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EASTERN NORTH PACIFIC TROPICAL CYCLOGENESIS USING SATELLITE-BASED OBSERVATIONS

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1. 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.

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

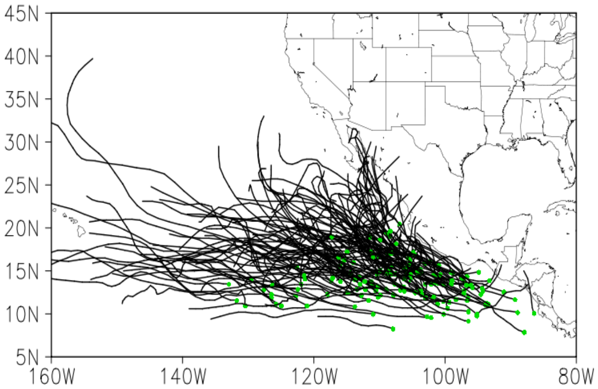

Figure 1: *NHC genesis locations and best tracks for 2001-2011. Only one decade shown for clarity in image. [Image courtesy of K. Wood]*

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). Convection may be one of the 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).

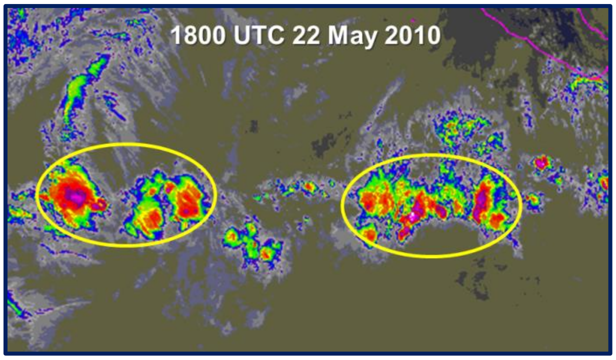

Figure 2: *Two representative eastern North Pacific cloud clusters from May 2010.*

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In this study we will attempt to differentiate between developing and non-developing cloud clusters by exploiting their inherently convective nature using lightning data as a proxy for convective activity.

2. DATA & METHODOLOGY

2.1 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 operates 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.

2.2 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).

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. 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.

2.3 Cluster tracking

The study region used is the eastern North Pacific basin bounded by 0°N to 30°N, and 80°W to the west coast of North America (Fig. 3).

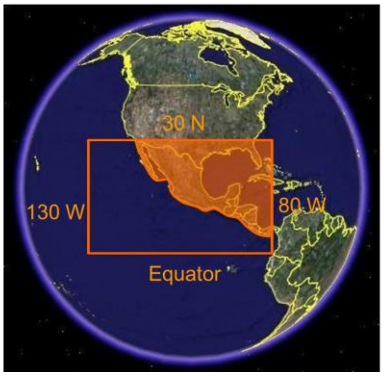

Figure 3: *The eastern North Pacific study region from 0˚-30˚N and 80˚-130˚W.*

All convective cloud clusters in the study region during May to October 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, which lasted for at least 72 hours were included in the analysis,.

The cloud clusters were separated into developing and non-developing categories. The developing cloud cluster category included all systems designated as at least tropical depressions in the NHC best track (http://www.nhc.noaa.gov/aboutgloss.shtml#t). Periods in which cloud clusters move over land are excluded from the study because the lightning flash rates increased an order of magnitude during those periods. 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 forty-eight cloud clusters during 2009 and forty-three cloud clusters during 2010 were tracked in the course of this study. Twenty of the 2009 clusters and twelve of the 2010 clusters developed into at least a tropical depression according to the NHC Best Track archives.

3. RESULTS

A 20-y climatology of the eastern North Pacific is reviewed in Lesley and Ritchie (2009). 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, which is not surprising considering the convective nature of TC genesis. The 2009 season was a relatively normal season with three tropical depressions and 17 named TCs developing through the season.

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. 4) coinciding with a developing strong El Niño. 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. 4) coinciding with a developing strong La Niña. Also coinciding with the lower 2010 SSTs are lower overall lightning flashes for the 2010 season (Fig. 4), CAPE values, low-level specific humidity, and higher vertical wind shear (not shown).

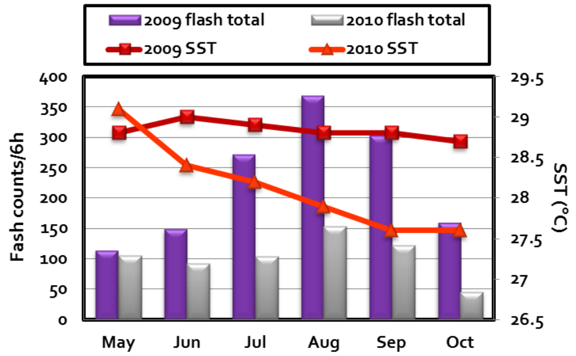

Figure 4: *Histogram of monthly flash counts per 6-hr period for the entire study region for 2009 (purple) and 2010 (grey). Time series of averaged SSTs in the main development regions for 2009 (red squares) and 2010 (red triangles).*

It is interesting to note that despite the overall lower activity in 2010 compared with 2009, the lightning flash rates per 6-hr period for the developing and non-developing cloud clusters are consistent across the two years (Fig. 5).

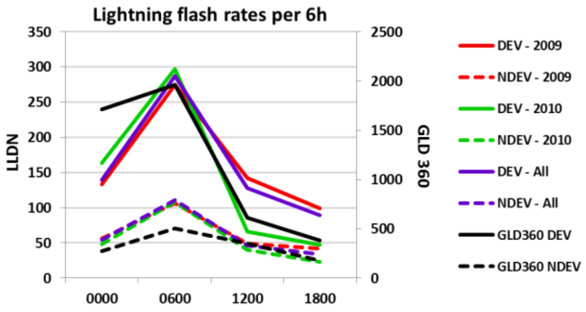

Figure 5: *Averaged lightning flash rates for each 6-hour synoptic period for developing (solid) and non-developing (dashed) cloud clusters using 2009 LLDN, 2010 LLDN, 2010 GLD360, and combined 2009&2010 LLDN data. .*

Note the close alignment of all the datasets in Fig. 5 regardless of year and source. GLD360 detects approximately 7 times the flashes of the LLDN, but captures the overall shape and ratio of developers to non-developers that the LLDN detects. Furthermore, the receiver operating characteristic (ROC) curves, which plot the probability of detection (POD) versus false-alarm rate (FAR) for various thresholds of lightning flash rates (Fig. 6, Leary and Ritchie 2009) also align closely. There is slightly higher predictability using the GLD360 dataset with various possible PODs to FARs highlighted in Fig. 6.

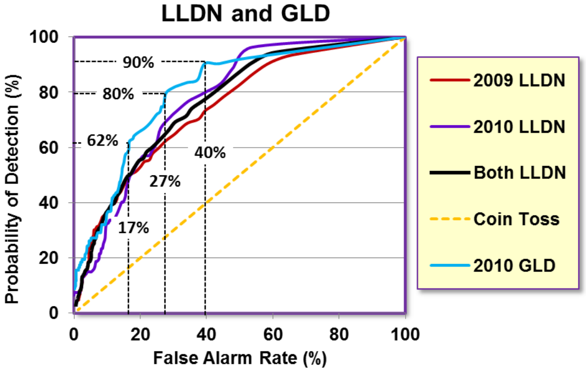

Figure 6: *Receiver Operating Characteristic Curve using 2009 LLDN, 2010 LLDN, 2010 GLD360, and combined 2009&2010 LLDN data.*

4. CONCLUSIONS

The results of Leary and Ritchie (2009) 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. Using the GLD360 and the LLDN to perform the exact same analysis for 2009 and 2010 we have confirmed that lightning flash rates are a way to differentiate developing cloud clusters. Furthermore, using these data an ROC curve was calculated, which could allow, for example, for a 80% detection rate with only a 27% 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.

Future work includes extending these results to other basins including the Atlantic and Gulf of Mexico, and testing a multi-parameter for genesis probability of development that includes the lightning flash rates.

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