# Lightning Over Three Large Tropical Lakes and the Strait of Malacca: Exploratory Analyses

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Abstract-Lightning stroke density measured by the Global Lightning Dataset GLD360 has shown several strong maxima around the globe. Several of these extremes are located over large water bodies surrounded by terrain features. Four prominent maxima are studied over Lake Maracaibo in South America, the Strait of Malacca in equatorial Asia, Lake Victoria in east Africa, and Lake Titicaca in South America. This study analyses meteorological factors that affect lightning occurrence over these four water bodies that are adjacent to mountains where diurnal effects dominate. Lake Maracaibo has a stroke density maximum at 0200 LST, and a minimum from 1000 through 1600 LST. The other water bodies have similar nighttime maxima. To understand these differences more completely, we compare daytime lightning activity over the adjacent mountains with nighttime activity over water. Such studies can help clarify meteorological factors causing lightning features less extreme than these in other parts of the world.

Keywords—lightning; GLD360; tropical lakes; diurnal variations; terrain modulation of convection.

#### I. INTRODUCTION

Much of the occurrence of convective precipitation and lightning in tropical regions is influenced by the diurnal cycle modulated by major topographical features. Some of the largest influences are due to contrasts between large water bodies adjacent to land masses, and along the slopes of mountains. Kikuchi and Wang [2008] examined global tropical precipitation data from TRMM. They identified a coastal regime in which the diurnal cycle on the land side shows inland-directed propagation between 0900 and 2100 solar time, under the influence of sea breezes with the daytime heating of nearby higher terrain also possibly drawing the sea breeze deeper inland. On the sea side, propagation was found to be offshore and maximum precipitation was overnight or in the morning hours. Land breezes have been found to be weaker than sea breezes, in part due to a relatively weaker temperature differential between land and adjacent water at night [e.g. Mapes et al., 2003a]. However, cooler and therefore stronger outflows from land-based moist convection during the afternoon, and/or gravity waves generated by daytime convection

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along and over elevated terrain, are better associated with an organized seaward-propagating nocturnal maximum in convective precipitation.

Several locations in the tropics have large enclosed or semi-enclosed water bodies with nearby mountainous terrain: (1) Lake Maracaibo in western Venezuela, with the lake at sea level but 5000-m peaks to the southeast, (2) the Strait of Malacca running between the Malaysian peninsula and the island of Sumatra in Indonesia, (3) Lake Victoria in east Africa, where the lake surface at ~1100 m altitude (MSL) is surrounded by higher terrain, especially over the Kenyan highlands to the east, and (4) Lake Titicaca in the Andes, which starts at a much higher altitude than Lake Victoria but has a similar altitude differential with the surrounding terrain. These water bodies were not specifically called out as belonging to the coastal regime by Kikuchi and Wang [2008], who provided a general picture of the global tropics. However, the phenomenology of the lightning activity around some of them has at least been described [Albrecht et al., 2016; Burgesser et al., 2013; Virts et al., 2013a,b] and, to a limited degree, possible mechanisms have been mentioned. In this study, we use lightning information from the Global Lightning Dataset (GLD360) to examine the time and space distributions of lightning over and around these four water bodies and show how their diurnal cycles are all broadly consistent with the coastal regime described by Kikuchi and Wang [2008], albeit with some of their own unique variations that depend on the size, shape, bathymetry and surface water temperatures and the surrounding topography.

Table 1 shows the lightning stroke and area parameters of the four selected water bodies in the order of the discussion in the following sections. The lightning stroke counts are the per-year averages during the calendar years 2012, 2013, and 2014, as measured by GLD360. Lake Maracaibo is first, with a very large stroke density (in fact, the world's largest, according to Albrecht et al. [2016]), followed by the Strait of Malacca, a semi-bounded water body. Finally, we discuss the two inland lakes Victoria and Titicaca, with much smaller stroke densities.

	Lake Maracaibo	Strait of Malacca	Lake Victoria	Lake Titicaca
Strokes	713,165	1,770,222	233,549	33,705
Area (km <sup>2</sup> )	12,110	83,810	68,220	6,984
Strokes km <sup>-2</sup>	58.9	21.1	3.4	4.8

Table. 1. Number of strokes per year, area, and stroke density per year of the four water bodies analyzed in this study.

#### I. GLD360 DATA

GLD360 is a ground-based lightning detection network providing worldwide coverage with the expectation of substantially uniform and high cloud-to-ground (CG) flash detection efficiency (DE) [Mallick et al., 2014a; Poelman et al., 2013; Pohjola and Mäkelä, 2013; Said et al., 2013]. It is expected that about 80% of all strokes detected by GLD360 are CG. Over the continental United States, Said et al. [2013] evaluated CG flash DE and stroke location accuracy (LA) of GLD360 relative to the National Lightning Detection Network (NLDN) and found the flash DE to be 63% when all GLD360 sensors were operational. Given that the NLDN at the time had a validated CG flash DE of 94% [Mallick et al., 2014b], the absolute CG flash DE of GLD360 was approximately 59%. Using rocket-triggered lightning in Florida from 2011 through 2013, Mallick et al. [2014a] found that the absolute CG flash DE of GLD360 was 67%. Poelman et al. [2013] found the GLD360 CG flash DE to be 96% in Belgium, using high-speed video and electric field observations. Validations of median CG stroke LA, whether absolute or relative to other networks, have generally fallen in the 1.5-2.5 km range.

In this study, we utilize GLD360 data from the calendar years 2012, 2013, and 2014. Given that there are some differences in the validated DE of GLD360 in different parts of the world, and that the available literature to date does not vet include a global model showing the estimated performance of GLD360 in our areas of interest, we do not attempt to apply any DE corrections to our stroke counts or stroke densities. Throughout this study, stroke density is computed on a 5 x 5 km grid. We also include analyses of the time of day when the maximum lightning density occurs. This is computed on a 20 x 20 km grid in order to minimize statistical noise and emphasize the important patterns of behavior, and it includes data from calendar year 2015 as well. Data from 2015 are also included in Hovmöller-like diagrams computed along crosssections through the four selected water bodies. All Hovmöller plots use a time bin of 15 minutes and a distance bin of 10 km, where distance is measured along the center line of the cross section. The cross-sections have swath widths designed to capture the boundaries of each water body in the selected direction; details are given in the respective figure captions. In the Hovmöller diagrams, instead of lightning density (in strokes km<sup>-2</sup> yr<sup>-1</sup>), we show the logarithm of the stroke count in each time-distance bin.

#### II. LAKE MARACAIBO

The geographical situation of Lake Maracaibo is shown in Fig. M1. By area, it is the largest lake in South America, but it is very shallow, with a maximum depth of only about 33 m in

east-central part [obtained from the website the www.costadevenezuela.org/cartas/lagomg.pdf]. The water temperature averages about 30 °C with little seasonal variation [Berghuis, 1995]. The maximum extent of the lake from north to south is 200 km and east to west is 120 km. It is actually a bay that opens to the ocean on the north side, and its surface is at sea level. Its basin is surrounded by high mountains that begin to rise from a mostly flat plain 30 to 150 km away in all directions but north. The highest elevation within the analysis area is 5007 m in the Merida Andes to the southeast. The black polygon shown in Fig. M1 limits the lightning data considered in portions of the diurnal cycle analysis, such as Figs. M3 and M5.

The annual lightning distribution across the region indicates an exceptional maximum over the lake (Fig. M2). While there are large lightning stroke densities over the slopes of several mountain ranges surrounding the lake, none are as strong as over the southwest portion of the water surface. The largest density over the lake is 141 strokes  $\text{km}^{-2} \text{ yr}^{-1}$  within one of the black 5x5 km grid squares in Fig. M2. The average number of strokes over the entire lake detected by GLD360 is 713,165 per year (Table 1).

In contrast, the highest mountains have the smallest stroke densities due to a lack of deep moisture in the atmosphere since vertical instability starts at a high altitude. In particular, there is a significant minimum in lightning density directly over the Merida Andes, which run from northeast to southwest close to the southeast side of the lake. Other stroke density minima in Fig. M2 are located over the Eastern Cordillera, Perijá Mountains, and Santa Marta Massif. Outside the lake itself, stroke densities are largest on the slopes of the mountain ranges rather than over them [López and Holle, 1986; Holle, 2014]. Interestingly, the lightning densities to the southeast of the Merida Andes are substantially smaller than to the northwest, including all of the land areas surrounding Lake Maracaibo and extending well into Colombia. Notably, the broad Magdalena valley of northern Colombia to the southwest of our polygon also has a prominent nocturnal maximum in precipitation [Mapes et al., 2003b], but absent a body of water. Thus, the water body itself is not a necessary ingredient in the generation of a nocturnal maximum in convective activity. However, the lake and its high surface temperature may serve as a source of additional latent and/or sensible heat into the nocturnal storms over the lake, possibly leading to the greater lightning production in the lake storms. The relationship between lightning and precipitation in the nocturnal maxima over northern Colombia and Lake Maracaibo would be an interesting subject of future research.



Fig. M1. Topography of the area surrounding Lake Maracaibo. Black polygon bounds the exterior analysis area, and brown line surrounds the lake. Major mountain ranges are labeled, and the boundary between Venezuela and Colombia is in red. Dashed blue lines are centers of cross sections.



Fig. M2. Annual stroke density detected by GLD360 over northwest Venezuela and northern Colombia in a 5 x 5 km grid from 2012 through 2014.

The diurnal variation of lightning shows a sharp separation between lake and exterior areas (Fig. M3). Lightning over the lake occurs mostly between midnight and noon. Over the land areas of the polygon identified in Fig. M1, lightning occurs mostly between noon and midnight. Note that Fig. M3 is expressed in stroke counts, which are smaller over the lake because its area  $(12,110 \text{ km}^2)$  is much less than the land areas enclosed by the polygon  $(129,900 \text{ km}^2)$ , although stroke density over the lake is several times larger than over the surrounding land areas.



Fig. M3. Diurnal variation of strokes over Lake Maracaibo (upper) and within polygon of Fig. M1 without the lake (lower) in Local Standard Time (UTC-5). Dashed vertical lines indicate noon.

Maps of the diurnal cycle (Fig. M4) in three-hourly intervals indicate how the daytime lightning on the slopes of the mountains transitions to nighttime strokes over the lake. Starting at noon in the upper left panel, the following diurnal cycle is noted:

- <u>1200 to 1500 LST:</u> Lake Maracaibo is devoid of lightning at midday. Lightning maxima are located over the slopes of the mountains to the northeast and northwest. In contrast, there is a notable minimum in strokes over the Merida Andes. Along the southeast shore of the lake, a line of enhanced lightning near the coast is due to a lake breeze at this time.
- <u>1500 to 1800 LST:</u> A very strong maximum in stroke density is to the northeast and extends a short ways over the water. Another strong maximum is to the northwest, and one is beginning to form to the southwest. The highmountain minima continue while the lake breeze on the southeast side has dissipated.
- <u>1800 to 2100 LST:</u> Lightning begins to increase over the lake while the northeast maximum diminishes. Activity on the west side of the lake continues.
- <u>2100 to 0000 LST:</u> A new pattern develops consisting of enhanced stroke density over the western portion of the

lake that extends to the west at a location between where the maxima were located three hours earlier.

- <u>0000 to 0300 LST:</u> Now the lake has the dominant lightning maximum in the entire region; weaker activity extends to the southwest.
- <u>0300 to 0600 LST:</u> Lightning activity in these pre-dawn hours is solidly centered on the lake and stroke activity

decreases outward in all directions.

- <u>0600 to 0900 LST:</u> Stroke activity continues mainly over the lake but is slowly decreasing in intensity after sunrise.
- <u>0900 to 1200 LST:</u> Scattered lightning persists over and near the lake through the late morning as the daily cycle begins again.



Fig. M4. Three-hourly maps of GLD360-detected lightning over the Lake Maracaibo region starting in the upper left at 1200-1500 LST. Time is in Local Standard Time (UTC-5). Exterior polygon is in light gray.

A composite diurnal pattern in the Lake Maracaibo region has been prepared using local solar time (Fig. M5). The color scale indicates the time of day with the maximum lightning frequency within each grid square. Over the lake, colors are shades of blue, indicating maximum lightning activity after midnight. The peak is near midnight over the southwest portion of the lake (darkest blue), then it is later at night to after sunrise over the northeast portion of the water. Over much of the rest of the area within the polygon, the most frequent time for a lightning maximum is from afternoon to early evening (1500 to 1900 local time) shown in yellow to light orange. The afternoon lightning maxima along the flanks of the Perijá and Eastern Cordillera ranges gradually migrate into the lower altitudes of the Catatumbo River valley between 1900 (dark orange) and 2300 (the darkest red on the color scale). This lightning maximum then either merges with or initiates the lightning maximum over the lake by 0200 to 0300.

Another representation of the diurnal cycle is shown by Hovmöller diagrams in Fig. M6. The top panel is centered in a swath through the center of the lake from northwest through southeast, and the lower is southwest through northeast; center lines are shown in Fig. M1. In both panels, the largest stroke counts (dark red) occur during the night and over the lake. The water surface has a minimum during the midday hours, then the large densities resume after dark. The northwest-southeast cross-section suggests that the maximum along the lake breeze on the southeast shore is separated from the nocturnal maximum over the lake, whereas there is some suggestion of propagation from the plain east of the Perijá Mountains towards the lake. The southwest-northeast cross-section suggests that the space-time evolution is dominated by the development of thunderstorms over the Catatumbo River valley (left side, bottom panel of Fig. M6) from about 1600 onward, leading into the nocturnal maximum over the lake itself.



Fig. M5. Hour of day with maximum lightning frequency in a 20 x 20 km grid within polygon of Fig. M1. Local time is indicated by color bar on right. Period of record is 01 October 2011 through 01 October 2015.



Fig. M6. Hovmöller diagrams of cross sections from northwest to southeast (upper panel) and southwest to northeast (lower) across Lake Maracaibo. Time of day is on left axis. Right axis is logarithm of the number of strokes in bins of 10 km in distance dimension by 15 minutes in time-of-day dimension. Cross-section swath widths are 100 km (NW-SE) and 200 km (SW-NE).

Based on the southwest-northeast cross-section, the Lake Maracaibo nighttime lightning maximum appears to be connected primarily with the extended stroke density maximum that occurs from late afternoon through the evening over the broad, flat Catatumbo River basin to the southwest of the lake. Muñoz et al. [2016] have described 4and 30-km WRF simulations of the processes involved. A strong southwesterly-directed low-level jet operates during the late afternoon and evening to transport CAPE and establish convergence along the terrain to the southwest of the lake. Cool outflows from the resulting convection apparently shift the convergence zone and convection maximum toward the Catatumbo River valley during the evening and eventually reverse the low-level wind anomaly to northerly, pushing the area of convergence to the lake during the middle of the night. In addition, based on the lower panel of Fig. M6, it also appears as though the convection over the northeast shore of the lake in the late afternoon is loosely connected to the nocturnal maximum, perhaps via its own cool outflows, which would serve to reinforce the convergence zone established to the southwest of the lake during the evening.

Lightning frequency is not uniform through the year (Fig. M7). Lightning is most frequent from August through October, and a secondary peak occurs during April and



Fig. M7. Number of strokes by month over Lake Maracaibo. and within the polygon of Fig. M1 exterior to the lake.

May. A distinct lightning minimum prevails from November through March. The Caribbean low-level jet that is cited by Muñoz et al. [2016] as having the dominant seasonal-scale influence over thunderstorm activity in the region, with the annual migration of the ITCZ, in turn, modifying the Caribbean low-level jet.

The number of hours and days with lightning over the lake is very large. GLD360 detects an average of 306 days per year when there is at least one stroke over the lake (84% of possible days). The range is 287 to 331 days per year during the 2012 to 2014 data period. There are 2,962 hours per year with at least one detected stroke over the lake (34% of possible hours). These days are not equally distributed through the year (Fig. M8). From May through November, almost every month has at least 29 days with lightning over the lake, but in January through March there are fewer days. The drop-off in these months coincides with the reduced number of strokes (Fig. M7). From this pair of graphs, it is apparent that more than enough strokes occur during the smaller stroke frequencies of June and July to achieve the occurrence of at least one stroke per day.



Fig. M8. Number of days per month of the year over Lake Maracaibo with at least one lightning stroke.

In summary, this Lake Maracaibo lightning study is the first to use data from a detection network with high detection efficiency and very good location accuracy. The lake has a strong isolated nighttime lightning maximum that is opposite to the afternoon maximum over adjacent mountain slopes. Nearly every day from April through December has at least one stroke over the lake due to collision of downslope outflows from the prior afternoon's thunderstorms over higher sloping terrain. This is one of the more extreme cases of lightning under such a diurnally forced regime in the world. Three more cases are now examined that are variations on this classic situation.

#### III. STRAIT OF MALACCA

The Strait of Malacca is one of the busiest shipping lanes in the world and extends from Singapore on the southeast to the Indian Ocean to the northwest (Fig. SM1). The mountains of Sumatra on the west side reach a peak altitude of 3466 m, while those to the east over Malaysia are somewhat lower. The strait is only about 75 km across from Singapore to Kuala Lumpur but gradually opens to 300 km across on the northwest end. It is quite shallow, like Lake Maracaibo, with depths of less than about 75 meters until it opens to the Indian Ocean at the northwest end. The average sea surface temperature is about 30 °C most of the year (www.esrl.noaa.gov/psd/map/clim/sst.anim.year.html).

Three analysis areas are considered in this case, shown in Fig. SM1. The large external polygon in black includes the mountains that affect convection over the strait. The brown line along the shore of the strait denotes what we consider the "confined" water body, and the inner red polygon is 25 km offshore from the brown line but only in areas where the strait is sufficiently wide. We refer to this smaller, red polygon as the "Interior Strait".



Fig. SM1. Topography of area surrounding Strait of Malacca. The black polygon bounds the exterior analysis area, the brown line from Singapore northwestward is the strait, and the smaller red line is the Interior Strait region. Boundaries between Indonesia, Malaysia, and Thailand are in red, and the country of Singapore is indicated. Dashed gray lines are centers of cross sections.



Fig. SM2. Annual stroke density detected by GLD360 over the Strait of Malacca and surrounding region in a 5 x 5 km grid from 2012 through 2014.

The annual lightning distribution across the region indicates a maximum over the strait and several stronger maxima on the slopes of surrounding mountains (Fig. SM2). The largest density is 82 strokes  $\text{km}^{-2}$  yr<sup>-1</sup> and is located near Kuala Lumpur. A total of 1,770,222 strokes per year is detected by GLD360 over the strait.

The diurnal variation of lightning shows a sharp separation between water and exterior areas (Fig. SM3). Lightning over the strait occurs mostly between midnight and noon. Over the land areas of the exterior polygon, lightning occurs mostly between 1400 and 1900 LST. The Interior Strait (lower Fig. SM3) has less afternoon activity than over the entire strait.

Maps of the diurnal cycle (Fig. SM4) in three-hourly intervals indicate how the daytime lightning on the slopes of the mountains switches to nighttime strokes over the strait. Starting at noon in the upper left panel:

- <u>1200 to 1500 LST:</u> The strait has weak lightning frequency, while lightning maxima begin to develop along sea-breeze fronts between the coastlines and the mountains, especially to the east. In contrast, there is a notable minimum in strokes to the northwest.
- <u>1500 to 1800 LST:</u> A very strong maximum in lightning is found to the east. Other well-defined maxima are along the sea-breeze fronts around the Malaysian peninsula and northwest Sumatra. The highest terrain areas have lower lightning densities than coastlines.
- <u>1800 to 2100 LST:</u> The northeast maximum diminishes, while lightning continues to be very frequent on the west side of the strait.
- <u>2100 to 0000 LST:</u> Thunderstorms begin along the coastlines of both Sumatra and the Malaysian peninsula, although nearly all areas are at a minimum in stroke density at this time in the diurnal cycle.



Fig. SM3. Diurnal variation of strokes over Strait of Malacca (top), the polygon exterior to the strait (middle), and the Interior Strait of Fig. SM1 (bottom) in Local Standard Time (UTC+7). Dashed vertical lines indicate noon.

- <u>0000 to 0300 LST:</u> The strait now has the dominant lightning in the entire region, although another well-defined local maximum is also seen just off the west coast of Sumatra.
- <u>0300 to 0600 LST:</u> Lightning frequency continues to increase in these pre-dawn hours over the strait. All oceanic areas are active at these hours, and in the subsequent morning hours.
- <u>0600 to 0900 LST:</u> Stroke frequency slightly increases and spreads horizontally over the strait after sunrise.

• <u>0900 to 1200 LST:</u> Scattered lightning persists over and near the strait through the late morning as the daily cycle begins again.

The composite diurnal pattern in the strait region in local solar time (Fig. SM5) shows blue colors over the strait, indicating that the maximum lightning activity occurs during the night. The peak lightning occurrence is closer to midnight over the southeast portion of the strait (darkest blue), then it is later at night to after sunrise over the northwest portion of the water surface. Nearly all other ocean areas also have their lightning density maxima during nighttime or early morning hours. Over land, the most frequent time for a lightning maximum is from afternoon to early evening (1500 to 1900 local time) in yellow to light orange. Several locations over the ocean offshore from the land reach maximum lightning activity between 2300 and 0000 (darker red).

The Hovmöller diagrams in Figure SM6 are across and along the strait; center lines are shown in Fig. SM1. The top panel shows the over-water maximum very well during the night to early morning. There is some indication that the decaying maximum over the strait actually pushes onshore at about 1200, perhaps reinforcing the sea breeze circulations on both shores, or even launching them. The land surfaces between the mountains and coastlines on both sides are clearly dominant between 1500 and 1800, as is also evident in the three-hourly maps of Fig. SM4. Between about 1900 and 2200, the maximum on the Malaysian side then appears to blend into the eventual nocturnal maximum over water. Along the strait (lower panel), there is a widespread moderate maximum for a long period from after midnight to nearly noon. There is a slight hint of a northwesterly drift in the along-strait maximum, consistent perhaps with the fact that the cool outflows from land take longer to converge upon the wider northwestern part of the strait than in the narrower sections. The second, afternoon maximum shown over the southeastern section of the alongstrait cross-section is an artifact due to the fact that the cross-section inevitably pulls in some of the coastal land areas where the strait starts to become very narrow.

Fig. SM7 shows monthly lightning counts to exhibit two maxima, one in March, April, May and the other in October and adjacent months. Both land and water areas show the same trends. These periods are likely related to the passage of the equatorial trough across the region due to the migration of the summer and winter monsoon. This is consistent with the changes in mean wind direction around May and September [Fujita et al. 2010].



Fig. SM4. Three-hourly maps of GLD360-detected lightning over Strait of Malacca region starting in the upper left at 1200 to 1500 LST. Time is in Local Standard Time (UTC+7). Exterior polygon is in light gray, strait is outlined in brown, and Interior Strait in red.



Fig. SM5. Hour of day with maximum lightning frequency in a 20 x 20 km grid over region of Fig. SM1. Local time is indicated by color bar on right. Period of record is 01 October 2011 through 01 October 2015.



Fig. SM6. Hovmöller diagrams of cross sections from southwest to northeast (upper panel) and northwest to southeast (lower) over the Strait of Malacca. Time of day is on left axis. Right axis is logarithm of the number of strokes in bins of 10 km in distance dimension by 15 minutes in time-of-day dimension. Cross-section swath widths are 240 km (SW-NE) and 150 km (NW-SE).



Fig. SM7. Number of strokes by month over Strait of Malacca, Interior Strait. and land areas of the polygon of Fig. SM1.

The Strait of Malacca time and space distributions follow those found in Section II for Lake Maracaibo in almost every respect. The strait nighttime lightning maximum appears more symmetric than that of Lake Maracaibo. In the latter case, the evening maximum is dominated by thunderstorms over the Catatumbo River basin to the southwest of the lake, eventually leading to, or blending with, thunderstorm activity over the lake itself. By contrast, at the Strait of Malacca, the evening development (2100 to 0000 LST) is clearly just offshore of both the peninsula and Sumatra, and then development proceeds to fill the strait during the overnight hours. The nocturnal thunderstorms over the strait are due to outflows descending from the slopes of surrounding mountains that meet over the warm waters of the strait after dark. Shipborne measurements by Fujita et al. [2010] showed cool offshore flow from both sides of the strait, with temperature differentials of 4-5 °C. According to a "dry" simulation performed by Fujita et al. [2010], straight katabatic land breezes would not have such a large temperature differential, indicating the dominance of convective outflow.

## IV. LAKE VICTORIA

Lake Victoria is the largest lake in Africa, largest tropical lake in the world, and second largest freshwater lake in the world by area. Unlike the previous two cases, Lake Victoria is in an elevated basin at about 1100 m above MSL, not at sea level. However, similar to both Lake Maracaibo and the Strait of Malacca, Lake Victoria is quite shallow, with a maximum depth of about 80 meters [Anyah 2005]. The surface water temperature ranges from 24-28 °C on average [Anyah 2005 and references therein], with warmer water along the west side [Sun et al. 2015]. The mountains of the Eastern Rift valley on the Kenyan side of the lake reach an altitude of 5188 m, while the high terrain of the Western Rift Valley includes several other large lakes and altitudes in excess of 3000 m.

The annual lightning distribution across the region includes one of the largest stroke densities in the world located several hundred km to the west [Albrecht et al.,



Fig. V1. Topography of the area surrounding Lake Victoria. The black square bounds the analysis area, and the brown line surrounds the main portions of the lake. Country boundaries are in red. Dashed gray lines are centers of cross sections.

2016], and a much less intense maximum over the lake (Fig.V2). GLD360 detects 233,550 strokes per year over the lake. Note in Table 1 that the lake is quite large, so the stroke density is only 3.4 strokes km<sup>-2</sup> yr<sup>-1</sup> per year, much lower than Lake Maracaibo (59) and the Strait of Malacca (21). The highest mountains generally have small stroke densities due to a lack of deep moisture since vertical instability starts at a higher altitude. The peaks and ridges to the east of the lake have weak lightning densities, but larger stroke densities along the slopes (Fig. V1). The ridges and peaks of the Western Rift Valley also have distinct lightning minima (yellow and light green in Fig. V2). The massive region of high density to the west extends from the western slopes of the mountain ranges into the Congo basin and is not over the mountains themselves.



Fig. V2. Annual stroke density detected by GLD360 over Lake Victoria and surrounding region in a 5 x 5 km grid from 2012 through 2014.

The time of day of lightning occurrence differs greatly over the lake compared with surrounding areas (Fig. V3). Lake Victoria lightning occurs mostly between 0300 LST and noon. Over the rest of the map area, strokes occur mostly between noon and 2000 LST.



Fig. V3. Diurnal variation of strokes over Lake Victoria (top) and the rectangle minus the lake (bottom) in Local Standard Time (UTC+2). Dashed vertical lines indicate noon.

Aside from the Congo basin, the three-hourly maps in Fig. V4 show maxima in lightning density over land areas around Lake Victoria during mid-afternoon. Specifically, starting at noon in the upper left panel:

- <u>1200 to 1500 LST:</u> The lake is nearly lightning-free at this time. The best-defined lightning densities in the vicinity of the lake are found near the east slopes of the Western Rift Valley mountain ranges. Also note the lightning minima over the lakes within the Western Rift Valley.
- <u>1500 to 1800 LST:</u> A fairly well-defined local maximum in lightning density sets up along the northeast and east shores of Lake Victoria between the lake and the high terrain in Kenya.
- <u>1800 to 0000 LST:</u> Lightning density everywhere is weakening.
- <u>0000 to 0600 LST:</u> Lake Victoria now has a lightning density that rivals that of the Congo basin. Note that other large lakes that have elongated shapes in a north-south direction in Fig. V1 in the Western Rift Valley also have lightning developing over them during this period.
- <u>0600 to 1200 LST:</u> Stroke frequency reaches its largest value over the western half of Lake Victoria and gradually weakens after sunrise.

The composite diurnal pattern in the Lake Victoria region in local solar time shows that the maximum lightning frequency occurs near midnight over the northeastern corner of the lake and then progresses to the southwest through the night and into the morning (Fig. V5). Maxima after midnight are also very apparent in blue shading over the larger Rift Valley lakes to the northwest and west. Nearly all other areas have an afternoon maximum from 1400 to 1800 local time.



Fig. V4. Three-hourly maps of GLD360-detected lightning over Lake Victoria region starting in the upper left at 1200-1500 Local Standard Time (UTC+2). Analysis region is the exterior rectangle of Fig. V1, and lake is outlined in brown.



Fig. V5. Hour of day with maximum lightning frequency in a 20 x 20 km grid over region of Fig. V1. Local time is indicated by color bar on right. Period of record is 01 October 2011 through 01 October 2015.

Hovmöller diagrams in Fig. V6 are taken along crosssections from southwest to northeast and from northwest to southeast, with center lines shown in Fig. V1. Both panels of Fig. V6 show the over-water maximum very well during the morning. The top panel shows clear evidence of propagation from northeast to southwest, starting from the afternoon maximum between the Kenyan highlands and the northeast shore of the lake, then extending into the nocturnal maximum over the lake, and ending with an early afternoon maximum to the southwest of the lake. Model studies by Anyah et al. [2006] show high sensitivity to moisture arriving from the western Indian Ocean and the set-up of the lake breeze front to the northeast of the lake in the afternoon. The Kenyan highlands evidently partially impede easterly flow from the Indian Ocean, and heating of this mountain range also draws the lake breeze front deeper into Kenya, setting up the convergence zone that creates the local maximum in thunderstorm activity along the eastern shore of the lake between 1500 and 1800 LST. The collapse of that convection then leads to a cool easterly outflow that penetrates deep into the west side of the lake where the water temperature is warmer. This leads to the absolute maximum in lightning density that is somewhat displaced to the west and somewhat later in the morning, consistent with Fig. V4 and with the diurnal cycle of cold cloud tops shown by Chamberlain et al. [2014]. Curiously, Burgesser et al. [2013] found maximum lightning density over the northern and central parts of the lake, with a two-peaked time distribution, which is inconsistent with the satellite and precipitation studies of the area and with the present results.

There are two seasonal maxima in lightning counts in this region, one in March-April and the other in September and adjacent months (Fig. V7). Both the lake and adjacent land areas show the same trends, although the number of strokes over the lake is very small compared with the massive lightning frequencies over the Congo basin. The two maxima are likely related to the passage of the equatorial trough across the region. Almost identical seasonal behavior is seen in the precipitation in this region [Chamberlain et al., 2014].



Fig. V6. Hovmöller diagrams of cross sections from southwest to northeast (upper panel) and northwest to southeast (lower) across Lake Victoria. Time of day is on left axis. Right axis is logarithm of the number of strokes in bins of 10 km in distance dimension by 15 minutes in time-of-day dimension. Cross-section swath widths are 260 km (SW-NE) and 300 km (NW-SE).

The Lake Victoria diurnal cycle of stroke density is similar to those for Lake Maracaibo and the Strait of Malacca. The pattern of cool outflow from afternoon convection along the slopes of higher terrain leading to convergence over water at night is a repeatable pattern of behavior at all three locations. In the case of Lake Victoria, convergence is asymmetric and dominated by outflow from the northeast side following afternoon convection in western Kenya, as opposed to a more symmetric, two-sided convergence pattern observed over the Strait of Malacca.



Fig.V7. Number of strokes by month over Lake Victoria. and within the rectangle of Fig. V1 exterior to the lake.

#### V. LAKE TITICACA

Lake Titicaca is at 15 S, somewhat farther from the equator than Lake Maracaibo. The lake surface is at an altitude of 3812 m MSL, considerably higher than the other three water bodies in this study. However, it is surrounded by mountains well in excess of 6000 m altitude, and thus the altitude differential between the lake and the surrounding terrain is quite similar to that of both Lake Victoria and the Strait of Malacca. Lake Titicaca is deeper than the other three water bodies, with a maximum depth of 284 m, and it is also considerably colder due to its altitude, with water surface temperatures varying between 11 and 15 °C over the year, as measured from a station on the northwest side [Delclaux et al., 2007 and references therein]. It is the highest navigable lake in the world, and the largest lake in South America by water volume. The highest ridges are to the northeast and southeast of the lake on a portion of the Andes whose northeastern flank drops quickly into the plains leading to the Amazon basin (Fig. T1). Due to its high altitude, there is less lightning overall, with only 33,708 strokes detected over the lake in Fig. T1 per year (Table 1).

The annual lightning distribution shows maxima extending northwest to southeast on both the east and west sides of the lake (Fig. T2). The largest stroke density on the west side is over high terrain, unlike previous lakes where maxima were over the slopes of steep mountains. However, the largest stroke density on the east is over the east-facing slope and the plains. GLD360 detects 33,705 strokes per year over the lake, a considerably smaller number than over the lakes at lower altitudes. However it is a much smaller lake than the other water bodies studied here, so the stroke density of 4.8 per km<sup>-1</sup> yr<sup>-1</sup> is actually higher than over Lake Victoria. Minima in stroke density are found over the Pacific Ocean and adjacent coastal plain where cold water offshore inhibits convection. Another minimum is observed over the middle-altitude portions of the eastern slope of the Andes, extending to the northwest and southeast. Stroke densities are particularly small over two deep river basins along the eastern slope.

Most of the lightning over Lake Titicaca occurs between 1600 and 0000 LST (Fig. T3). This time period constitutes a nocturnal maximum, but is obviously several hours earlier than maxima observed over Lake Maracaibo, the Strait of Malacca, and Lake Victoria. The land areas immediately adjacent to the lake exhibit their maximum stroke count during the afternoon, with the predominant peak centered around noon. That peak integrates lightning activity from both the Andes and the lower plains in northeastern Bolivia.



Fig. T1. Topography of the area surrounding Lake Titicaca. The white polygon bounds the analysis area, and the gray line surrounds the main portions of the lake. Country boundaries are in red. Dashed gray lines are centers of cross sections.



Fig. T2. Annual stroke density detected by GLD360 over Lake Titicaca and surrounding region in a  $5 \times 5$  km grid from 2012 through 2014.



Fig. T3. Diurnal variation of strokes over Lake Titicaca (top) and the polygon minus the lake (bottom) in Local Standard Time (UTC-5). Dashed vertical lines indicate noon.

The three-hourly maps in Fig. T4 show a distinct Lake Titicaca cycle. Lightning is minimal during the morning until strokes begin to encroach from the adjacent higher land located to the west, and an all-night maximum over the lake is very evident. Starting at noon in the upper left panel and proceeding through the diurnal cycle:

- <u>1200 to 1500 LST:</u> The lake is nearly lightning-free at this time, but a major lightning region is located nearby in all directions except for immediately to the east of the lake.
- <u>1500 to 1800 LST:</u> A very strong maximum in lightning to the west is at its peak, and beginning to move over the western portion of the lake.
- <u>1800 to 2100 LST:</u> Lightning is found mainly in a northwest to southeast swath that advances slightly northeastward from the peak of the previous few hours off the southwest flank of the lake, and starts to extend over the lake itself.
- <u>2100 to 0000 LST:</u> All land-based thunderstorms over the high terrain have dissipated; the only lightning in the high terrain is now found exclusively over the lake. The nocturnal maximum over the lower elevations to the east also begins to ramp up.
- <u>0000 to 0900 LST:</u> Lake Titicaca now has one of the two areas with lightning; the other is at lower elevations to the east.



Fig. T4. Three-hourly maps of GLD360-detected lightning over the Lake Titicaca region, starting in the upper left at 1200 to 1500 Local Standard Time (UTC-5). Analysis region is the exterior rectangle of Fig. V1, and the lake is outlined in brown.

The composite Lake Titicaca diurnal pattern shows maximum lightning to begin in the evening and extend after midnight over the center of the lake (Fig. T5). Maxima after midnight are also apparent over lower elevations to the east. Nearly all other land areas have peak lightning between noon and sunset (yellow to light orange). There is a progression from a near-noon maximum over high terrain along the southwest and northeast flanks of the lake toward a later afternoon peak along a northwest-to-southeast axis through the lake itself. As noted above, the nighttime lake maximum is earlier than over the other large water bodies in this study, with the time of the maximum mostly between 1900 and 2300 LST. The most likely cause of the shift toward an earlier peak time is the lack of very warm surface waters at this high elevation to sustain convection later into the night.



Fig. T5. Hour of day with maximum lightning frequency in a 20 x 20 km grid over region of Fig. T1. Local time is indicated by color bar on right. Period of record is 01 October 2011 through 01 October 2015.

Hovmöller diagrams in Fig. T6 are taken from crosssections across the short and long dimensions of Lake Titicaca; that is, the southwest-northeast and northwestsoutheast center lines in Fig. T1. Convection over the surrounding high terrain both to the southwest and northeast ramps up strongly and suddenly near 1200 LST. The top panel of Fig. T6 shows a slow drift of the southwest flank maximum (left of the lake) toward the northeast as the afternoon progresses, consistent with the three-hourly densities shown in Fig. T4. The long-dimension cross section shows the maximum density occurring between 1500 and 1800 on both the northwest and southeast sides of the lake, with a relative minimum in lightning density over the lake until after about 1800. As the land-side thunderstorms decay after 1900 LST, the maximum over the lake picks up. Although the peak lightning density over the lake occurs prior to midnight, both panels of Fig. T6 show that a weak over-water maximum persists into the morning, with a tendency to be displaced toward the southwest shore, which is where the lake is somewhat shallower and water temperatures a bit higher.

The persistence of the maximum through the night is consistent with the findings of Giovannettone and Barros [2009], who looked at TRMM precipitation features having reflectivity of at least 20 dBZ and 85-GHz polarizationcorrected temperature of 250 K or less. They noted a distinct local maximum in such features, representative of convective clouds containing ice, over Lake Titicaca during the 0000 to 0600 LST time period, as well as a distinct minimum in these features directly over the lake between 1200 to 1800 LST. They attributed the nocturnal maximum to "downslope" flow from the surrounding terrain, but not explicitly to cool outflow from preceding afternoon convection over the terrain. However, it is important to note that they did not explicitly look at the 1800 to 0000 time period, when we find the absolute maximum in lightning density over the lake.



Fig. T6. Hovmöller diagrams of cross sections from southwest to northeast (upper panel) and northwest to southeast (lower) across Lake Titicaca. Time of day is on left axis. Right axis is logarithm of the number of strokes in bins of 10 km in distance dimension by 15 minutes in time-of-day dimension. Cross-section swath widths are 220 km (SW-NE) and 80 km (NW-SE).

Lake Titicaca has a strong seasonal variation in its thunderstorm activity with a significant maximum between November and March and very little lightning occurrence from May through July (Fig. T7). Both land and lake areas have the same trends, although the number of strokes over the lake is very small compared with the adjacent high mountain slopes. The strong annual cycle is associated with the transport of mid- to upper-level moisture from the east through the setup of the Bolivian high late in the southern-hemisphere spring [Garreaud, 1999; Jones and Carvalho, 2002]. The South American Low-Level Jet is a significant source of moisture along the east slope of the Andes, but evidently only up to about 2500 m altitude. At higher altitudes, the exact position of the Bolivian high regulates the flow of moisture into the high terrain, resulting in relatively wet periods when the high is farther south and easterly flow is enhanced.



Fig. T7. Number of strokes by month over Lake Titicaca. and within the rectangle of Fig. T1 exterior to the lake.

### VI. SUMMARY ANALYSES

A consolidated analysis of lightning frequency over the land areas surrounding the four bodies of water in this study is in the top panel of Fig. S1. The bottom panel shows a similar analysis over the water bodies themselves. Both panels are expressed in percent of all lightning occurring within the day by hour in local solar time for each water body.

The lightning frequencies over the land masses are nearly in phase with distinct peaks between 1500 and 1700 LST. With the exception of the river valley to the southwest of Lake Maracaibo, the land masses are all very quiet between 2000 and 1100 LST.

By contrast, the maxima in lightning frequency over water are out of phase in the different locations. Lake Titicaca has its peak during the hours immediately after sunset. Given its very high altitude and cold temperatures, it is reasonable to expect that deep, lightning-producing convection would not survive deep into the night. In addition, Lake Titicaca is land-locked and thus cut off from any low-level jets and warm water sources such as are available at Lake Maracaibo and the Strait of Malacca. The nocturnal maxima over those latter two water bodies occur after midnight. The maximum in the Strait of Malacca is broader and less sharp, as the average thunderstorm activity maximum is able to migrate slowly along the elongated body of water in the northwestward direction, as suggested by our cross-section analysis. Finally, Lake Victoria exhibits a ramp-up of lightning frequency during the night, but the actual peak is delayed until after sunrise, when the thunderstorm activity reaches the warmer waters along the southwest shore of the lake.

#### VII. CONCLUSIONS

We have examined the diurnal cycles of lightning activity over and around four large tropical water bodies that are surrounded by significant terrain gradients of various configurations. It was found that all four water bodies have nocturnal maxima in lightning density that follow large afternoon lightning densities over the surrounding terrain. Overall, this pattern of behavior is consistent with the "coastal regime" of convective diurnal cycles identified by Kikuchi and Wang [2008], in which cool outflows generated by after-



Fig. S1. Percent of lightning over each lake and Strait of Malacca (top) and over surrounding land areas (bottom) by hour of day in Local Standard Time.

noon convection over the heated land surfaces converge during the night over the adjacent water. In the case of these four water bodies, the nocturnal storms essentially do not propagate because the water bodies are mostly confined by the surrounding terrain. However there is evidence of some propagation over Lake Victoria due to the strong easterly outflow from the high terrain in Kenya, and there is also evidence of a slight northwestward development, if not propagation, over the Strait of Malacca, whose width increases in the northwesterly direction.

It is important to note that the diurnal cycle is just one component, albeit an important one, of the overall climatology of thunderstorms in the areas of these four water bodies, as well as the tropics in general. For instance, Laing et al. [2011] have shown that convection over all of equatorial Africa, including the Lake Victoria region, is modulated on weekly time scales by equatorial Kelvin waves, as well as on longer time scales by the Madden-Julian Oscillation (MJO). The MJO also has an important role in regulating thunderstorm activity over the entire Maritime Continent, not just the Strait of Malacca, as demonstrated by Virts et al. [2013b]. Future studies of these four water bodies and their surroundings might seek to investigate how the non-diurnal cycles affect or modulate the occurrence of lightning over the water vs. over the surrounding terrain, and whether or not these cycles alter in any way the general patterns that we have presented in this study.

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