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Detection of tropical cyclone genesis via quantitative satellite ocean surface wind pattern and intensity analyses using decision trees

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ABSTRACT

Microwave remote sensing can be used to measure ocean surface winds, which can be used to detect tropical cyclone (TC) formation in an objective and quantitative way. This study develops a new model using WindSat data and a machine learning approach. Dynamic and hydrologic indices are quantified from WindSat wind and rainfall snapshot images over 352 developing and 973 non-developing tropical disturbances from 2005 to 2009. The degree of cyclonic circulation symmetry near the system center is quantified using circular variances, and the degree of strong wind aggregation (heavy rainfall) is defined using a spatial pattern analysis program tool called FRAGSTATS. In addition, the circulation strength and convection are defined based on the areal averages of wind speed and rainfall. An objective TC formation detection model is then developed by applying those indices to a machine-learning decision tree algorithm using calibration data from 2005 to 2007. Results suggest that the circulation symmetry and intensity are the most important parameters that characterize developing tropical disturbances. Despite inherent sampling issues associated with the polar orbiting satellite, a validation from 2008 to 2009 shows that the model produced a positive detection rate of approximately 95.3% and false alarm rate of 28.5%, which is comparable with the pre-existing objective methods based on cloud-pattern recognition. This study suggests that the quantitative microwave-sensed dynamic ocean surface wind pattern and intensity recognition model provides a new method of detecting TC formation.

1. Introduction

Tropical cyclones (TCs) that originate over warm tropical and subtropical oceans are characterized by surface low pressure systems with organized cloud systems, thunderstorms, strong winds and heavy rainfall. Abrupt (unexpected) TC formation can result in significant human and economic damage (Park, Kim, Ho, Elsberry, & Lee, 2015). Of the hundreds of tropical disturbances that occur over the western North Pacific each year, only a few (~20) develop into TCs (Kerns & Chen, 2013). It is important to forecast which disturbances develop into a TC and which ones will just decay. TC formation designation primarily considers the dynamic features (e.g., pattern and strength) of a circulating storm system. Officially, the U.S. Joint Typhoon Warning Center initiates the warning of TC formation when a tropical disturbance develops into the category of tropical depression (TD), in which the maximum sustained surface wind speed (MSW) within a closed tropical circulation meets or exceeds 25 knots in the North Pacific (http://www.usno.navy.mil). MSW is an important metric used to identify TCs at various TC warning centers (e.g., JTWC and National Hurricane Center).

In situ wind measurements are rarely available over the open ocean. Thus, dynamic TC measurements are typically inferred from infrared/visible radiation signatures from the top of clouds. The Dvorak technique (Dvorak, 1972) considers the strength and distribution of TC-organizing circular winds, the degree of distortion in the cloud pattern, and convective vigor using infrared-based cloud-top temperatures (Velden et al., 2006). It has been a very valuable tool in monitoring TCs for more than three decades. However, the infrared technique has an inherent insensitivity to low-level dynamics, which may be obscured by significant convection or cirrus clouds. Microwave (MW) radiation, which is based on the emission and scattering of cloud and precipitation particles, can be used to identify strong convective areas and cloud organization. The difference between the horizontal and vertical polarization MW radiances is related to ocean surface roughness. Therefore, the MW imagery can be used to retrieve ocean surface wind velocity (e.g., 10-meter wind speed; Meissner & Wentz, 2013). Moreover, satellite MW radiometers, such as WindSat (Gaiser et al., 2004), can provide wind angle information via measuring diversely-polarized radiances. Satellite-derived ocean wind vector data provides essential information for detecting and forecasting TC formation.

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The Dvorak technique is also limited by the requirement of subjective human input during the formation stage, which can lead to performance variations. Velden, Olander, and Zehr (1998) developed an objective version of the Dvorak technique. However, it cannot be applied during the pre-formation stage when the center (eye) is not well defined. Pineros, Ritchie, and Tyo (2010) proposed a new objective technique for detecting tropical cyclone formation. The Deviation Angle Variation (DAV) technique measures the axisymmetry of a cloud cluster with a predefined radius by performing a statistical analysis based on the orientation of the infrared brightness temperature gradient in the cluster. More recently, Wood et al. (2015) showed the ability of DAV technique in detecting TC formation over the western North Pacific with a hit rate of 96.8%, false alarm rate of 25.6%, and about 18.5 h detection lead time before a tropical disturbance reaches a wind intensity of 30 knots. This technique overcame ambiguities in the conventional Dvorak technique and demonstrated that the single use of the cloud symmetric index (i.e., DAV) could be practically useful for the early detection of TC formation.

While large-scale environmental conditions (e.g., sea surface temperature, large-scale vorticity, and vertical wind shear) as in Gray (1968) can increase the possibility of TC formation, convective clouds within a tropical disturbance are intricately connected to the dynamics of a TC. Some intense convection contributing to cyclogenesis has rotational, deep intense updraft (Houze, 2010). Thus, inner-core cloud and/or dynamic features of a system should be generally focused first when detecting TC formation, followed by large-scale environmental conditions (e.g. Schumacher, DeMaria, & Knaff, 2009; Zhang, Fu, Peng, & Li, 2015). Schumacher et al. (2009) defined both environmental and convective parameters using multiple geostationary satellite platforms and the National Centers for Environmental Prediction Global Forecasting System. These previous studies represented the convection strength using a cold pixel count and the average brightness temperature from the water vapor channel. The purely satellite-based methods (e.g., the original Dvorak and DAV techniques) focus on cloud pattern recognition and convective intensity. Despite the improved capabilities of satellite-based ocean-surface wind retrieval methods, the identification of dynamic patterns and intensities requires further research. Satellite ocean surface wind data has not been used to quantify dynamical TC genesis.

Various statistical techniques have been applied to relate satellite-derived indices to TC formation. For example, the original Dvorak technique (1975, 1984) used an empirical look-up table to derive MSW from the satellite index (i.e., current intensity index and T-number), while the Advanced Dvorak Technique uses a regression-based model (Velden et al., 2006). A machine learning approach, decision trees, has been applied by Zhang et al. (2015) to TC formation detection to classify developing and non-developing systems. Zhang et al. (2015) calculated large-scale environmental indices from coarse-resolution global forecasting systems, such as the Navy Operational Global Atmospheric Prediction System. An 800-hPa relative maximum vorticity, average sea surface temperature, average precipitation rate, divergence ranging from the 1000- to 500-hPa levels and 300-hPa air temperature anomaly were used as input variables for the decision trees. Friedl and Brodley (1997) noted that the advantages of the decision tree include the ability to model nonlinear relationships between the predictors and the final products, and provide rules, thresholds and relative importance values of predictors. Thus, the decision trees method has been widely used for numerous applications, such as land cover change analysis (Im & Jensen, 2005) and convection initiation/absence classification (Han et al., 2015).

This study used WindSat data to quantify the dynamic surface wind patterns and intensities that correlate with TC formation over the western North Pacific. A new TC genesis detection model was developed based on the decision tree approach by quantitatively analyzing representative low-level wind system patterns (i.e., organization and symmetry) and strengths. A TC genesis model development flowchart is presented in Fig. 1. Section 2 describes the data (WindSat and TC precursor track data) and WindSat image sample selection for multiple TC precursor disturbances. Section 3 describes the development of new TC genesis indices based on the satellite images and creation of the TC detection model using the decision tree approach. Section 4 includes a statistical comparison of the indices between developing (Dev) and non-developing (Non-dev) disturbances, and the results of the decision tree approach. Hindcast validation of the new TC genesis model is provided in Section 5. The summary and conclusion are presented in Section 6.

2. Data and definitions

2.1. WindSat

WindSat was the first passive MW polarimetric radiometer developed by the Naval Research Laboratory for the U.S. Navy and the National Polar-orbiting Operational Environmental Satellite System Integrated Program Office. The sensor was launched on board the Coriolis satellite mission on January 6, 2003 and is still operating. The satellite travels in an 840-km circular sun-synchronous orbit, with an ascending node local time of 17:59. WindSat records observations during both the forward and aft looking scans, providing a wider and more continuous swath (~1000 km) than the Advanced Scatterometer (ASCAT; Figa-Saldaña et al., 2002). The wide swath enables more frequent measurements that encompass tropical disturbances at the system-scale. Thus,

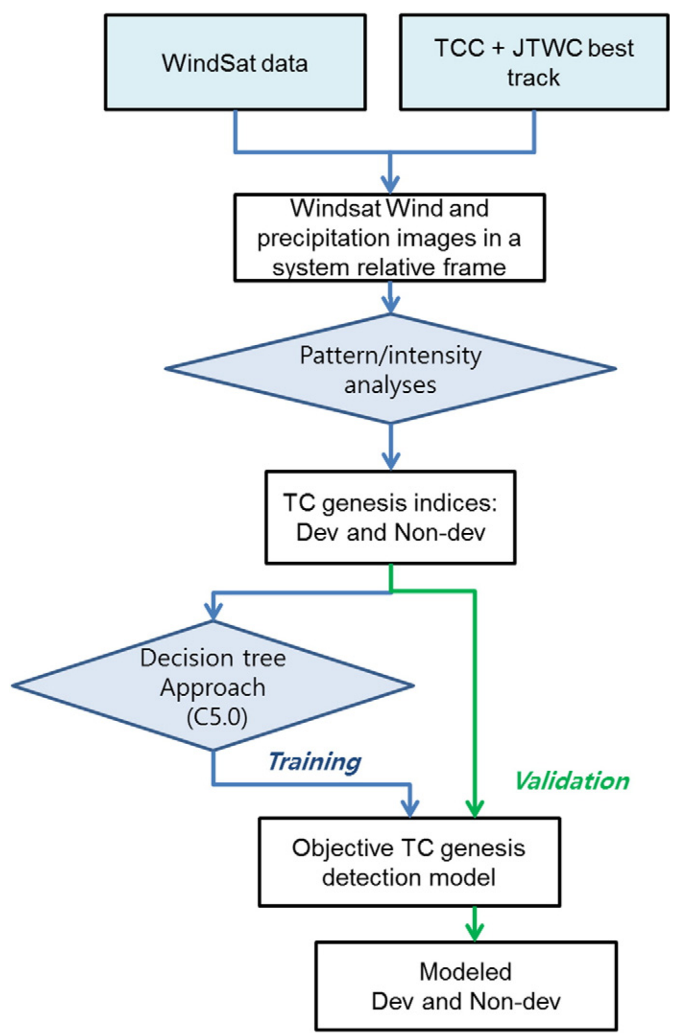

Fig. 1. A TC genesis model development flowchart.