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High lightning activity in maritime clouds near Mexico

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Abstract

Lightning activity detected by the World Wide Lightning Location Network (WWLLN) over oceanic regions adjacent to Mexico is often as high as that observed over the continent. In order to explore the possible cause of the observed high flash density over those regions, the relationships between lightning, rainfall, vertical hydrometeor profiles, latent heating, wind variability and aerosol optical thickness are analyzed. The characteristics of lightning and precipitation over four oceanic zones adjacent to Mexican coastlines are contrasted against those over the continent. In addition, we compare two smaller regions over the Tropical Pacific Ocean: one located within the Inter-Tropical Converge Zone and characterized by high rainfall and weak lightning activity and the other influenced by a continental jet and presenting high rainfall and strong lightning activity over the Gulf of Tehuantepec. Maritime precipitating clouds that develop within the region influenced by offshore winds exhibit similar properties to continental clouds: large content of precipitation ice and an increased height range of coexistence of precipitation ice and cloud water. During the rainy season, monthly distribution of lightning within the region influenced by the continental jet is contrary to that of rainfall. Moreover, the monthly variability of lightning is very similar to the variability of the meridional wind component and it is also related to the variability of aerosol optical depth. The analysis strongly suggests that the high lightning activity observed over the Gulf of Tehuantepec is caused by continental cloud condensation nuclei advected over the ocean.

1 Introduction

Lightning activity in the tropics is usually much higher over land than over the ocean. The contrast between land and ocean lightning density is so significant that it can be used to identify precipitation regimes. Takayabu (2006) evaluated rain-yields per flash (RPF) over the entire tropics and found that the difference in RPF value between land

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and ocean was about one order of magnitude. Even though rainfall amounts over tropical oceanic zones are similar to those over land, lightning activity is much weaker in the maritime regime, which results in higher RPF. Petersen and Rutledge (1998) calculated RPF values based on cloud-to-ground lightning data and found that the difference between tropical land and ocean RPF can reach two orders of magnitude. Zipser (1994) defined a similar index to RPF, a rain-thunderstorm ratio, and proposed it as an indicator of the *continentality* of convective rainfall.

The reasons for different rates of lightning flashes over continents and oceans are quite complex. The electric field in clouds develops as a result of the interaction between different types of hydrometeors (Saunders, 2008). Among the factors that influence the processes of cloud electrification are precipitation ice content (Petersen et al., 2005) and updraft velocity (Zipser and Lutz, 1994). The aforementioned factors are related, as strong updrafts lead to greater vertical cloud development and higher ice concentrations. Takayabu (2006) showed that large amounts of tall convective rainfall with a precipitation top height above −20 °C are associated with intense updrafts and strong lightning activity. Zipser and Lutz (1994) argued that updraft velocities over tropical oceans are weaker than those over land, which implies that oceanic convective cells can hardly lift large raindrops above the freezing level or allow the formation of large particles of solid phase. Small amounts of ice in maritime clouds lead to reduced lightning activity. Petersen et al. (2005) found that there is a very high correlation between precipitation ice and lightning flash density in cumulonimbus clouds and that this correlation is so similar for maritime, coastal and continental regimes, that it can be considered as regime independent.

However, not only the amount of ice is highly correlated with lightning, also the size distribution of ice particles plays an important role. Sherwood et al. (2006) showed that climatological maxima in lightning activity are associated with small effective diameter of ice crystals near the tops of cumulonimbus clouds and that the relationship is consistent over land and ocean. This finding points toward the role of aerosols in cloud electrification, since high concentrations of atmospheric aerosols may reduce the

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effective diameter of ice particles generated by the freezing of supercooled droplets. Recently, direct and indirect evidences on the influence of aerosol particles on lightning activity have been reported in the scientific literature (e.g., Yuan et al., 2011; Altaratz et al., 2010; Bell et al., 2009; Khain et al., 2008). It is widely agreed that the mechanisms of charge separation involve the participation of graupel, ice crystals and supercooled droplets (e.g., Takahashi, 1978; Avila et al., 1999; Saunders, 2008); therefore the impact of aerosol particles on lightning would be a consequence of their role in the formation of hydrometeors that participate in cloud electrification. Avila et al. (1999) proved that the sign of charged graupel depends on the size distribution of supercooled droplets, so it can be expected that charge separation depends not only on the concentration but also on the size distributions of atmospheric particles that serve as cloud condensation nuclei (CCN) and that determine the cloud droplet spectra. In addition to their role in nucleation of cloud droplets and ice crystals, high concentrations of soluble atmospheric particles could influence lightning through a greater release of latent heat that increases updraft velocities (Kucieńska et al., 2010a; Rosenfeld et al., 2008).

The factors responsible for the contrast in lightning activity between land and ocean are not completely understood but it is clear that on a global scale, lightning over the oceans is much less frequent than over land (Williams and Stanfill, 2002). However, there are maritime regions where lightning activity seems to be of continental type. Kucieńska et al. (2010b) presented very high number of flashes in maritime clouds that develop relatively close to the Mexican coast (up to 800–1000 km). The main objective of the present paper is to study the precipitating maritime clouds that exhibit continental characteristics and propose possible reasons for their high lightning activity.

2 Database

The lightning activity was registered by the World-Wide Lightning Location Network (WWLLN) during the period 2005–2009. The WWLLN has been developed through collaborations between research institutions across the globe to provide global real-time

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locations of lightning discharges. The lightning is located by using the time of group arrival of the VLF (3–30 kHz) radiation from a lightning stroke (Rodger et al., 2005). The dispersed waveform of the lightning impulse is processed at each receiving site. Each lightning stroke location requires the time of group arrival from at least five WWLLN sensors. The current network includes 40 stations which cover much of the globe and detect strokes with an efficiency larger than 10 % (35 %) for currents stronger than ± 35 kA (−130 kA) and smaller than 2 % for currents between 0 and −10 kA (Abarca et al., 2010).

The surface precipitation and the profiles of hydrometeors and latent heating are obtained from the products of the Tropical Rainfall Measuring Mission (TRMM), which is a joint mission between the National Aeronautics and Space Administration of the United States and The National Space Development Agency of Japan. The objectives of the TRMM are to measure rainfall and energy exchange of tropical and subtropical regions of the world (Kummerow and Barnes, 1998; Tao and Adler, 2003).

The rainfall climatology is derived from the 3B42 TRMM product based on the Adjusted Geostationary Operational Environmental Satellite Precipitation Index technique (Adler et al., 1994; Kummerow et al., 2000). It uses an optimal combination of other products and precipitation estimates to produce merged high quality infrared precipitation. The gridded estimates are on a three-hour temporal resolution and a 0.25° by 0.25° spatial resolution in a global belt extending from 50° S to 50° N. The vertical profiles of hydrometeors are retrieved from the 2A12 TRMM algorithm which relates observed multichannel brightness temperatures to the hydrometeor profiles computed by cloud resolving models (Kummerow et al., 1996).

The aerosol data are retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS), which is a key instrument onboard the Terra and Aqua satellites. The Level-3 MODIS Atmosphere Monthly Global Product, with a resolution of one degree, was used to evaluate monthly variability of average aerosol optical thickness (AOT) at 550 nm, over the study region.

Near-surface wind speed and direction data from the SeaWinds microwave radar on the QuikSCAT (QSCAT) satellite are used for the analysis. QSCAT mission collected data for a decade (1999–2009) in a continuous 1800-km wide swath, covering around 93 % of the ice free global oceanic surface in one day, providing high spatial and temporal resolution wind measurements over global oceans. QSCAT swath wind speed and direction daily data, referenced to a height of 10 m, were downloaded from the Center for Ocean-Atmospheric Prediction Studies website (http://coaps.fsu.edu/scatterometry/swath), from which meridional wind components were calculated and averaged within 0.25° × 0.25° latitude-longitude boxes. In this study, wind variability within the region influenced by the Tehuantepec Jet (see Fig. 1) is analyzed by means of the long-term monthly means of meridional wind component and wind convergence for the period 2000–2007.

3 Results

In order to better present our results, this section is divided into three subsections. First, the observed relationship between lightning activity and rainfall for the four oceanic regions shown in Fig. 1 is described, and the properties of maritime precipitating clouds are compared against those of continental clouds over Mexico. In the second subsection, the characteristics of the vertical profiles of hydrometeors and latent heating for the four oceanic regions and continental Mexico are presented. And finally, the third subsection is focused on the cloud characteristics in two maritime sub-regions of the Tropical Pacific: an area influenced by the Tehuantepec Jet (locally intense offshore winds in the lee of the low-elevation gap through the Sierra Madre mountain range in the Isthmus of Tehuantepec) that exhibits high values of both rainfall and lightning flashes and an area within the Inter-Tropical Convergence Zone (ITCZ), in which clouds exhibit high rainfall and low lightning activity.

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3.1 Relationship between lightning flashes and rainfall in clouds over continental Mexico and adjacent oceanic regions

Takayabu (2006) used TRMM databases to calculate rain-yields per flash (RPF) over the entire tropics. His results confirmed that the RPF is a reliable indicator of precipitation regimes, with a marked land–ocean contrast and intermediate values over monsoonal regions and intra-continental seas. In the present study, the number of flashes per rainfall (FPR, which is the inverse of RPF) for the four oceanic regions adjacent to Mexico (shown in Fig. 1) is analyzed. The monthly spatial variability of the number of flashes per rainfall [fl kg^{-1}] shows the highest values during the spring (Fig. 2). Although the maximum lightning activity occurs during the summer months (Kucieńska et al., 2010b), the FPR is higher during spring, before the onset of the rainy season (Fig. 3), when very high temperatures and moderate humidity may cause evaporation of raindrops before they reach the surface. Also, during spring there is an increased emission of particles to the atmosphere originated by biomass burning. Altaratz et al. (2010) showed that smoke aerosols from Amazonian fires have a significant influence on lightning. The results discussed in Sect. 3.3 of the present paper indicate that smoke particles increase lightning activity over the Pacific during spring.

Note in Fig. 2 that there are several regions where the value of FPR over the ocean is similar or even higher than over the continent. Next, each region is discussed separately.

3.1.1 Gulf of Mexico (area d in Fig. 1)

The FPR over the Gulf of Mexico presents very high values during April and May (Fig. 2). The spring precipitation over this area is smaller than during summer (Fig. 3), but the lightning density is quite significant in spring (Kucieńska et al., 2010b). Note that the FPR does not exhibit a land-ocean contrast over the Gulf of Mexico. In fact, if the FPR is used as an indicator of precipitation regimes, as suggested by Takayabu (2006), then the precipitation over the Gulf of Mexico would be interpreted as continental.

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The northern part of the Gulf of Mexico exhibits the highest values of FPR. An exceptionally strong lightning activity registered by the WWLLN over this area was already highlighted by Abarca et al. (2010), who suggested that it could be attributed to the bias of the WWLLN toward stronger flashes. Kucieńska et al. (2010b) evaluated the annual variability of the flash density [flashes km^{-2}] and showed that, in the northern region of the Gulf of Mexico, more flashes are recorded over the ocean than over the land during July and August. Note that the rainfall over this part of the Gulf of Mexico is largest from July to September (Fig. 3), but the FPR decreases in September (Fig. 2). This indicates the existence of a factor which has a monthly variability that impacts lightning differently than precipitation. The monthly variability in lightning activity could be related to the wind variability. Over this particular area, during the rainy season, the onshore winds are weakest in July and August (Fig. 2 in Romero-Centeno et al., 2007), corresponding to the months that exhibit the highest lightning density (Kucieńska et al., 2010b). The decrease in the intensity of onshore winds enhances the role of land breezes and the transport of continental cloud condensation nuclei (CCN) toward the sea. During summer, high values of FPR are also observed at the southern part of the Gulf of Mexico, close to coast of the states of Veracruz, Tabasco and Campeche. This area is characterized by a persistent low-level convergence and convection, which leads to high rainfall amounts, as shown in Fig. 3. In fact, over the continental Mexico, these coastal zones present the maximum climatological precipitation. The large lightning activity observed over this region is probably related to dynamical factors.

3.1.2 Tropical Pacific (area c in Fig. 1)

This region comprises the oceanic area between 93° W and 117° W in longitude and in latitude from 10° N up to an arbitrary limit at 19° N. Figure 2 shows that during spring the FPR values for the Tropical Pacific area close to the Mexican coast are similar to the continental FPR values. In summer, the FPR values over the ocean are even larger than over the land. The monthly signal of high precipitation along the Pacific coast propagates northward (Fig. 3) following the migration of the ITCZ. The mountains of

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the Sierra Madre del Sur are located fairly close to the coast and cause orographic forcing and locally enhanced precipitation. The complex topography prevents the high rainfall signal, that is clearly observed over the ocean, from migrating inland; therefore, the highest precipitation is observed over the coastal region. The spatial distribution of FPR (Fig. 2) is also clearly related to the topography.

Note that the area over the Tropical Pacific located farthest from the coast, within the main ITCZ (ITCZ sub-region of area c in Fig. 1), exhibits very high values of precipitation (Fig. 3) and very low values of FPR (Fig. 2). Strong low-level convergence over this zone (Romero-Centeno, 2007) enhances convection and precipitation development but seems to have no influence on lightning activity. In contrast, the wind convergence over the areas of Tropical Pacific located close to the coast is weaker (Romero-Centeno, 2007), but the lightning activity is very strong. Kucieńska et al. (2010b) suggested that the lightning activity over the Tropical Pacific areas closer to the coast is not primarily influenced by low-level convergence, but could instead be related to the continental CCN transported by the land breeze. This hypothesis is explored further in this paper.

3.1.3 Subtropical Pacific (area b in Fig. 1)

The convection in this oceanic region located North of 18° N is dominated by the North American Monsoon (Higgins et al., 2006), with precipitation observed only very close to the coast and in the Sea of Cortez during summer. The diurnal cycle of precipitation (Nesbitt et al., 2008) is related to the combination of upslope flows and sea breeze during the daytime and land breeze during the night, that results in precipitation close to the coast. The Subtropical Pacific presents the narrowest seasonal distribution of lightning among the four oceanic regions adjacent to Mexico: 95 % of all the flashes occur between July and October, with maximum observed in August (Kucieńska et al., 2010b). This seasonal cycle of lightning is clearly tied to the convection observed during the North American Monsoon. Lightning activity is confined very close to the coastline, with rainfall exhibiting the same spatial pattern (Fig. 3).

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3.1.4 Caribbean Sea (region e in Fig. 1)

Lightning activity over the Caribbean Sea is strongest over coastal regions and the highest lightning density is observed in October (Kucieńska et al., 2010b), corresponding to the maximum precipitation (Fig. 3). However, the highest number of flashes per rainfall occurs in September (Fig. 2), when the precipitation at the coastal regions is less than a half of October rainfall. This means that the conditions that influence lightning activity over this region are not necessarily the same that influence rainfall, at least not in the same degree. The maritime regions located to the south of the island of Cuba exhibit FPR values similar to those observed over land. The high lightning activity in the coastal regions could be possibly related to the advection of continental aerosol particles from the surrounding islands.

3.2 Vertical hydrometeor profiles and latent heating

The vertical profiles of hydrometeors and latent heating provide additional information on the microphysical processes that take place in the precipitating clouds. The profiles of the hydrometeors (Fig. 4) are estimates from the average over the pixels with non-zero surface precipitation detected during the summer months (June to September) for the five years included in the study (2005–2009). Given the short observing time from TRMM for individual clouds, *snapshots* are captured at different phases of their development and the results must be interpreted with caution. The curves represent average profiles of water content in the different hydrometeor categories of precipitating clouds and do not correspond to the total amount of rainfall. Each panel in Fig. 4 (one for each of the 5 areas indicated in Fig. 1) contains several vertical profiles, corresponding to cloud water, precipitation water, cloud ice and precipitation ice concentrations. Vertical profiles of each hydrometeor were estimated for daytime (6 a.m. to 6 p.m. LT) and nighttime (6 p.m.–6 a.m. LT) and are depicted by solid and broken lines, respectively.

The vertical profiles of cloud ice and cloud water concentrations (blue and red curves in Fig. 4) are fairly similar for all the regions; the main differences can be noticed between the amounts of precipitation ice (black curve) and precipitation water (green

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curve). Some regions show a clear difference between day and night, such as the precipitation ice over the Subtropical Pacific (Fig. 4b) and Caribbean (Fig. 4e) regions.

Continental Mexico (Fig. 4a) exhibits the greatest amounts of precipitation ice content (black curve), with a maximum located 6 km above the surface, and the largest height range of coexistence of precipitation ice and cloud water content, relevant for charge separation and lightning production. There is about 7 % more precipitation ice during nighttime (6 p.m.–6 a.m. LT) than during the day. This is in agreement with the diurnal cycle of lightning flash density over continental Mexico, since the maximum lightning activity is observed between 6 p.m. and 9 p.m. (Kucieńska et al., 2010b). The corresponding vertical profile of the latent heating (Fig. 5a) exhibits a clear maximum at about 7 km, corresponding to the level of maximum ice formation at the temperature of about −12 °C. The secondary maximum in latent heating related to condensation, located at about 3 km of altitude, is much smaller than that of freezing, suggesting that continental precipitation over Mexico results mainly from mixed-phase processes.

The maritime regions adjacent to Mexico represent primarily the characteristics of areas located far from the coastlines, but also include the coastal areas (see Fig. 1), which should be taken into account when interpreting the vertical profiles of hydrometeors. The largest concentrations of precipitation ice are observed over the Subtropical Pacific and the Gulf of Mexico. Rainfall and lightning over the Subtropical Pacific occur only very close to the coast and the profiles of the hydrometeors should be interpreted as profiles representative of coastal regions. Large precipitation ice concentration and a significant interval of coexistence of the precipitation ice and supercooled cloud water indicate that the processes involved in charge separation in these clouds are similar to those that occur in continental clouds. The highest lightning activity over this region occurs at night and during the early morning; it is associated with land breeze periods (Nesbitt et al., 2008; Kucieńska et al., 2010b) and corresponds to the maximum in the concentration of precipitation ice (Fig. 4b). The shape of the latent heating profile, shown in Fig. 5b, is also similar to that of continental Mexico, although the absolute values are much smaller.

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The Tropical Pacific zone covers the areas located both close and far away from the coast (see Fig. 1); therefore over this region there is less precipitation ice during the night than over the Subtropical Pacific and the interval of coexistence of precipitation ice and cloud water is also smaller (Fig. 4c). The profile of latent heating (Fig. 5c) is similar to that of the Subtropical Pacific, but the peak corresponding to condensation is larger, which indicates greater participation of warm-rain processes occurring in the clouds that form far from the coast and are less influenced by continental CCN.

Vertical hydrometeor profiles over the Gulf of Mexico (Fig. 4d) are averaged over the areas close and away from the coast, but most of the rainfall occurs basically over the coastal areas (see Fig. 3); therefore, the amount of ice in the precipitating clouds is slightly higher than over the Tropical Pacific. Note that the latent heating maximum in Fig. 5d, corresponding to the formation of solid phase, is also slightly greater than in the case of the Tropical Pacific. The peak corresponding to condensation is quite significant, indicating that over the Gulf of Mexico warm rain processes could play a noteworthy role in the formation of precipitation.

The hydrometeor profiles over the Caribbean Sea (Fig. 4e), are averaged over areas mainly located away from the coastlines, or at least not in their immediate vicinity (see Fig. 1), and therefore there is less precipitation ice over this zone than over other maritime regions analyzed in this study. The concentrations of precipitating hydrometeors are larger during daytime (6 a.m.–6 p.m.) than during the night (6 p.m.–6 a.m.). Diurnal cycles of rainfall and lightning are not modulated by land and sea breezes; Kucieńska et al. (2010b) showed that the diurnal distribution of lightning over the Caribbean Sea is quite uniform. Note in Fig. 5e that the latent heating maxima corresponding to the formation of liquid and solid phases are comparable in magnitude. The role of warm rain processes in the development of precipitation at the surface is greatest over Caribbean Sea among all regions considered. However, as the latent heat of condensation is about seven times larger than that of freezing, most of the precipitation over this area forms by mixed-phase processes, and the role of precipitation ice is clearly dominant, as shown in Fig. 4e.

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3.3 Lightning activity in clouds over the Gulf of Tehuantepec and the ITCZ in the Eastern Tropical Pacific

Kucieńska et al. (2010b) hypothesized that the high lightning activity observed over the Mexican coastal areas over the Pacific Ocean was caused by the advection of continental aerosol particles over the ocean. This hypothesis will be explored by comparing two sub-regions over the Pacific Ocean: a coastal sub-region that presents high rainfall and high lightning density (hereafter referred as Tehuantepec sub-region) and a sub-region within the ITCZ that exhibits high rainfall but low lightning density. These two sub-regions are indicated by dashed lines in Fig. 1 and are characterized by high sea-surface temperatures throughout the year (Romero-Centeno et al., 2007).

The Tehuantepec sub-region is under the influence of the Tehuantepec Jet (Romero-Centeno et al., 2007), an orography-confined northerly flow through the Isthmus of Tehuantepec, from the Gulf of Mexico to the Gulf of Tehuantepec in the Pacific Ocean, that advects aerosol particles from the continent to the ocean. Particle concentrations are very high over this region, as one of Mexico's largest oil refineries is located on the coast of the Gulf of Tehuantepec, in the town of Salina Cruz. The Tehuantepec Jet is responsible for the transport and dispersion of particles over very large oceanic areas. Baumgardner et al. (2005) found that the concentration of condensation nuclei over the ocean, about 700 km south from the coastline, was four to five times higher when winds were from the continent than when winds were from the Central Pacific. Moreover, Kucieńska et al. (2010b) showed that during summer the signal of high lightning density over the Gulf of Tehuantepec extends more to the south than over other zones along the Pacific coastline. Changes in the intensity of the Tehuantepec Jet modulate monthly rainfall variability near the coast. Kucieńska et al. (2012) noticed that the monthly variability of lightning over the coastal area close to the town of Salina Cruz is related to the wind variability: the mid-summer months, when the Tehuantepec Jet strengthens (Romero-Centeno et al., 2007), correspond to those with highest lightning density. An interesting feature of this region is that when the Tehuantepec Jet

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of northerly flow strengthens during July and August, it inhibits the moisture advection from the Pacific resulting in a decrease in rainfall over the coastal zones, the so-called *mid-summer drought*, that is also observed further inland (Magaña et al., 1999; Curtis, 2004; Romero-Centeno et al., 2007). Therefore, the region under study may be one of a few regions in the world where the changes in wind intensity have opposite effects on rainfall and lightning. Kucieńska et al. (2012) studied a small area in the immediate vicinity of the coast of Oaxaca state. The zone analyzed in the present paper is centered on the Isthmus of Tehuantepec and covers a large area which is under the influence of the Tehuantepec Jet and extends hundreds of kilometers away from the coast.

The ITCZ sub-region (see Fig. 1) is an area with very high rainfall and very low lightning activity (compare Figs. 2 and 3) and it is reasonable to expect that the clouds that form over this sub-region must be quite different than those developing in the Tehuantepec sub-region.

The profiles of hydrometeors over the Tropical Pacific, shown in Fig. 4c and discussed in the previous section, were averaged over a very large area where coastal clouds and typical maritime clouds are present. The hydrometeor profiles of the Tehuantepec (Fig. 6a) and ITCZ (Fig. 6b) sub-regions are presented separately for comparison, since they can be considered as two different regimes. The basic difference between the two regimes is the amount of precipitation ice: Tehuantepec clouds exhibit more precipitation ice than ITCZ clouds. Some additional tests of the oceanic areas located very close to the coast were performed and the amounts of precipitation ice in the immediate vicinity of the Mexican coast of the Tropical Pacific (not shown) are found comparable to those over the continent.

Note also that the amount of precipitation water is greater for the Tehuantepec clouds (Fig. 6). This doesn't mean that the total rainfall over the Tehuantepec sub-region is greater than that over the ITCZ; it only means that an average instantaneous profile of the ITCZ sub-region exhibits less precipitating water, which implies smaller precipitation rates.

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The profile of precipitation ice over the Tehuantepec sub-region indicates larger concentrations during the day (6 a.m.–6 p.m., solid curve in Fig. 6a), whereas over the ITCZ sub-region there is more ice at night (6 p.m.–6 a.m., dashed curve in Fig. 6b). The precipitation ice is proportional to the lightning density (Petersen et al., 2005); therefore, different diurnal distributions of lightning are to be expected for the two sub-regions. The diurnal cycles of lightning densities for both sub-regions are presented in Fig. 7 in terms of the percentage of daily flashes observed during three-hour intervals. The highest lightning activity over the Tehuantepec sub-region (Fig. 7a) is observed between 3 a.m. and 9 a.m. and the lowest one between 3 p.m. and 6 p.m. Baumgardner et al. (2006) measured the highest frequency of land breeze between 5 a.m. and 9 a.m. and the minimum between 2 p.m. and 6 p.m. The diurnal distribution of lightning over the Tehuantepec sub-region is clearly related to the cycle of the land breeze that increases convergence over the ocean and advects aerosol particles from the continent. In contrast, the diurnal cycle of lightning over the ITCZ sub-region (Fig. 7b) is much more uniform, although a bimodal distribution with maxima at 9 a.m. and 9 p.m. is noticeable.

The profiles of latent heating for the Tehuantepec and ITCZ regimes also exhibit significant differences (Fig. 8). Latent heating corresponding to the level of maximum ice formation is about 20 % larger for the Tehuantepec sub-region than for the ITCZ one. Also note that the latent heating associated with the formation of cloud droplets is larger for the Tehuantepec regime, indicative of a greater role of warm-rain processes in precipitation development. Over the Tehuantepec sub-region, more liquid phase forms at night, while solid phase formation is greater during daytime. The opposite situation occurs over the ITCZ sub-region (Fig. 8).

Kucieńska et al. (2012) noticed that monthly variability of lightning at the coast of Oaxaca state is related to the variability of Tehuantepec Jet. Here we explore this relation by comparing monthly distribution of lightning over the coastal region with the variability of meridional wind component. Figure 9 shows the monthly variability of lightning densities for the Tehuantepec and ITCZ regimes during rainy season; also

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the variability of rainfall, averaged over the years 1998–2009, is shown in the figure.

Lightning density over the ITCZ sub-region (Fig. 9b) is about one order of magnitude smaller than that over the Tehuantepec sub-region (Fig. 9a). Note that the monthly distribution of lightning in the ITCZ regime exhibits a maximum in May, which is the month with lowest rainfall within the rainy season.

The monthly distribution of lightning over the region influenced by the Tehuantepec Jet is remarkable since the variability of lightning is contrary to that of rainfall. There is a dramatic increase in rainfall from May to June over the Tehuantepec regime; however, note that lightning flash density decreases from May to June (Fig. 9a). Rainfall over the Tehuantepec sub-region decreases from June to July due to the onset of the *mid-summer drought*, but the lightning density *increases* for the same period (Fig. 9a). Note that the highest lightning density is observed during July and August, months corresponding to the mid-summer drought. In September, rainfall increases, but lightning density decreases (Fig. 9a), while in October there is a decrease in rainfall and an increase in lightning activity.

The monthly variability of meridional wind component (Fig. 10) is analyzed in order to explore the hypothesis that the Tehuantepec Jet influences monthly variability of lightning activity over the Tehuantepec sub-region by advection and dispersion of continental particles. Because of the location and the shape of the Tehuantepec sub-region (see Fig. 1), the meridional wind component of the Tehuantepec Jet would have a critical impact on aerosol particle concentration. Note that the meridional wind component decreases from May to June, increases from June to July, doesn't change from July to August, decreases from August to September, and increases from September to October. This monthly variability in meridional wind components coincides with the variability of monthly lightning flash density described above.

The influence of the Tehuantepec Jet on lightning activity could be related to the dynamic conditions that the jet creates in the region and/or to the microphysical properties of aerosol particles advected from the continent to the ocean. In order to determine the role of dynamics, the monthly variability of horizontal convergence was calculated on

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a grid with 0.5° resolution and averaged over the Tehuantepec Jet sub-region (Fig. 11). Note that the monthly distribution of convergence is opposite to that of lightning density. Low values of convergence in July and August are related to the mid-summer decrease in rainfall but not lightning. Therefore wind convergence is not the factor that determines the variability of lightning activity over this area.

In order to evaluate the influence of aerosols on lightning, the measurements of particle concentrations are needed. At the moment only satellite measurements of aerosol optical thickness (AOT) are available for the areas and months of interest. During the rainy season, the aerosol data are scarce because of extended cloud coverage and particle scavenging by raindrops; therefore 10 yr of Terra satellite and 7 yr of Aqua satellite records were averaged in order to obtain a climatological product. The monthly distributions of AOT for Tehuantepec and ITCZ sub-regions are shown in Fig. 12a,b, respectively.

Over both sub-regions, there is a pronounced maximum of AOT in May (Fig. 12a,b). This maximum is clearly related to May AOT peak over continental Mexico (not shown) caused by biomass burning, which is most intense in the Yucatan Peninsula and on the Pacific coast (Yokelson et al., 2011). Note that the ITCZ sub-region is located more than a thousand kilometers away from the coastlines (see Fig. 1) and it is still affected by continental aerosol particles. The AOT peak in May over the ITCZ sub-region (Fig. 12b) is probably responsible for the maximum in lightning activity in May, shown in Fig. 9b. Also, the AOT maximum over the Tehuantepec sub-region in May (Fig. 12a) seems to be the most probable reason for the lightning activity peak observed at the beginning of the rainy season, which is unusually high when one takes into account the low value of rainfall (Fig. 9a). Moreover, the monthly variability of flash density over Tehuantepec sub-region (Fig. 9a) is similar to that of AOT (Fig. 12a), there is an AOT minimum in June and September, although the variability is much less pronounced.

The hypothesis that offshore winds influence lightning activity through the transport of aerosol particles from the continent seems to be the most probable explanation for

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the results presented here. Baumgardner et al. (2005) concluded that the concentrations of condensation nuclei measured over the Gulf of Tehuantepec are highly dependent on wind direction and magnitude and it is also known that condensation nuclei have a strong effect on electrical activity in clouds. For example, Altaratz et al. (2010) analyzed the relationship between lightning strokes registered by the WWLLN and the aerosol optical depth (AOD) in the Amazonian region influenced by smoke from biomass burning. They showed that there is a range in the values of AOD where a small increase in particle loading results in a very strong enhancement of electrical activity. In a more recent study, Yuan et al. (2011) estimated that over the West Pacific Ocean, a 60 % increase in aerosol loading leads to more than 150 % increase in lightning flashes.

In the present study we also find that the Tehuantepec sub-region of the Tropical Pacific exhibits more precipitation ice that the ITCZ sub-region, indicative of a larger role of cold-rain processes in the development of precipitation. The amount of precipitation ice is highly correlated with lightning flash density (Petersen et al., 2005). Continental clouds exhibit very large concentrations of ice particles, which can develop from ice nuclei (IN) or from other mixed-phase collision-processes in the presence of large concentrations of small water droplets that result from large CCN concentrations. The continental CCN spectra generate cloud droplet spectra composed of many small particles which are not able to grow to precipitation size by the process of collision-coalescence. Moreover, if a cloud forms in a polluted environment, there is a great release of latent heat which results in very strong updrafts (Van den Heever et al., 2006; Kucieńska et al., 2010a). Therefore, the clouds composed of small and numerous droplets do not generate warm precipitation; instead the droplets are carried by the updrafts above the 0 °C isotherm and participate in mixed-phase processes involved in charge separation. Hence, the high amounts of precipitation ice observed over coastal regions can be the result of the presence of CCN spectra of continental type. However, the influence of CCN on lightning can be much more complex than only through its impact on ice amounts. Many other factors related to condensation nuclei could be

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involved. For example, the effect of CCN concentrations on updraft velocities could be a very important mechanism of influence on lightning activity, as it is known that flash densities are related to updraft speeds. Zipser and Lutz (1994) concluded that a necessary condition for rapid cloud electrification is that the updraft speed of a convective cell must exceed a threshold value. They estimated this threshold value as 6–7 $m\,s^{-1}$ for mean speed and 10–12 $m\,s^{-1}$ for peak speed. Another possible factor of influence of CCN concentration on lightning is through its impact on the supercooled liquid water content, as it was proven that supercooled water has an important role in the process of charge separation (Avila et al., 1999).

4 Summary and conclusions

The relationships between lightning, rainfall, vertical profiles of hydrometeors and latent heating over oceanic regions adjacent to Mexican coastlines were analyzed in order to explore possible reasons for very high lightning activity registered by the WWLLN. It is found that, for certain coastal areas, the number of flashes per rainfall (FPR) over the seaside is as high as or even higher than the FPR over land. Vertical hydrometeor profiles over the coastal oceanic areas with high lightning density exhibit characteristics similar to those of continental clouds: large precipitation ice content and an increased height range of coexistence of precipitation ice and cloud water.

The coastal area of the Tropical Pacific influenced by the Tehuantepec Jet was analyzed in detail and it was found that the monthly variability of lightning over this sub-region is similar to the monthly variability of the meridional component of the wind, but it is not related to the variability of the wind convergence. An interesting characteristic of this sub-region is that the intensification of the Tehuantepec Jet has opposite effects on rainfall and lightning: it decreases the former and increases the latter. The influence of the Tehuantepec Jet on rainfall is associated with large scale dynamic conditions and local thermodynamic conditions (Magaña et al., 1999; Romero-Centeno et al., 2007). We explore here the hypothesis that the impact of the jet on lightning is related to the advection of aerosol particles from the continent.

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The analysis of the characteristics of clouds, precipitation and lightning over the oceanic regions adjacent to Mexican coastlines indicates that the continental cloud condensation nuclei (CCN), and possibly also the ice nuclei (IN), transported by off-shore winds to the maritime coastal zones could have an important influence on lightning activity. The very strong winds associated with the Tehuantepec Jet can transport particles for hundreds of kilometers, affecting the microphysics of the clouds that develop under such influence. Small and numerous continental CCN lead to the conditions that favor the development of electric field: stronger updrafts, higher ice contents, greater cloud vertical development and longer cloud lifetimes. Recent findings reported in the literature (i.e. Altaratz et al., 2010; Yuan et al., 2011) prove that changes in the concentrations of CCN have a great impact on the processes of cloud electrification, especially over oceanic regions.

Even though Petersen et al. (2005) argued that the very high correlation between precipitation ice and lightning flash density in cumulonimbus clouds is independent of regime (maritime, coastal and continental) we find that in fact there is a difference in this relationship in the Eastern Tropical Pacific. In-situ observations by an instrumented aircraft during EPIC in September 2001, showed peak updrafts up to 17 $m\,s^{-1}$ in convective clouds in the Tehuantepec sub-region about 600 km from the shore when the winds flowed from the continent to the ocean (Baumgardner et al., 2005). The estimated peak threshold for rapid cloud electrification (Zipser and Lutz, 1994) of 10–12 $m\,s^{-1}$ is regularly exceeded in those clouds, precipitation forms by mixed-phase processes and the precipitation ice can be considered as an indicator of surface rainfall. However there is an inverse relationship between rainfall and lightning density when there is advection of continental aerosols into the Tehuantepec sub-region.

In this study the main arguments in favor of the hypothesis that relates strong lightning activity over the Tehuantepec regime to the CCN advected from the continent are the relationships between lightning density, intensity of the meridional wind component and mean aerosol optical thickness observed over the area influenced by the jet of Tehuantepec. These three variables exhibit very similar monthly distributions.

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The phenomenon of lightning is very complex since it is related to many physical processes occurring within spatial scales that range from micrometers to thousands of kilometers. This paper is aimed at indicating the possible reasons for exceptionally high lightning activity observed over certain oceanic areas and the analysis presented here are mainly qualitative. The relationships between variables analyzed in this study point toward the possible lines of further research that will contribute to deepen our understanding of lightning.

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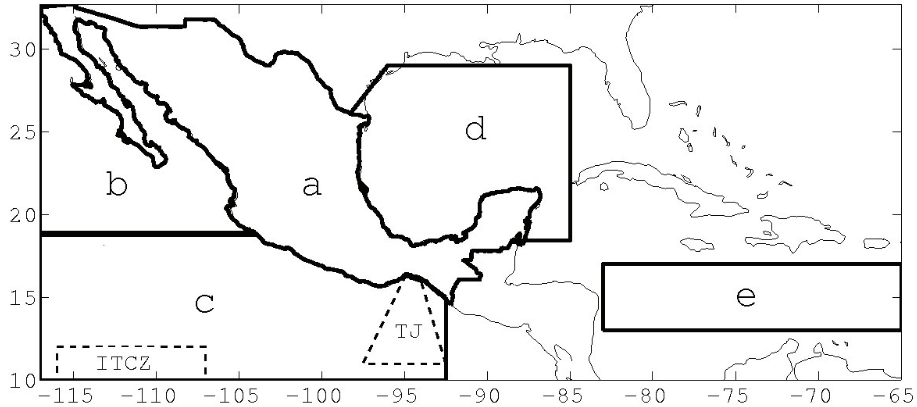

Fig. 1. Study regions: (a) Continental Mexico, (b) Subtropical Pacific, (c) Tropical Pacific, (d) Gulf of Mexico, (e) Caribbean Sea. The areas indicated by dashed lines correspond to the Tehuantepec Jet and ITCZ sub-regions that will be discussed further in Sect. 3.3.

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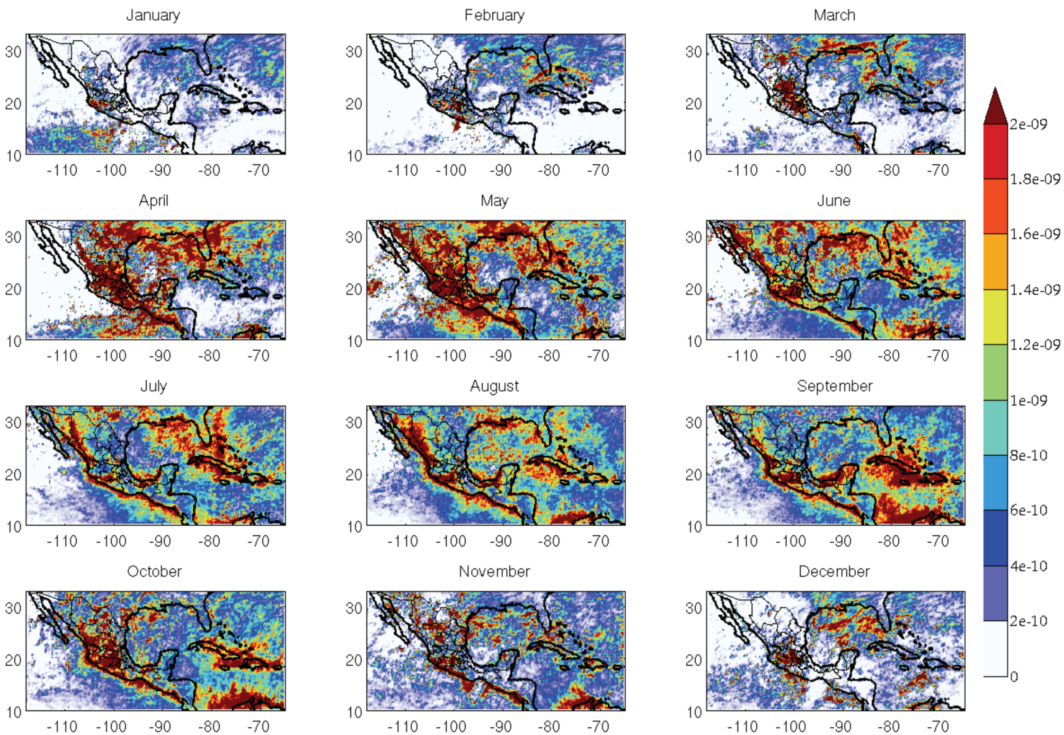

Fig. 2. Monthly distribution of flashes per rainfall [fl kg^{-1}] over Mexico and adjacent oceanic regions, averaged over the years 2005–2009.

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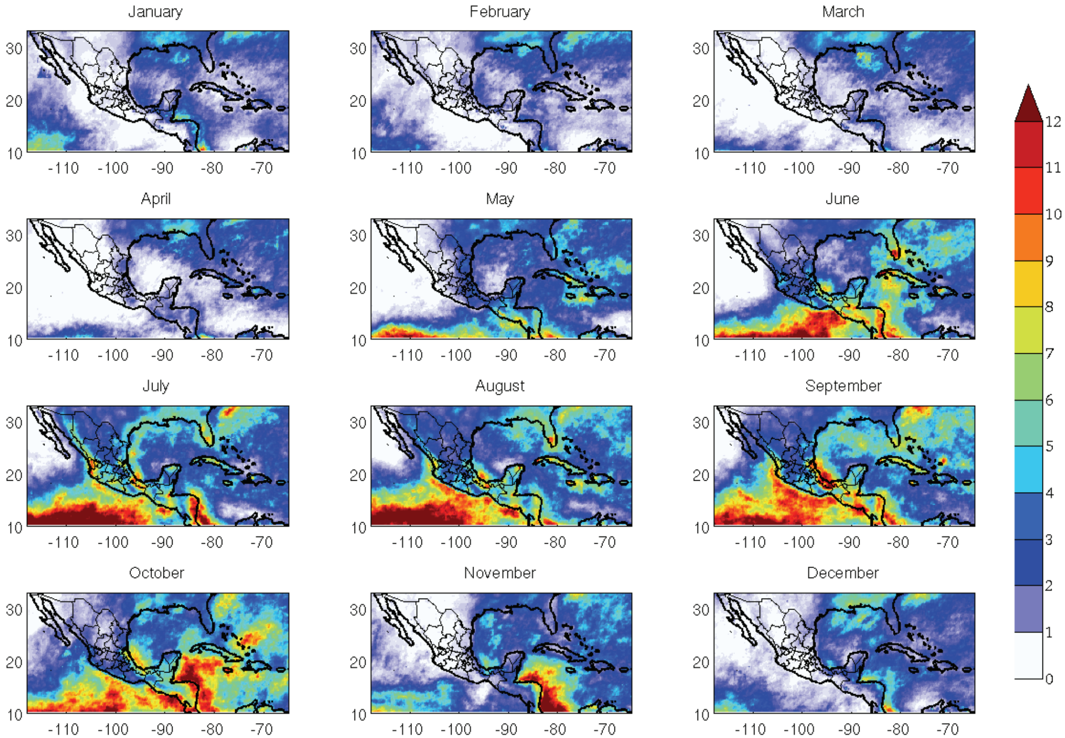

Fig. 3. Monthly distribution of rainfall [mm day^{-1}] over Mexico and adjacent oceanic regions, averaged over the years 2005–2009.

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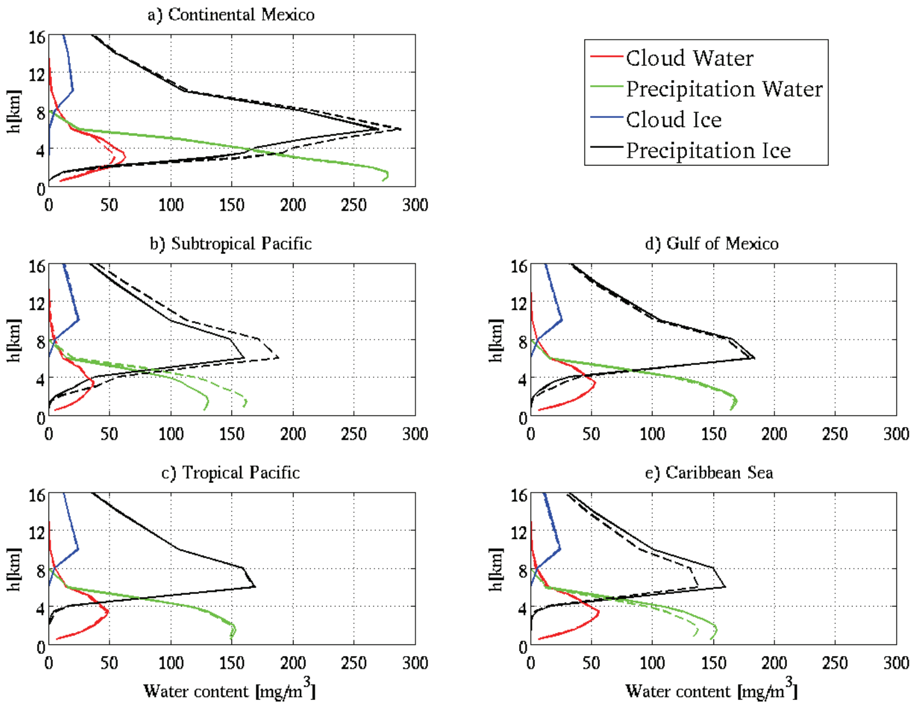

Fig. 4. Vertical profiles of hydrometeors in precipitating clouds averaged over four summer months (June to September) for the period 2005–2009, and spatially averaged over the regions shown in Fig. 1. Solid lines correspond to daytime profiles (6 a.m.–6 p.m.) and dashed lines correspond to nighttime profiles (6 p.m.–6 a.m.).

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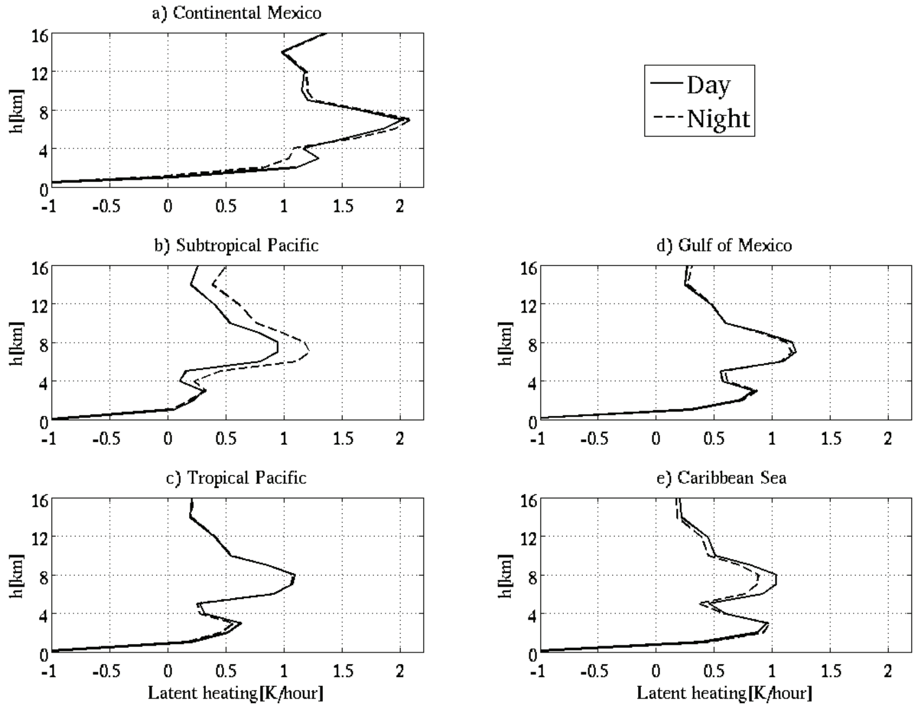

Fig. 5. Vertical profiles of the latent heating averaged over four summer months (June to September) for the period 2005–2009, and spatially averaged over the regions shown in Fig. 1. Solid lines correspond to daytime profiles (6 a.m.–6 p.m.) and dashed lines correspond to night-time profiles (6 p.m.–6 a.m.).

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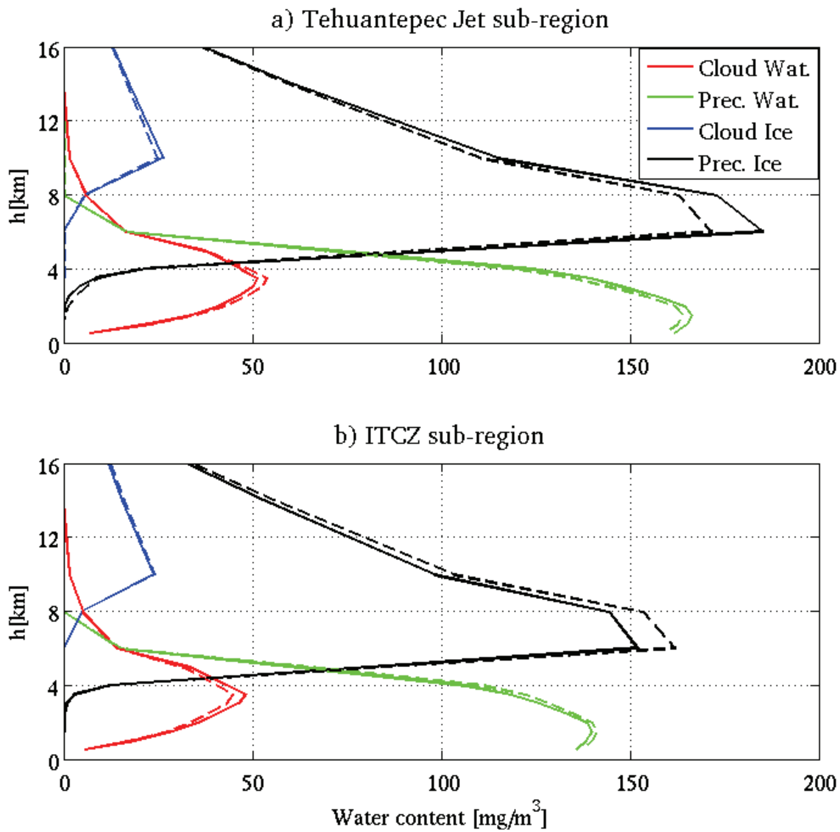

Fig. 6. Hydrometeor vertical profiles of precipitating clouds for: **(a)** Tehuantepec Jet and **(b)** ITCZ sub-regions over the Pacific Ocean. Solid lines correspond to daytime profiles (6 a.m.–6 p.m.) and dashed lines correspond to nighttime profiles (6 p.m.–6 a.m.).

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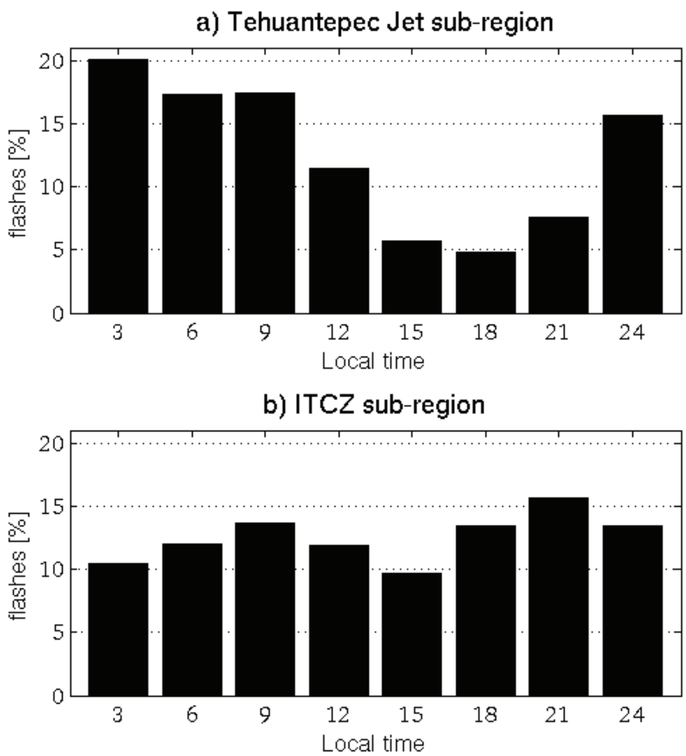

Fig. 7. Diurnal cycles of flashes in the **(a)** Tehuantepec Jet and **(b)** ITCZ sub-regions of the Pacific Ocean. The three-hour averages are centered at the hours indicated.

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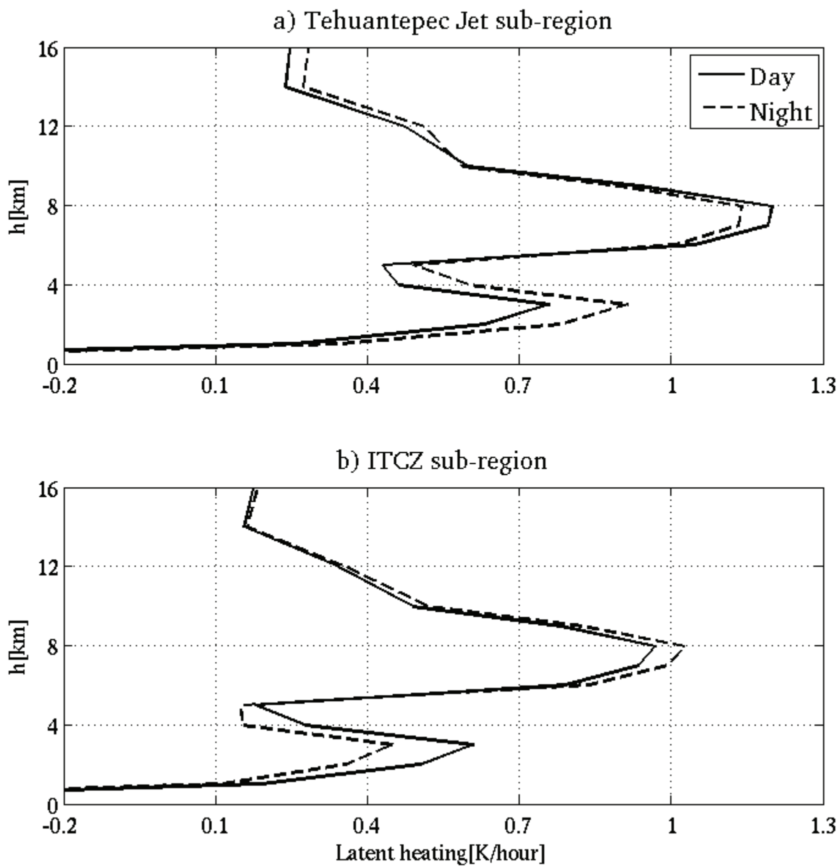

Fig. 8. Vertical profiles of the latent heating averaged over four summer months (June to September) for the period 2005–2009, and spatially averaged over the sub-regions: **(a)** Tehuantepec Jet and **(b)** ITCZ. Solid lines correspond to daytime profiles (6 a.m.–6 p.m.) and dashed lines correspond to nighttime profiles (6 p.m.–6 a.m.).

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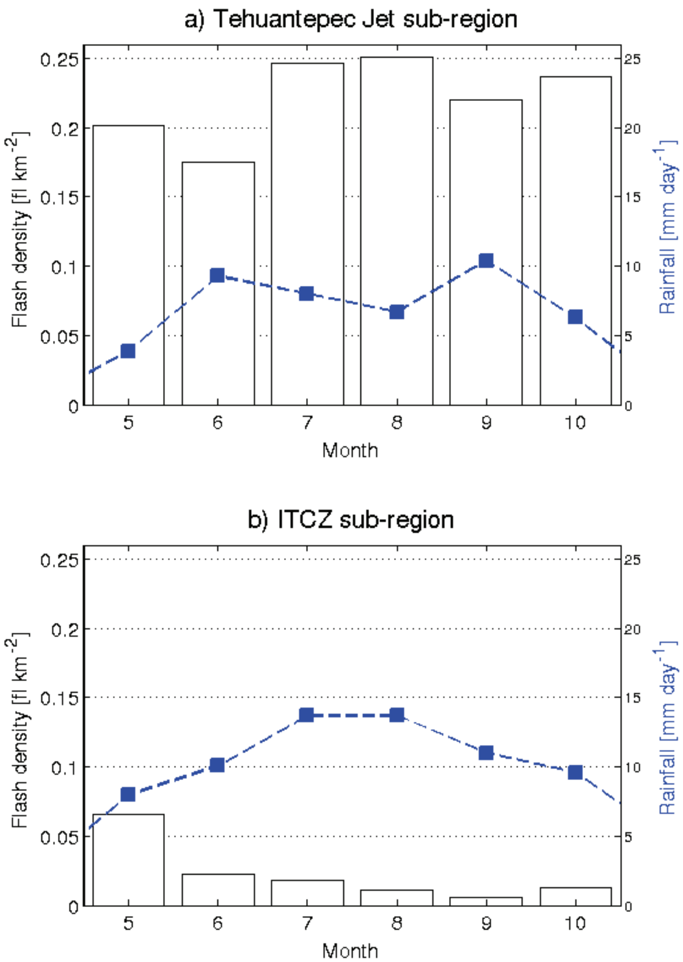

Fig. 9. Monthly variability of lightning flash density (bars) and precipitation (blue line) over the **(a)** Tehuantepec Jet and **(b)** ITCZ sub-regions during rainy season over the Pacific Ocean.

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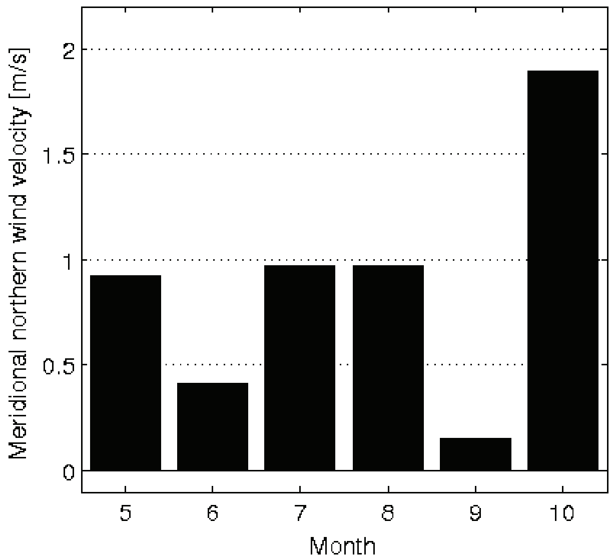

Fig. 10. Monthly variability of meridional northern wind velocity averaged over the Tehuantepec Jet sub-region during rainy season.

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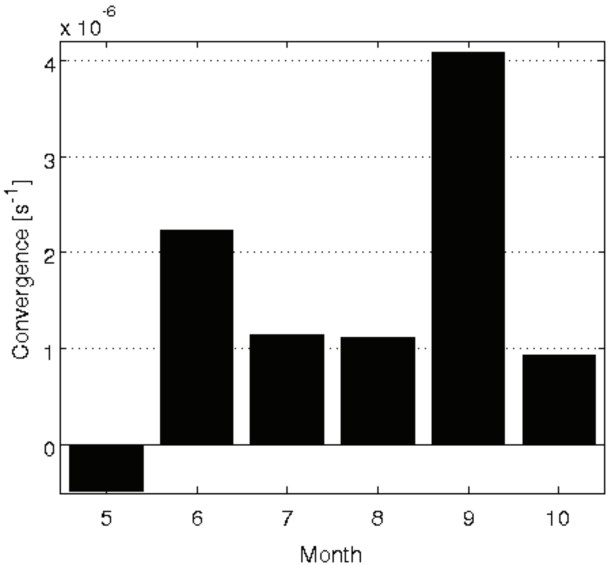

Fig. 11. Monthly variability of convergence averaged over the Tehuantepec Jet sub-region during rainy season.

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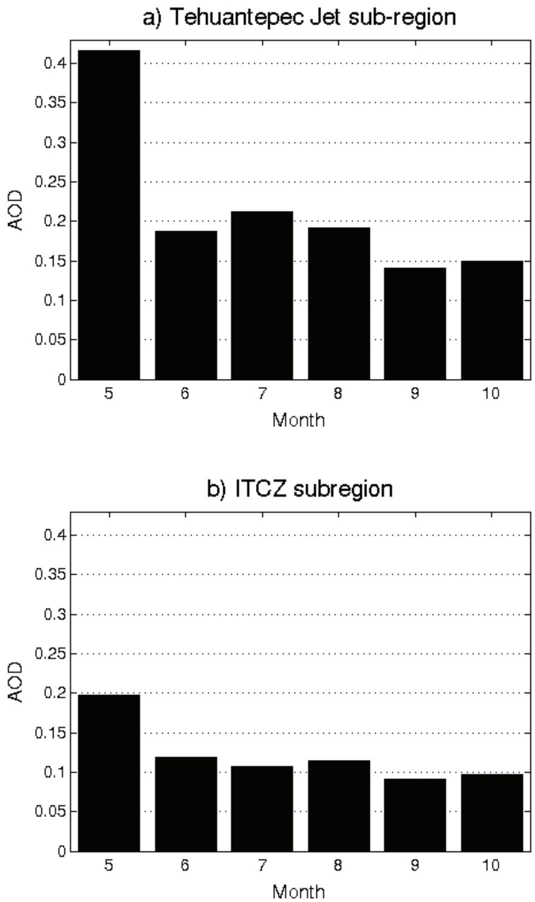

Fig. 12. Monthly variability of aerosol optical thickness during rainy season averaged over the Tehuantepec Jet and ITCZ sub-regions for years from 2000 to 2009 (Terra satellite) and 2003–2009 (Aqua satellite).

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