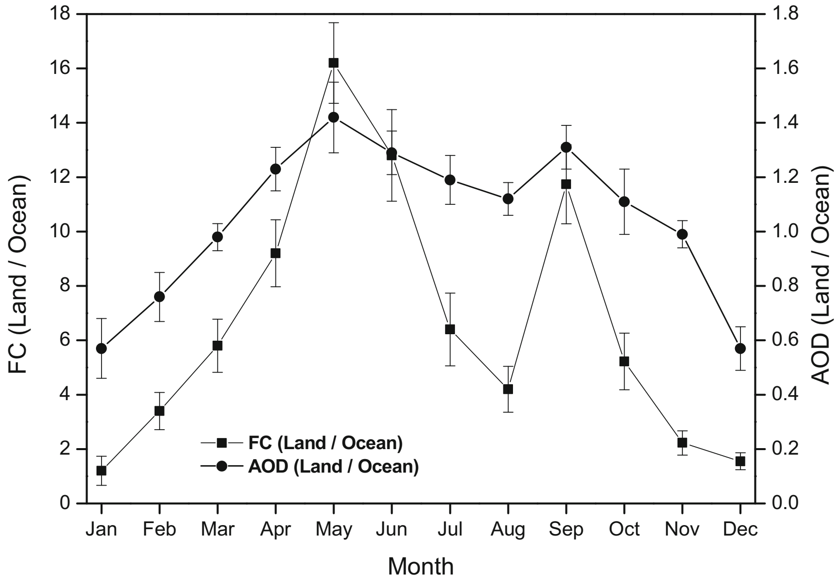
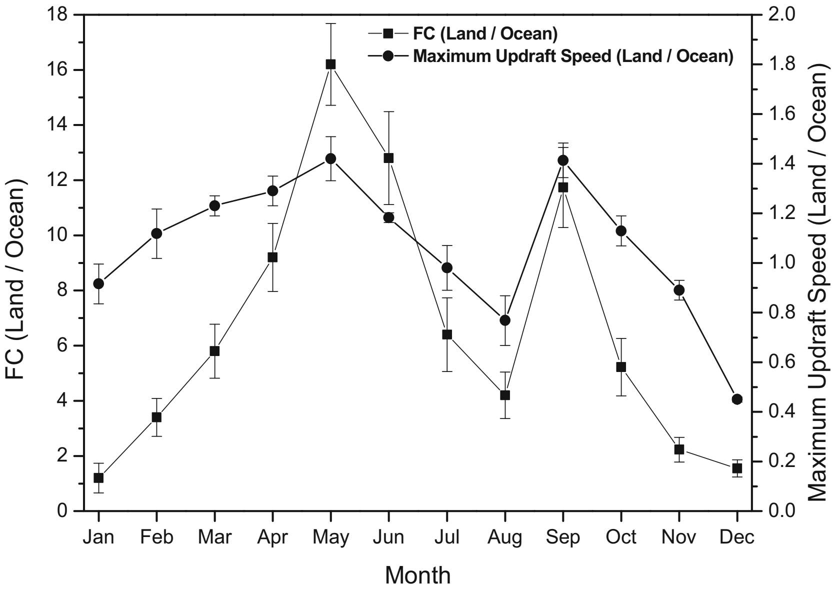


Fig. 9 Annual variation of FC (land/ocean) and maximum updraft speed (land/ocean) over India



atmosphere (Fig. 6a, b). Furthermore, moisture convergence over land predominantly takes place at levels significantly colder than the surface level, though evaporation over land upon warming limits the moisture supply. This process reduces the relative humidity in the boundary layer over land and hence enhances the land-ocean warming contrast.

Figure 7 is a plot of annual variations of the ratio of flash count over the land to ocean (FC (land/ocean)) and AOD over land to ocean (AOD (land/ocean)). The figure shows the first peak of FC (land/ocean) and AOD (land/ocean) in May and the second one in September. The distribution of AOD over the land is about 49% higher than that over the ocean. AOD represents number and size distributions of atmospheric aerosols (Altaratz et al. 2010; Tang et al. 2014) which are responsible for cloud condensation nuclei (CCN) distributions in large-scale monsoon dynamics (Tao et al. 2012; Grandey et al. 2013). The first higher peak during pre-monsoon period (May) is due to the dominance of lightening activity with increased AOD over land (Yuan et al. 2011) than that over the ocean (Takahashi 1984; Deierling and Petersen 2008; Mansell et al. 2005). The deep ocean is of pristine environment where low-level marine clouds with low updrafts do not allow the suspension of ice particles, which are essential ingredient for cloud electrification (Black et al. 1996; Szoke et al. 1986; Jorgensen et al. 1985; Williams and Satori 2004; Thornton et al. 2017). Figure 8 shows that the correlation coefficient between FC (land/ocean) and AOD (land/ocean) is found to be 0.75 significant at 0.003. As stated above, the 49% higher AOD over land to that over pristine ocean supplies more CCN for thunderstorm formation over land that results in enhanced lighting activity over land.

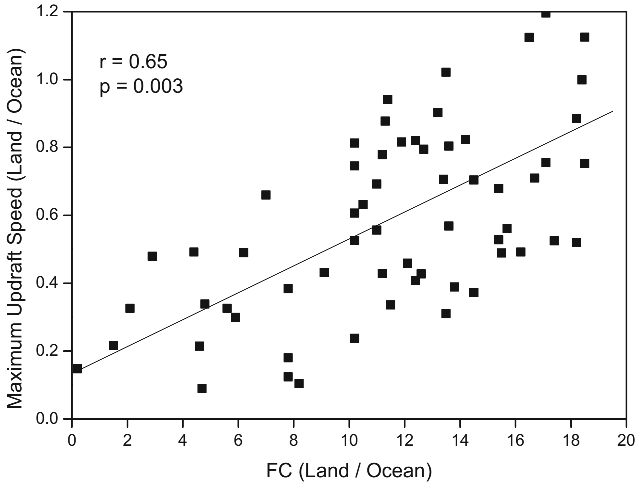


Fig. 10 Correlation coefficient of FC (land/ocean) and maximum updraft speed (land/ocean) over India

Figure 9 shows the annual variation of FC (land/ocean) and maximum updraft speed (land/ocean) for the period of 17 years over the Indian region. The figure shows for FC (land/ocean) and maximum updraft speed (land/ocean) a relatively higher peak in May followed by a lower peak in September. The first higher peak in May could be due to the maximum updraft speed that provides a larger source of condensate, thereby promoting the growth of larger graupel and hail. The electrification of clouds caused by collisions of graupel and ice crystals in a supercooled cloud is the main charging mechanism in the presence of supercooled water in the mixed-phase clouds that relate the updraft to the high lightning activity over land than oceanic region (Lang and Rutledge 2002). The maximum updraft speed leads to the production of more supercooled water droplet collisions and causes intensive charging of ice particles. Zipser and Lutz (1994) showed that updraft speeds in the maritime clouds are weaker than those in the thunderclouds over the land. As seen in Fig. 10, the correlation coefficient of FC (land/ocean) and maximum updraft speed (land/ocean) is 0.65 and is significant at 0.003. The relationship of FC (land/ocean) with maximum updraft speed with a correlation coefficient of 0.65 corroborates the formation of deep convective thunderstorm clouds over land as compared with shallow maritime clouds over ocean.

4 Conclusions

This study presents the lightning activity in comparative analysis of the land-ocean contrast over a period of 17 years (1998–2014) for the Indian region.

1. The annual variations of FC/CAPE and CAPE × rainfall show first peak in May followed by next peak in September. The higher amplitude of FC/CAPE during pre-monsoon is due to intense conditional instability over the land with precipitation particles lifted above the freezing level that triggers ice nucleation processes developing more lightning activity over land than in the oceanic region. The higher peak of CAPE × RF during pre-monsoon is characterised by higher lightning activity over land than over the oceanic region.
2. The relationship between higher FC/CAPE and Bowen ratio over land and ocean during the study period suggests that the continental clouds are of high cloud bases and cloud tops above the freezing level. The rainfall from such deep convective clouds is isolated with high lightning activity. On the other hand, over oceanic region, shallow convection limits the mean updraft speed within the maritime clouds where supercooled water droplets, graupel and ice particles rarely form. Therefore, marine clouds are weakly charged and are of low lightning activity.
3. It is seen from the temperature profile that the same temperatures exist over land and ocean in the lower troposphere followed by a temperature difference of about 8 °C at about 16000 m during pre-monsoon and post-monsoon periods. The temperature gradients in the tropical free troposphere over land and ocean indicate that moisture convergence over land predominantly takes place at levels significantly colder than the surface, which reduces the relative humidity in the boundary layer and shows the enhancement in the land-ocean warming contrast.
4. An increase in AOD during pre-monsoon season shows more lightning activity over Indian landmass than over ocean. Over pristine oceanic region, low aerosol concentration leads to the formation of maritime clouds. The marine clouds with weak charging mechanism are responsible for low lightning activity over oceanic region.
5. The annual variations of FC (land/ocean) and maximum updraft speed (land/ocean) show higher peaks in May. The high correlation of FC (land/ocean) with maximum updraft speed with a coefficient of 0.65 substantiates the formation of deep convective thunderstorm clouds over land as against shallow maritime clouds over ocean in the tropical regions.

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