Tropical Cyclone Formation Guidance Using Pregenesis Dvorak Climatology. Part I: Operational Forecasting and Predictive Potential

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ABSTRACT

While there are a variety of modes for tropical cyclone (TC) development, there have been relatively few efforts to systematically catalog both nondeveloping and developing cases. This paper introduces an operationally derived climatology of tropical disturbances that were analyzed using the Dvorak technique at the National Hurricane Center (NHC) and the Central Pacific Hurricane Center from 2001 to 2011. Using these Dvorak intensity estimates, the likelihood of genesis is calculated as a historical baseline for TC prediction. Despite the limited period of record, the climatology of Dvorak analyses of incipient tropical systems has a spatial distribution that compares well with previous climatologies. The North Atlantic basin shows substantial regional variability in Dvorak classification frequency. In contrast, tropical disturbances in the combined eastern and central North Pacific basins (which split at 125°W into an eastern region and a central region) have a single broad frequency maximum and limited meridional extent. When applied to forecasting, several important features are discovered. Dvorak fixes are sometimes unavailable for disturbances that develop into TCs, especially at longer lead times. However, when probabilities of genesis are calculated by a Dvorak current intensity (CI) number, the likelihood stratifies well by basin and intensity. Tropical disturbances that are analyzed as being stronger (a higher Dvorak CI number) achieve genesis more often. Further, all else being equal, genesis rates are highest in the eastern Pacific, followed by the Atlantic. Out-of-sample verification of predictive skill shows comparable results to that of the NHC, with potential to inform forecasts and provide the first disturbance-centric baseline for tropical cyclogenesis potential.

1. Introduction

Identifying when a tropical cyclone (TC) has formed is a challenging and subjective determination. Even with the benefit of hindsight and postevent analysis, the frequent lack of sufficient data and the inherent ambiguity in the definition of a TC introduce uncertainties into the analysis of tropical cyclogenesis. The National Hurricane Operations Plan (OFCM 2012) allows a wide range of subjective interpretation when it defines a TC as "a warm-core, nonfrontal synoptic-scale cyclone, originating over tropical or subtropical waters, with organized deep convection and a closed surface wind circulation about a well-defined center." Forecasts of when and where genesis will occur are even more daunting given the spatial and temporal scales of the physical interactions involved, the variety of types of initiating disturbances and surrounding environments (e.g., McTaggart-Cowan et al. 2008), and the limitations of numerical weather prediction (e.g., Halperin et al. 2012). Tropical cyclogenesis has therefore become the subject of extensive research. Further, the operational community has begun to enhance their public products, including forecasts of TC formation, due to great user interest in that information. This paper describes historical data and analyses and their use in

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producing a forecasting tool that can assist operational centers in making present-day genesis forecasts and in assessing the skill of new and future forecast capabilities arising from ongoing research. While this approach could be applied to any TC basin in the world covered by available data, the focus here is on the North Atlantic and eastern North Pacific basins, which are served by the National Hurricane Center (NHC), and the central North Pacific basin, which is served by the Central Pacific Hurricane Center (CPHC).

Since the inception of geostationary meteorological satellites in the 1970s, forecasters have been able to monitor—on a nearly continuous basis—not just active TCs, but also candidate weather systems and their environments to assess the potential for TC formation. The Dvorak technique (Dvorak 1972, 1973, 1975, 1982, 1984; Dvorak and Smigielski 1995) has been used worldwide for about four decades to classify and estimate the intensities of TCs and incipient systems via the analysis of cloud patterns and features in geostationary imagery. The impact of this technique on operational analysis and forecasting and the historical record of TCs is substantial (Velden et al. 2006). However, prior to this study, a climatology of Dvorak classifications for predevelopment candidate tropical systems has not been systematically examined. While the Dvorak technique was originally based on scaled, "typical" intensification rates, it does not provide forecast guidance per se. Both intensity and genesis forecasting remain huge challenges; operational TC intensity forecast errors have not significantly changed since the 1990s, during the same period in which track forecast errors have been dramatically reduced (Cangialosi and Franklin 2012). Meanwhile, substantial research has been conducted to better understand tropical cyclogenesis [e.g., the Pre-Depression Investigation of Cloud-Systems in the Tropics (PREDICT; Montgomery et al. 2012) and Genesis and Rapid Intensification Processes (GRIP; Braun et al. 2013) field campaigns], but predictive skill on the formation of TCs has only made relatively modest progress (Brown et al. 2008; Cangialosi and Franklin 2011; Halperin et al. 2012).

Despite the challenges, operational forecasters strive for better genesis predictions and forecast products. While not usually as important as forecasts of existing TCs, genesis forecasts—especially for systems close to land—can provide affected users with greater lead time to make preparations. Since deterministic forecasts of the location and timing of genesis—as for TC track, intensity, and size—have significant uncertainties given the current state of the science, probabilistic approaches and products have been or are being developed. This paper describes one such effort to utilize historical satellite analyses of tropical weather systems using the Dvorak technique to establish a limited climatology and baseline forecasting tool for the probabilistic prediction of tropical cyclogenesis. Several years' worth of past systems that either later became TCs ("pregenesis") or never became TCs ("nongenesis") are examined.

Section 2 discusses the state of operational genesis forecasting by summarizing public products at NHC and CPHC and their currently available data and analysis and forecasting tools. Section 3 describes the data and methods used. The first part briefly explains the Dvorak analysis technique, especially as it relates to cyclogenesis, before discussing operational Dvorak technique analysis output, the tropical cyclone best-track data, and how these were both used to compute the historical probabilities of tropical cyclogenesis. Key results of the paper, which include the Dvorak climatology and cyclogenesis frequencies based on historical Dvorak classifications of incipient tropical systems, appear in section 4. Implications of this work for future forecasting capabilities conclude the paper in section 5.

2. Operational genesis forecasting at NHC–CPHC

We begin with a summary of the current state of forecasting TC genesis at regional specialized meteorological centers (RSMCs) in the United States, including the tools used and products produced by forecasters, since these products are later compared to the performance of our climatological probabilities. The Tropical Weather Outlook (TWO) product is routinely issued in both text and graphical formats by the NHC and CPHC every 6 h (at synoptic times of 0000, 0600, 1200, and 1800 UTC) during hurricane season, which runs 1 June (15 May)–30 November in the North Atlantic and central (east) North Pacific basin. Special TWOs are issued at any time as needed to provide updates on significant changes that occur in between synoptic times or outside of hurricane season. In the TWO, forecasters qualitatively discuss areas of disturbed weather and their potential for tropical or subtropical cyclone formation, often accompanied by brief statements about weather impacts (e.g., winds, rainfall, floods, ocean waves). In addition, forecasters explicitly provide, for each system mentioned in the TWO, their subjectively determined chance, to the nearest 10%, of TC formation within the next 48 h. Each percentage is also categorically stated as falling within one of the following ranges that have been used since 2009: low (0%–20%), medium (30%–50%), or high (>50%). The graphical TWO depicts each system in a color corresponding to its categorical chance of genesis, where a low chance is shown in yellow, medium in orange, and high in red (Brown et al. 2008).

The qualitative text version of the TWO existed in essentially the same form for decades. NHC experimentally introduced a simple graphical version in 2007, which was enhanced with categorical forecasts of the chance of genesis in 2008 that were operationally implemented in both the text and graphical TWO in 2009. CPHC issued similar experimental graphical TWOs in 2008–09 that led to operational categorical genesis forecasts in their text and graphical TWOs in 2010. The explicit percentage chances of genesis to the nearest 10%, upon which the categorical forecasts are based, were not disseminated to the public until NHC (CPHC) did so in both their text and graphical TWOs starting in 2010 (2011).

Despite these product enhancements, NHC and CPHC have no explicit probabilistic tropical cyclogenesis guidance for individual weather systems. In fact, there has not even been any system-specific, climatologically based guidance for forecasters to reference for the TWO, even though similar climatological guidance exists for other forecast parameters [e.g., the Climatology and Persistence model (CLIPER; Neumann 1972) for track and the Statistical Hurricane Intensity Forecast model (SHIFOR; Jarvinen and Neumann 1979) for intensity]. The probabilities in the TWOs are subjectively determined by forecasters, based on their assessment of all available observational data and model guidance, heavily leveraging the forecasters' knowledge and experience (Pasch et al. 2003; Brown et al. 2008). Verification of NHC genesis forecasts during 2007–11 reveals that forecasters, despite the lack of explicit guidance, generate relatively reliable probabilistic predictions, especially for the Atlantic basin (Cangialosi and Franklin 2011, 2012). The Atlantic forecasts do have room for improvement, however (as further shown in the verification results in section 4), and the reliability is much less for the east North Pacific basin; thus, improved genesis guidance remains an operational need.

Objective guidance for tropical cyclogenesis forecasting assimilates output from various global dynamical models, including from the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS), the European Centre for Medium-Range Weather Forecasts (ECMWF) model, the Met Office (UKMET) model, the Navy Operational Global Atmospheric Prediction System (NOGAPS), and the Canadian Meteorological Centre (CMC) model. Chan and Kwok (1999) examined environmental conditions around tropical disturbances that became TCs in the western North Pacific using the UKMET global model, comparing successful genesis cases with model failures to predict actual genesis. Cheung and Elsberry (2002) also looked at the western North Pacific basin to assess NOGAPS skill at forecasting tropical cyclogenesis by developing model genesis criteria and discussing differences in large-scale features between verification modes. Walsh et al. (2007) compiled and refined the methods of TC detection in gridded data, though determination of TC genesis in global models by forecasters remains a subjective analysis of various meteorological parameters. Recent assessments of most of these models' ability to forecast genesis in the Atlantic basin reveal that they have severe limitations, including some high false alarm rates and/or low probabilities of detection, although the GFS and UKMET models have exhibited improvements in the past few years (Halperin et al. 2012). There is ongoing work on dynamical models as part of the Hurricane Forecast Improvement Program (HFIP), which demonstrated, for example, that the GFS ensembles initialized with a different data assimilation system performed rather well in 2011 compared to the operational GFS with regard to genesis forecasts out to 5 days or more (Gall et al. 2012). The Statistical Hurricane Intensity Prediction Scheme (SHIPS; DeMaria et al. 2005), based largely on output from the GFS model, is a statistical–dynamical model that yields generally skillful intensity forecasts for existing TCs. SHIPS was not designed or intended to forecast genesis, however, and has not been shown to have any skill in doing so (M. DeMaria 2011, personal communication). Nonetheless, SHIPS can provide (through its component predictors) an assessment of the environment in which a specific incipient disturbance might be located during the next few days.

The Tropical Cyclone Formation Probability (TCFP) product from the National Environmental Satellite, Data, and Information Service (NESDIS; DeMaria et al. 2001; Schumacher et al. 2009) comes the closest to providing explicit guidance for the 48-h, system-specific genesis probabilities in the TWO products. The TCFP estimates the probability of TC formation within a $5° \times 5°$ latitude–longitude region, but not explicitly for a specific weather system, and only out to 24 h. A new algorithm (Dunion et al. 2012a,b) is under development, with testing and evaluation performed via the Joint Hurricane Testbed (JHT; Rappaport et al. 2012), and offers the potential for operational forecasters to have system-specific guidance within the next couple of years. This algorithm incorporates the Dvorak climatology and guidance presented in this study as part of a statistical–dynamical probabilistic genesis forecasting tool. The JHT project is testing the Dvorak information along with total precipitable water (TPW; DeMaria et al. 2008) as new predictors in tandem with the NESDIS TCFP work with the operational SHIPS-based Rapid Intensification Index (Kaplan et al. 2010). Even in that case, no baseline or climatological probabilistic genesis guidance has existed up to now for measuring the skill of such an algorithm. Further, there has previously been no comprehensive climatology of incipient disturbances assembled to use for such tools. The results described in this paper provide such a baseline and climatology.

All of the currently available objective guidance options described above have limitations in forecasting the genesis potential of a specific weather system and do not explicitly forecast the probabilities expressed in the TWO product. As a result, operational forecasters still rely heavily on their subjective assessment of observations, primarily geostationary satellite imagery. Other remotely sensed data from ground-based radars and polar-orbiting satellites, along with in situ data from reconnaissance aircraft and conventional surface and upper-air stations, collectively offer critical information to accompany the geostationary imagery. None of these other data sources, however, is capable of the nearly continuous monitoring of essentially every incipient tropical weather system from the geostationary platform. Furthermore, geostationary satellites provide a long-term dataset that can be used to develop a quantitative climatology of, and basic probabilistic forecast guidance for, TC formation. In particular, the Dvorak technique (e.g., Dvorak 1984), using geostationary satellite imagery as input, provides a repository of classifications and intensity estimates for TCs as well as incipient disturbances, as described in more detail next.

3. Data and methodology

a. The Dvorak technique

A more complete description of the TC life cycle became possible with the advent of satellite imagery during the 1960s and early 1970s. To facilitate TC identification and forecasting, Dvorak (1972, 1973) used satellite data to quantify TC evolution from patterns of cloud growth and deterioration. The patterns in cloud structures were related to phases of TC intensity, creating a tool that allowed a system's cloud organization to help forecasters estimate the current state of the TC. Dvorak (1975) also introduced standards to define tropical weather systems before and near genesis. Also that year, Hebert and Poteat (1975) adapted and modified Dvorak's technique to identify subtropical cyclone types. Further refinements by Dvorak (1982, 1984; Dvorak and Smigielski 1995) removed some subjectivity in the intensity estimates by further establishing objective measurement rules of cloud characteristics (such as infrared brightness temperature and distance from the center) as well as greatly increasing constraints of intensity criteria. There have also been substantial advances in objective Dvorak satellite analysis of TC intensity (e.g., Velden et al. 1998, Olander and Velden 2007), though the variability of genesis modes (McTaggart-Cowan et al. 2008) makes an objective classification of pregenesis systems elusive thus far (C. Velden 2011, personal communication).

Forecasters can use Dvorak classifications to estimate the intensity of a TC or analyze the status of an incipient disturbance, in a consistent manner, even in the absence of in situ observations. In fact, the Dvorak technique is the standard operational tool used worldwide to estimate TC intensity (Velden et al. 2006), and frequently it is the only available method at a given time (Brown and Franklin 2004). However, large errors in intensity estimation can and do occur, especially in basins without calibration (Henderson-Sellers et al. 1998), but also in well-sampled areas (Lowry 2009; Knaff et al. 2010). Brown and Franklin (2004) showed that approximately 50% of Dvorak intensity estimates in the Atlantic basin are within 5 kt (2.6 m s^{-1}, where 1 kt = 0.514 m s^{-1}) of the best-track intensity when the latter is based on aircraft reconnaissance data. Additionally, a nonlinear best-fit relationship with reconnaissance data shows a statistically significant relationship with Dvorak estimations (Brown et al. 2006), although there can be large case-to-case disagreement. More recent work has shown that errors in the Dvorak classifications as compared to best-track TC intensities may be reduced through bias correction (Knaff et al. 2010).

The subjective Dvorak analysis is composed of a series of steps, which progress from identifying the system in satellite imagery to determining its current intensity (CI) number that corresponds to an estimated intensity in knots. Accurately locating the center of the system is among the most important parts of Dvorak analysis, as some of the subsequent calculations utilize that location in order to help determine the data T number (DT). Depending on the type of satellite image (visible or infrared), there are different methods for establishing the DT based on the overall organization of the convective clouds relative to the system's circulation center. This DT value is then compared to the cloud pattern (pattern T number or PT) and Dvorak's model of TC development (model expected T number, or MET). The final T number (FT) is chosen from among the DT, PT, and MET values, and the CI number is set to the FT unless time and model constraints prohibit that and dictate a different CI (e.g., holding a steady CI for 24 h if diurnal variations produce large fluctuations in the T numbers of a tropical disturbance). Sometimes, a Dvorak analysis is attempted but the system is found to be "too weak to classify" (TWTC).

The overall satellite appearance of an incipient tropical system and the quantification of that appearance via the Dvorak technique's T and CI numbers are

TABLE 1. Availability of Dvorak classifications by forecasting agency. Note that the ATCF database is used for all TCs and some data for invests in the Atlantic and eastern North Pacific basins and are available starting in 2009. In addition, SAB performs Dvorak analyses for TCs worldwide; depending on the basin, the availability of their data is different.

	CPHC	SAB	TAFB
ATCF	2001–present	2004–present	2001–present
Internal electronic archive	2001–08 TCSCP 2009–present TCSNP	2007–present	2003–present
Paper fixes	2001–present	2004–07 (Atlantic) 2005–07 (EP and CP)	2001–02

considered by forecasters in assigning their subjective genesis probability for the TWO products. Dvorak numbers are available when a system attains sufficient convective organization to be classifiable via the technique. When it qualifies to become classifiable is a subjective determination, but classifications (or lack thereof) for incipient systems provide some measure of how much organization the system has or lacks relative to what would generally be needed for genesis. In most cases, the NHC operationally requires a Dvorak T number of 2.0 to satisfy the convective organization requirement for a TC, although occasionally a T number of 1.5 is considered adequate (J. Franklin 2012, personal communication). Quantification of the relationships between Dvorak classifications and the time of best-track genesis will be performed for the first time in this study.

In part due to the inherent limitations in the Dvorak technique, as well as a lack of a digitized record of Dvorak estimates until recently, there has been no climatological relationship established between a system's Dvorak classifications and the frequency and timing distribution of future genesis. Such a climatology would provide forecasters with a new guidance product that could also be used as a baseline by which to measure the skill of more elaborate techniques. A description of the data and approach used to create this tool are discussed next.

b. *Historical Dvorak classifications in the Atlantic and east-central North Pacific basins*

Conceivably, given the many decades since the advent of geostationary satellite imagery, Dvorak classifications spanning many years of pregenesis and nongenesis systems could be cataloged to analyze genesis climatology and frequency. Only within the past decade or so, however, has electronic storage of Dvorak classifications for TCs and their pregenesis systems been performed routinely. In addition, classifications for nondeveloping systems have only been saved for the past few years. Such nondeveloping systems may be operationally designated by NHC or CPHC as an "invest"—a system for which the operational forecast center assigns a number in the Automated Tropical Cyclone Forecast (ATCF; Sampson and Schrader 2000) system and obtains additional investigational data, usually including Dvorak classifications. Therefore, a preexisting electronic database of pregenesis and nongenesis systems was not available at the outset of this study and had to be constructed.

Forecasting agencies in the United States that perform Dvorak analyses of tropical systems have varying lengths of records (see Table 1). The NHC's Tropical Analysis and Forecast Branch (TAFB) performs operational Dvorak classifications for systems in the Atlantic and eastern Pacific basins. All Dvorak analysis data for TCs, including their pregenesis period, are available in the ATCF fix file archives. Since 2003, TAFB has also internally archived their Dvorak classification data for all TCs and incipient systems they handled, including for systems that never became a tropical cyclone. Handwritten paper worksheets of TAFB Dvorak analyses for nongenesis systems in 2001–02 have also been gathered.

Dvorak analyses by CPHC are released as an official public product, the Central Pacific Tropical Cyclone Summary [TCSCP; renamed the TCSNP in 2009 to differentiate systems north of the equator from those in the Southern Hemisphere (TCSSP)]. The electronic archive of TCSCP products begins in 2001. Data have also been gathered from the CPHC's ATCF database for TCs and invests, as well as from paper worksheets for noninvests (i.e., nondeveloping disturbances that were not designated as an invest) these data help to fill in information missing from the TCSCP data.

In addition, the Satellite Analysis Branch (SAB) at the NOAA/NESDIS provides Dvorak classifications that supplement those of operational TC centers around the world. SAB started to electronically archive their Dvorak classifications in 2007. Paper worksheets have been used to augment the archive back to 2004 for the Atlantic and 2005 for the east and central North Pacific basins. Finally, SAB classifications contained in the ATCF fix databases were compared and added where necessary. While the SAB data archive does not extend as far back as that of TAFB, having two concurrent

Dvorak analyses for many systems in the past few years allows for the possibility of measuring analysis (dis) agreement and how that information could benefit an operational forecaster. In general, the lack of digitized Dvorak classifications for nongenesis systems is the chief limitation to extending this climatology further back in time. Although other agencies, such as the Air Force Weather Agency (AFWA) and the Joint Typhoon Warning Center (JTWC), have historically performed Dvorak estimates in the Atlantic or east/central North Pacific basins, these records are not current and could not be used to create future forecast guidance.

To facilitate comparisons between different agencies and information formats, inconsistencies in the Dvorak analyses were standardized. The temporal resolution of the Dvorak classifications is nominally 6 h, so each analysis fix was rounded to the nearest synoptic time (e.g., 1715 UTC rounds to 1800 UTC). Fixes from agencies that perform Dvorak analyses were also frequently done at intermediate times (i.e., 0300, 0900, 1500, and 2100 UTC) but those fixes usually contain only position estimates and, unless intensity information was provided, were not added to our database.

There are also instances in the historical Dvorak analyses of the same fix being attributed to separate systems, or a single system being given multiple invest numbers. Such instances of redundant locations and dates/times were removed. A rigorous synoptic study of every system was not possible, but data for several pairs of systems were concatenated when added to our dataset (if supported by temporal and spatial continuity as well as satellite analysis). Despite the benefits to quantifying the number of nongenesis and pregenesis incipient systems, the precise count of such systems is not important for the goals of this study and is reserved for future research. However, for reference, the system counts are shown by basin in Table 2.

c. *Genesis probabilities calculation method*

All available Dvorak analysis and system identification information (ATCF ID numbers) for pregenesis and nongenesis systems has been preserved and compiled into a single archive. For the purpose of this study, however, only those Dvorak fixes from TCs before and nearest the time of genesis were examined. If a system did not become a TC, then all of its data were also included to study nongenesis classifications. For those systems that attained genesis, the ATCF best-track data, as compiled during postevent analysis by NHC and/or CPHC, were used to determine the location, date, and time of genesis in place of operational designations, which can slightly differ (though occasionally the timing difference can be on the order of a day).

TABLE 2. Number of CPHC and TAFB Dvorak fixes used in the cyclogenesis climatology, where the Pacific is separated by regions (the Pacific eastern region is east of 125°W, while the Pacific central region spans from 125°W westward to 180°). Pregenesis fixes reflect Dvorak classifications before genesis on systems that developed into TCs, whereas nongenesis fixes are classifications for systems that do not undergo cyclogenesis. Unique systems, number of TCs, and development rate are based on the total number of disturbances identified through the Dvorak technique. Note that disturbances that cross 125°W are represented in both of the Pacific central and eastern regions for the ''unique systems'' and ''No. of TCs'' counts; however, Dvorak fixes are not double counted. Also note that a rigorous synoptic analysis was not performed to verify system counts.

	Pacific central region	Pacific eastern region	Atlantic basin
No. of fixes	393	2224	2886
Pregenesis fixes	131	1239	1299
Nongenesis fixes	262	985	1587
Unique systems	83	278	385
No. of TCs	30	170	178
Development rate (%)	36.1	61.2	46.2

Although it would be preferable for operational centers to perform our Dvorak-based climatological analyses separately for each operational area of responsibility served by NHC and CPHC, the less frequent TCs and candidate systems in CPHC's central North Pacific basin between 140°W and the date line result in insufficient Dvorak classification data to yield robust statistics. The relationships between genesis and both TAFB and CPHC Dvorak classifications are interdependent regardless of the human-imposed operational boundary at 140°W. The conflated central/east North Pacific basin dataset does not, however, differentiate between the fundamentally different genesis regimes in opposite halves of the combined basin, decreasing the applicability of the results throughout the combined area. The 125°W meridian was chosen to delineate a ''central region'' and an ''eastern region'' of tropical cyclogenesis based on the following observational and operational considerations:

1) A system at 125°W traveling westward at 20 kt or faster (infrequent but plausible in that region) will reach the central North Pacific basin at 140°W in less than 48 h, necessitating its mention in the CPHC TWO products, and meaning that the results from our wider ''central'' region are directly relevant to CPHC operations.
2) Roughly half of the TCs that form between 125° and 140°W (still within NHC's east North Pacific area of responsibility) eventually cross 140°W into the CPHC area of responsibility. During 2001–11, the observed ratio was 8 of 15, or 53%. This fact creates an additional physical and operational linkage between the 125°–140°W region and the existing CPHC area.

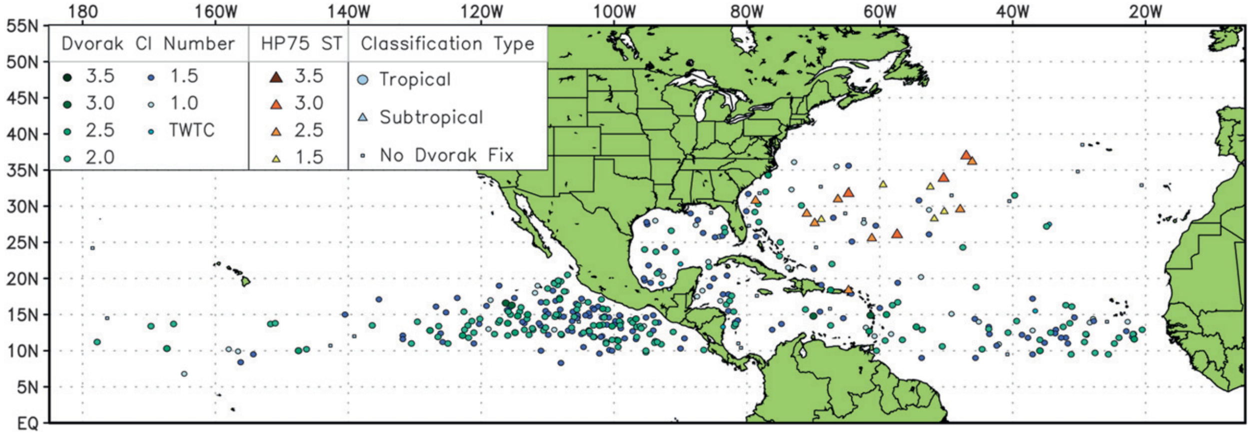

FIG. 1. The center position and Dvorak intensity (if available) for every tropical cyclone genesis event from 2001 to 2011 by TAFB in the Atlantic and eastern North Pacific basins and CPHC in the central North Pacific basin. The marker size and color represents the CI number, with a separate color scale for subtropical systems as designated by the Hebert and Poteat (1975) technique and the smallest gray dots representing no Dvorak fix at the time of genesis.

3) The maximum westward extent of the mean southwesterly low-level, cross-equatorial flow into the tropical east North Pacific basin, which occurs during the peak of hurricane season, is roughly 125°W, marking a climatological boundary of environmental vorticity that aids in TC genesis south of Mexico (not shown).

In the results section that follows, Dvorak fixes in the North Pacific east of 125°W are included in the eastern region, while fixes between 125°W and 180° are placed in the central region. For example, if an incipient disturbance is developing near 120°W and moves westward to 130°W, those Dvorak classifications east of 125°W are included in the eastern region dataset and statistics, while those classifications at or west of 125°W are included in the central region dataset. Therefore, the results of this study are divided into three principal TC genesis regions: the Pacific eastern region (east of 125°W), the Pacific central region (125°W–180°), and the North Atlantic basin. However, the traditional operational areas of responsibility will be referred to as the east North Pacific basin and central North Pacific basin.

The climatological tropical cyclogenesis rates by Dvorak numbers were determined using several discriminating factors. First, the Dvorak analyses were separated by the analysis region in which each system was classified via the Dvorak technique (i.e., Pacific central region, Pacific eastern region, or Atlantic basin). The agency that performed the classification was retained to facilitate separate calculations and interagency comparisons. Furthermore, the nature of the classification (tropical via the Dvorak technique versus subtropical via the Hebert and Poteat technique) was marked. If an individual Dvorak analysis was performed on a system that eventually achieved genesis, the difference in time between that Dvorak fix and genesis was calculated. No such calculation was needed for the nongenesis cases. In this study, the CI number is used to differentiate the intensities of systems, but results are similar using the FT number. Finally, the center location, date, and synoptic time of the analysis were also saved into the database.

The probability of TC genesis was then calculated, at a variety of lead times with varying Dvorak CI numbers, by dividing the number of pregenesis cases by the total number of pregenesis and nongenesis cases satisfying the lead time and Dvorak criteria. For example, the probability of genesis within 48 h for a tropical system with a Dvorak CI number of 1.0 in the Pacific eastern region was determined by

1) counting the number of cases in the archive in which a tropical system was in the Pacific eastern region (i.e., east of 125°W in the Pacific), with a Dvorak CI number of 1.0, and became a TC (according to the postevent best track) within 48 h or less of the Dvorak classification time, and
2) dividing the result from the first step by the total number of occurrences in the archive in which a tropical system was in the Pacific eastern region and given a Dvorak CI number of 1.0.

This calculation was performed separately for all lead times at 6-h intervals out to 126 h, for all Dvorak CI classifications, for each basin, and for both tropical and subtropical system types. However, genesis frequency of subtropical systems will not be considered in the following results due to the relative infrequency of such occurrences.

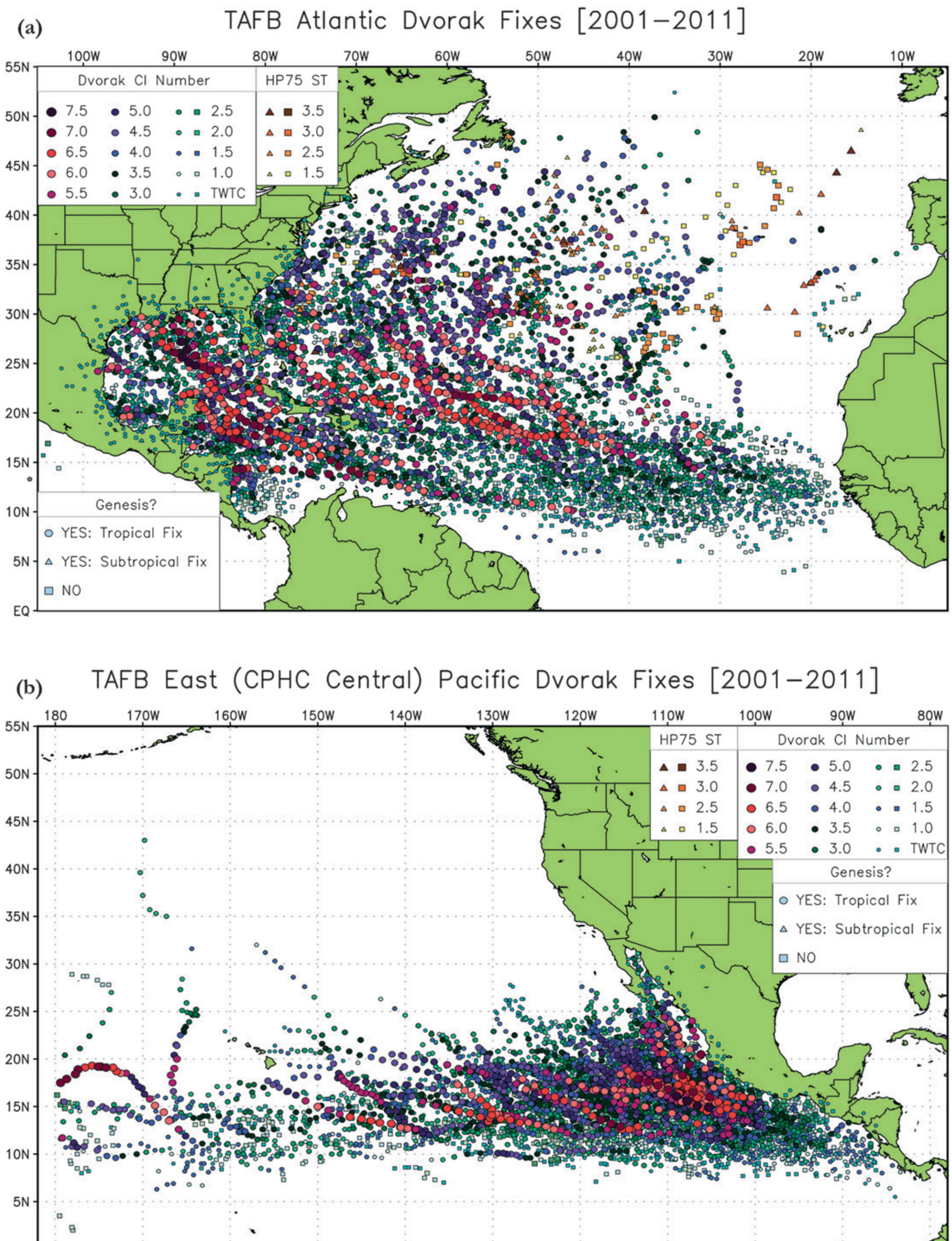

FIG. 2. The center position and intensity for every Dvorak fix from 2001 to 2011 by (a) TAFB in the Atlantic and (b) TAFB (CPHC) in the eastern (central) North Pacific. The marker shape represents if the tropical system eventually underwent genesis (and if so, whether it is a tropical or subtropical observation). The marker color represents the CI number, with higher values plotted on top and a separate color scale for subtropical systems as designated by the Hebert and Poteat (1975) technique. This database is consistent with the location and intensity distributions found in other climatologies (e.g., best track).

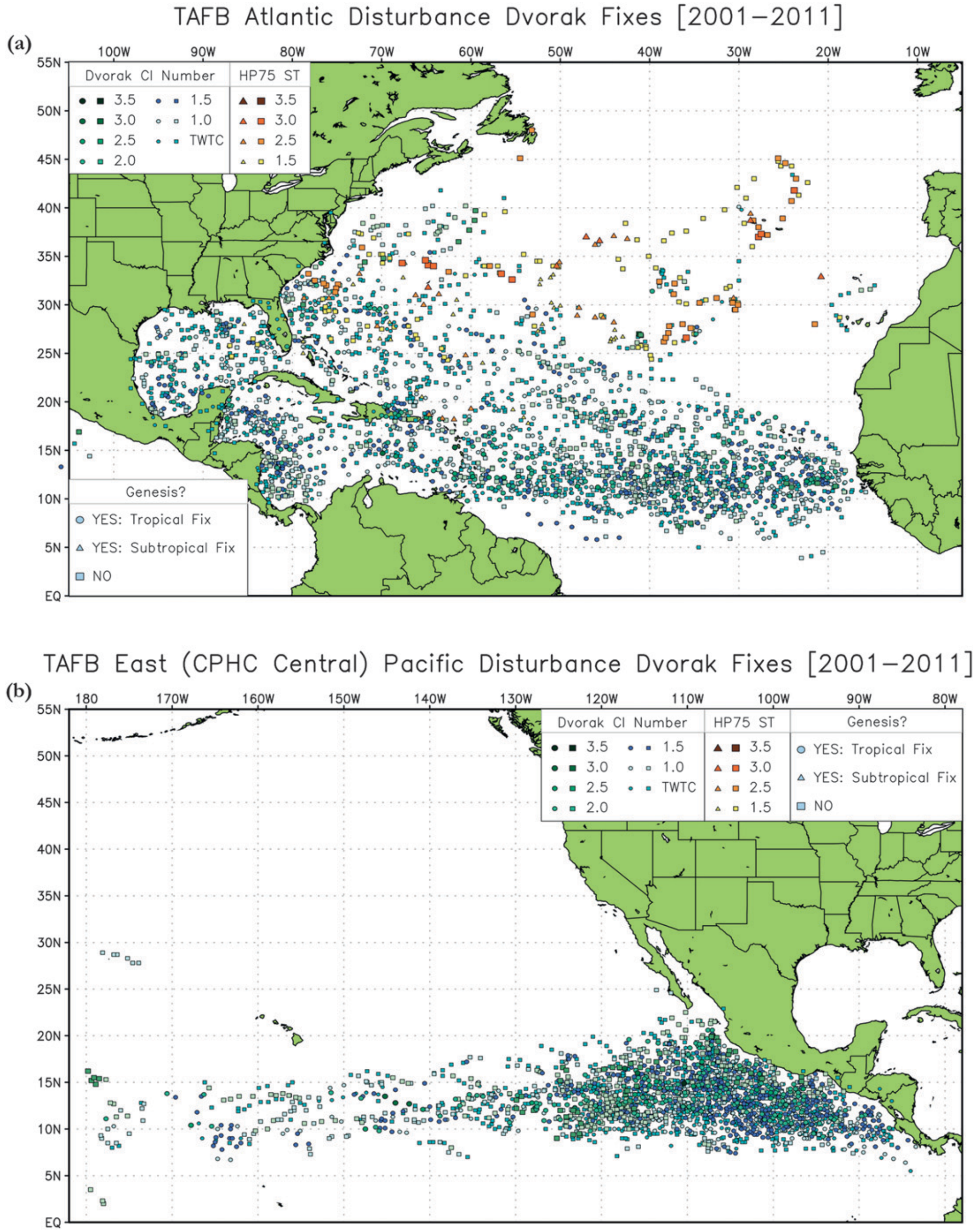

FIG. 3. As in Fig. 2, but only for those pregenesis or nongenesis events.

4. Results: Tropical cyclogenesis climatology based on Dvorak classifications

The relatively limited time frame (11 yr) of the collected Dvorak data necessitates a brief examination of the representativeness of the data as a pregenesis tropical disturbance climatology, especially when compared to actual TC genesis locations (Fig. 1). The following discussion will first describe and examine the distribution of all Dvorak center fixes and intensity estimates. For the remaining analysis, only the subset valid for pregenesis or nongenesis disturbances is shown.

The location and intensity for every Dvorak analysis performed on a TC or candidate system during 2001–11 by TAFB for the Atlantic and east North Pacific basin and by CPHC for the central North Pacific basin is

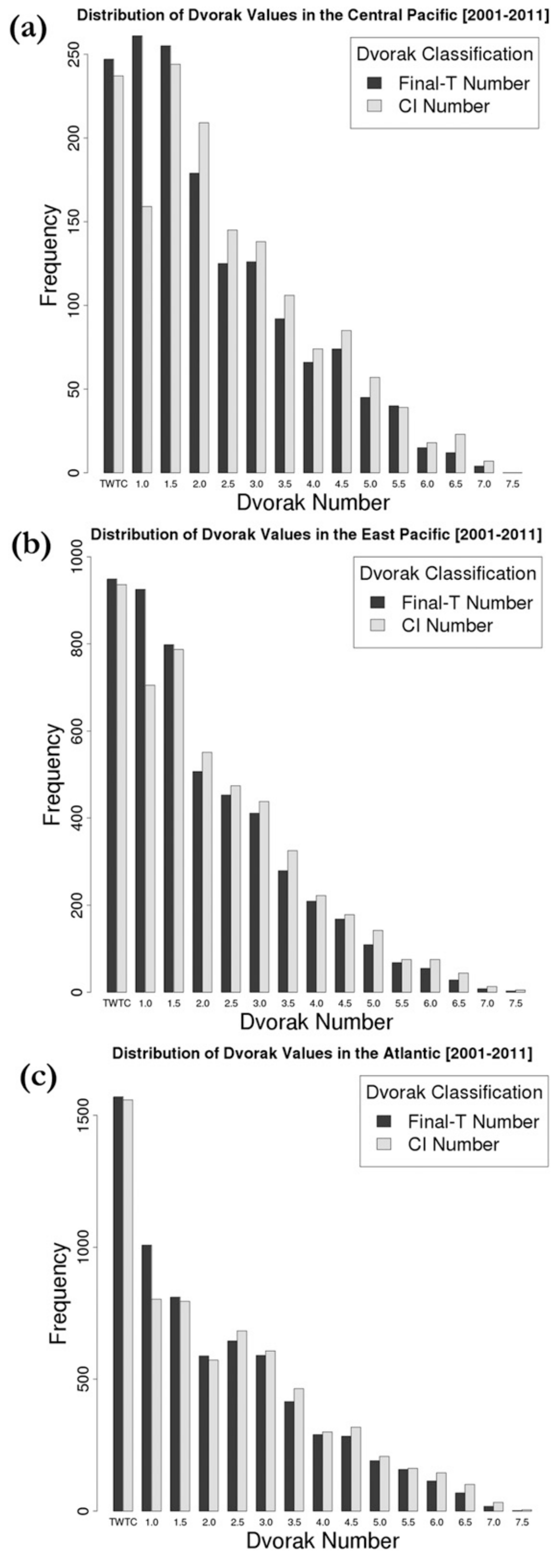

FIG. 4. Tallies of Dvorak fixes (FT and CI numbers) in the (a) Pacific central region (west of 125°W), (b) Pacific eastern region (east of 125°W), and (c) Atlantic datasets by classification value. Note that the frequency axis is different for each region.

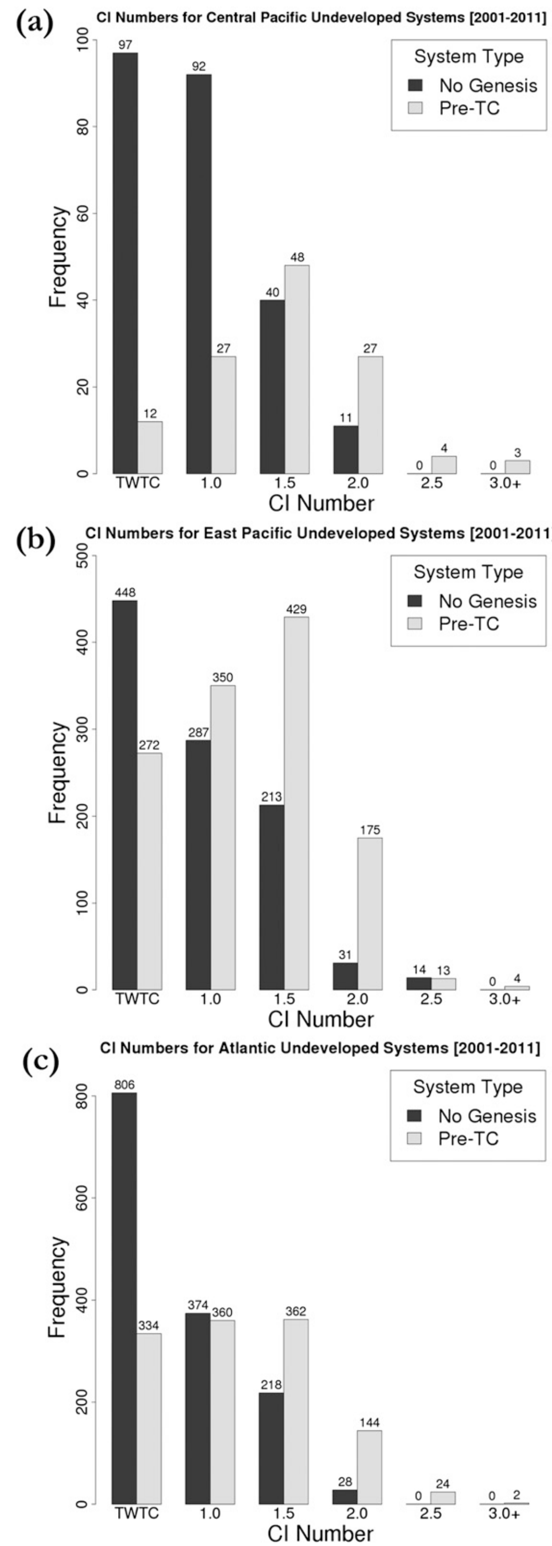

FIG. 5. Tallies of CI Dvorak fixes used in tropical cyclogenesis analysis for the (a) Pacific central region (west of 125°W), (b) Pacific eastern region (east of 125°W), and (c) Atlantic basin. All fixes from disturbances that do not undergo cyclogenesis (No-Genesis) and systems that developed into a TC (Pre-TC) are shown. Note that the frequency axis is different for each region.

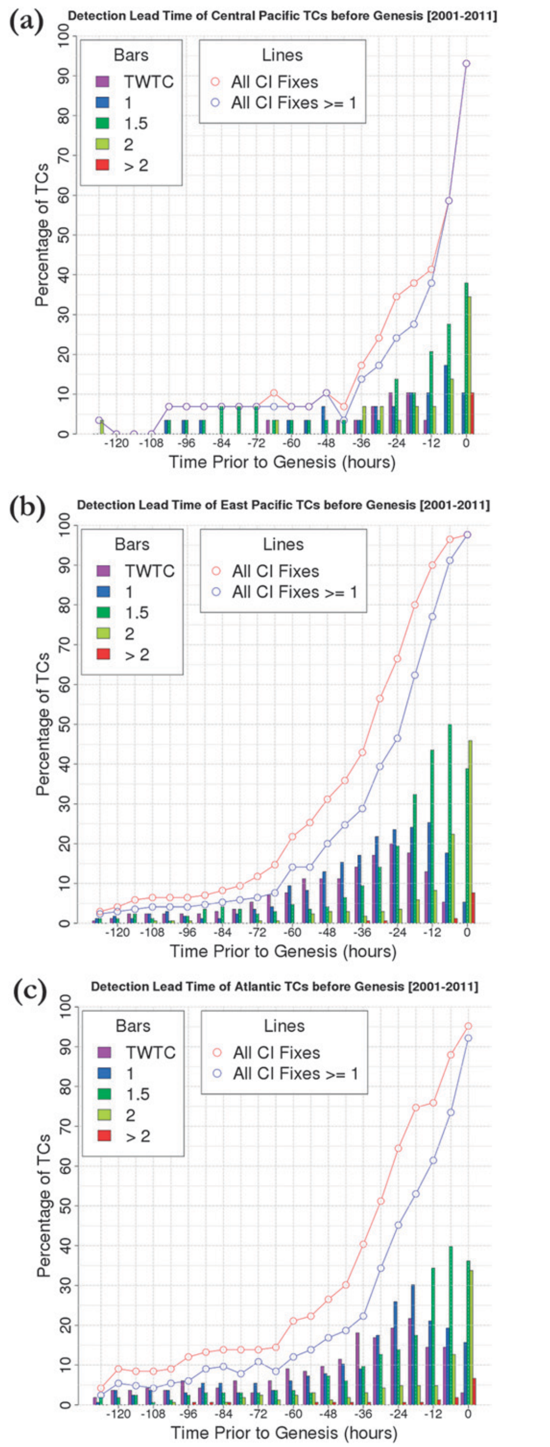

FIG. 6. Percentage of time Dvorak fixes are available for systems that eventually developed into TCs, by lead time (h, prior to genesis); data reflect Dvorak CI-numbers from TAFB and CPHC from 2001 to 2011 in the (a) Pacific central region (west of 125°W), (b) Pacific eastern region (east of 125°W), and (c) Atlantic basin. Colored bars indicate the Dvorak CI classification; the red line (all CI fixes) sums all available Dvorak fixes including TWTC at the specified lead time; the blue line (all CI fixes ≥1) aggregates only those Dvorak CI fixes at or above 1.

TABLE 3. Average time (h) of first Dvorak classification prior to cyclogenesis in the Pacific central region (125°W and westward to 180°), Pacific eastern region (east of 125°W), and Atlantic basin; data reflect only systems that eventually developed into TCs.

Pacific central region	All fixes	Dvorak fix ≥ 1
Median	12	12
Mean	32.7	31.2
Std dev	57.8	58.1
Pacific eastern region	**All fixes**	**Dvorak fix ≥ 1**
Median	33	24
Mean	41.9	34.4
Std dev	30.7	29.3
Atlantic Basin	**All fixes**	**Dvorak fix ≥ 1**
Median	30	24
Mean	37.4	29.9
Std dev	42.5	41.2

shown in Fig. 2. Figure 3 presents the subset from Fig. 2 for those points at which a classified system was pregenesis (candidate system later became a TC) or nongenesis (candidate system never attained genesis). In general, the distribution of intensities and the spatial range displayed in these maps are consistent with other similar climatologies, such as the best-track database (Jarvinen et al. 1984; McAdie et al. 2009). However, the limited period of the Dvorak record used allows individual storm tracks to be visualized (emphasized here since the most intense fixes are plotted last) and shows the sampling resolution. Environmental factors that constrain TC development, as described by Gray (1968) and McBride (1995), help shape the distribution and density of fixes in these figures. It is important to note that the Dvorak technique does not allow operational intensity classifications over land; therefore, most points lying over land are noted as ''unclassified'' and are shown in Figs. 2 and 3 with the TWTC symbol.

The source dataset for our computations of Dvorak classification climatologies, visualized in Fig. 3, is summarized in Table 2, which provides counts of Dvorak fixes and the numbers of systems in each of our three basins/regions during the period 2001–11. The dataset includes hundreds of classifications for systems that were not a TC at the time of the classification, with a fairly even distribution of classifications for pregensis and nongenesis cases. The breadth of classifications is reflected graphically in the 11-yr distributions of all Dvorak CI and FT numbers (Fig. 4). Figure 5 shows only those CI numbers from pregenesis and nongenesis systems, which were used in creating the probabilistic genesis guidance shown later in this section. A relative comparison of these observations suggests the stratification of probabilities that occurs between Dvorak CI numbers and TC development basins.

Pregenesis systems are infrequently—less than a third of the time in each basin—first identified by the Dvorak technique (with at least a center fix position, even if TWTC) at any particular time more than a couple of days in advance of TC formation (red lines in Figs. 6a–c). In addition, until pregenesis systems in any of the three basins are within about 48 h of genesis, generally less than 15%–20% of them at any particular time are even classifiable with a CI number ≥ 1.0 (blue lines in Figs. 6a–c). The means, medians, and standard deviations in each of the basins of the times (in hours prior to genesis) of first Dvorak identification (at least TWTC) and classification (CI at least 1.0) are displayed in Table 3. The Pacific eastern region has the greatest average lead time, 34.4 h, for a pregenesis system to be classified (CI ≥ 1.0), while the Atlantic and Pacific central regions have slightly shorter lead times. More striking is that the median lead time to be classifiable in the Pacific eastern region and Atlantic basin is just 24 h, while it is a mere 12 h in the Pacific central region. In other words, the majority of systems that become TCs are not first classified with a CI number of at least 1.0 until within a day or less of genesis. Even at best-track genesis (0 h in Fig. 6), there is a wide variety of Dvorak CI classifications that are observed; nevertheless, a majority of cases exhibit a CI of 1.5 or 2.0.

Unfortunately for operational forecasting, all of these means and medians in Table 3 are well within the 48-h forecast window of the TWO products, increasing the difficulty of 24–48-h genesis forecasts since the candidate systems are often very poorly organized that far in advance. Figure 6 shows that, on average, Dvorak CI numbers noticeably increase up to the time of genesis starting about 60 h ahead of time, but do so only gradually until a faster increase begins about 36 h out. Therefore, Dvorak classifications do occasionally provide a signal of impending genesis throughout and even beyond the 48-h forecast time frame, but detection is not very robust. This information is also difficult to implement operationally, especially since it only considers systems that are known to have become TCs. The remainder of our results therefore focuses on genesis probabilities based on historical classifications of not only pregenesis but also nongenesis systems at various lead times.

a. *Eastern and central North Pacific probabilistic genesis guidance*

Figures 7a and 7b show the cumulative probabilities of tropical cyclogenesis in the Pacific central and eastern regions, respectively, using all TAFB and CPHC Dvorak fixes for both pregenesis and nongenesis systems during 2001–11. To demonstrate how to interpret these results for operational, real-time use, consider how one would apply Fig. 7b in conjunction with the east North Pacific basin TWO product having a 48-h forecast horizon. Suppose there is a tropical disturbance with a Dvorak CI number of 1.0 east of 125°W. The 48-h climatological probability of genesis is found on the ordinate where the green line (for the CI number of 1.0) meets the 48-h lead time on the abscissa. In this case, one retrieves a probability of about 43%, meaning there is a 43% chance of genesis at some point within 48 h for this system based only on its Dvorak classification of 1.0. Using the same approach, the 48-h probability rises to about 58% for a system with a CI number of 1.5. It is worth emphasizing that these probabilities are calculated independent of both time of year as well as location (besides the region itself), and are oblivious of the specific meteorological environment for a given case.

Several aspects of Figs. 7a and 7b bode well for being useful in making genesis predictions. Primarily, the historical CI numbers stratify well with the historical frequency of genesis. That is, the greater the CI number, the more likely that a tropical disturbance will eventually undergo cyclogenesis. Since these figures are cumulative, the increase in probabilities with additional lead time suggests that there is the ability to provide reliable probabilistic genesis forecasts out to several days in advance. This utility is essentially limited, however, out to the lead time at which the probabilities start to asymptote—near 5 days, when there are not many available Dvorak classifications (as shown in Fig. 6). Another feature of these probability curves is their smoothness, especially for the Pacific eastern region (Fig. 7b) for which our climatology includes a large number of historical classifications (Table 2). The smaller numbers of classifications in the Pacific central region (Table 2) appear to result in a more jagged appearance in the probability curves (Fig. 7a).

Despite being geographical neighbors, without a physical boundary between them, the genesis characteristics of our Pacific eastern and central regions, divided at 125°W, are quite different. The eastern region has a larger number of historical classifications and higher overall genesis rates (Table 2) than the central region. Not surprisingly, then, the Pacific eastern region yields greater genesis probabilities for a given Dvorak CI number. For example, a disturbance with a Dvorak CI number of 1.0 in the eastern region has a 43% chance of tropical cyclone formation within 48 h, as compared to only 16% in the central region. These results confirm the need for separate probability curves for the Pacific eastern and central regions. They also provide custom rather than combined

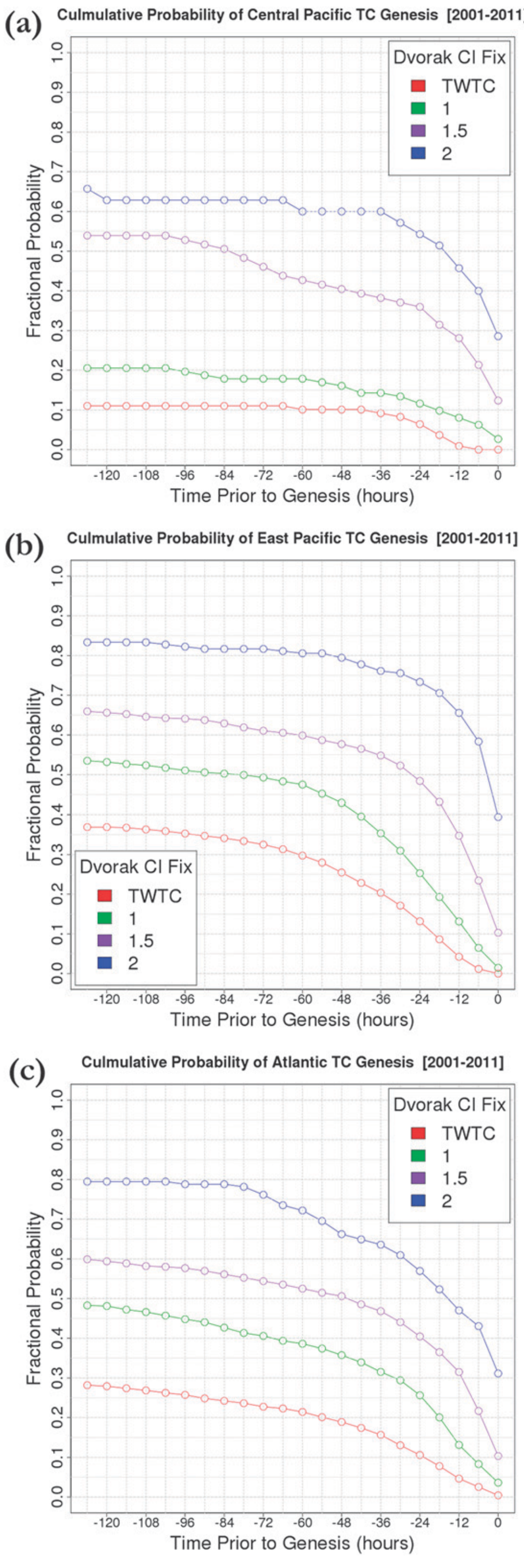

FIG. 7. The climatological rates of genesis using Dvorak CI numbers from TAFB and CPHC from 2001 to 2011 in the (a) Pacific central region (west of 125°W), (b) Pacific eastern region (east of 125°W), and (c) Atlantic basin. The colors represent the Dvorak CI number, as denoted in the legend. The abscissa represents the desired lead time of the genesis forecast and the ordinate plots the genesis probability for a given curve.

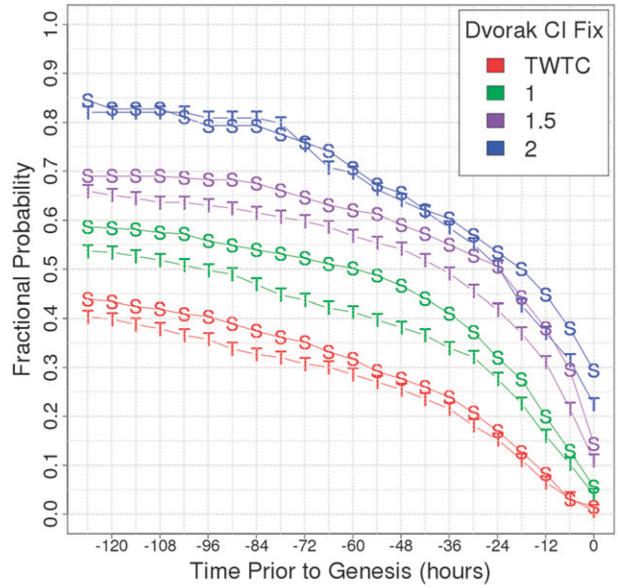

FIG. 8. The climatological rates of genesis using Atlantic Dvorak CI numbers from TAFB (T) and SAB (S) incorporating all available data from the respective agencies during 2005–10. (Thus, the probabilities are calculated using different numbers of Dvorak classifications and are nonhomogeneous.) The colors represent the Dvorak CI number, as denoted in the legend. The abscissa represents the desired lead time of the genesis forecast and the ordinate plots the genesis probability for a given curve.

guidance, based on the physical and operational considerations outlined in section 3c, for the two different TWO products issued separately by NHC and CPHC.

b. Atlantic probabilistic genesis guidance

Figure 7c displays the Atlantic basin's probabilities of TC genesis based on historical TAFB classifications from 2001 to 2011. For comparison to the two Pacific regions, an incipient system with a Dvorak CI number of 1.0 in the Atlantic has a 36% chance of tropical cyclone formation within 48 h. That probability falls in between the corresponding chances in the Pacific central and eastern regions. Figure 8 shows the cumulative probabilities of tropical cyclogenesis in the Atlantic using all available Dvorak fixes from just 2005 to 2010. This shorter time frame accommodates the inclusion of all available SAB historical classifications, and it does not significantly change the probabilities based on TAFB data as compared to those obtained by extending the historical classification dataset back to 2001 (cf. with Fig. 7c).

Despite sharing the same period of record, TAFB and SAB classifications were not always performed at the same time for a given system. The probabilities in Fig. 8 are therefore nonhomogeneous in the sense that all available data were used, and not just overlapping instances of TAFB and SAB classifications. This method is preferred to provide tropical cyclone forecasters with probabilities that are the most representative of the available data in their operational environment. Due to this nonhomogeneity, however, the total sample of SAB data generally has a smaller number of nongenesis entries than that from TAFB. In addition, during this time period TAFB issued more Dvorak fixes than SAB. Thus, the database of TAFB Dvorak classifications contains more information on nondeveloping disturbances and, as a consequence, SAB probabilities based on any given Dvorak classification are generally greater than those derived from TAFB.

The 48-h probabilities for the Atlantic shown in Figs. 7c and 8 fortuitously align rather well with the demarcations between genesis potential categories conveyed in the TWO products from NHC. A system that is classified as TWTC by either TAFB or SAB has, based on historical Dvorak classifications, about a 25% chance of tropical cyclone formation within 48 h, which falls within the ''low'' category (0%–20%, or essentially less than 30%) in the TWO. Similarly, a Dvorak CI number of 1.0 yields a 48-h probability of about 40%–45%, falling into the ''medium'' category of 30%–50%, and CI numbers of 1.5 and greater provide probabilities of at least 55%, corresponding to a ''high'' (greater than 50%) chance of genesis in the TWO. Five-day forecasts are also provided by the Dvorak-based probabilities in Fig. 8, with TWTC cases having about a 40% chance of tropical cyclone formation. Classifiable systems (CI number at least 1.0) are more likely than not to attain genesis within 5 days, including about an 80% chance for CI numbers of 2.0. These results provide basic guidance to the NHC hurricane specialists issuing the TWO, to which they can add value by considering all other available observations and model guidance. Comparisons between these probabilities and the explicit operational genesis forecast probabilities in the TWOs from NHC will be presented in section 4c.

Figure 9 provides the probabilities of genesis when Dvorak estimates from TAFB and SAB agree exactly. Only the particular times at which disturbances have both a TAFB and SAB Dvorak classification are included. In contrast with Fig. 8, Fig. 9 constitutes a homogeneous dataset because the same systems and times are represented by both TAFB and SAB. The general shapes of the curves in Fig. 9 are similar to those in Fig. 8, except for the following notable differences:

1) Disturbances that are shown to be TWTC by both TAFB and SAB have a smaller probability of developing than if only one agency has shown it to be TWTC.
2) In general, if TAFB and SAB agree on an actual Dvorak CI number (1.0 or higher), the probability is higher than if there is the same classification from only one agency.
3) For shorter lead times between 6 and 36 h, a consensus CI number of 1.5 is very similar to the probability given by a single CI number of 2.0.

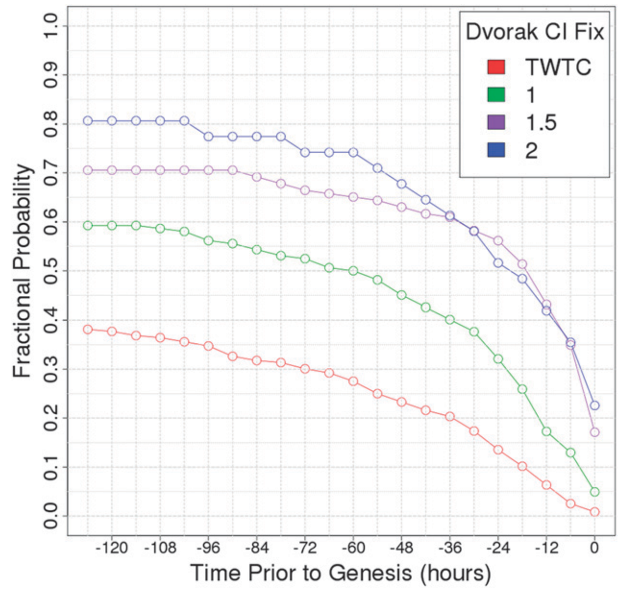

FIG. 9. The climatological rates of genesis using Atlantic Dvorak CI numbers from TAFB and SAB when both agencies share the same intensity estimate during 2005–10 (e.g., both TAFB and SAB show TWTC for the same system at the same time). The probabilities are calculated using the same subset of systems and times and are thus homogeneous. The colors represent the Dvorak CI number, as denoted in the legend. The abscissa represents the desired lead time of the genesis forecast and the ordinate plots the genesis probability for a given curve.

c. *Comparison of Dvorak genesis guidance to operational genesis forecast probabilities*

To show the viability of using Dvorak CI numbers as a forecasting tool for TC genesis, Fig. 10 compares the reliability of the NHC genesis probabilities in the Atlantic TWO products to that of the probabilities developed in this study based on the various combinations of historical Dvorak classifications in the Atlantic basin from TAFB and SAB. For clarity, verification results were not attempted for the eastern and central Pacific since our division between the two basins at 125°W, for reasons described in section 3c, differs from the operational boundary at 140°W. Forecasts from the 2010 and

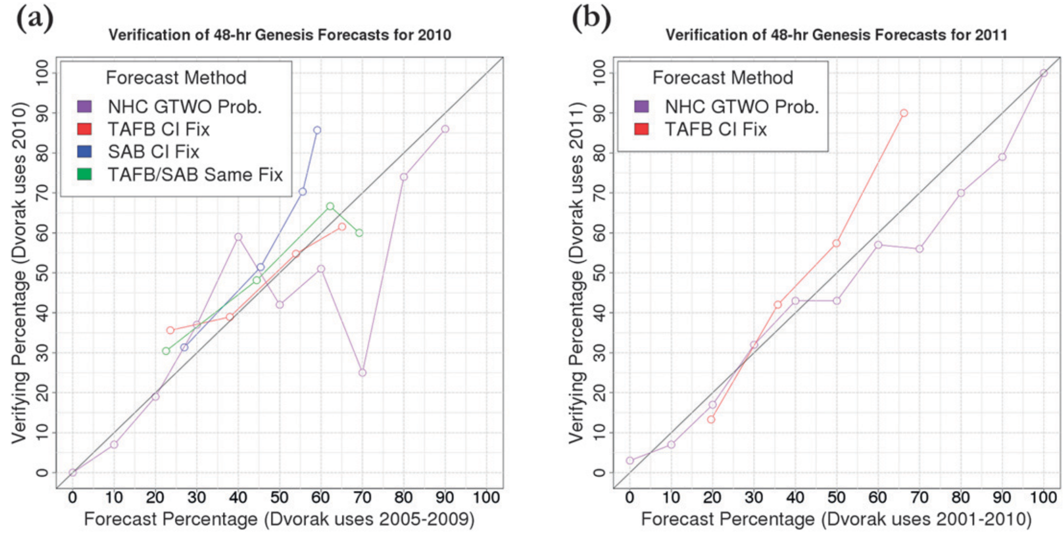

FIG. 10. Genesis verification comparison between NHC forecasts and Dvorak probabilities using all available NHC forecasts and Dvorak fixes (nonhomogeneous). (a) Comparison of genesis verification for the 2010 Atlantic hurricane season between the NHC GTWO probability [purple curve; adapted from Cangialosi and Franklin (2011), where the forecasts are the operational values determined by the hurricane specialists and the verification is the percentage of time the forecast actually occurred], TAFB Dvorak CI fixes (red curve; as in Fig. 8), SAB Dvorak CI fixes (blue curve; as in Fig. 8), and consensus TAFB and SAB fixes that agree (green curve; as in Fig. 9). Forecasts from Dvorak classifications are created from 2005–09 data and verified with 2010 data. (b) 2011 Atlantic hurricane season verification between NHC forecasts (adapted from Cangialosi and Franklin 2012) and TAFB Dvorak fixes (as in Fig. 7c), where Dvorak forecasts are created from 2001–10 data and verified with 2011 data.

2011 Atlantic hurricane seasons are verified, keeping those years completely independent from the years of historical Dvorak classifications used to derive the probabilities based on CI numbers. While Fig. 10b uses the full Dvorak dataset during 2001–10 for 2011 predictions, only classifications from 2005 to 2009 are used as predictors to simulate the available data during the 2010 season (Fig. 10a), as well as to maintain consistency between TAFB and SAB comparisons (the latter agency is only available for that time period). Only the 48-h forecasts are examined, to make the Dvorak-based predictions consistent with those of the NHC TWO forecast time frame. NHC operational forecasts and verification results are adapted from Cangialosi and Franklin (2011, 2012).

Table 4 summarizes the climatological probabilities of genesis within 48 h using the full historical database of TAFB and CPHC Dvorak classifications in each basin. Note that the Atlantic probabilities all fall in between the corresponding values for the eastern and central Pacific, and that they are confined to between 18.9% and 65.1%. Despite the limited range of probabilities that can be generated by the Dvorak-based method, owing to the discrete nature of the CI numbers (i.e., TWTC, 1.0, 1.5, 2.0, rather than a continuous range), probabilities of genesis are generally quite reliable and comparable to NHC forecasts. In Fig. 10a, genesis forecasts using TAFB classifications perform the best, with very reliable forecasts using probabilities corresponding to CI numbers of 1.0, 1.5, and 2.0 (second, third, and fourth circles from the left on the red line). Forecast probabilities near 25% that are based on Dvorak classifications of TWTC (left-most circles on the red, green, and blue lines) from both TAFB and SAB yield an underestimate of the frequency of genesis, however. All SAB-based forecasts in 2010 were biased low by at least 5%; forecast probabilities greater than 50% corresponding to CI numbers of 1.5 and 2.0 were

TABLE 4. Interbasin comparison of cyclogenesis probabilities using all Dvorak data from 2001 to 2011. MEAN, TWTC, 1, 1.5, and 2 refer to the TAFB–CPHC Dvorak CI number of a disturbance, with the associated percentages based on the probability of genesis within 48 h.

	Pacific central region	Pacific eastern region	Atlantic
MEAN (%)	24.9	44.6	33.4
TWTC (<1) (%)	10.1	25.5	18.9
1 (%)	16.1	42.9	35.7
1.5 (%)	40.4	57.7	50.6
2 (%)	60.0	79.4	66.2

much lower than the observed genesis frequencies of greater than 70%. These biases were much less, however, using the consensus forecasts when TAFB and SAB provided concurrent classifications. While NHC performed quite well for forecasts of ≤30% as well as ≥80%, the predictions in between these extremes exhibited some lack of reliability. However, NHC performance in 2011 improved (Fig. 10b), while TAFB predictions verified somewhat higher in 2011 than in previous years for the higher CI numbers. Despite these improvements, NHC forecasters are still reluctant to forecast the middle and higher percentages of genesis [as seen in the refinement distribution in Fig. 16a of Cangialosi and Franklin (2012)]. Since the Dvorak estimates provide more reliable guidance in that difficult middle range of percentages, the guidance provided here could help NHC forecasters increase the reliability in the TWO of the probabilities in that critical range.

5. Concluding summary and future work

Predicting tropical cyclogenesis remains among the most challenging problems facing operational hurricane forecasters. Although a plethora of studies have been performed in this area and various tools have been created in an attempt to address this concern, prior to this study no system-specific genesis forecast guidance product had been developed. While NHC and CPHC have for years given consideration to real-time Dvorak classifications in the course of making their genesis forecasts, this study quantifies the relationships between CI numbers and genesis frequency and, for the first time, provides basic but explicit probabilistic guidance that can be used by NHC and CPHC in issuing their genesis probabilities. Furthermore, to date the forecasters have had very limited access to historical Dvorak classifications and their relationships with past TC formation tendencies. The chief issue with this obstacle stems from the lack of recordkeeping in an electronic or otherwise readily accessible format on nongenesis disturbances until relatively recently. Through this study, both nongenesis and pregenesis systems are incorporated into a single digitized climatology of Dvorak classifications. Pairing that modernized data with the existing historical TC best-track database facilitated the production in this study of both the climatological Dvorak classification statistics and the Dvorak-based genesis probabilities that can be applied to individual systems in an operational forecast mode.

The Dvorak technique, which is used to analyze the organization and intensity of tropical systems, is subjective by design, especially for weaker systems including pregenesis and nongenesis ones. Nevertheless, the method enforces sufficient consistency and constraints to enable reasonably objective comparisons of similar Dvorak classifications from the past. The compilation and quality control of the Dvorak dataset was performed for the North Atlantic, eastern North Pacific, and central North Pacific basins from 2001 to 2011. The dataset includes Dvorak classifications that had been retained as part of the pregenesis fix history of systems that later became TCs (our pregenesis systems), classifications from invests that did not ever become TCs, and classifications from a small number of disturbances not designated as invests. Due to their small sample size, subtropical cases were not analyzed.

The cumulative genesis probabilities products statistically analyze the historical rate of TC genesis based on a disturbance's Dvorak intensity classification and the lead time considered. All of the above results demonstrate fundamental differences in genesis characteristics among the considered regions and provide a climatological baseline that may be used in tropical cyclogenesis forecasting. An analysis of the availability of TAFB and CPHC Dvorak classifications before TC genesis (Table 3 and Fig. 6) shows that, on average, there is only 1–2 days of lead time from the first Dvorak fixes up to the time of cyclogenesis. Despite this data limitation, probabilities of genesis calculated by these historical Dvorak classifications scale well with different CI numbers through lead times of 5 days before leveling off (Fig. 7). Consensus forecasting with SAB Dvorak fixes (Figs. 8 and 9) can add value as well. In particular, the 48-h probabilities have operational value for NHC and CPHC forecasts and can be compared to their efforts. Verification of the 2010 and 2011 Atlantic seasons (Fig. 10) shows that Dvorak CI numbers provide a reliable climatological metric for genesis likelihood, which can be used to inform NHC forecasts, especially in the middle probability ranges. The 48-h probabilities for each basin and operationally applicable CI number are summarized in Table 4.

The detailed climatological and environmental differences between and within TC basins, and the complexities in the relationships between Dvorak classifications and genesis occurrence and timing, strongly suggest there is a great opportunity to improve upon this admittedly basic genesis forecasting tool. Possible future work includes expanding the dataset back in time through the digitization of a longer historical period of archived Dvorak fixes, analysis of Dvorak fixes by other agencies (such as by other RSMCs or JTWC) for worldwide genesis probabilities, and further research into additional statistics to better determine forecast analogs.

Perhaps most importantly, our climatology of Dvorak estimates and the resulting genesis probabilities have been specifically intended from the outset to be used as a baseline by which to assess the performance of more elaborate, operational genesis prediction schemes using many more predictors, such as in ongoing work by Dunion et al. (2012a,b). Much like the SHIPS model (DeMaria et al. 2005), which uses input from dynamical models and statistical relationships between storm behavior and environmental conditions to predict TC intensity change, the objective genesis guidance could incorporate input from both numerical model guidance and Dvorak development rates to produce better probabilistic genesis guidance. In fact, preliminary JHT research testing (Dunion et al. 2012a) shows Dvorak information providing the highest skill at differentiating between developing and nondeveloping cases in a multiparameter statistical genesis scheme. Further, as dynamical models, including ensembles with many members, eventually gain more skill in explicitly forecasting tropical cyclogenesis, they could perhaps be used someday to directly generate genesis probabilities, and their reliability could be assessed relative to the results from our technique. The Dvorak dataset itself can be used in other capacities, such as a location and intensity reference database of tropical disturbances. For example, efforts to extend objective intensity analyses such as the advanced Dvorak technique (ADT; Olander and Velden 2007) to pregenesis disturbances may be informed and constrained by our collection of subjective Dvorak analyses.

As the coastal population continues to increase, evacuation clearance times grow longer and longer. In 2010, the National Weather Service and NHC increased the lead time of their tropical storm and hurricane watches (now 48 h) and warnings (now 36 h) to provide earlier support to evacuation orders from emergency management agencies and to generally encourage coastal residents to prepare sooner for tropical cyclone impacts (OFCM 2010). However, for TCs that develop close to land and impact a coastal region within a day or two thereafter, less advance warning is given. It is in these situations when more accurate and timely TC genesis guidance is especially needed. Not surprisingly, some emergency managers have expressed the desire for additional product enhancements with longer lead times when TCs develop near land. Improved TC genesis forecasts could eventually allow the NHC and local NWS forecast offices to begin issuing watches and warnings before TC formation. In 2011, NHC began creating in-house track, intensity, and size (wind radii) forecasts for disturbances that were deemed likely to develop into a TC within 48 h. This could be the initial step toward someday issuing TC watches and/or warnings for systems that are not yet a TC. Hurricanes Humberto (2007) and Tomas (2010) are recent examples of systems that developed, rapidly strengthened, and affected land as a hurricane, all within about 24 h. Through further scientific research and operational product development, the rudimentary TC genesis forecast tool provided by Dvorak classifications shown here could directly contribute to more expanded and advanced cyclogenesis forecasting tools to help extend and improve TC warning lead time.

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