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Determining Hurricane Formation in the eastern North Pacific Using the Global Lightning Dataset 360 and the Long-Range Lightning Detection Network

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***Abstract*— Tropical cyclones and ambient cloud clusters from the eastern Pacific 2009 and 2010 tropical seasons are examined using remotely-sensed data to see if differences between the two populations can provide insight into whether a given disturbance will develop into a tropical depression. Data used includes infrared satellite imagery from the Geostationary Observational Environmental Satellites (GOES) as well as lightning flash counts from the Global Lightning Dataset 360 and the Long-range Lightning Detection Network. All tropical disturbances that develop within the inter-tropical convergence zone and surrounding eastern North Pacific basin which exist over the ocean and maintain organized convection for 72 hours are included. Analysis of the remotely-sensed observations is then preformed to determine if there is a difference between the two groups in the 6 hourly lightning flash counts, which is used as a proxy for deep convection.**

Keywords—hurricane genesis; lightning; detection; GLD360; LLDN

I. INTRODUCTION

Studied for over a century, tropical cyclogenesis, or the formation of a tropical cyclone (TC), still puzzles generations of scientists. The conditions necessary for the formation of a TC have been well documented (Gray 1968, 1975), and are often fulfilled throughout tropical basins of the world, sometimes for extended periods of time, without a TC forming. The conditions include a disturbed area of convection coinciding with a region of low-level cyclonic vorticity, lower-tropospheric convergence, upper-tropospheric divergence, with weak vertical wind shear, and average sea surface temperatures above 26.5 ˚C. Some of the difficulties in understanding tropical cyclogenesis include: 1) a lack of data coverage over large tropical basins; 2) a lack of TC formation despite the presence of persistent necessary large-scale conditions for TC genesis; and 3) differences in the physical processes associated with genesis because of basin differences including land masses, ocean currents, atmospheric patterns and the corresponding air-sea interactions.

The eastern North Pacific is a prolific generator of TCs with more genesis events per unit area per unit time than all other basins globally (Molinari et al. 2000). Most TCs of the eastern North Pacific form on or near the west coast of North America and then propagate parallel along the shore or more generally westward to north-westward away from land; tracks and genesis locations shown in figure 1. Over 96% of genesis occurs east of 130°W in this basin according to the National Hurricane Center (NHC) best track (http://www.nhc.noaa.gov/data/#hurdat) using data from 1970-2011. As a result, this basin offers a unique opportunity to study genesis using the Vaisala Long-Range Lightning Detection Network (LLDN), which has limited offshore capability and an efficiency of lightning detection that decreases with distance from land.

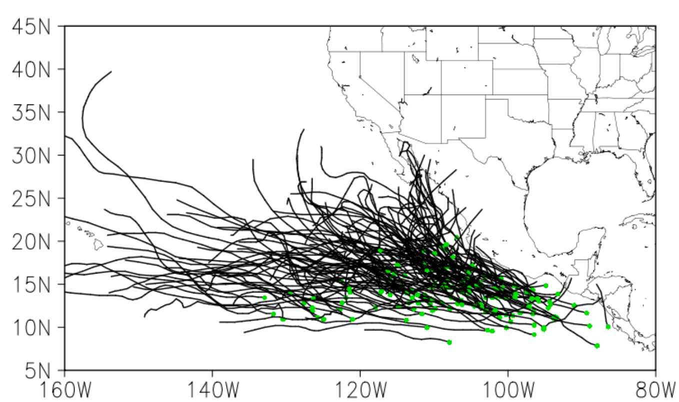

Figure 1: NHC genesis locations and best tracks for 2001-2011. Only one decade shown for clarity in image. [Image courtesy of K. Wood]

Convective cloud clusters in the eastern North Pacific likely to undergo genesis can be described as one or more meso-scale

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convective systems with some embedded deep cores of convection loosely organized by large scale-forcing such as an easterly wave or convergence within the inter-tropical convergence zone (ITCZ) (Fig. 2). There is a diurnal pattern to the convection with afternoon suppression of convection and a peak in the early morning, consistent with oceanic convection (e.g., Yuter et al. 2005; Liu and Monrieff, 1998; Leary and Ritchie 2009). These convective disturbances form on or near the coast of Mexico and Central America and slowly propagate west or west-northwestward with 20% of disturbances evolving into TCs in the study period.

Many studies have focused on the importance of convection in the formation of tropical cyclones (e.g., Riehl and Malkus 1958; Ooyama 1982; Simpson et al. 1997; Tory et al. 2006; Hendricks et al. 2006 to name a very few). Convection may very well be one of the critical triggers for genesis as deeply convective plumes, called "hot towers" (Riehl and Malkus 1958) bring warm moist tropical air from the sea surface un-entrained high into the troposphere. The deep convective plume may also stretch ambient, large-scale, near-surface vorticity, both decreasing the scale and increasing the intensity of the vorticity through a deep layer in the vicinity of the connective plume (Hendricks et al. 2006; Montgomery et al., 2006).

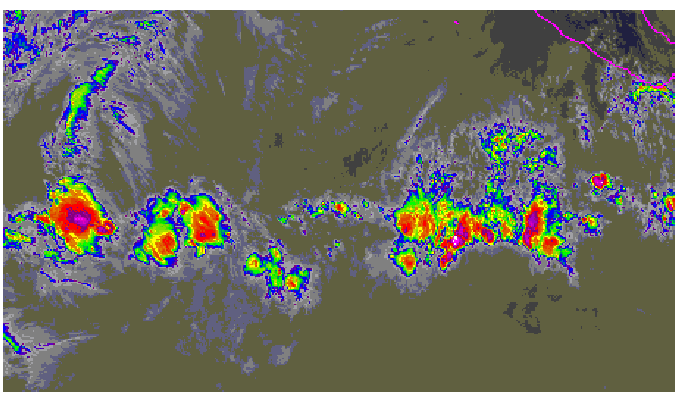

Figure 2: Example of a series of convective clusters being tracked in the eastern North Pacific basin at 1800 UTC on May 22, 2010.

The mechanisms driving the interaction of the meso- and convective-scales in tropical disturbances are not fully understood, and the ability of complex numerical models to properly simulate convective processes is limited. However, the convective-scale processes can be utilized for the purpose of targeting disturbances early in the TC formation process. If convective processes are important, then developing cloud clusters will display a heightened level of convective activity, which can be detected using remote-sensing instruments and used to develop an indicator for genesis. In previous work, Leary and Ritchie (2009; hereafter LR09) used the Vaisala Long-range Lightning Detection Network (LLDN; Demetriades and Holle 2005) to investigate whether cloud clusters that developed into tropical cyclones in the eastern North Pacific 2006 season displayed higher levels of lightning than their non-developing counterparts. The major findings of that study were that developing cloud clusters displayed a level of raw flash counts 1.78 times that of non-developing cloud clusters. Furthermore, a receiver operating characteristic (ROC) curve (e.g., Marzban 2004) was developed using thresholds of 24-hr averaged lightning flash counts, which showed that developing cloud clusters could be detected with skill relative to an equal chance line. Depending on a user's desired detection to false alarm rate, a threshold of flash rates could be used to detect genesis. For example, a threshold of 210 flashes per 6 hr distinguished developing cloud clusters 67% of the time with a false alarm rate of 27%. Since that time, Vaisala has developed a more reliable oceanic lightning detection dataset – the Global Lightning Detection 360 (GLD360) dataset – with detection rates and efficiencies much higher than those of the LLDN. In the eastern North Pacific, the detection efficiency of lightning with the LLDN drops off quickly with distance from the coastline as well as with daylight. The GLD360 can provide better coverage using a geo-location method which decreases the number of sensors necessary from four to three, and can capture a cloud-to-ground (CG) stroke with a distance-indexed, logarithmically based canonical waveform bank (Said et al., 2010). In this study we will utilized the 2009 and 2010 eastern North Pacific seasons to investigate the ability of the GLD360 to reproduce, and to improve on the LLDN for the purpose of detecting developing cloud clusters. We will first validate the results in LR09 using the LLDN data and then compare the LLDN with the GLD360 data to see if the ability to detect developing cloud clusters holds for the GLD360 data. The GLD360 dataset begins in late 2009 and so the main comparison between the LLDN and GLD360 data will be for the 2010 season.

II. Data and Methodology

A. The Long-Range Lightning Detection Network

Vaisala owns and operates the United States National Lightning Detection Network (NLDN), which is a collection of sensors across the United States that operate between 0.5 and 400 kHz. These sensors detect lightning flashes that produce peak frequencies near 10 kHz and extend into the very low frequency (VLF) band in the interval from 3-30 kHz. Due to the earth-ionosphere structure, and the ability for NLDN sensors to operate over a broad band of frequencies, the VLF signals that reflect between the earth's surface and the ionosphere, called sferics, can be detected at long ranges. The Long-Range Lightning Detection Network (LLDN) uses these VLF signals to sense lightning flashes up to thousands of kilometers away (Demetriades and Holle 2005).

The VLF signal can be attenuated during its travel over longer distances due to the number of times the signal must reflect between the Earth's surface and the ionosphere. During the daylight hours, when free electrons and ions are being produced by the photodissociation of molecules high in the atmosphere, the efficiency of the network decreases and fewer flashes are detected. Detection efficiency of the LLDN is highest at night when the ionosphere is "uncharged," meaning the sferics are able to propagate away from the lightning discharge to the land based sensor with less attenuation. Mainly affected is the amplitude of the discharge, thus this parameter was not discussed in LR09 nor was it examined here. However, the detection of discharges is considered to be fairly accurate near the coasts, having efficiencies as high as 90-99% accurate, but with efficiency tapering off with increased distance from the coasts. The daytime efficiency in the region of study ranges from 70% – 1% (Fig. 3), with a few clusters propagating into very inefficient areas (Pessi *et al.* 2008). Correction of the daytime detection efficiency for the average flash rates did not meet the efficiency threshold for this study and flash counts during the daytime were frequently set to zero. However, these clusters are not removed from consideration because the night time efficiency is high enough to give us confidence in the raw flash counts. When corrected for detection efficiency, the overall results for the average night time flash rates do not differ from the raw data, and for this reason the raw data were used.

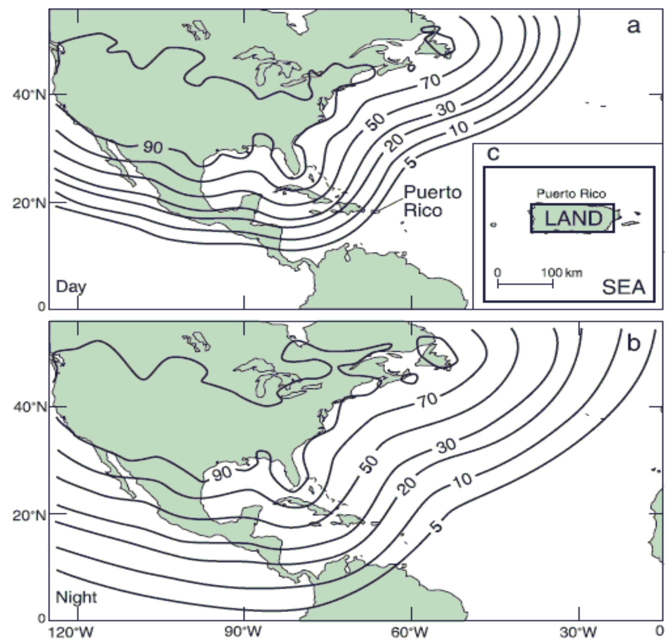

Figure 3: Day and night efficiencies for the LLDN (from Pessi et al. 2008).

B. *Global Lightning Dataset*

The GLD360 also uses the VLF band (3-30 kHz) of the electromagnetic spectrum, however, the dataset is considerably improved by using a different geo-location algorithm and the number of sensors used has been modified. As previously stated long-range detection methods were constricted by distance due to the sferics' numerous oscillations. In addition, the signal could be corrupted by any small angle error from the detected impulse azimuthal angle. Both of these factors can lead to large location errors. The improvements of the GLD360 include decreasing the number of sensors necessary, and changing how the timing of the lightning discharge's waveform impulse is detected at the sensor. Detection of a discharge is determined by the arrival time of the front of the wave form at different sensors through different pathways. Overtime these waveform banks can be collected around sensors to have knowledge of the path the waveform will take and its arrival time, hence it's accuracy. All paths were recorded and checked against the National Lightning Detection Network (Said et al., 2010).

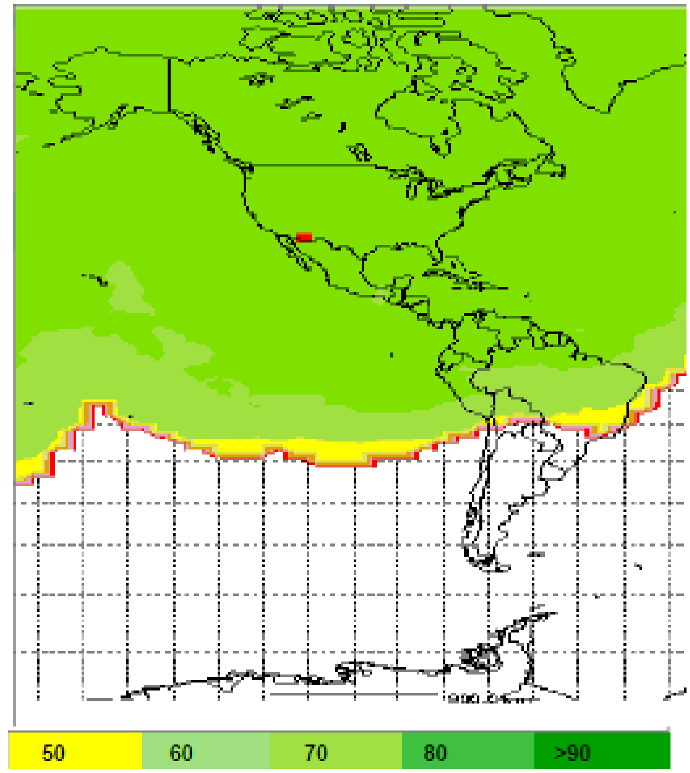

Figure 4: GLD 360 efficiency in the eastern North Pacific basin (from Holle 2009)

Added improvements from the introduction of the GLD360 include the ability to detect a lightning flash up to 8000 km away from its ground contact with 70% detection efficiency or higher globally (Fig. 4). The average location accuracy for a lightning stroke is 5-10 km, which is accurate enough for this study since the convective clusters under inspection are on the order of degrees of latitude.

C. *Cluster tracking*

The study region used is the eastern North Pacific basin bounded by 0°N – 30°N, and 80°W – 130°W (Fig. 5),

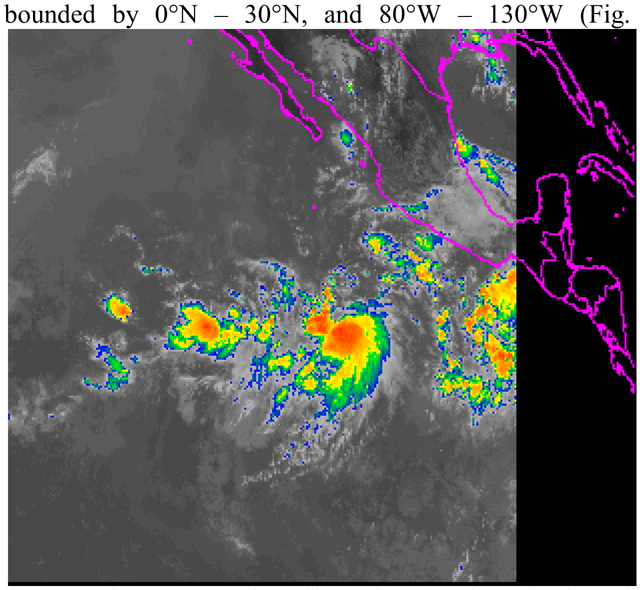
Figure 5: The eastern North Pacific study region from 0˚-30˚N and 80˚-130˚W.

excluding the area east of the western coast of North America. This is the same region used in LR09 and is maintained in this study in order to compare results between the two studies. Similar to LR09, all convective cloud clusters in the study region during May to November of 2009 and 2010 were tracked using Geostationary Observational Environmental Satellites (GOES-8 and GOES-9) infrared (IR) imagery every 6 hours from their first appearance as a convective cluster with cloud top temperatures below -55°C until either the disturbance dissipated (cloud tops dropped and warmed to above -55°C, or in some cases complete dissipation) or propagated outside the study region. Only deeply convective cloud clusters were only included in the analysis, which is why the threshold of cloud top temperatures at or below -55°C at the diurnal maximum, and the stipulation that the disturbance must be able to be continuously tracked for at least 72 hours were put into place.

Next, the cloud clusters were separated into developing or non-developing categories. The developing cloud cluster category included all systems designated as at least tropical depressions in the NHC best track archives that did not form over land. NHC defines a cloud cluster as a tropical depression when deep, organized convection accompanies a closed surface circulation with sustained 1-min surface winds of less than 34 kts (http://www.nhc.noaa.gov/aboutgloss.shtml#t). LR09 found that when the cloud clusters were over land the flash rates increased by an order of magnitude compared to those over water, most likely because of the difference in external forcing of the convection from the land surface (Christian et al., 2003). Periods in which cloud clusters move over land are excluded from the study for these reasons and only those periods when the storm was over water were included. The non-developing cloud cluster population included all other cloud clusters that met the above persistence criteria but did not develop into tropical depressions. In addition, clusters that were still active but continued west of 130° W, out of the study region, and clusters that joined already existing disturbances were kept in the study. Using this methodology a total of eighty-three cloud clusters during 2009 and fifty-nine cloud clusters during 2010 were tracked in the course of this study. Sixteen of the 2009 clusters and twelve of the 2010 clusters developed into at least a tropical depression according to the NHC Best Track archives.

Finally, using McIdas-X software a center location was determined for each cluster at each time period, and a box that encompassed the deeply convective regions of each cluster at each 6-h time was recorded. Lightning flash data from the LLDN and GLD360 were filtered using the location information to identify all strokes associated with each cloud cluster being tracked at each time. Finally, these data were analyzed to differentiate differences in convective activity between developing and non-developing systems.

III. Results

A 20-y climatology of the eastern North Pacific is reviewed in LR09. Of note, the tropical genesis season peaks in the period between June and September when the large-scale environmental conditions are optimal for tropical cyclogenesis (National Hurricane Center, 2013). This peak in the TC genesis season generally coincides with the peak in electrical activity in the basin (Fig. 6), which is not surprising considering the convective nature of TC genesis. The 2009 season was a relatively normal season with two tropical depressions and 18 named TCs developing through the season.

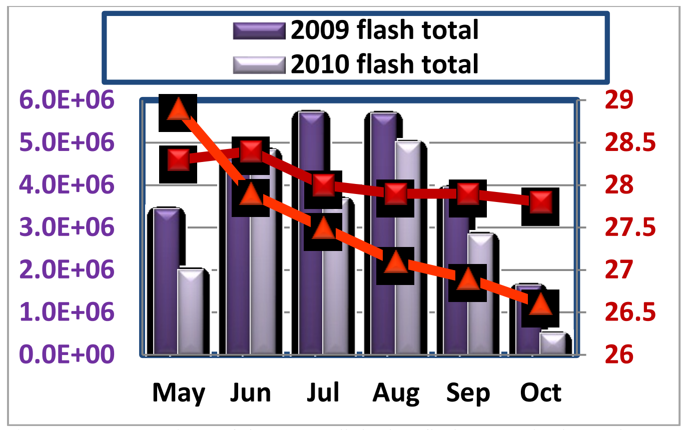

Figure 6: A comparison of the LLDN lightning flash counts in the study area (flash counts on the left vertical axis) and average sea surface temperatures (in degrees Centigrade on the right vertical axis) in the main genesis region of the eastern North Pacific by month for 2009 and 2010.

The average SSTs in the main development region (MDR) for the eastern North Pacific approximately followed the 20-y trend with maximum SSTs in May and June gradually decreasing. The SSTs increased slightly in September and then decreased in October (Fig. 6). The 2010 season was one of the least active on record with only 5 tropical depressions and seven named storms (NHC, 2010). The average SSTs were substantially lower than normal from June through October (Fig. 6). Coinciding with the lower 2010 SSTs are lower overall lightning flashes for the 2010 season (Fig. 6).
The 2006 (from LR09), 2009, and 2010 flash rates using the LLDN data are shown in Table 1.

TABLE 1: Comparison of the eastern North Pacific LLDN lightning flash rates for developing, non-developing, and the ratio between the two for 2006, 2009, and 2010.

Time (UTC)	2006			2009			2010		
	NDEV	DEV	DEV/NDEV	NDEV	DEV	DEV/NDEV	NDEV	DEV	DEV/NDEV
00-06	152	324	2.13	103	162	1.57	102	241	2.36
06-12	290	591	2.04	188	251	1.34	225	572	2.54
12-18	128	239	1.86	79	134	1.70	100	211	2.11
18-24	105	205	1.94	87	129	1.48	97	393	4.05
Total Avg.	157	339	2.16	114	169	1.48	131	354	2.70
# clusters	80	18		71	16		45	12	

The overall flash rates for all cloud clusters in 2006 and 2010 are generally similar while the flash rates for 2009 are generally lower. Furthermore, the differences in flash rates for 2006 and 2010 between the two cloud cluster populations are quite similar except for an unusual second maximum in the 2010 data for 18-24 UTC perhaps indicating that some overland flashes were not properly filtered out. The differences in flash rates for 2009 between the two cloud cluster populations are lower than the other two years, and the ratio of developing to non-developing cloud cluster flash rates is also lower (Table 1) suggesting that while overall flashes were higher during the season (Fig. 6), the convective activity in cloud clusters was less than for either 2006 or 2010

The comparison between the LLDN and GLD360 flash rates for 2010 are shown in Table 2 and Fig. 7. The monthly flash rates over the entire study region using the GLD360 data are approximately twice that of the LLDN and show the same unusual monthly trends with a significant dip in July and then recovering in August. It is interesting to note that there were no cloud clusters that developed in July. The overall flash rates for all 2010 cloud clusters are 6.5 times higher using the GLD360 data compared with the LLDN demonstrating the much higher efficiency with which the GLD360 network detects lightning flashes in over-ocean cloud clusters.

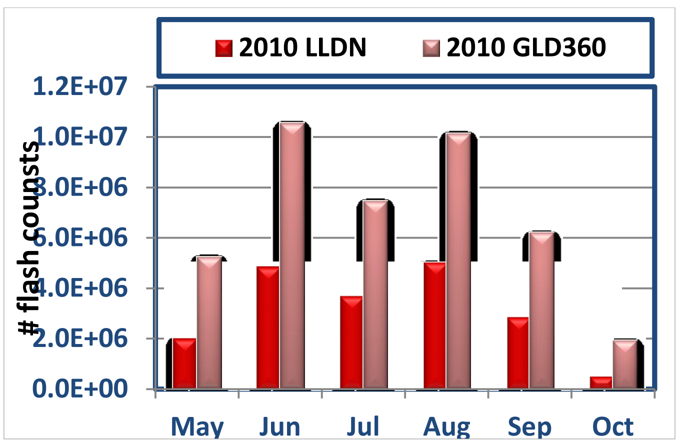

Figure 7:A comparison of the total LLDN and GLD360 lightning flash count in the study area by month for the 2010 tropical season.

TABLE 2: A comparison of the LLDN and the GLD 360 lightning flash rates for the 2010 tropical season

Time (UTC)	LLDN			GLD360		
	NDEV	DEV	DEV/NDEV	NDEV	DEV	DEV/NDEV
00-06	102	241	2.36	781	2221	2.84
06-12	225	572	2.54	1329	3540	2.66
12-18	100	211	2.11	953	1186	1.24
18-24	97	393	4.05	570	1597	2.80
Total Avg.	131	354	2.70	908	2136	2.35
# clusters	45	12		45	12	

However, the overall rates at which the developing and non-developing cloud clusters are characterized are very similar, but offset by a factor of 6, as demonstrated in Figure 8. This suggests that the conclusion of LR09 that lightning flash rates can be used to differentiate developing cloud clusters holds for the GLD360 data as well. However, because of the higher rate of detection in the GLD360 data, it will be possible to better differentiate the differing cloud cluster populations.

Similar to LR09 an ROC curve has been constructed for the LLDN 2009, 2010, and the GLD360 2010 datasets (Fig. 9). One main difference between these ROC curves and those calculated in LR09 is that these are calculated for each individual 24-h period. The ROC curves in LR09 were calculated over the life of the cloud cluster and thus are blockier because less individual pieces of information are in the calculation. All ROC curves in Fig. 9 show skill relative to the equal chance line (purple dashed line). The 2010 GLD360 ROC curve has slightly higher positive detection rates compared with the other two datasets. For a false alarm rate of 34% a detection rate of ~60% is possible using this one metric alone. One can achieve higher detection rates for a higher false alarm rate (Fig. 9).

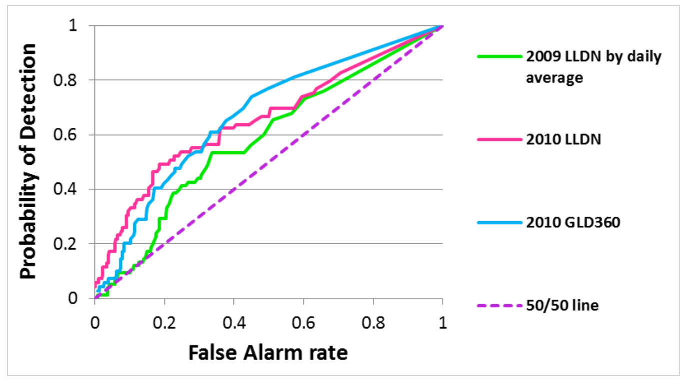

Figure 9: ROC curve calculated using the lightning flash data from the LLDN (2009 and 2010) and the GLD360 (2010) data sets.

IV. SUMMARY AND CONCLUSIONS

The results of LR09 indicated that lighting is a good pre-indicator for tropical cyclogenesis. However, the drop-off of detection efficiency of the LLDN with distance from the coast left questions regarding the validity of those results. Here, a comparison study using the newer more sophisticated GLD360 lightning detection network dataset has been undertaken to test the validity of LR09. Using the GLD360 and the LLDN to perform the exact same analysis we have confirmed the veracity of LR09 that lightning flash rates are a way to differentiate developing cloud clusters. Using the GLD360 dataset, an overall lightning flash ratio of developing to non-developing cloud clusters of 2.35 with maximum 6-h period of 2.84 indicates considerable separation of the two types of cloud clusters. Using these data an ROC curve was calculated, which would allow for a 60% detection rate with only a 34% false alarm rate, which is quite remarkable for a one variable detection index. The GLD360 provides more complete oceanic coverage of lighting detection and will be an asset to operational TC forecasting. Not only can these datasets provide tropical meteorologists with unique tool for early detection, but major trends throughout the tropical season can be seen via lightning signatures.

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