Lightning activity in tropical cyclones in the South-West Indian ocean

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ABSTRACT: Lightning activity is investigated within tropical convective events of the South-West Indian Ocean (SWIO). The World Wide Lightning Location Network (WWLLN) provides global lightning data since 2005 and is therefore a well suited network for the study of systems like tropical cyclones as they remain over ocean most of their life.

Firstly, a 7-year lightning climatology over the South West Indian Ocean has been performed using the WWLLN data from 2005 to 2011. Results show the same main features presented in other studies: the "hot spots" in this region are found in Madagascar and over the Great Lakes in East Africa ($>$ 10-20 fl. km^{-2} yr^{-1}). Lightning flashes within tropical cyclones represent 50% to 100% of the total lightning activity in some oceanic areas (between 10°S and 20°S). Moreover, lightning activity is more intense during the November-to-April period which corresponds to the wet/cyclonic season.

Then, lightning activity in tropical storms of the basin was studied using both WWLLN data and best-tracks from the Regional Specialized Meteorological Center La Réunion from January 2005 to May 2013. The South-West Indian Ocean is divided into three distinct regions (open ocean, Mozambique channel, and the oceanic region 400 km offshore the eastern coast of Madagascar) to account for the impact of land on the tropical storm structure. The tropical storms are divided into annular rings based on a radius of maximum wind criteria. We show that lightning activity is mainly found in the eyewall region whatever the system stage in the open ocean.

The possible link between lightning activity and tropical cyclone intensity change is investigated using different thresholds for the intensification rate. We show that, whatever the intensity stage is, the proportion of 6-h period with lightning activity is higher during rapid intensifications. For systems rapidly intensifying, 20 to 50% of the 6-h periods are associated to lightning flashes.

INTRODUCTION

First studies related to lightning activity in tropical cyclones have used the National Lightning Detection Network (NLDN) that primarily detects cloud-to-ground (CG) lightning strokes within 400 km of the United States coasts. TCs in this region start interacting with land and usually make landfall. Most of the works using the NLDN focused on few hurricanes in the Atlantic basin [*Samsury and Orville*, 1994; *Lyons and Keen*, 1994; *Molinari et al.*, 1999] while *Corbosiero and Molinari* [2003] studied the flash distribution relative to storm motion and wind shear in 35 named tropical cyclones.

Lightning data from satellites have been used by *Cecil and Zipser* [1999] and *Cecil et al.* [2002] to study the relationship between lightning activity and storm intensity. However, because the OTD and LIS data do not provide a continuous coverage of lightning within TCs, they are by design not the most suitable tool to examine the relationship between lightning activity and intensity change.

Other systems such as the Long-Range Lightning Detection Network (LLDN) or the World Wide Lightning Location Network (WWLLN) allow a detailed analysis of lightning activity (primarily CG lightning strokes) during the entire lifetime of TCs and over large regions (especially the open ocean). While

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Squires and Businger [2008] focused on the electrical signature of hurricanes Rita and Katrina (2005), the coming of this long range detection networks allowed the study of a larger set of systems over the open ocean [*Abarca et al.*, 2011] and the analysis of lightning distribution in tropical cyclones of different basins [*Price et al.*, 2009; *DeMaria et al.*, 2012].

Up to now, the South West Indian Ocean (SWIO) remains one of the less studied basin while TC activity in this region represents 10-12 % of the total annual TC activity [*Neumann*, 1993]. This basin spreads from 30°E to 90°E and from the equator to 40°S (Fig. 1). Before analysing lightning activity in tropical cyclones of the SWIO, a lightning climatology of the south-west Indian ocean is presented.

DATA AND METHODOLOGY

A full description of the dataset and methodology is available in *Bovalo et al.* [2012] and *Bovalo et al.* [2014]. The main characteristics of the lightning and cyclone data is recalled hereinafter.

Lightning data

Lightning data from January 2005 to May 2013 have been extracted from the WWLLN database. The WWLLN (`http://www.wwlln.net/`) is a global coverage ground-based network that detects impulsive signals of very low frequency radiation (3-30 kHz). The time of group arrival is used to determine the location of lightning strikes [*Dowden and Rodger*, 2002].

Intra-cloud (IC) and cloud-to-ground (CG) lightning flashes are both detected by the WWLLN but as the CG flashes have higher peak currents, the network mainly records CG flashes. Using data from the NLDN, *Abarca et al.* [2010] showed that the WWLLN's DE has improved from 2.31% in 2006 to 6.19% in 2010 in their subject area (US territory and adjacent waters). *DeMaria et al.* [2012] computed the WWLLN's DE in the Atlantic and East/Central Pacific basins as the ratio between the annual average flash density for each year and the average LIS/OTD flash density over the same domain. For the Atlantic (East Pacific) basin, the DEs range from 2.6% (0.9%) in 2005 to 20% (17.5%) in 2010. *Bovalo et al.* [2012] used the same method but found a slower evolution of the DE in the SWIO basin: from 2.0% in 2005 to 10.9% in 2013.

Even if the WWLLN's DE increased during these past years, it still remains low. To get more realistic lightning density values, the WWLLN data have been calibrated following the procedure of *DeMaria et al.* [2012]. They computed the WWLLN DE in each region using the LIS/OTD annual mean lightning climatology. Then, the WWLLN data were multiplied by the inverse of the DE in each region.

Best-tracks

Information relative to tropical cyclones is obtained from the Regional Specialized Meteorological Centre (RSMC) La Réunion best-track dataset. In particular, this dataset includes the latitude and longitude of the storm center, the 10-min averaged maximum wind speed v_{max} (in kt where 1 kt = 0.514 m s^{-1}), the radius of maximum wind (RMW) and the radius of the outer closed isobar (ROCI) every 6 hours. Four categories of TC have been defined, based on the classification of the RSMC La Réunion and the presence of a RMW: moderate tropical storm ($34 < v_{max} < 47$ kt, MTS), strong tropical storm ($48 < v_{max} < 63$ kt, STS), tropical cyclone ($64 < v_{max} < 89$ kt, TC) and intense tropical cyclone ($v_{max} > 90$ kt, ITC). A total of 70 systems from MTS to ITC has been investigated, corresponding to 1281 6-h periods.

A LIGHTNING CLIMATOLOGY OF THE SOUTH-WEST INDIAN OCEAN

The SWIO is characterized by two seasons: the wet season is November to April and the dry season is May to October. Thus the mean flash density over the SWIO for the wet and dry seasons is shown in Fig. 1.

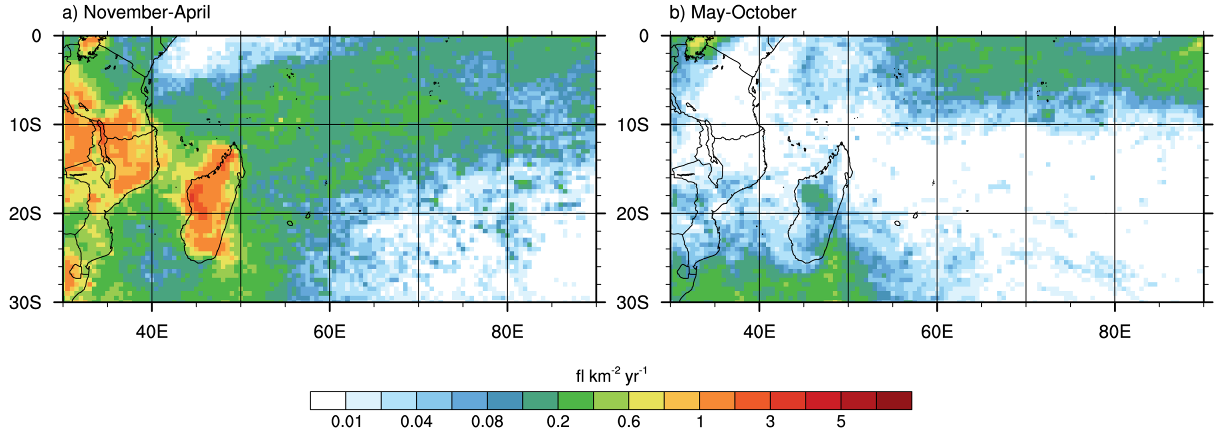

Figure 1: The seasonal distribution of lightning activity (fl km^{-2} yr^{-1}) for the period 2005-2011: (a) November to April, and (b) May to October.

During the wet season, the Inter Tropical Convergence Zone (ITCZ) is located in the southern hemisphere. Over Madagascar, lightning flashes are preferentially triggered over the low highlands and plains in the northwestern and western parts of the country (10-20 fl. km^{-2} yr^{-1}). The flash density stays between 2 and 8 fl. km^{-2} yr^{-1} in the southern and eastern parts of the country. Lake Malawi and Lake Victoria exhibit flash densities higher than 8 fl. km^{-2} yr^{-1}. Maximum lightning activity is found over land and in the southwestern part of the basin during the west season. The wet season also corresponds to the period when tropical storms and cyclones form and propagate over the basin. It was shown that over some oceanic region of the SWIO, tropical cyclones are responsible for 50 to 100 % of the total lightning activity.

During the dry season, the deep convective activity is limited by the presence of the Mascarene high that reinforces the trade wind inversion. In the southwestern part of the SWIO [30°S-40°S ; 30°E-50°E], the significant lightning activity (4-8 fl. km^{-2} yr^{-1}) can be related to cold fronts and mid-latitudes storms.

LIGHTNING ACTIVITY ASSOCIATED TO TROPICAL CYCLONES

Two main areas of cyclogenesis are identified in the SWIO: one over the Mozambique Channel and the other one over the open ocean. Due to the particular basin configuration with the presence of Madagascar, TCs are expected to behave differently depending on their position: open ocean behavior and/or interaction with land. This led us to define three different regions in the SWIO to analyze the lightning activity detected by the WWLLN within 70 TCs: the open ocean, the region 400 km offshore the eastern coast of Madagascar, and the Mozambique Channel. Moreover, systems are not classified using their maximum intensity, but they are sorted by intensity stage per 6-h interval. For each date, the storm is divided in 3 regions: the eyewall, the inner rainbands and the outer rainbands.

The WWLLN's low DE brings some questions concerning the analysis of lightning activity within TC. Since TC generate a few amount of flashes, a period without lightning activity could result from electrical conditions non conducive to lightning triggering or from a weak lightning activity not detected by the low DE network. To avoid any ambiguity, the 6-h periods without lightning activity are not considered in this study and lightning activity will refer hereinafter to lightning activity detected by the WWLLN. While previous studies used arbitrary thresholds to determine these regions, we use the radius of maximum wind (RMW) and the radius of the outermost closed isobar (ROCI) which are available in the best-tracks.

Lightning distribution relative to storm intensity

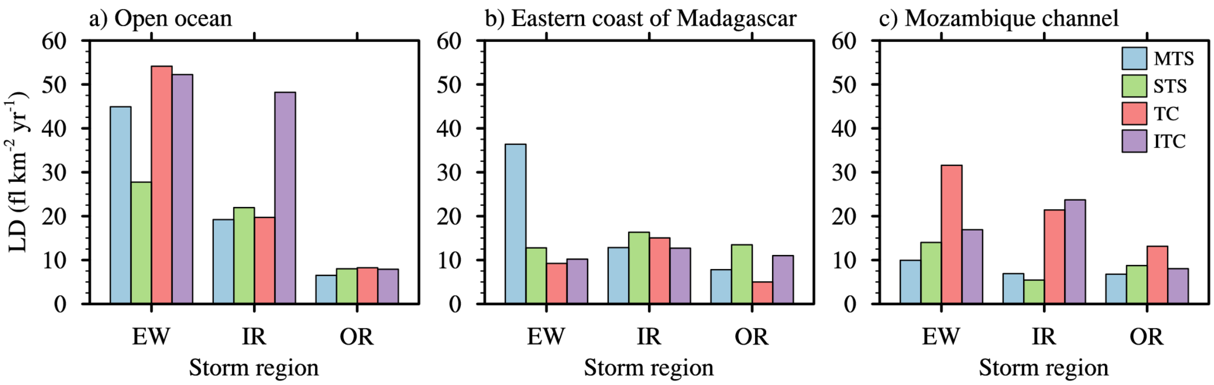

Figure 2: Radial distribution of lightning density (fl km^{-2} yr^{-1}) as a function of intensity stage for a) the open ocean, b) the eastern coast of Madagascar (ECM) and c) the Mozambique Channel. EW, IR and OR stand for eyewall, inner rainbands and outer rainbands, respectively. The blue, green, pink and purple bars stand for MTS, STS, TC and ITC, respectively.

Figure 2 displays the geometric mean of radial distribution of lightning activity for MTS, STS, TC and ITC over the open ocean. Lightning flashes are mainly detected in the eyewall region whatever the storm intensity, and the lightning density decreases when the distance from the storm center increases. Lightning activity in the eyewall is less intense at STS stage (28 fl km^{-2} yr^{-1}) but exceeds 50 fl km^{-2} yr^{-1} for TC and ITC stages. In the inner rainbands, lightning activity is quite similar for MTS, STS and TC stages ($\sim$ 20 fl km^{-2} yr^{-1}) while for the ITC stage, it reaches 48 fl km^{-2} yr^{-1}. In the outer rainbands, lightning activity is low and does not exceed 8 fl km^{-2} yr^{-1} whatever the intensity stage.

The radial distribution of lightning activity over the open ocean is somehow consistent with previous studies [*DeMaria et al.*, 2012; *Jiang et al.*, 2013], with lightning activity mainly located in the eyewall. However, a significant difference is found in the inner rainbands which could be due to the different methodologies and instruments used in each study.

As the most vigorous updrafts are found in the eyewall [*Black et al.*, 1996], the ice particles are generated in this region and grow by riming, producing conditions favorable to cloud electrification and lightning. The inner rainband is composed by several convective cells whose vertical extension and updraft strength is limited by the eyewall outflow. Rainbands are hypothesized to act like squall lines. The low lightning activity detected by the WWLLN in the outer rainbands is consistent with the observations of low electrified maritime squall lines during TOGA-COARE [*Orville et al.*, 1997].

Lightning distribution relative to the proximity of land

Near the eastern coast of Madagascar, the electrical activity is mainly located in the inner rainbands (Fig. 2b). It is important to note that lightning density in the eyewall of systems close to Madagascar is much less intense than for systems over the open ocean.

In the Mozambique Channel, the radial distribution of lightning flashes is different at each intensity stage (Fig. 2c). As near the ECM, lightning activity is lower than in the open ocean. TCs in the Mozambique Channel are surrounded by land, which can explain the large variability in function of the intensity and the difference in lightning behavior with the ECM. Indeed, systems moving through the Mozambique Channel have different trajectories, and can land over the eastern coast of Africa or over the western coast of Madagascar. The diversity of the trajectories in this region makes the analysis of lightning activity more difficult than in the other regions.

COULD LIGHTNING ACTIVITY BE A PROXY FOR TROPICAL CYCLONE INTENSIFICATION?

Using the intensification thresholds defined by *Kaplan et al.* [2010], the link between lightning activity and intensity change of tropical cyclones have been investigated. In this part, we grouped MTS and STS (TC and ITC) into the TS (TC) category to enhance the sample size and for simplicity's sake. Only lightning activity over the open ocean is examined. Hereinafter, 6-h periods will be referred to as individual time periods (ITP) [*Abarca et al.*, 2011].

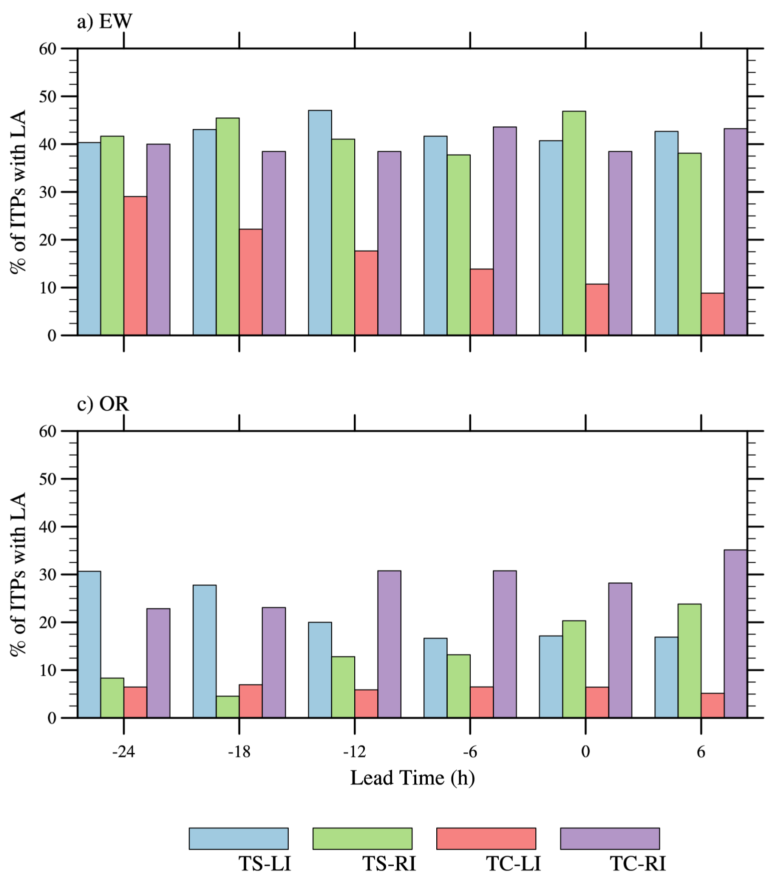

Figure 3: Percentage of ITPs with lightning activity for TS and TC in (a) the eyewall region (EW) and (b) the outter rainbands, over the open ocean. Two thresholds are used for the rate of intensification: low intensification (LI) rates are defined by $0 < \Delta v_{max} < 6.6$ kt (6-h)$^{-1}$ (blue and pink bars for TS and TC cases, respectively) while rapid intensification (RI) rates are described by $\Delta v_{max} \geq 6.6$ kt (6-h)$^{-1}$ (green and purple bars for TS and TC cases, respectively).

Figure 3 represents the percentage of ITPs with lightning activity during each intensity change: low or rapid intensification. Whatever the intensity stage, the proportion of 6-h periods with lightning activity is higher during rapid intensifications. We show that 20 to 50 % of 6-h periods are associated to lightning flashes for systems rapidly intensifying. In the outer rainbands of TSs rapidly intensifying, the proportion of ITPs with lightning activity increases as the storms deepen. Since the outer rainbands are far from the potential vorticity core, they are unconstrained by the dynamics of the inner core.

During rapid intensification, convection in the outer rainbands is enhanced due to the favorable environmental conditions instead of internal processes. Short-lived convective bursts are hypothesized to play a role in rapid intensification [*Rogers*, 2010; *Kelley and Halverson*, 2011; *Fierro et al.*, 2011]. According to *DeMaria et al.* [2012], storm intensification could be linked to a positive interaction between the inner core potential vorticity and the vertical shear. The tilting of the vortex induced by the vertical shear would result in asymmetric intense convection in the eyewall, favorable to lightning activity.

CONCLUSIONS

Lightning data from the WWLLN have been used to study lightning activity within tropical storms and cyclones of the SWIO for cyclonic seasons 2005/2006 to 2012/2013. Based on the basin configuration, lightning activity within tropical cyclones has been studied for three different regions: over the open ocean, near the ECM (until 400 km) and in the Mozambique channel.

The radial distribution of lightning activity is affected by several conditions: the location and the intensity. Lightning activity depends on intensity stage but, unlike previous studies, lightning density in the eyewall is higher at higher intensity (TC and ITC) over the open ocean. Lightning activity in the rainbands is less important than in the eyewall. In the ECM, lightning are preferentially detected during MTS stages. In the Mozambique channel, lightning activity is more sustained when the systems reach the TC stage.

The relationship between lightning activity and intensity change have been studied over the open ocean using different thresholds of intensification. Only two types of intensity were kept to simplify the analysis. For TS cases, an increase in the proportion of ITPs with lightning activity is observed in the outer rainbands. At TC intensity, whatever the region, there are more periods with lightning activity prior to a rapid intensification. During low intensification, the frequency of ligthning activity decreases in the eyewall and in the inner rainbands.

We have shown that lightning activity in the SWIO is not only dependant on the intensity stage of the system, but also on the system location and proximity of land. The SWIO lacks in observations so it is difficult to determine the physical processes involded in tropical cyclone electrification. A better understanding of what happens in tropical cyclones in term of microphysics and electric charge is possible thanks to modeling studies. The radial and azimuthal distributions and the potential of lightning activity in forecasting intensity change is examined in ongoing simulations of electrified tropical cyclones in the SWIO.

ACKNOWLEDGMENTS: The authors wish to thank the World Wide Lightning Location Network, a collaboration among 40 universities and institutions, for providing the lightning location used in this study. Funding for this work is provided by the Fondation MAIF through the PRECYP project. C. Bovalo's PhD was financially supported by La Région Réunion and the European Union Council.

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