The diurnal cycle of the lightning potential index over the Mexican tropical continental region during tropical cyclone Bud

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Abstract
Atmospheric processes over the Mexican continental territory can be influenced by the occurrence of tropical cyclones (TCs) over the adjacent oceans. Furthermore, the Mexican territory is characterized by the presence of diurnal cycles of lightning. The Lightning Potential Index (LPI), that is a measure of the potential for charge generation and separation that leads to lightning production in convective storms, was assessed for the diurnal variability of lightning that exhibited a strong diurnal cycle over the Mexican continental territory when TC Bud was over the adjacent eastern Pacific Ocean. The assessment, from 0000 UTC 10 June to 2000 UTC 15 June 2018, used the Weather Research and Forecasting (WRF) model with a new hybrid terrain-following sigma-pressure vertical coordinate. Two ensembles with various cumulus and microphysical parameterizations were performed with a grid spacing of 2 km. In one ensemble, sea surface temperature (SST) was prescribed from the Real-time global (RTG) SST analysis product and allowed to evolve interactively with the modeled atmosphere. Then, all the ensemble members were compared against available observations from the World Wide Lightning Location Network (WWLLN) to evaluate which model configurations perform best. It is not known if the LPI is capable of reproducing diurnal cycles of lightning over tropical regions; and the results allow gaining an understanding of the LPI when it reproduces the observed diurnal variability of lightning over land. The ensemble members that had better performances were those that included the prescribed SST.

Keywords
diurnal cycle, lightning, LPI, tropical cyclone, WRF, WWLLN

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1 | INTRODUCTION

It is well known that tropical cyclones (TCs) can cause deaths and considerable damage over coastal areas (Bouwer, 2011; Emanuel, 2005; Mendelsohn et al., 2012). However, when TCs occur near the coast they can also have indirect impacts over distant inland areas. The transport of moisture and latent heat can induce changes in the surrounding atmosphere influencing the convective activity over distant regions. According to Domínguez and Magaña (2018), in the tropical Americas a single TC can induce intense precipitation over inland arid regions. When TCs are present over ocean areas adjacent to the Mexican continental territory, convective storms occur over the land, bringing associated lightning activity. In addition, the Mexican territory is characterized by the presence of diurnal cycles of lightning (Kucieńska et al., 2010). They are generally observed over tropical regions and are more accentuated over the land than over the ocean (e.g., Gong et al., 2018; Liu & Zipser, 2008; Minobe et al., 2020).

The Lightning Potential Index (LPI) is an important lightning index used to simulate the potential for charge generation and separation in thunderstorms (Lynn & Yair, 2010). However, it is not known if it can reproduce diurnal cycles of lightning over tropical regions and specifically over the Mexican territory. The LPI has been evaluated for individual thunderstorms and mesoscale convective systems in many regions of the world (e.g., Gharaylou et al., 2019; Lagasio et al., 2017; Lynn et al., 2012; Lynn & Yair, 2010; Sokol & Minárová, 2020). Nevertheless, it has not been evaluated over the Mexican territory for periods of several hours. The few studies that do exist about lightning over Mexico (e.g., Beirle et al., 2006; Kucieńska et al., 2012) have not simulated lightning indirectly or directly (explicitly resolving charge separation at microphysical scale) for long periods of time.

The LPI is defined as the kinetic energy of the updrafts scaled by the potential for charge separation. The LPI depends on the mixing ratios of supercooled liquid water, graupel, and snow between the 0°C and −20°C isotherms as well as on the vertical velocity (Yair et al., 2010). The LPI is expressed as

\[
LPI = \frac{1}{V} \iiint \varepsilon w^2 \, dx \, dy \, dz
\]

(1)

where \( V \) is the volume of air in the layer between 0°C and −20°C, \( w \) is the vertical velocity and \( \varepsilon \) is a dimensionless number that takes values between 0 and 1. The \( \varepsilon \) factor depends on the mixing ratios of the hydrometeors as follows

\[
\varepsilon = 2 \left( \frac{Q_i Q_l}{Q_i + Q_l} \right)^{0.5}
\]

(2)

where \( Q_i \) is the total liquid water mass mixing ratio and \( Q_l \) is the fractional mixing ratio defined by

\[
Q_l = q_i \left( \frac{\left( \frac{q_i q_g}{q_i + q_g} \right)^{0.5} + \left( \frac{q_i q_s}{q_i + q_s} \right)^{0.5}}{\left( q_i + q_g \right)^{0.5}} \right)
\]

(3)

and \( q_i, q_g, \) and \( q_s \) are the mass mixing ratios for cloud ice, graupel and snow, respectively.

Because the LPI is calculated from cloud microphysical fields and vertical velocity, it is sensitive to microphysical parameterizations in numerical weather prediction (NWP) models (e.g., Bovalo et al., 2019; Choudhury et al., 2020; Rajeevan et al., 2010). Lightning has a strong microphysical origin, which is important for electrical charge transfer and buildup inside thunderstorms, although there is not a firm theory. Several electrification mechanisms have been proposed and the non-inductive ones are the most accepted. The latter do not depend on the presence of an external electric field and charge transfer takes place during collisions between ice crystals and graupel (Saunders, 2008). This mainly occurs in the region between the 0°C and −20°C isotherms, where there are strong updrafts (Latham et al., 2004) that are associated with the production of hydrometeors (e.g., Ben Ami et al., 2015; Giannaros et al., 2015). The sign of the charge transfer depends on the supercooled liquid water content and the temperatures inside the regions in which the hydrometeors are present (Jayaratne & Saunders, 1983). The electric field created by the charge distributions in these regions triggers lightning (Saunders, 2008; Wang et al., 2015).

Although the LPI is an important index, lightning proxies have also been used to simulate lightning indirectly (e.g., Barthe et al., 2010; Bovalo et al., 2019; Choudhury et al., 2020). They are mainly based on relationships between lightning flash rates and storm parameters such as vertical fluxes of ice, graupel, and snow during updrafts (Cecil et al., 2005; Petersen et al., 2005). Examples of important storm parameters are precipitation ice mass (PIM), cloud top height (CTH), and maximum vertical velocity (MVV). Nevertheless, the studies that do exist at present have not proposed relevant lightning proxies for tropical regions that could be evaluated in this study.

In this study, the LPI was assessed to determine if it can reproduce the observed diurnal variability of lightning, which exhibited a strong diurnal cycle over the Mexican continental territory, when TC Bud was occurring over the
adjacent eastern Pacific Ocean. The assessment was performed from 0000 UTC 10 June to 2000 UTC 15 June 2018. Two ensembles with various physics parameterizations were carried out. In one ensemble, sea surface temperature (SST) was prescribed from a SST product and allowed to evolve interactively with the modeled atmosphere. The ensemble members were defined according to the different model configurations. Three microphysics schemes and four cumulus schemes were used. The WRF-ARW model with a new hybrid terrain-following sigma-pressure vertical coordinate was used. It was configured with a parent domain and two nested domains. The assessment of the LPI was performed over most of the Mexican tropical continental territory, contained in the innermost domain with a grid spacing of 2 km.

This article is organized as follows. Section 2 describes the case study. Section 3 describes the model setup and methodology, including the model configurations and the lightning observations. Section 4 presents the results. Section 5 presents the comments on the results and the diurnal variability of PIM, CTH, and MVV storm parameters with prescribed SST. However, a full analysis of these variables as lightning proxies is beyond the scope of our analysis. Finally, in Section 6 the conclusion is presented.

## 2 | CASE STUDY

During TC Bud, heavy precipitation and flooding were present over the Mexican tropical continental (MTC) region. This region covers most of the Mexican tropical continental territory and is established as the continental area inside domain d03, shown in green in Figure 1a; and also the continental region shown in Figure 1b. The selected period of time for the present case study goes from 0000 UTC 10 June to 2000 UTC 15 June 2018. This case study was selected because TC Bud spent most of its lifespan over the Eastern Pacific Ocean, dissipating over the Gulf of California (Figure 1b). The TC did not traverse the whole MTC region but just the tip of the Baja California Peninsula at the end of its lifespan.

Lightning was present during and before the TC event over the MTC region. Figure 2b shows the spatial distribution of the observed lightning activity by the World Wide Lightning Location Network (WWLLN) at 0000 UTC 9 June, before the TC event. At that same instant of time, the spatial distribution of the observed precipitation is shown in Figure 2c. During the period of time studied, the diurnal variability of the lightning activity (red curve in Figure 2a) over the MTC region is coincident with the diurnal variability of the precipitation rate (blue curve in Figure 2a). The latter was calculated as the average of the precipitation rate over the enclosed area by the black rectangle present in Figure 2b, which represents the central area of the Mexican continental territory.

From 10 to 12 June (during the first 48 hours in Figure 2a), an increase in the maximum wind speed (MWS) of TC Bud occurred (green line in Figure 2a). Also, an increase in the magnitude of the maxima of the lightning activity detected by WWLLN (red curve in Figure 2a) over the MTC region occurred. On 13 June
FIGURE 2  In (a) the time evolution of observed lightning from WWLLN (red curve) over the MTC region. Also in the same panel, the time evolution of the precipitation rate (blue curve) over the area bounded by the black rectangle in (b), which covers part of the MTC region; as well as the intensity evolution of TC bud (green curve). The start time in (a) corresponds to 0000 UTC on June 10. The spatial distributions of observed lightning in (b) and precipitation rate in (c) on 9 June at 0000 UTC, eighteen hours before the TC event. In (d–f) the spatial distributions of the daily evolution of the accumulated precipitation from 11 to 13 June. Figures (c–f) were produced with the Giovanni online data system, developed and maintained by the NASA GES DISC.
FIGURE 3  Evolution of TC bud from 0400 UTC on June 10 to 0400 UTC on June 12, according to a WRF simulation. Near the center of the TC, the sea level pressure (SLP) (at the top) and the MWS (at the bottom)
(around hour 72 in Figure 2a), the magnitude of the maxima of the lightning activity started to decrease, but the MWS of TC Bud began to decrease one day before. Besides, an increase of the area extension of the daily accumulated precipitation over the MTC region occurred from the beginning of 10 June to the end of 12 June. On 13 June, the area extension of the accumulated precipitation decreased. When comparing the horizontal distribution over the MTC region in Figure 2d (on 11 June) with that of Figure 2e (on 12 June), an increase of the area extension of the daily accumulated precipitation is observed. Conversely, a decrease of the area extension of the accumulated precipitation over the MTC region is observed when comparing Figure 2e with Figure 2f (the accumulated precipitation during 13 June). The maxima of the lightning activity were present around 0000 UTC each day and the start time in Figure 2a corresponds to 0000 UTC on 10 June.

TC Bud could have influenced the development of convention and lightning over the MTC region, but it is not known how. Dominguez and Magaña (2018) mention that in the tropical part of the American continent a single TC can induce intense precipitation over arid regions. However, at present there are no studies about the processes associated with the connection between TCs and the development of convection and lightning over the Mexican continental territory.

TC Bud occurred from 1800 UTC 9 June to 0600 UTC 16 June 2018 over the Eastern Pacific Ocean (Figure 1b). A low pressure formed on 9 June and the associated thunderstorm cluster started to rotate, causing the formation of a tropical depression at 1800 UTC and 528 km south of Acapulco. The tropical depression became a tropical storm on 10 June at 0000 UTC, reaching hurricane stage on 10 June at 1800 UTC. The MWS reached 61.7 m/s at 0000 UTC on 12 June near Manzanillo. Later, Bud became a tropical storm on 13 June at noon UTC and made landfall over Baja California Sur on 15 June at 0200 UTC, with wind speeds of 20.5 m/s and a central pressure of 999 hPa. Subsequently, it crossed Baja California Sur. Over the Gulf of California, the circulation was weakened by the presence of high vertical wind shear. A graphical representation showing part of the evolution of the TC Bud is shown in Figure 3.

3 | METHODS AND DATA

3.1 | Modeling setup

The WRF (ARW) model, version 4.1.2 (Skamarock et al., 2019), was used to simulate the atmospheric variables on which the LPI depends over the MTC region from 0000 UTC 10 June to 2000 UTC 15 June 2018, when TC Bud was over the adjacent eastern Pacific Ocean. The WRF model is a mesoscale numerical model developed for research and operational forecasting. It features a fully compressible and non-hydrostatic dynamic core with many parameterizations associated with sub-grid scale processes.

For each model integration, the outer domain was set with a grid spacing of 18 km while the innermost domain with a grid spacing of 2 km (Figure 1a), using a ratio of 3 to 1 between nests with two way nesting between outer and inner domains. The initial and boundary conditions (IBCs) were obtained from the National Center for Environmental Prediction (NCEP) FNL (Final) operational global analysis and forecast dataset, which is available with a horizontal grid spacing of 0.25° at 6 h intervals (NCEP, 2015). In this dataset, the data in the IBCs are made with the same model used in the Global Forecast System (GFS). The data was interpolated at intervals of 3 h and used to update the lateral boundary conditions of the parent domain (d01, shown in Figure 1a) every 3 h. The innermost domain, covering the MTC region and the adjacent Pacific Ocean, is represented as a horizontal grid of 886 x 886 points. The model was configured with 51 vertical levels, using a hybrid sigma-pressure vertical coordinate, which follows the terrain and gradually makes transition to constant pressure, reducing the numerical noise, at higher levels (Beck et al., 2020; Powers et al., 2017). A time-step of 3 s was used for the innermost domain. For the middle and outermost domains, a time-step ratio of three was chosen. Before analysis, a spin-up time of 17 h was selected.

Four cumulus and three microphysics schemes were used. The microphysical schemes used were the Purdue Lin scheme (Chen & Sun, 2002), the WRF single-moment 6-class scheme (Hong & Lim, 2006), and the Thompson scheme (Thompson et al., 2008). The cumulus schemes used were the Kain-Fritsch scheme (Kain, 2004), the Betts-Miller-Janjic scheme (Janjic, 1994), and the simplified Arakawa-Schubert scheme (Han & Pan, 2011). Also, the moisture advection-based trigger scheme for the Kain-Fritsch cumulus scheme was used (See Table 1).

The parameterizations used in all simulations are: the Yonsei University scheme (Hong et al., 2006) for the planetary boundary layer, the MM5 similarity scheme (Beljaars, 1994; Dyer & Hicks, 1970; Paulson, 1970; Webb, 1970; Zhang & Anthes, 1982) for the surface layer, the unified Noah land surface model (Tewari et al., 2004) for the land surface, the Dudhia shortwave scheme (Dudhia, 1989) for the shortwave radiation, and the RRTM Longwave scheme (Mlawer et al., 1997) for the longwave radiation.

Two ensembles were defined. In one ensemble, SST was provided from the Real-time global (RTG) SST High
Resolution analysis product, with a one twelfth degree resolution. In this ensemble, the SST was modified to include daily SST variations during the simulation period using the interactive scheme proposed by Zeng and Beljaars (2005) (hereafter referred to as interactive SST). This scheme takes into account the effects of the heat and changes in the radiative fluxes (e.g., diurnal variations in shortwave radiation). In the other ensemble, just the IBCs from NCEP FNL were used, and the names for each ensemble member will end in “-GFS”. The ensemble members with interactive SST are listed in Table 1.

Although this research is not focused on TC Bud but on the LPI over the adjacent land, TC tracks for each

### Table 1: Member ensembles with interactive SST

| Simulation | Simulation acronym | Microphysics | Cumulus |
|------------|--------------------|--------------|---------|
| 1          | LIN-KF-RTG         | Purdue Lin scheme | Kain-Fritsch scheme |
| 2          | LIN-BMJ-RTG        | Purdue Lin scheme | Betts-Miller-Janji scheme |
| 3          | LIN-SAS-RTG        | Purdue Lin scheme | Simplified Arakawa-Schubert Scheme |
| 4          | LIN-KF-TR-RTG      | Purdue Lin scheme | Kain-Fritsch scheme | Moisture advection-based trigger scheme |
| 5          | THOM-KF-RTG        | Thompson scheme  | Kain-Fritsch scheme |
| 6          | THOM-BMJ-RTG       | Thompson scheme  | Betts-Miller-Janji scheme |
| 7          | THOM-SAS-RTG       | Thompson scheme  | Simplified Arakawa-Schubert scheme |
| 8          | THOM-KF-TR-RTG     | Thompson scheme  | Kain-Fritsch scheme | Moisture advection-based trigger scheme |
| 9          | WSM6-KF-RTG        | WRF Single-moment 6-class scheme | Kain-Fritsch scheme |
| 10         | WSM6-BMJ-RTG       | WRF Single-moment 6-class scheme | Betts-Miller-Janji scheme |
| 11         | WSM6-SAS-RTG       | WRF Single-moment 6-class scheme | Simplified Arakawa-Schubert scheme |
| 12         | WSM6-KF-TR-RTG     | WRF Single-moment 6-class scheme | Kain-Fritsch scheme | Moisture advection-based trigger scheme |

### Table 2: Mean track error (in km) for the ensemble members with interactive SST

| Simulation acronym | Mean track error (in km) |
|--------------------|--------------------------|
| LIN-KF-RTG         | 70.041                   |
| LIN-BMJ-RTG        | 78.262                   |
| LIN-SAS-RTG        | 62.864                   |
| LIN-KF-TR-RTG      | 39.551                   |
| THOM-KF-RTG        | 47.002                   |
| THOM-BMJ-RTG       | 85.028                   |
| THOM-SAS-RTG       | 57.524                   |
| THOM-KF-TR-RTG     | 32.207                   |
| WSM6-KF-RTG        | 47.031                   |
| WSM6-BMJ-RTG       | 68.875                   |
| WSM6-SAS-RTG       | 46.091                   |
| WSM6-KF-TR-RTG     | 26.314                   |

### Table 3: Mean track error (in km) for the ensemble members without interactive SST

| Simulation acronym | Mean track error (in km) |
|--------------------|--------------------------|
| LIN-KF-GFS         | 110.062                  |
| LIN-BMJ-GFS        | 83.624                   |
| LIN-KF-TR-GFS      | 44.551                   |
| THOM-KF-GFS        | 64.651                   |
| THOM-BMJ-GFS       | 95.147                   |
| WSM6-KF-GFS        | 79.583                   |
| WSM6-BMJ-GFS       | 76.741                   |
| WSM6-SAS-GFS       | 56.172                   |
| WSM6-KF-TR-GFS     | 34.471                   |
ensemble member were compared with the best track data from the National Hurricane Center (NHC) before calculating the LPI over the MTC region. Of the two ensembles, the one with interactive SST performed better. In Table 2, the average track errors (in km) for the ensemble members with interactive SST are shown. In Table 3, the mean track error for most ensemble members without interactive SST are shown.

The track error was calculated as the distance between a point in the simulated track and a point in the best track along the corresponding great circle. Then, the average track error for each track was calculated as the average of all track errors in the track.

The tracks obtained from the THOM-BMJ-RTG, WSM6-KF-TR-RTG, WSM6-BMJ-RTG, and LIN-KF-TR-RTG ensemble members are shown in Figure 4a. In Figure 4b, the WSM6-KF-RTG and WSM6-KF-GFS ensemble members are shown, the second without interactive SST. In each panel of Figure 4, the best track and the track calculated from the NCEP FNL (Final) dataset (denoted as GFS track) are also shown.

### Figure 4

In (a), tracks from the THOM-BMJ-RTG, WSM6-KF-TR-RTG, WSM6-BMJ-RTG, and LIN-KF-TR-RTG ensemble members. In (b), the tracks from WSM6-KF-RTG and WSM6-KF-GFS ensemble members. In (a) and (b), the best track (in black) and the track calculated from the NCEP FNL (final) dataset (in red, denoted as GFS track).

The track error was calculated as the distance between a point in the simulated track and a point in the best track along the corresponding great circle. Then, the average track error for each track was calculated as the average of all track errors in the track.

The tracks obtained from the THOM-BMJ-RTG, WSM6-KF-TR-RTG, WSM6-BMJ-RTG, and LIN-KF-TR-RTG ensemble members are shown in Figure 4a. In Figure 4b, the WSM6-KF-RTG and WSM6-KF-GFS ensemble members are shown, the second without interactive SST. In each panel of Figure 4, the best track and the track calculated from the NCEP FNL (Final) dataset (denoted as GFS track) are also shown.

### 3.2 The fractions skill score over the MTC region

The Fractions Skill Score (FSS) (Roberts & Lean, 2008) was adapted to spatially evaluate the LPI over the MTC region because it is not a rectangular region. The FSS uses the concept of nearest neighbors as the means of selecting the scales of interest and it is applied to thresholds. This method provides a measure of the simulation skill against spatial scale for a chosen threshold. The FSS is computed as follows:

$$FSS = 1 - \frac{MSE(n)}{MSE(n)_{ref}}$$

where the numerator in the right side of expression (4) is expressed as

$$MSE(n) = \frac{1}{Z} \sum_{i \in x_{MTC}} \sum_{j \in y_{MTC}} [O_f(n)(i,j) - M_f(n)(i,j)]^2$$

To follow the border of the MTC region, including the coastlines, in expression (5) $i \in x_{MTC}$ and $j \in y_{MTC}$ mean that the summation indices $i$ and $j$ took values for each grid square or pixel inside the MTC region. The variable $Z$ is the total number of grid squares inside the MTC region. Also, in expression (5)

$$O_f(n)(i,j) = \sum_{k=1}^{n} \sum_{l=1}^{n} I_{obs} \left( i + k - 1 - \frac{(n-1)}{2} \right) \left( j + l - 1 - \frac{(n-1)}{2} \right) \text{Ker}(n)(k,l)$$

and

$$M_f(n)(i,j) = \sum_{k=1}^{n} \sum_{l=1}^{n} I_{obs} \left( i + k - 1 - \frac{(n-1)}{2} \right) \left( j + l - 1 - \frac{(n-1)}{2} \right) \text{Ker}(n)(k,l)$$
\[
M_f(n)(i,j) = \sum_{k=1}^{n} \sum_{l=1}^{n} \left[ I_m \left( i + k - 1 - \frac{(n-1)}{2} j + l - 1 \right) - \frac{(n-1)}{2} \right] Ker(n)(k,l)
\]

are the observed and model fractions, respectively, where \( n \) is the spatial scale. A square of \( n \times n \) was centered at each grid point \((i,j)\) over the MTC region. When \( i \) and \( j \) changed, during iterations, the \( n \times n \) square swept the MTC region. The points outside the MTC region, when the square was near the boundary, were assigned a value of zero. \( Ker(n)(k,l) \) is the \( n \times n \) kernel for a mean filter. \( I_{obs} \) and \( I_m \) are the binary fields for the observed and the model variable, respectively, over the mesh. These binary fields were obtained by converting the observed values and the model values to binary values choosing suitable thresholds according to Roberts and Lean (2008).

The expression in the denominator of the right hand side of Equation (4),

\[
MSE(n)_{ref} = \frac{1}{Z} \left[ \sum_{i \in xMTC} \sum_{j \in yMTC} \{ O_f(n)(i,j) \}^2 + \sum_{i \in xMTC} \sum_{j \in yMTC} \{ M_f(n)(i,j) \}^2 \right]
\]

is equivalent to the Fraction Brier Score (FBS) of the worst possible forecast, when overlap between the forecast and the observations is nonexistent.

A useful FSS, according to Roberts and Lean (2008), is defined as

\[
FSS_{useful} \geq \frac{1}{2} (1 + f)
\]

where \( f \) is the ratio between the observed-covered area and the total area of the domain. A value of 0.5 can be used as a lower limit when \( f \) is not very large, (Mittermaier & Roberts, 2010).

### 3.3 Data

Lightning observations were obtained from WWLLN. It consists of a set of lightning sensors located around the world that detect lightning strokes worldwide in real-time. It operates in the very low-frequency band (3–30 kHz). Lightning emits very low-frequency radio atmospheric signals that travel through the ionosphere (Dowden et al., 2008). The electromagnetic pulses are received by the lightning sensors and five of them are required to reliably determine the location of flashes through the Time of Group Arrival (TOGA) algorithm (Dowden et al., 2002; Hutchins et al., 2012). There are currently more than 70 lightning sensors around the world. WWLLN detects both CG and large IC pulses, but it is more sensitive to high-peak-current lightning strokes (e.g., Abreu et al., 2010; Jacobson et al., 2006; Rodger et al., 2006; Rodger et al., 2009). This allows WWLLN to detect lightning producing storms with deep convection (Jacobson et al., 2006). By 2010, the location accuracy was estimated as 2 to 5 km (Abarca et al., 2010; Dowden et al., 2002). The WWLLN’s detection efficiency has been increasing with the increasing number of lightning sensors through the years (Mezuman et al., 2014). However, the detection efficiency varies from region to region and there have not been studies assessing the WWLLN’s efficiency over the Mexican territory. A reason is the lack of lightning detection networks. Also, Mexico does not have a wide coverage radar network capable of monitoring convection over the whole country.

### 4 RESULTS

Lightning cannot be spatially evaluated with traditional grid-point-by-grid-point verification techniques because they are affected by the “double-penalty problem” (e.g., Roberts & Lean, 2008; Sokol & Minářová, 2020; Zhao & Zhang, 2018). Simulated storms show either spatial or temporal displacements with respect to observations. Spatial distributions of lightning from simulations do not always coincide with observed lightning distributions.

Before finding an adequate threshold to evaluate the LPI spatially with the FSS, time series for each ensemble member were obtained over the MTC region. The total number of lightning flashes over the MTC region were divided by the total number of grid points where lightning was observed. Similarly, the total LPI was divided by the total number of grid points with LPI values greater than zero. The resulting time series for each ensemble member, along with the time series for the observed lightning, are shown in Figure 5. For each ensemble member, the Spearman correlation coefficient was calculated to compare the LPI and the observed lightning (Table 4). Because the LPI and lightning are two different types of quantities, the Spearman correlation coefficient is adequate to use. The focus on trends between the average evolution of the LPI and the observed lightning over the MTC region also makes appropriate the use of the Spearman correlation coefficient.

The observed diurnal variability of lightning is captured in most of the ensemble members. It is
observed that the calculated LPI from both THOM-KF-RTG (Figure 5a) and THOM-KF-TR-RTG (Figure 5b) ensemble members reproduce well the observed diurnal variability of lightning. The LPI from these two ensemble members show the highest correlations (see Table 4).

However, when not using interactive SST over the adjacent ocean, both the LPI from THOM-KF-GFS and the LPI from LIN-KF-GFS did not capture the diurnal variability of lightning around the interval of 85–90 h (Figure 5d). The highest correlation values, between the LPI and the observed lightning, were obtained with interactive SST over the adjacent Pacific Ocean.

In order to evaluate the LPI spatially, the spatial scale (n) and thresholds were obtained. LPI and observed lightning thresholds were increased gradually to get the optimal values associated with the highest FSS values. Then, the threshold used for the observed lightning was 1 flash per grid square (1 flash per 4 km²) and for the LPI was 0.001 J kg⁻¹.

The FSS results suggest that the LPI from most of the different ensemble members with interactive SST performed adequately over the MTC region. The differences between the FSS for the ensemble members with interactive SST and the ones without it are not significant, but the FSS values for the ensemble members with interactive SST were greater. It means that the difference in the spatial displacements between the ensemble members with interactive SST and the ones without it is not considerable. In Figure 6, the FSS for most of the ensemble members with interactive SST are shown. The FSS for the

### Table 4

| Ensemble Member | Correlation Coefficient |
|-----------------|--------------------------|
| LIN-KF-RTG      | 0.703                    |
| LIN-BMJ-RTG     | 0.765                    |
| LIN-SAS-RTG     | 0.720                    |
| LIN-KF-TR-RTG   | 0.841                    |
| THOM-KF-RTG     | 0.934                    |
| THOM-BMJ-RTG    | 0.567                    |
| THOM-SAS-RTG    | 0.520                    |
| THOM-KF-TR-RTG  | 0.922                    |
| WSM6-KF-RTG     | 0.702                    |
| WSM6-BMJ-RTG    | 0.742                    |
| WSM6-SAS-RTG    | 0.601                    |
| WSM6-KF-TR-RTG  | 0.867                    |

FIGURE 5 LPI for the different ensemble members with interactive SST (see Table 1 for acronyms) along with the observed lightning variability from WWLLN. Each panel in (a–c) corresponds to a different cumulus scheme. In (a) Kain-Fritsch, in (b) the moisture advection-based trigger scheme with Kain-Fritsch, and in (c) Betts-miller-Janjić. In (d), as in (a) but without interactive SST. The start time corresponds to 0000 UTC on June 10.
Kain-Fritsch cumulus scheme performed with the highest values; while the FSS for the Betts-Miller-Janjic scheme performed worse than the other cumulus schemes, regardless of the microphysics scheme (see Figure 6). The FSS values, with the thresholds of 1 flash per 4 km² and 0.001 J kg⁻¹, for the ensemble members with the simplified Arakawa-Schubert cumulus scheme were too low and decreasing along the TC event. Considering the whole simulation period, the FSS for the THOM-SAS-RTG ensemble member was not useful. Besides, the LPI, along the TC event, for the ensemble members with the simplified Arakawa-Schubert cumulus scheme did not reproduce the diurnal variability during the TC event.

The LPI was able to reproduce the diurnal variability of lightning over the MTC region for the two ensembles of simulations. However, the ensemble with interactive SST showed the best results. Simulating lightning directly or indirectly, using NWP models, depends on parameterized processes at cloud resolving scale. This is why the diurnal variability of the LPI is dependent on both the cumulus and the microphysical parameterizations.

In addition to the LPI, lightning proxies have also been used in many studies, but they were not included as part of this study. The relationships or lightning proxies that do exist between lightning flash rates and storm parameters were not developed for tropical storms, so they are not suitable for the Mexican territory. However, PIM, CTH, and MVV storm parameters, that are present in lightning proxies, are discussed in the following section, when interactive SST was taken into account.

5 | COMMENTS ON THE RESULTS AND THE DIURNAL VARIABILITY OF PIM, CTH AND MVV STORM PARAMETERS WITH INTERACTIVE SST

Inside a convective storm, charge transfers occur during collisions between solid hydrometeors, making the PIM an important storm parameter in lightning proxies. In a convective storm, maximum values of lightning are associated with peaks in PIM (Gauthier et al., 2006). In each ensemble member, the total amount of PIM over the MTC region was divided by the total number of grid points where PIM had values greater than zero. The variations of PIM along the simulated period, for most ensemble members, followed the observed diurnal variability of lightning. In Figure 7a, the ensemble members with the Kain-Fritsch cumulus scheme are shown. However, the ensemble members with the Betts-Miller-Janjic cumulus scheme (shown in Figure 7b), did not accurately follow the observed diurnal variability of lightning.

In cumulus schemes moisture plays an important role. The presence of moisture in the atmosphere is important for the production of solid hydrometeors, when deposition of water vapor occurs. Thus, it seems that moisture changes in PIM with the Betts-Miller-Janjic cumulus scheme did not vary enough from maximum to minimum values to markedly reproduce the observed diurnal variability. Cumulus schemes are associated with redistribution of moisture, as well as heat, in the vertical direction, but they do not depend on the latent heat generated during condensation and deposition of water vapor. However, the Kain-Fritsch cumulus scheme detrains moisture and heat.
Another storm parameter present in lightning proxies is CTH. According to the simulations, the variations of CTH are in accordance with the observed diurnal variability over the MTC region. During the production of hydrometeors, phase changes are present and the release and transfer of latent heat occurs. Here, the microphysical parameterizations play an important role. This is reflected in the performance of CTH when different microphysical parameterizations are used (see Figure 7c).

As aforementioned, the microphysical parameterizations used in this study were the Purdue Lin, the WRF single-moment 6-class, and the Thompson scheme. The first includes cloud water, cloud ice, non-precipitable water, rain snow, and graupel (Chen & Sun, 2002). In the second scheme the ice crystal number concentration is expressed as a function of the ice amount (Hong & Lim, 2006). Finally, the Thompson scheme is a 6-class microphysics scheme with graupel, ice, and rain number. It includes a generalized gamma distribution for each hydrometeor species with a snow parameterization, depending on both the ice water content and the temperature.

The land-atmosphere interactions over the MTC region are the most important. However, the response of the atmosphere over the MTC region to the interactive SST can be a consequence of the propagation of SST changes, mainly reflected through heat and moisture fluxes, during the simulation period. As a consequence, the variability of SST influenced the diurnal variability of the LPI over the MTC region. In Figure 7d the LPI obtained from the ensemble members with the Thompson microphysical scheme and the Kain-Fritsch cumulus scheme, with interactive SST (in red) and without interactive SST (in green), are shown. In contrast to the ensemble member with interactive SST, it is noted that the ensemble member without interactive SST presents a local maximum in the interval of 85–90 h of simulation, opposite to the observed lightning variability. However, these two ensemble members are highly correlated with the observed lightning variability along the studied period of time.

Finally, the maximum vertical velocity (MVV) is also used as a storm parameter in proxies for lightning (e.g., Barthe et al., 2010). The vertical velocity is indirectly associated with the transfer of electrical charge between solid hydrometeors during collisions inside thunderstorms. To know if the diurnal variability is captured by the simulations over the whole MTC region, the MVV was averaged over the latter, without restricting with storm thresholds. This makes it possible to identify if each ensemble member captures the observed diurnal variability over the whole MTC region.

The averaged MVV reproduced the observed diurnal variability over the entire MTC region for all the ensemble members (Figure 8). And it was sensitive to the microphysics and the cumulus schemes. This implies that...
there is a diurnal variation of the vertical velocity in the troposphere over the MTC region.

6 | CONCLUSION

This study evaluated the performance of the LPI in reproducing the observed diurnal variability of lightning over the MTC region, when TC Bud (2018) occurred over the adjacent Eastern Pacific Ocean. The LPI has been used in several studies as an index to forecast lightning potential for individual storms and for short-term atmospheric events. However, it has not been evaluated over continental tropical regions for long periods of time. Also, it is not known if the LPI can reproduce strong diurnal cycles. The results show that the LPI was capable of reproducing the observed diurnal variability of lightning that exhibited a strong diurnal cycle over the MTC region.

The results also show that the LPI performed better in reproducing the diurnal variability of lightning when interactive SST was taken into account. The LPI depends on microphysical fields obtained from NWP models, and it is known that lightning has a strong microphysical origin. Consequently, parameterized processes at cloud resolving scale play an important role in simulating lightning directly or indirectly. Furthermore, TCs, and even other atmospheric phenomena, occurring over the adjacent ocean to the Mexican continental territory can have an indirect impact on the development of convection and lightning over land. However, the processes involved in the connection between TCs and the development of convection over the Mexican continental territory are not well known.

Finally, this study is the first that attempts to evaluate an important lightning index over the Mexican territory for a long event, and also it attempts to start filling in the research gap of lightning over tropical regions.

AUTHOR CONTRIBUTIONS

Jorge Clouthier-López: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing – original draft; writing – review and editing. Ricardo Barrón-Fernández: Funding acquisition; project administration; resources; supervision; writing – review and editing. David Alberto Salas-de-León: Resources; supervision; writing – review and editing.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

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