Lightning Flash Rates as an Indicator of Tropical Cyclone Genesis in the Eastern North Pacific

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ABSTRACT

Lightning flashes in convective tropical clusters of the eastern North Pacific Ocean are detected by the Long-Range Lightning Detection Network and are analyzed for temporal patterns in electrical activity. The rates of lightning flash discharge in the 2006 season are analyzed for both tropical cyclones and nondeveloping cloud clusters to 1) determine if there is a difference in the convective activity of these two populations and 2) find a level of electrical activity that constitutes development in a particular system. Convective activity is associated with tropical cyclogenesis and thus we use the rate of electrical discharge as a proxy for convection associated with the likelihood of organization of individual cloud clusters into a tropical depression strength system. On the basis of the rates of lightning flashes in the cloud clusters, four levels of development are defined, ranging from non- and partially developing to fully developing cloud clusters. The levels of development are further supported by the analysis of other remotely sensed observations, such as surface scatterometer winds, that allow for the description of the mesoscale and large-scale circulation patterns in which the cloud clusters are embedded. It is found that lightning flash rates distinguish those cloud clusters that do not fully develop into tropical depressions from those that do. Receiver operating characteristic curves for these groupings are calculated, and a level of flash rate can be chosen that gives a probability of detection of 67% for a false-alarm rate of 24%.

1. Introduction

The physical processes that create a tropical cyclone have been studied for many years and from a variety of different standpoints, and yet they continue to be not fully understood. There is agreement that multiple processes contribute to transform a cold-core wavelike vortex into a warm-core vertically developed disturbance that is capable of drawing energy from the ocean’s surface. Furthermore, the necessary conditions for genesis to occur include a region of convective weather with upper-level divergence, lower-level convergence, low-level vorticity, and little vertical shear over the center of the disturbance (Gray 1968, 1980). Although these conditions are satisfied over long time scales in the tropical regions, potential disturbances rarely form into tropical cyclones.

A typical pretransition cyclone weather disturbance in the tropical Pacific Ocean is generally characterized

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whether there are significant differences in convective activity that can be used as an indicator of genesis.

The paper is organized as follows: Section 2 discusses the role of convection in genesis and why lightning is a good indicator of deep convective activity. The data and methodologies employed in the study are described in section 3. Results of the study are described in section 4, and an overall discussion and summary are provided in section 5.

2. Theory and background

a. The role of deep convection in genesis

Early theoretical studies (Riehl and Malkus 1958) suggest that cumulus convection is an integral part of organizing an ambient disturbance into a tropical depression (TD). Hot towers act as a vertical mode of transport for warm, moist surface air into the upper troposphere following the upward branch of the Hadley cell. Oceanic air is brought to the upper parts of the atmosphere without entrainment, in a large vertical circulation of tropical air. Corresponding convergence at the surface and divergence aloft helps to support the development of the critical secondary circulation.

Conceptual models of tropical cyclone formation revolve around the power contributed by cumulus convection. Conditional instability of the second kind (CISK) is based on the ability of a large-scale vortex and cumulus convection to combine and create a self-sustaining cycle of surface convergence leading to convection and latent heat release, which then amplifies the surface low, causing increased surface convergence (Ooyama 1964; Charney and Eliassen 1964). A more widely accepted theory holds that a wind-induced surface heat exchange (WISHE) explains the primary mode of tropical cyclone intensification by drawing heat from the ocean to aid in cumulus convection. The rapid transport of heat into the upper troposphere enhances the surface wind circulation and convergence into the system (Ooyama 1969; Rotunno and Emanuel 1987).

The most likely scenario for producing a hot tower is within an environment containing above-average amounts of cyclonic vorticity, so that mesoscale convective vortex can form. Many mesoscale convective systems and associated mesoscale convective vortices form throughout the tropics, and mesoscale convective vortices commonly contribute to the development of tropical cyclones (e.g., Harr et al. 1996; Ritchie and Holland 1997; Simpson et al. 1997). More recently, hot towers have been reexamined in numerical simulations. Hendricks et al. (2004) found that in a vorticity-rich environment, absolute vorticity \( \zeta_a \sim 10^{-4} \text{ s}^{-1} \), intense convection favors the formation of narrow plumes (approximately 10 km) of cyclonic vorticity. With the aid of warm, moist air from the ocean’s surface, buoyancy allows the plume to stretch and extend through the depth of the troposphere. These plumes act to produce intense mesoscale vortex tubes—vortical hot towers (Hendricks et al. 2004) that occur on the order of 10–30 km and have a lifetime of approximately one hour and occurring in groups in environmental conditions similar to those of pregensis tropical clusters.
Mergers of these convectively generated vortices and a trend toward axisymmetric orientation enhance the likelihood a particular disturbance will develop into a tropical cyclone-like vortex (Montgomery et al. 2001). In addition, the convective activity, whether pulsing or steady, acts to support the secondary circulation, which converges large-scale vorticity into both the existing mesoscale convective vortex and smaller-scale vortical hot towers (Montgomery et al. 2006; Tory et al. 2006).

If vortical hot towers form in the real atmosphere, they must be accompanied by deep, intense convection. Presumably, the greater the convective activity, the greater the likelihood of genesis from a particular cloud cluster will occur. Thus, convective activity is theorized to be an integral part of the genesis process. Here we explore whether an observational network capable of measuring the electrical activity within cloud clusters can be used to determine if there are differences in convective activity in cloud clusters that develop into tropical cyclones compared with those that do not.

b. Lightning as a proxy for convection

In general, cloud electrification occurs when a variety of precipitation particles are present within a cold (i.e., temperatures less than freezing) cloud. Supercooled droplets are critical components of cloud electrification. As more supercooled droplets freeze onto the graupel, it becomes heavy enough to fall back through the cloud and collide with lighter ice crystals.

During the processes, positive charge is transferred to the ice crystals, which are swept higher into the cloud in the updraft, leaving a negative charge on the graupel that is falling through the cloud. Thus, there is an accumulation of negative charge in the lower parts of the cloud where the heavier graupel resides and positive charge in the upper parts of the cloud, resulting in a separation of charge in the cloud. The highest electrification is located with the smallest ice crystals, in the lowest temperatures of the cloud (Takahashi 1978). When the separation of electric charge in the cloud is large enough, the necessary conditions are available for lightning to occur. For a cloud to contain an appreciable number of ice crystals, supercooled water drops, and graupel, there must be intense updrafts present, and by association, intense convection.

After an electrical discharge occurs, the charge centers in the cloud are reduced and the process repeats. The more intense the convective updrafts, the more rapidly charge separation can redevelop within the cloud, allowing multiple flashes to occur in rapid succession. When convection becomes organized enough for the updrafts to be uninterrupted by the downdrafts, a continuous repetition of charge separation and discharge will occur. Furthermore, the rate at which lightning discharges indicates the intensity of convective updrafts. Therefore, as long as lightning can be detected, it may be possible to use lightning as a proxy for deep convection.

Tropical oceanic convection often lacks the intense updrafts necessary for high lightning flash rates compared with continental mesoscale convective systems. However, satellite-based lightning studies (Orville and Henderson 1986) have shown that oceanic convection does produce lightning. Observations of lightning in tropical cyclones date back decades and have been reported in reviews of the topic and observational studies (e.g., Lyons and Keen 1994; Black and Hallett 1999; Black et al. 2003). Only deeply convective clouds have the necessary components (strong vertical updrafts and supercooled water) to separate charge within the cloud and produce an electrical discharge. It is also known that tropical cyclones have their beginnings in deeply convective cloud clusters. Lightning produced by deep convection can be an important feature that allows us to track and monitor the location and strength of the system as well as provide a means to distinguish which cloud clusters will undergo genesis and which ones will not. If deep convection is indeed one of the distinguishing features of the cloud clusters that develop compared to those that do not, then the amount of lightning that occurs within cloud clusters may allow us to distinguish developing from nondeveloping cloud clusters. Using data collected and processed by the Vaisala Long-Range Lightning Detection Network (LRLDN; Demetriades and Holle 2005), it may be possible to find a difference in the average lightning flash rates that occur in developing tropical convective systems as opposed to cloud clusters that never reach full development.

3. Data and methodology

a. The long-range lightning detection network

Vaisala owns and operates the U.S. 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 cloud-to-ground (CG) lightning flashes—approximately 10% of all flashes—that produce peak frequencies near 10 kHz and extend into the very low-frequency (VLF) band in the interval from 3 to 30 kHz. Because of 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 can be detected at long ranges. The LRLDN uses these VLF signals to sense lightning flashes up to thousands of kilometers away (Demetriades and Holle 2005).
The distance traveled by the VLF signal affects the type of signal that can be received by the land-based sensor because of 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 LRLDN is highest at night when the ionosphere is relatively “uncharged,” meaning there are fewer free electrons and ions in the atmosphere to attenuate the VLF signal during its propagation. The amplitude of the discharge is mainly affected, and thus this parameter will not be used in this study. 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% to 1%, with a few clusters propagating into very inefficient areas (Pessi et al. 2009). 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 nighttime efficiency is high enough to give us confidence in the raw flash counts. When corrected for detection efficiency, the overall results for the average nighttime flash rates do not differ from the raw data, and for this reason the raw data were used. The modeled location accuracy of the CG strikes decreases with distance from the coast, similar to the detection efficiency (Pessi et al. 2009).

b. Cluster tracking

The boundaries of this study contain the average genesis locations and directions of propagation of tropical cyclones in the eastern North Pacific basin between 0°–30°N and 80°W–130°W (Fig. 1). All clusters remaining convectively active for at least 72 h were considered. Two populations of cloud clusters during 2006 were tracked using Geostationary Operational Environmental Satellites-8 and -9 (GOES-8 and GOES-9) infrared imagery every 6 h from their first appearance as a convective cluster until dissipation. Following Maddox (1980) and Miller and Fritsch (1991) for mesoscale convective complexes, and to ensure that only deeply convective disturbances were analyzed, tracking began when minimum cloud-top temperatures were less than –55°C. Because of the diurnal nature of convection, there is often suppression of the cloud tops from midday to afternoon. For this reason, if a cluster had reached the cold threshold but then fell to warmer temperatures, it was included in the study, as long as the cloud-top temperatures returned to temperatures below the indicated threshold within 12 h.

The developing cloud-cluster category included all systems that were designated as tropical depressions (or greater) by the National Hurricane Center’s (NHC) best-track archives. For the purposes of this study, developing clusters were tracked until they reached tropical storm (TS) strength. Upon inspection, tropical systems that moved over land produced lightning flash rates that were orders of magnitude higher than those over water. Because of this drastic increase of flash rates over land, and the difference in external forcings on the system, any disturbance that spent time over land was excluded from the study. This criterion excluded several tropical cyclones that were recorded in the NHC’s best-track archive. The NHC considers a system to be a tropical depression when deep, organized convection is accompanied by a closed surface circulation with sustained winds less than 33 kt (1 kt = 0.5 m s⁻¹; available online at www.nhc.noaa.gov). A similar genesis classification was used by Ritchie and Holland (1999) when examining the 24 h prior to tropical cyclone formation alerts issued by the Joint Typhoon Warning Center to classify tropical cyclogenesis in the western North Pacific.

The nondeveloping category included all clusters that met the time requirement for convection, did not move over land, or did not fall to warmer cloud-top temperatures of –55°C for more than 12 h. In addition, clusters that were still active but propagated out of the boundaries (west of 130°W) and clusters that joined already existing disturbances were kept in the study if they did meet the 72-h time requirement.

Using McIDAS-X software, a center location was determined for each cluster at each period, and a latitude/longitude boundary that encompassed the convective regions of the cluster was recorded (Fig. 1). Next, CG lightning flash data from the LRLDN was filtered by location to identify any strokes associated with the particular system being tracked. Finally, after the lightning flashes associated with all clusters had been recorded, any differences between developing and nondeveloping cluster flash rates were determined.

4. Results

a. The eastern North Pacific basin in 2006

A 20-yr composite study shows that the eastern North Pacific basin is characterized by a warming of the near-coastal waters beginning in the month of May (Fig. 2). However, in the tropical cyclone genesis region, the low-level moisture in the atmosphere is still relatively low
As the season progresses into late summer and early autumn, the areal extent of sea surface temperatures (SSTs) exceeding the genesis threshold of 26.5°C (Gray 1980) shifts further northward (Fig. 2) and the low-level moisture increases. By mid-to-late autumn, threshold sea surface temperatures once again progress toward the equator and the areal extent of very warm water (>28°C) is significantly reduced, although the low-level moisture in the atmosphere still increases. In general, the genesis season can be described as having a peak in the period from June to September (Fig. 2), encompassing the months that have environmental conditions best suited for tropical cyclone formation. This peak is characterized by the movement of the warm SSTs to higher latitudes and an increase in low-level moisture. Prior to and following the peak season (May, October, and November), much of the eastern North Pacific basin still meets the requirements for genesis to occur and is still part of the tropical season—however, genesis is less likely to occur. For the 2006 season, the large-scale patterns were typical of the 20-yr mean (not shown) that has a warm pool of water located off the west coast of Central America in May but with a greater extent of threshold sea surface temperatures and low-level moisture developing through June to September that shifts latitudinally with the sun. A late-developing El Niño slightly enhanced the sea surface temperatures in the late season (October and November) of 2006.

The incidence of cloud clusters matched the 2006 trend of large-scale warm SSTs and enhanced moisture in the eastern North Pacific (Fig. 3). For this study, a total of 98 cloud clusters were tracked from May through November to match the tropical cyclone season in the eastern North Pacific. The monthly distribution of cloud clusters during this period is shown in Fig. 3. The population was approximately normally distributed, with a mean of 13.7 and a standard deviation of 4.6 (Fig. 3). The tails of the distribution (April and December) do not decrease to zero because in the eastern North Pacific, the intertropical convergence zone is present year-round and produces weak cloud clusters in all months. The peak of the 2006 cloud-cluster genesis occurred in August. However, July and September were also extremely active, with genesis falling off rapidly as the winter months approached.

Electrical activity over the entire region of study (0°–30°N and 80°–130°W) in 2006 was compiled (Fig. 4). The CG lightning counts (and hence, convective activity) also increased into the late summer, had a clear maximum in August, and dropped off rapidly in the late season. The overall trend of lightning counts in the region appeared to match the combination of seasonal movement of warm

![Fig. 2. The 20-yr mean SST composites by month in the eastern North Pacific. Isotherms 26.5°C and 28°C are highlighted. Panels are plotted using the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis plot page (available online at http://www.cdc.noaa.gov/cgi-bin/composites/comp.pl) using the National Oceanic and Atmospheric Administration (NOAA) optimum interpolation (OI) SST dataset.](image-url)
SSTs and low-level moisture in the region, as might be expected. The correlation between the monthly regional lightning counts and the number of cloud clusters is equal to 0.83, which indicates that there is a relationship between electrical activity and the presence of cloud clusters.

The number of cloud clusters that continued to develop into TDs according to the NHC by month in 2006 is shown in Fig. 5, together with the 20-yr mean TD genesis counts. The correlation between TDs and total cloud clusters in 2006 is slightly less (0.76) than that between the monthly regional lightning counts and the number of cloud clusters as is the correlation between TDs and regional lightning counts (0.7). This is because the development of cloud clusters into TDs is closely tied to the available ocean heat content, and this was marginal during May but increased during the mid-to-late summer and early autumn (e.g., Fig. 5), and then dropped off again by December. During 2006 the genesis counts were somewhat larger than the 20-yr mean (Fig. 5), particularly late in the season, and perhaps due to the gradual development of an El Niño in late autumn.

b. Lightning counts in cloud clusters

A total of 98 individual convective cloud clusters developed in the specified region in May–November of 2006. Of the 21 storms identified by the NHC, only 13 qualify as overwater clusters and reached TD status or greater and...
The distribution of flashes in both the developing and nondeveloping categories were lognormally distributed, with the daily average of CG flash counts in nondeveloping clusters approximately 140 flashes per 6 h lower than the developing clusters (Table 1). This is a statistically significant difference using a Student’s t test at the 5% level, and it clearly suggests that there is a good differentiation between the two populations and is a promising indicator that we may be able to set a threshold value to differentiate developing from nondeveloping cloud clusters. The largest separation was during the 0600–1200 UTC period, with developing storms averaging approximately 190 flashes more per 6 h (Fig. 6; Table 1). These larger counts during the evening to early morning are partly because of a tendency for more convective activity during the nighttime hours over the ocean. In addition, the increased detection efficiency of the LRLDN at long ranges during the night causes a bias in the detected flash counts at night compared with the daytime hours. Although smaller, the actual counts and differences in the daytime rates for developing and nondeveloping cloud clusters scale relative to the efficiency of the daytime detection. Clearly, an enhancement of the network to improve its overall detection efficiency will only increase the usefulness of the network to discriminate between developing and nondeveloping cloud clusters.

If it is possible to use the lightning signals to differentiate between these groups, then there is considerable potential for enhancing the forecasting of the genesis of tropical cyclones. To test the idea of a threshold value of lightning counts above which a cloud cluster will develop into a TD, the average 6-h flash count over the lifetime of each cloud cluster was calculated and plotted as a function of the time of day, and a receiver operating characteristic (ROC) curve was derived [see Marzban (2004) for background information]. Used as a method of signal detection, the ROC curve compares two datasets (sensitivity and specificity, where the sensitivity represents the proportion of positive cases correctly identified, or true positives, and the specificity represents the proportion of correctly identified negative cases, or true negatives) while applying a variable threshold of detection to each population. The variable threshold for detection allows different thresholds to be applied to the

<table>
<thead>
<tr>
<th>Time (UTC)</th>
<th>Time (LT)</th>
<th>NHC-designated developers</th>
<th>Nondevelopers</th>
</tr>
</thead>
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<tr>
<td>0000</td>
<td>1600</td>
<td>341</td>
<td>163</td>
</tr>
<tr>
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<td>229</td>
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</tr>
<tr>
<td>Avg per 6 h</td>
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<td>187</td>
</tr>
<tr>
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</tr>
<tr>
<td>Percent of total</td>
<td></td>
<td>13.3%</td>
<td>86.7%</td>
</tr>
</tbody>
</table>
same situation to analyze which level will provide the best
detection and the lowest false-alarm possibility. For our
purposes, a positive case will be a developing cloud
cluster and a negative case will be a nondeveloping cloud
cluster. The sensitivity in this study monitors the detec-
tion rate (DR) of positive cases and represents the per-
centage of developers out of all of the developers that had
flash counts higher than the threshold for comparison
during that period. The false-alarm rate (FAR) is found
by taking 1 minus the specificity (SPC) and accounts for
the percentage of nondevelopers (or negative cases) out
of the total of all nondevelopers that did not pass the
threshold for comparison at that period. The detection
rate and false-alarm rate are given by

\[
DR = \frac{TP}{TP + FN} \quad \text{and} \quad \text{FAR} = 1 - \frac{TN}{TN + FP} = 1 - SPC,
\]

where TN is the number of true negatives, or non-
developers with flash counts below the threshold; TP is
the number of true positives, or developers with flash
counts above the threshold; FP is the number of false
positives, or nondevelopers with flash counts above the
threshold; and FN is the number of false negatives.

Figure 7 shows the ROC curve plotted for the detec-
tion rate versus the false-alarm rate for the cloud-cluster
average CG flash counts. The dashed line is the “equal
chance” line. Because the ROC curve lies above the
equal chance line, our system has added predictability
compared with, for example, tossing a coin. We can slide
a vertical line along the x axis and choose a threshold
value that will give us a DR for a given FAR based on
the dataset. In Fig. 7, a threshold value of 210 flash
counts per 6 h over the life of the cluster gives a DR of
66.7% for a FAR of 26.7%; that is, we would expect that
if we used a threshold of 210 flash counts per 6-h period
over the life of the cluster (or up to TS designation for
NHC developers), then we would correctly predict a
cloud cluster to develop into a TD 66.7% of the time and
incorrectly predict a nondeveloping cloud cluster to
develop into a TD 26.7% of the time. If we wished to
have a higher DR, we could choose a lower threshold of
average flash counts but the FAR would also increase.

c. Four-category classification

During the analysis of nondeveloping cloud clusters
that exceeded the threshold value in the previous ex-
ample (i.e., were false positives), it became quickly ap-
parent that some disturbances were quite unlike the rest
of the population. Figure 8 shows a time series of 6-h
flash counts for all nondeveloping cloud clusters during
July 2006. There were two particular cloud clusters that
had one 6-h period during which flash counts exceeded
5000—more than any developing tropical cyclone dur-
ing that month—and overall average flash counts for
their duration of more than 450 flashes per 6 h, clearly
exceeding any threshold that could be reasonably set by
analysis of the ROC curve. These systems were tracked
throughout their lifetime using QuikSCAT imagery, an
ocean surface wind product from NASA, and evidence
was found in both cases for the existence of a near-
surface circulation that could support and enhance con-
vection in that region. In fact, for one cluster there was
evidence that the circulation reached tropical depression
strength for a period of \( \sim 5 \) days (Fig. 9). Therefore,
a careful analysis of all nondeveloping cloud clusters
was undertaken using Quick Scatterometer (QuikSCAT)
imagery and as a result, two additional categories were
defined. These were nondesignated developers (systems
that resemble a TD but were not designated as that by
the NHC) and partial developers, which were systems that developed circulation at the surface but either did not continue for more than 24 h or never developed into a clear closed tropical cyclone–scale circulation. The final four categories are defined next.

1) **NHC-DESIGNATED DEVELOPERS**

This category only includes tropical cyclones that have been designated as a TD or stronger by the NHC. By the NHC’s definition, a tropical depression is a closed surface circulation with sustained winds less than 33 kt. When examined further in infrared satellite imagery, multiple organized convective plumes with cloud-top temperatures lower than \(-55^\circ\)C could be identified. In addition, a well-defined (usually) rain-flagged surface circulation can be seen in the QuikSCAT observations. The pre-TD cloud cluster of the NHC-designated developer is tracked backward in infrared satellite imagery to its earliest beginnings over water. Thus, the total duration of the NHC-designated developer is determined by the length

![ROC curve for NHC-designated developers vs all other cases.](image1)

**Fig. 7.** ROC curve for NHC-designated developers vs all other cases. The dotted line represents an equal-chance line for the two categories. The gray dashed line represents the threshold for differentiation between these two groups, with 66.7% DR and a 26.7% FAR.

![Time series of all cases in July 2006.](image2)

**Fig. 8.** Time series of all cases in July 2006. Gray lines are nondevelopers and black lines are developers. The two peaks in the nondeveloping time series are the flash counts for the anomalous July cloud clusters discussed in section 4c.
of the convective activity that can be seen from the satellite, not according to the date of TD designation by NHC. Lightning counts for this category only include flashes in the system prior to TS designation because we are interested in the lightning signal during the genesis period only.

2) NONDEVELOPED CLOUD CLUSTERS

Nondeveloping clusters that exhibit the same characteristics as the NHC-designated developers for an extended period of time but are not recorded in the NHC best-track archive are placed into a nondesignated developer category. If a closed surface circulation with wind speeds exceeding 25 kt can be identified in the QuikSCAT imagery for a minimum of three days, then it is considered to be a physically developing system. An example of such a system is shown in Fig. 9. The cluster physically resembled an NHC-designated developer in the satellite imagery but was never recorded in the NHC best-track archives as a tropical depression. Notice that we are not attempting to replace the NHC best track. However, there are physical characteristics associated with these unnamed cloud clusters that closely resemble TDs. Thus, any tracking system based purely on physical observations such as lightning flashes (and by inference, convective activity) will not differentiate these systems from those identified as a TD by the NHC.

3) PARTIAL DEVELOPERS

Another group of clusters that has characteristics of the NHC-designated developer is the partial developer. These storms display either a loose circulation (Fig. 10a) or are imbedded in an open wave (Fig. 10b) that is not closed in the large-scale pattern. Partial developers may begin to rotate or have signs of development but do not persist as a closed surface circulation for more than a few hours. Although these clusters are considered physically to be nondeveloping, they have periods of large-scale, low-level circulation and surface wind speeds greater than 25 kt that can organize and enhance convection. Thus, they can contain periods with above-average flash counts per 6 h for multiple days scattered throughout their lifetime.

4) NONDEVELOPERS

The nondeveloping clusters are those cases that do not meet the criteria for any higher level of development. All of the nondevelopers lasted at least 72 h, unless they moved over land or joined a preexisting cluster. However, there was no evidence of a wave or other organizing circulation feature at the surface in QuikSCAT imagery (e.g., Fig. 11). Although there is not a minimum requirement for the area covered by a cluster, convection was only tracked if the cloud top remained at temperatures...
below the required $-55^\circ C$, indicating convection was occurring at a high enough rate to be considered in the study. The exception to this is in the case of convective suppression in the afternoon during the convective minimum, but the convection must resume within 12 h.

A separation into these four groups by month is shown in Fig. 12. On the basis of this classification scheme, a total of 17 cases were reclassified from nondeveloping to either nondesignated developers or partial developers and the flash counts for each category were recalculated (Table 2). Although the nondevelopers make up the majority of the cases—that is, 69.4% were categorized as a nondeveloping cloud cluster—this group only produced 36.5% of the electrical activity throughout the tropical season, and the average flash count was 140 per 6 h (Table 2)—the lowest flash counts in any 6-h period (Fig. 13a). Partial developers were 12.2% and NHC-designated developers made up 13.3% of the 2006 season, but the developers produced slightly more lightning strikes per season, that is, 28.9% as compared with the 21.9% for the partial developers. The developers also had a higher average per 6 h, with 329 flashes as compared with 250 for the partial developers (Table 2). The nondesignated developers were only 5.1% of the total population, but they produced 12.7% of the electrical activity at 369 flashes per 6 h, which is 40 flashes per hour more than the developing systems (Table 2).

A difference in geographical location could be seen when looking at the density tracks of the different categories (Fig. 14). The track densities are plotted by assigning a numerical value of one at the center location of the cloud cluster for that time and a radial dependence of $1/r$ away from the center to a value of zero at the edge, where $r$ is the radius of the extent of the $-55^\circ C$ cloud-top temperatures. For all times and all cloud clusters, the values calculated using this density function are accumulated in an array and displayed in Fig. 14 as an accumulated track. NHC-designated developers tended to propagate westward with a northwestward deviation along the coastline once development has occurred (Fig. 14a). The partial developers and the nondesignated developers tend to move directly to the west with very little meridional movement (Figs. 14b,c). They are generally located equatorward of the developing storms but are still well within the envelope of warm sea surface temperatures required for genesis to occur (e.g., Fig. 2). The nondesignated developers make up a small percentage...
of the total number of clusters and although there are not enough cases to make a generalization of this category’s track tendencies, there is a clear tendency for locations to be northward of the nondeveloping clusters and more similar to the NHC-designated developers (Fig. 14d).

The clusters were then regrouped into two new categories: developers, including both NHC-designated and nondesignated developers; and nondevelopers, including partial developers (the hardest to distinguish) and completely nondeveloping cloud clusters (the majority of the cases) (Fig. 13b). The NHC-designated developers and the nondesignated developers are both considered physically developing systems and are grouped together for comparison to the physically nondeveloping group, which contains the partial and nondeveloping categories. When comparing the physically developing group to the physically nondeveloping group, a statistically significant difference using a Student’s $t$ test was also found at the 5% level, and it further suggests that there is a good differentiation between the two populations. With this new classification of convective clusters, the ROC analysis is performed and compared with the original curve. Figure 15 shows a comparison of the new curve with the original ROC curve in Fig. 7. There is some improvement in the predictability with the new classification scheme. For the same threshold value of 210 flash counts per 6 h, a 3% decrease in the false-alarm rate is achieved while maintaining the same detection rate of 66.7%. Alternatively, for a FAR of 36%, the old ROC curve predicted a DR of 66.7% (threshold 125) and the new curve has a DR of 83.3% (threshold 110; black dashed line in Fig. 15). Thus, the new ROC curve is noticeably improved from the initial classification, implying an improved probability of forecasting cases of genesis through lightning flash detection.

5. Summary and conclusions

Cloud clusters in the eastern North Pacific were identified and tracked in infrared satellite imagery during May–November 2006 and categorized according to whether they developed into tropical cyclones or dissipated. LRLDN lightning flashes were then filtered for each cloud cluster and analyzed for electrical activity. The underlying assumption was that a higher flash count corresponds to greater convective activity within the

<table>
<thead>
<tr>
<th>Time (UTC)</th>
<th>Time (LT)</th>
<th>NHC-designated developers</th>
<th>Nondevelopers</th>
<th>Partial developers</th>
<th>Nondesignated developers</th>
<th>All cases</th>
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</thead>
<tbody>
<tr>
<td>0000</td>
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<td>341</td>
<td>133</td>
<td>201</td>
<td>279</td>
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<td>2200</td>
<td>522</td>
<td>237</td>
<td>438</td>
<td>755</td>
<td>379</td>
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<td>0400</td>
<td>223</td>
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<td>200</td>
<td>278</td>
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<tr>
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<td>1000</td>
<td>229</td>
<td>89</td>
<td>155</td>
<td>147</td>
<td>132</td>
</tr>
<tr>
<td>Avg per 6 h</td>
<td></td>
<td>329</td>
<td>140</td>
<td>250</td>
<td>369</td>
<td>218</td>
</tr>
<tr>
<td>No. of clusters</td>
<td></td>
<td>13</td>
<td>68</td>
<td>12</td>
<td>5</td>
<td>98</td>
</tr>
<tr>
<td>Percent of total</td>
<td></td>
<td>13.3%</td>
<td>69.4%</td>
<td>12.2%</td>
<td>5.1%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

Fig. 12. Histogram of the number of clusters in each group from the four-category classification per month.
cloud cluster and a higher likelihood of development into a tropical cyclone. The lightning discharge rates were analyzed to determine not only whether there was a difference in the convective activity of cloud clusters that develop into tropical cyclones when compared with those that do not but also to determine whether there was a threshold of electrical activity that could be used to predict the development of a particular system.

Initially, the average flash counts per 6 h for the 98 clusters were separated into two groups: NHC-designated developers and all other storms. There was clear differentiation between the two populations, with developers having an average 142 more flashes per 6 h than nondeveloping clusters. The highest flash counts were detected during the late afternoon through the nighttime hours, partly because of a tendency for oceanic

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**FIG. 13.** (a) Four-category classification of the 2006 season and the (b) gray dashed-line groups (nondevelopers and partial developers) and black dashed-line groups (NHC-designated developers and nondesignated developers).

**FIG. 14.** Density plots of the 6-h positions for all cloud clusters during the 2006 season divided into the four-category classification.
convection to occur at night and partly because of an increased efficiency in the lightning detection system during the nighttime hours. To determine the most favorable threshold to distinguish between developing and nondeveloping clusters, a ROC curve of the average 6-h flash counts for all cloud clusters was plotted, with developers designated as positive cases and nondevelopers as negative cases. The ROC curve clearly showed that a threshold value of average flash counts provided improved predictability over equal chance. However, further investigation of individual nondeveloping cloud clusters that failed the threshold test suggested that there were levels of development of individual clouds clusters that were not appropriately identified with the original two-category classification scheme. Using QuikSCAT imagery, all the original nondeveloping cloud clusters were reclassified based on convective activity and low-level circulation characteristics.

The new four-category classification included 1) NHC-designated developers (13.3%); 2) nondesignated developers, which developed persistent low-level circulation and high levels of convective activity (5.1%); 3) partial developers, which contained brief periods of weak circulation or open wave low-level wind field patterns (12.2%); and 4) nondevelopers, which exhibited no low-level open wave features in the wind field but persisted in satellite imagery for 72 h or more (69.4%).

Although it is not clear why the nondesignated category were not labeled as TDs in the best-track database, in terms of electrical activity they were indistinguishable from NHC-designated developers. For the purposes of determining genesis, the threshold of electrical activity would be most useful if it could differentiate between the partial and nondeveloping cloud clusters and the first two categories. An ROC curve was plotted and an improvement in detectability over the original two-class system was found. Using a threshold that provides the same 66.7% detection rate in the initial classification, the false-alarm rate was reduced by 3% by including the nondesignated developers in with the developers for analysis. Alternatively, a detection rate of 83% could be achieved with a false-alarm rate of 36% with the new classification scheme.

Although these results were extremely encouraging, the thresholds apply more appropriately to the peak season of June–September when 68% of the total cases examined formed. The number of cloud clusters in the months of May, October, and November were too low to allow representative sampling of all four classifications of cloud clusters. Thus, future work includes expanding the training set to include 2004, 2005, and 2007 because the LRLDN data extend back only to 2004. In this way, a more representative sample from all months of the tropical cyclone season for the eastern North Pacific may be obtained. In addition, we would like to use 2008 LRLDN data to test a prediction scheme that assigns a threshold of development based on the number of flashes per 6 h. This is not a true prediction system because it will
not be possible to know a priori the average flash counts over the life of a cloud cluster that is currently in existence. To develop a true prediction system, the data will be examined to determine whether there are time-dependent patterns in the 6-h counts that discriminate the four categories of development.

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