Tropical Cyclogenesis Detection in the North Pacific Using the Deviation Angle Variance Technique

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ABSTRACT

The deviation angle variance technique (DAV-T) for genesis detection is applied in the western and eastern North Pacific basins. The DAV-T quantifies the axisymmetric organization of cloud clusters using infrared brightness temperature. Since axisymmetry is typically correlated with intensity, the technique can be used to identify relatively high levels of organization at early stages of storm life cycles associated with tropical cyclogenesis. In addition, the technique can be used to automatically track cloud clusters that exhibit signs of organization. In the western North Pacific, automated tracking results for the 2009–11 typhoon seasons show that for a false alarm rate of 25.6%, 96.8% of developing tropical cyclones are detected with a median time of 18.5 h before the cluster reaches an intensity of 30 knots (kt; 1 kt = 0.51 m s⁻¹) in the Joint Typhoon Warning Center best track at a DAV threshold of 1750°C. In the eastern North Pacific, for a false alarm rate of 38.0%, the system detects 92.9% of developing tropical cyclones with a median time of 1.25 h before the cluster reaches an intensity of 30 kt in the National Hurricane Center best track during the 2009–11 hurricane seasons at a DAV threshold of 1650°C. A significant decrease in tracked nondeveloping clusters occurs when a second organization threshold is introduced, particularly in the western North Pacific.

1. Introduction

The North Pacific Ocean is a vast basin that features numerous tropical cyclogenesis events each year. The western North Pacific produces the most tropical cyclones (TCs) of all tropical basins (Ritchie and Holland 1999), and the eastern North Pacific has the greatest density of cyclogenesis in time and space (Molinari et al. 2000). However, the North Pacific is dominated by wide expanses of open ocean with few in situ observations. As opposed to the North Atlantic, aircraft reconnaissance is performed infrequently on both sides of this ocean basin. Satellites thus provide the only reliable source of observations at high temporal resolution with wide spatial coverage. Cloud clusters identified in these satellite images are monitored by operational centers for potential development, but subjective tracking of all observed cloud clusters presents a significant cost in man hours. As a result, an automated system that detects cloud clusters in these images given objective criteria and rejects those clusters that would not develop could provide an important tool to forecasters.

Techniques have been recently developed that apply statistical procedures to detect and predict the formation of TCs. Some of these techniques divide the analysis into a spatial grid and search for favorable environmental conditions that are known to trigger cyclogenesis. For example, Schumacher et al. (2009) describe a methodology that includes several environmental and convective parameters. Their technique applies linear discriminant analysis to determine the largest contributing parameters to TC formation, and the cyclogenesis probability is calculated from these results. Chand and Walsh (2011) use environmental variables and climatology and persistence statistical models (CLIPER), and they apply a Bayesian approach to predict tropical cyclogenesis in the Fiji region.
Other techniques differentiate environmental characteristics between developing and nondeveloping tropical cloud clusters using analysis fields, an approach that requires tracking numerous cloud clusters (e.g., Perrone and Lowe 1986). More recently, Hennon and Hobgood (2003) examined 3 yr of satellite-based cloud cluster data in the North Atlantic in conjunction with reanalysis data to identify large-scale predictors that could be incorporated into probabilistic genesis forecasts. Similarly, Kerns and Chen (2013) classified the environments associated with developing and nondeveloping cloud clusters in the western North Atlantic using global model analysis output. These and other forecasting methods are often based on environmental variables, numerical weather products, and statistical analysis. Elsberry et al. (2007) discussed the performance of some of these models, though their assessment of genesis forecasting was restricted to North Atlantic tropical depressions. They found that CLIPER, as well as the statistical–dynamical techniques, provided some information regarding the timing of development, but the technique also intensified all tropical depressions, producing false alarms. The dynamical models did not forecast all depressions and often delayed development compared to reality. Elsberry et al. (2007) concluded that further research is needed to improve the robustness of the genesis guidance provided to the National Hurricane Center (NHC).

An application of the deviation angle variance technique (DAV-T) to detect the formation of TCs in the North Atlantic basin was described in Piñeros et al. (2010). This technique quantifies the axisymmetry of cloud clusters in infrared (IR) satellite imagery by performing a statistical analysis of the direction of the gradient of the IR brightness temperatures. The brightness temperature gradient vectors are more aligned along radials pointing directly into or out from the center of a well-organized, developing cloud cluster compared with a weaker, more diffuse system. This alignment occurs because the developing cloud cluster is associated with an intensifying and increasingly well-organized vortical wind field that is developing through the depth of the troposphere. This cloud organization, which is well correlated to the deep tropospheric wind field organization, can be quantified by calculating the variance of the angular difference between the gradient vectors and the radials extending from a center point in the cloud cluster to each pixel in the scene. This technique captured 93% of TCs that developed in the North Atlantic during 2004 and 2005 with a false alarm rate of 22% and a lead time of 0.6 h before tropical depression (TD) designation by the NHC (Piñeros et al. 2010). Given the relative dearth of in situ observations in the North Pacific, it is worthwhile to investigate the potential of the DAV-T to distinguish between developing and nondeveloping cloud clusters using satellite data with high temporal resolution.

In this paper, the DAV-T is applied to the western and eastern North Pacific basins to detect cyclogenesis. Differences exist between these basins and the North Atlantic, and the methodology must be adapted accordingly. First, the eastern North Pacific requires a combination of Geostationary Operational Environmental Satellite–West (GOES-West) and Geostationary Operational Environmental Satellite–East (GOES-East) imagery in order to obtain complete coverage of the genesis region for continuous tracking of cloud clusters. The western North Pacific requires the use of the Japanese Multifunctional Transport Satellite (MTSAT) dataset, which is available at hourly resolution rather than the half-hour availability of GOES. Second, the tropical environment of the western North Pacific produces a wide range of TC sizes and structures, ranging from “midget” storms to vast monsoon depressions. Though the range is not as extreme as in the western North Pacific, varied TC structures, particularly small TCs with tight cloud fields, can develop in the eastern North Pacific as well. Finally, the North Pacific basin lacks the aircraft reconnaissance program found in the North Atlantic; thus, the best-track dataset used to compare the results of the DAV-T in the North Pacific may not be as robust.

The data and methodology used in each basin, including a recently developed automated tracking system described in Rodriguez-Herrera et al. (2015), are summarized in the next section. Section 3 describes the results on cyclogenesis detection for both basins and examines the utility of the automated system for comparing cloud cluster activity in different years. Finally, section 4 presents some conclusions and discusses future development work.

2. Data and methods
a. Satellite data

The data for the western North Pacific portion of this study are derived from MTSAT longwave (10.7 μm) IR imagery. The images used in the study are resampled to a spatial resolution of 10 km per pixel and encompass an area from 0° to 40°N and from 100°E to 180° (Fig. 1a). Similar to previous versions of the technique, those portions of the images over land are not analyzed in this part of the study because the presence of land may affect the structures identified by the DAV-T (e.g., the land mask shown in Fig. 1b).

In the eastern North Pacific, IR imagery is obtained from GOES-West and GOES-East in order to provide complete coverage of the basin. Data from both sources are blended to produce a composite image following the
methodology described in Ritchie et al. (2014). These images are also resampled to a spatial resolution of 10 km per pixel and encompass an area from 0° to 30°N and from 140° to 79°W (Fig. 1c), as no recorded eastern North Pacific TC has formed farther east than 86.5°W (Blake and Pasch 2010). In contrast to the western North Pacific, where precursor cloud clusters largely develop over open ocean, many incipient disturbances in the eastern North Pacific develop over land or along the coastline. A reduced land mask (e.g., see Fig. 8) is applied to the blended GOES imagery to ensure that these clusters can also be captured.

b. DAV maps

Following the genesis detection methodology documented in Piñeros et al. (2008, 2010), maps of the DAV are calculated from each original IR image by using each pixel in turn as the reference center for the DAV calculation and then mapping the computed DAV value back to that pixel (e.g., Figs. 1b,d). The DAV value at each pixel is found using a radius of 350 km. To ensure that the DAV values are associated with cloudy regions, the average brightness temperature within a 250-km radius of the pixel is required to meet a threshold criterion of 145 (−15.5°C) using 8-bit brightness temperature values. Because of the smaller size of TCs in the eastern North Pacific (e.g., Knaff et al. 2014), a 200-km radius and a threshold criterion of 150 (−18°C) is used. This reduces the number of false alarms by eliminating regions of warm temperature in the IR image, such as low clouds or ocean values, which can still be detected as very axisymmetric by the objective DAV-T (e.g., Figs. 1b,d).

c. Tracking cloud cluster activity

In this study, a manual approach was initially applied for cloud clusters in the western North Pacific during 2009 and 2010. However, the amount of time required to add clusters from 2011 and repeat this procedure in the eastern North Pacific proved prohibitive, and an objective tracking approach is applied to both basins instead. The use of objective tracking is similar to studies that explore characteristics associated with developing and nondeveloping cloud clusters (e.g., Perrone and Lowe 1986; Hennon and Hobgood 2003; Kerns and Chen 2013).

Available satellite images and their associated DAV maps (e.g., Fig. 1) during the 2009–11 TC seasons are provided to an automated tracking system (Rodríguez-Herrera et al. 2015). These years include a strong El Niño event (2009) and a strong La Niña event (2010). Once a cloud cluster is detected in the automatic tracking system and meets the given DAV value and brightness temperature, future detections must occur within a certain amount of time and within a predefined radius from that detection in order to be associated with the same cluster. A time frame of 24 h and a radius of 500 km are used for the purposes of tracking in the western North Pacific, while this radius is reduced to 350 km in the eastern North Pacific because the cloud clusters and TCs that subsequently develop tend to be...
smaller in this basin (Knaff et al. 2014). A given cloud cluster is no longer tracked if its minimum DAV value within the predefined radius goes above the critical threshold of 2000$^2$ and remains above that value for longer than 24 h or if the average brightness temperature falls below the brightness temperature threshold value.

d. Cyclogenesis detection

Previous work using manual tracking in the North Atlantic (e.g., Piñeros et al. 2010) established that two seasons' worth of data, which included 36 TCs and 136 nondeveloping cloud clusters, were satisfactory to develop DAV-T statistics that differentiate developing from nondeveloping cloud clusters. As this study uses an automatic tracking system, the 2009–11 seasons are explored in both basins. In the western North Pacific, available satellite data include 61 TCs (30 typhoons, 18 tropical storms, and 13 tropical depressions) as well as 1814 nondeveloping cloud clusters, reflecting the cloudier environment of this basin. In the eastern North Pacific, available satellite data include 42 TCs (20 hurricanes, 14 tropical storms, and 8 tropical depressions) and 404 nondeveloping cloud clusters.

Furthermore, typical values of the DAV in the North Atlantic range between 3000$^2$ for extremely disorganized cloud clusters and 600$^2$ for the most intense TCs (Ritchie et al. 2012). Piñeros et al. (2010) determined that, for the purposes of calculating the probability of detecting a developing cloud cluster using a receiver operating characteristic (ROC) curve (Marzban 2004), the DAV saturates at a value of approximately 2000$^2$. Thus, for the purposes of detecting the early stages of a developing cloud cluster in this study, a set of threshold DAV values from 1350$^2$ to 2000$^2$ (in steps of 50$^2$), which reflects the range of threshold values used for the North Atlantic (Piñeros et al. 2010), is applied to characterize the performance of the cyclogenesis detection in both basins. Ideal values on an ROC curve have high true positive rates (TPRs), or probabilities of detection, and low false positive rates (FPRs), or false alarm rates. An additional metric, the Heidke skill score (HSS), is also used to evaluate the performance of each DAV threshold value (e.g., Wilks 2006; Hennon and Hobgood 2003). Values of HSS are positive for forecasts that are better than chance, zero for forecasts equal to chance, and negative for forecasts worse than chance. Previous studies have shown that HSS values of at least 0.4 demonstrate significant skill (e.g., Kerns and Chen 2013).

Tracked clusters are designated as “of interest” if their minimum DAV value falls below the critical DAV threshold for 24 h, which is 2000$^2$ in this study (hereafter referred to as DAV$_{2000}$). These systems are then followed through time, and those that are eventually designated as TCs by JTWC or NHC are categorized as correct detections while those that dissipate without undergoing cyclogenesis are categorized as false alarms. The probabilities of correct detection and false alarms are computed by applying, in turn, each of the threshold DAV values from 1350$^2$ to 2000$^2$. This procedure produces a set of points that can be plotted on an ROC curve or evaluated using the HSS and analyzed for statistical significance.

Using a given DAV threshold value, the time of detection for each developing cloud cluster that is correctly determined by the DAV-T is stored as an additional metric and compared to the time of genesis in the JTWC or NHC best-track archive. For the purposes of this study, the time of genesis is defined as the first instance of an intensity of 30 knots (kt; 1 kt $= 0.51$ m s$^{-1}$) in the best track. Cases with missing satellite imagery leading up to this time are not included in the calculation of the detection statistics. Negative detection time values indicate that, for a particular DAV threshold value, the DAV-T flagged the storm prior to the first 30-kt time in the best track. It should be noted that the first time of 30-kt winds in the best track can be $\pm 12$ h compared to the operational working best track. As discussed later, the use of high DAV thresholds produces high false alarm rates but also early detection times. In contrast, low threshold values reduce the number of false alarms but also delay the detection time.

3. Cyclogenesis detection results

a. Western North Pacific

Figure 2a illustrates that, for high threshold values of the DAV-T (e.g., $\geq 1850^2$), all western North Pacific TCs are correctly detected. However, the false alarm rate is also very high ($\geq 47\%$) because cloud clusters detected at high DAV values are extremely disorganized, and a large percentage of them do not go on to develop into TCs. Decreasing the threshold value to 1750$^2$ removes one positive detection but also reduces the false alarm rate to 25.6%.

There are two main reasons why the number of false alarms decreases by reducing the DAV threshold. The first is that the cloud must reach a much higher level of axisymmetry to achieve lower DAV values. Fewer nondeveloping cloud clusters reach this level of organization in the western North Pacific; thus, lower values of DAV correlate with a much higher probability that the system is truly a developing cloud cluster. The second reason is that short-lived cloud clusters that were included in the nondeveloping cloud cluster population but that would have been rapidly eliminated...
by a subjective assessment achieve high DAV values but do not achieve the lower threshold values. The addition of a 48-h existence threshold will help to reduce the number of false alarms at higher DAV threshold values and improve the overall performance of the genesis detector.

Overall, the ROC curve for the western North Pacific using DAV\textsubscript{2000} to classify cloud clusters of interest (Fig. 2a) has a similar probability of genesis detection and a slightly lower false alarm rate than the North Atlantic for the same DAV threshold value [Piñeros et al. (2010), their Fig. 5]. However, this may be a function of a greater number of nondeveloping cloud clusters within the monsoon environment of the western North Pacific being classified as of interest by the DAV-T yet correctly categorized as nondeveloping systems, as more true negative cases decrease the false positive rate associated with the ROC curve.

The DAV-T produces the best HSS value at 1350°\textsuperscript{2} (0.59) and decreases with increasing DAV thresholds (Fig. 2b). This is an expected result in part because lower DAV values reflect more organized cloud clusters, and thus the likelihood of the cluster developing or having already developed is much greater at these lower thresholds. A score of 0.156 is achieved for the 1750°\textsuperscript{2} threshold, which detects all but one developing TC.

As stated earlier, higher DAV thresholds increase the false alarm rate but also increase the lead time of detection relative to 30 kt. Figure 3 provides the mean and median detection times at each threshold. Developing TCs are detected at a mean (median) time of 32.0 h (18.5 h) before the TC first intensifies to 30 kt in the JTWC best track at 1750°\textsuperscript{2}. The spread in these detection times is shown in Fig. 4. Most developing cloud clusters are detected by the automated system between 40 h before and 20 h after an intensity of 30 kt is reached, with some extreme cases at the tail ends of the distribution.

The best western North Pacific case shown in Fig. 4 is Typhoon Chaba (2010), which is detected about 6 days before it reaches an intensity of 30 kt (Figs. 5a,b). Of note is the fact that Chaba was tracked as a weak system for nearly 4 days in the JTWC best-track dataset, fluctuating between 20 and 25 kt during this time. However, the automatic tracking system did detect Chaba more than 2 days prior to its first entry in the JTWC best-track archive.

The worst case shown in Fig. 4 is Tropical Storm Malou (2010), which was not detected until 1.5 days after it first reached an intensity of 30 kt (Figs. 5c,d). Largely disorganized convection is observed near the center of Malou’s broad, asymmetric circulation at the 30-kt time (Fig. 5c), and such complex structures are known to negatively affect DAV estimates in this basin.
As that study found that calculating the DAV from two different radii added skill to the intensity estimates, future work will examine the utility of a similar approach for detecting developing cloud clusters.

While these results are promising, the use of a single DAV value (DAV$_{2000}$) to classify positive detections also produces far too many nondeveloping cloud clusters. To reduce the number of these clusters, a second threshold is added. This threshold is chosen to be 1750$^\circ$C (hereafter DAV$_{1750}$) because of its performance, as discussed above. The number of nondeveloping clusters in the dataset subsequently decreases from 1814 to 128; though two developing clusters are missed as a result. Also, the use of two thresholds significantly alters the ROC curve in the western North Pacific (Fig. 2a), as false alarm rates increase greatly for similar true positive rates. This occurs because of the reduction in total detections and thus the number of true negatives at each threshold, as the FPR is calculated based on the number of false positive and true negative cases.

This additional threshold depresses the HSS compared to DAV$_{2000}$, and the HSS subsequently drops to 0 at 1750$^\circ$C (Fig. 2b). The highest score remains at 1350$^\circ$C (0.49), which, for intensity estimation, represents TCs stronger than 64 kt in both the western and eastern North Pacific (Ritchie et al. 2014). As a result, it stands to reason that such a low threshold would show much higher skill. However, the mean (median) time of detection for such a low threshold is 12 h (17 h) after the
TC first reached 30 kt, which reduces its utility for operational use. A compromise among TPR, FPR, time of detection, and skill is needed.

Mean and median detection times for developing cloud clusters at DAV1750 are very similar to the results from DAV2000 (not shown), though this is only true up to 1750^2, as clusters that do not reach this second threshold are excluded from consideration. Given the marked reduction in the volume of nondeveloping clusters while maintaining similar positive detection rates, the use of two DAV thresholds with the automated tracking system shows potential for future research and operational applications.

b. Eastern North Pacific

Figure 2a also shows the ROC curve for the eastern North Pacific using the automated tracking system and DAV2000. Once a threshold value of 1900^2 or greater is reached, all 42 developing systems are detected. In contrast to the western North Pacific, a threshold of 1750^2 produces a much higher false alarm rate, implying that many nondeveloping cloud clusters in the eastern North Pacific exhibit remarkably high levels of axisymmetric organization. Nondeveloping tropical waves, mesoscale convective systems that form during the North American monsoon season, and non-developing disturbances that result from the breakdown of the intertropical convergence zone may contribute to these false alarm rates (e.g., Ferreira and Schubert 1997; Molinari et al. 2000; Serra and Houze 2002; Seastrand et al. 2014). In addition, Hennon et al. (2013) noted that the eastern North Pacific boasted the highest number of tropical cloud clusters per unit area, which implies that more clusters can be identified by the DAV in this basin. Despite these larger false alarm rates, the HSS metric produces only slightly lower values for DAV2000 in the eastern North Pacific compared to the western North Pacific (Fig. 2b).

A similar false alarm rate to that found at 1750^2 in the western North Pacific is achieved at a threshold of 1550^2 in the eastern North Pacific for a true positive rate of 92.9%. However, the median detection time at this threshold is 4.5 h after the TC reached 30 kt (Fig. 3). Detection times very close to the official first instance of 30 kt winds are not surprising for such a low threshold value, as they again reflect the level of organization already achieved by the cloud cluster. Improved detection times (mean of 10.6 h and median of 1.3 h before the first 30-kt record) are found at a threshold of 1650^2, though the false alarm rate increases to 38%. The HSS for this threshold is 0.21, approximately double the score for 1750^2 (0.10). The 1650^2 threshold thus represents a compromise between FPR, TPR, time of detection, and skill.

For comparison with the western North Pacific, detection times for the eastern North Pacific are shown in Fig. 4 for DAV1750. Many more detections occur at times near the first instance of 30 kt compared to the western North Pacific, though some cases are detected well before they reach this intensity. The longest lead time occurs for Tropical Storm Estelle (2010), as convection associated with the precursor tropical wave was detected 3.5 days before the developing cloud cluster reached an intensity of 30 kt (Figs. 6a,b). The worst case is Hurricane Hilary (2011), first detected over 1 day after it reached an intensity of 30 kt (Figs. 6c,d), largely because of the asymmetric presentation of the convection associated with Hilary when the TC first reached 30 kt.

c. Interannual variability

The automated tracking system also allows for assessments of interannual cloud cluster variability. Figures 7 and 8 show the yearly activity of developing cloud clusters in each basin over a 4-yr period from 2009 to 2012. These density plots are created from positions generated by the automated tracking system. The system continues to track cloud clusters and tropical cyclones throughout their lifetimes following the methodology of Leary and Ritchie (2009). As the 2009 season was associated with a strong El Niño event and the 2010 season with a strong La Niña event, two relatively neutral years (2011 and 2012) are included for comparison. The core region of activity varies little from year to year in the western North Pacific (Fig. 7), as the maximum is located near the eastern coast of the Philippines in all four years. The observed level of activity elsewhere in the basin fluctuates greatly with a peak in 2010 in the South China Sea and more extensive activity well east of the Philippines in 2012. The 2009 season also exhibits a wider longitudinal extent of activity, albeit with fewer clusters than in 2012.

In the eastern North Pacific, the extent of developing cloud cluster activity is somewhat more variable with a greater spread across the basin in 2009 and 2011 compared with 2010 and 2012 (Fig. 8). Overall, developing cloud clusters remain north of 5°N and are most frequent near the Mexican coastline. The broad swath of cluster tracks across much of the basin in 2009 is likely related to the above-average sea surface temperatures associated with an El Niño event that year, and the far more confined activity in 2010 is likely related to that year’s La Niña. The effects of ENSO may be more pronounced in the eastern North Pacific than the western North Pacific as a result of the basin’s proximity to the peak warming or cooling SSTs associated with the oscillation.
4. Conclusions

In this paper, the objective DAV-T that was developed for the North Atlantic basin to detect tropical cyclogenesis from IR imagery (Piñeros et al. 2010) is applied to the western and eastern North Pacific basins. The main difference in the technique as applied to the western North Pacific is the use of hourly MTSAT data instead of the GOES-East imagery that is used in the North Atlantic basin. In addition, the DAV technique is applied to a slightly larger region, encompassing 0°–40°N and 100°E–180°. Further changes are made to the application of the technique in the eastern North Pacific by using half-hourly blended GOES-East and GOES-West imagery. Unlike the North Atlantic study, an automated tracking system (Rodríguez-Herrera et al. 2015) is used to detect cloud clusters in both basins.

In the western North Pacific, the DAV-T shows skill in detecting pregenesis cloud clusters. For DAV2000 during the 2009–11 seasons, a positive detection rate of about 97% can be achieved with a false alarm rate of about 26% at 1750°C. These statistics are similar to those achieved in the North Atlantic basin using manual tracking (Piñeros et al. 2010). In addition, the system detects TCs at a mean (median) time of 32.0 h (18.5 h) before the first 30-kt record in the JTWC best-track archive.

The large number of nondevelopers in the western North Pacific is significantly reduced by adding 1750°C as a second DAV threshold (DAV1750). This indicates that

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Fig. 6. Infrared blended GOES-East and GOES-West images (8-bit brightness temperature) of Tropical Storm Estelle (2010) for (a) NHC best-track 30-kt time of 0000 UTC 6 Aug and (b) 3.5 days earlier at DAV-T time of detection of 0900 UTC 2 Aug. Infrared GOES-East and GOES-West images of Hurricane Hilary (2011) for (c) NHC best-track 30-kt time of 0600 UTC 21 Sep and (d) 1 day later at DAV-T time of detection of 0900 UTC 22 Sep. These detections occur at the 1750°C threshold.
developing clusters exhibit increasing levels of axisymmetric organization compared to those clusters that do not. However, this second threshold also significantly increases the false alarm rate. The time at which a developing cluster is detected in the automated tracking system is largely unaffected by the use of $DAV^{1750}$.

Results in the eastern North Pacific for $DAV_{2000}$ show similar detection rates but larger false alarm rates, in part because there are fewer nondeveloping cases at this same threshold in this basin. A 92.9% detection rate is found for a false alarm rate of 25.9% at a $DAV$ value of 1550, but the corresponding median detection time is 4.5 h after the TC.

![Density plots of automated tracked clusters that developed in the western North Pacific during (a) 2009, (b) 2010, (c) 2011, and (d) 2012. Black dots indicate the location at which a developing cloud cluster reached 30 kt in the JTWC best-track archive.](image1)

![Density plots of automated tracked clusters that developed in the eastern North Pacific during (a) 2009, (b) 2010, (c) 2011, and (d) 2012. Black dots indicate the location at which a developing cloud cluster reached 30 kt in the NHC best-track archive. The thick black line indicates the reduced land mask used in this study.](image2)
first reaches 30 kt. The 1750\textsuperscript{2} threshold has a mean detection time of about 17.3 h and a median of 7 h before the first 30-kt record in the NHC best-track archive, and less spread is found in the detection times at this threshold compared with the western North Pacific. However, the false alarm rate increases sharply. A compromise is found at a threshold of 1650\textsuperscript{2}, which detects 92.9\% of developing TCs with a false alarm rate of 38.0\% and a mean (median) detection time of 10.7 h (1.3 h) before the first 30-kt record. Applying DAV\textsubscript{1750} in the eastern North Pacific decreases the number of nondeveloping cloud clusters and increases the false alarm rate, though not to the same extreme found in the western North Pacific.

Future work includes the examination of DAV maps calculated using different radii, as preliminary results indicate that eastern North Pacific TCs may be detected more readily at smaller radii. In addition, the application of the automated tracking system to the generation of a genesis probability metric based on time spent below different DAV thresholds is being explored. Finally, DAV intensity estimates following Ritchie et al. (2014) will be initiated on cloud clusters that meet these thresholds.

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REFERENCES


