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THESIS

**APPLICATION OF TROPICAL CYCLONE LIFE-CYCLE
PREDICTIONS FROM PRE-FORMATION STAGE:
EASTERN NORTH PACIFIC 2021 SEASON**

by

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March 2022

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**APPLICATION OF TROPICAL CYCLONE LIFE-CYCLE PREDICTIONS
FROM PRE-FORMATION STAGE: EASTERN NORTH PACIFIC 2021 SEASON**

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ABSTRACT

This thesis documents advancements made during the 2021 season test of pre-formation tropical cyclone (TC) forecasts in the eastern North Pacific (ENP) using Marchok vortex tracker outputs from the European Centre for Medium-Range Weather Forecasts ensemble. Critical Warm Core Magnitude thresholds are established to predict Time-to-Formation and Time-to-Hurricane timings and positions along 15-day Weighted-Mean Vector Motion ensemble tracks. This thesis develops and tests a decision flowchart to assist forecasters in the critical task to efficiently select the pre-formation ensemble storms most likely to become TCs, and to non-select false alarm storms. The flowchart effectiveness is demonstrated, and validations of these techniques are provided for hurricanes Enrique and Felicia, strong Tropical Storm (TS) Guillermo and weak TS Jimena, and a non-developing disturbance. Thus, an opportunity exists for TC warning centers to provide accurate long-range intensity and track predictions of potential TCs from the pre-formation stage. This thesis is prepared as guidance to forecasters to facilitate integration of these techniques into operational centers and increase forecast confidence at much earlier stages of developing and non-developing TCs. While this thesis confirms the effectiveness of this forecast process for ENP pre-formation TCs, the findings suggest a promising capability for application in other basins.

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LIST OF ACRONYMS AND ABBREVIATIONS

AOR	area of responsibility
CPHC	Central Pacific Hurricane Center
DOD	Department of Defense
ECEPS	ECMWF ensemble prediction system
ECMWF	European Centre for Medium-Range Weather Forecast
ENP	Eastern North Pacific
ERC	eyewall replacement cycles
GEFS	Global Ensemble Forecast System
JTWC	Joint Typhoon Warning Center
LSC	Likely Storm Category
NHC	National Hurricane Center
NOAA	National Oceanic and Atmospheric Administration
RI	rapid intensification
SST	sea-surface temperature
T2F	Time-to-Formation
T2H	Time-to-Hurricane
TC	tropical cyclone
TUTT	tropical upper-tropospheric trough
TWO	Tropical Weather Outlook
VWS	vertical wind shear
WBT	working best track
WCM	Warm Core Magnitude
WMO	World Meteorological Organization
WMVM	Weighted-Mean Vector Motion
WNP	Western North Pacific

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I. INTRODUCTION

A. MOTIVATION AND HYPOTHESES

Tropical cyclones (TCs) cause devastating impacts to people, property, and resources every year across the globe. Correct forecasts are crucial for mitigating the damage caused by TC threats such as strong winds, storm surge, heavy rainfall, and tornadoes. Early formation detection and accurate track and intensity forecasts early in the TC's life cycle can inform the public and allow time for effective storm preparation measures. The United States Department of Defense (DOD) is also a significant stakeholder in early TC detection and accurate predictions of TC development. Early and accurate forecasts are crucial to minimizing the potential operational impacts and damage to DOD personnel and assets through timely and cost-effective resource protection measures. Additionally, high confidence forecasts of the non-developing tropical disturbances can prevent initiating unnecessary protective actions and spending on storm preparation, which saves money and resources and allows DOD personnel uninterrupted focus on their primary missions.

Tropical cyclone prediction has always presented a unique challenge and has captivated the interest of forecasters worldwide. Thus, tremendous efforts have been put forth to improve these forecasts. The scientific community's continued interest in the persistent problem of early formation detection, and demonstrating the opportunity for early and accurate forecasts, are the primary motivators of this study. A review in Hendricks et al. (2019) describes some notable research advances on tropical cyclone intensity change, and specifically the "improved understanding of the role of vertical wind shear (VWS) and its impact on convection, surface fluxes, ocean eddies, dry/dusty air intrusions, eyewall replacement cycles (ERCs), spiral rainband dynamics, eyewall instability and inner-core mixing, and the mechanisms by which TCs intensify." As summarized in Hendricks et al. (2019), recommendations to the research community and to the World Meteorological Organization (WMO) include advancing visualization and integration of enhanced forecast guidance, developing models and techniques, ensemble approaches for probabilistic output, and best practices in handling difficult cases, and

finally, integrating these research advances into operational centers to ultimately improve the forecasts of those operational centers.

As summarized by Gray (1975), the six physical conditions required for tropical cyclone formation are the following: sufficiently warm sea-surface temperatures (SSTs) to a depth of 60 m, low-level relative vorticity, the effect of the Coriolis parameter, moist instability from the surface to 500 mb, weak vertical wind shear, and high mid-tropospheric relative humidity. The World Meteorological Organization (2017) defines the seven typical TC formation areas as the following: North Atlantic, Eastern and Central North Pacific, Western North Pacific, North Indian, Southwest Indian, Australian and Southeast Indian, and Australian and Southwest Pacific. The boundaries of these basins of TC formation along with some typical TC tracks are illustrated in Figure 1.

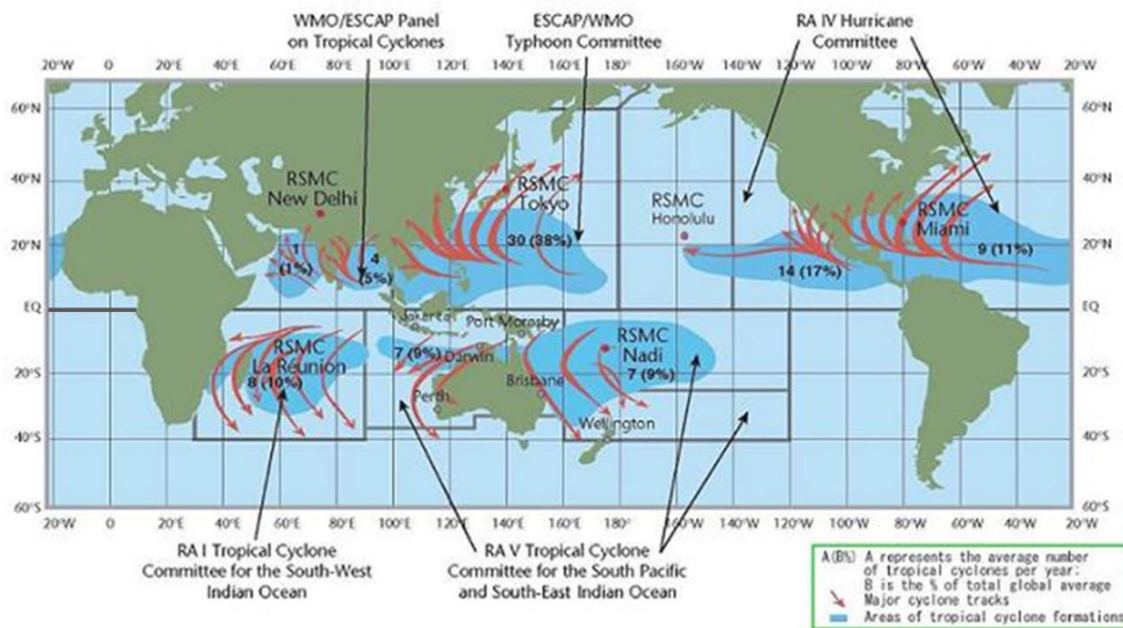


Figure 1. Areas of Tropical Cyclone Formation.
Source: World Meteorological Organization (2020).

The focus of this study is the TCs in the eastern North Pacific (ENP) basin because improved TC forecasts in ENP would be particularly valuable and practically useful due to the many DOD assets located in Hawai'i as well as maritime assets throughout the region.

Specifically, Joint Base Pearl Harbor-Hickam is the primary U.S. mobility hub in the Pacific and is one of the U.S. Navy's busiest harbors (US Navy 2015).

Most tropical cyclones within the Eastern and Central North Pacific typically begin as tropical disturbances that form in the favorable region of the far eastern ENP, just south of the Gulf of Tehuantepec. The range of subsequent TC tracks from the Gulf of Tehuantepec formation area is illustrated in Figure 2.

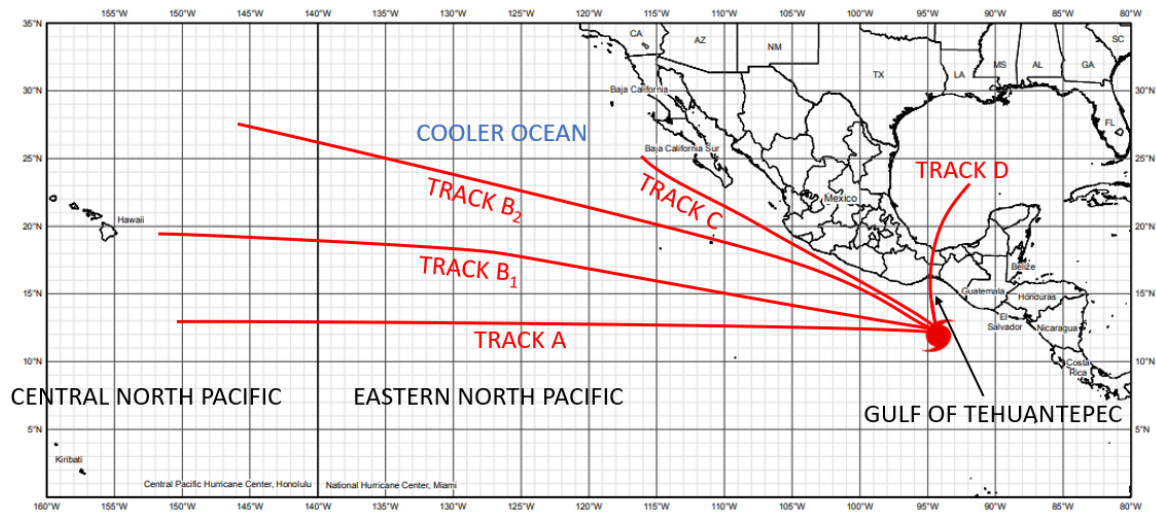


Figure 2. Range of Typical Eastern North Pacific TC Tracks

Track D is representative of a typical landfalling TC into southern Mexico or surrounding areas. These TCs are often difficult cases to predict as they frequently make landfall shortly following formation. Tracks C and B₂ and represent tracks that decay for reasons other than landfall, but still may bring significant TC impacts to the southwestern coastline of Mexico and/or Baja California. These TCs track generally northwestward into a cooler ocean region poleward of an ocean thermal front that extends westward from the southern tip of Baja California and eventually these TCs decay primarily due to a lack of warm SSTs, and therefore the thermal energy that supports TC development. Track B₁ is representative of a TC that does not become too inhibited by cooler ocean poleward, and perhaps is aided in development by a subtropical trough or tropical upper-tropospheric trough (TUTT), and therefore sustains intensity on a track generally west-northwestward.

The TCs that may potentially impact Hawai'i are most likely similar to those that take a track similar to Track B₁. Track A is representative of a long-lived TC with a westward track that crosses into the Central North Pacific at a low enough latitude so as not to pose a major threat to DOD assets in and near Hawai'i.

Most TC warning centers across the globe advise the public with probability guidance ahead of possible TC formation. As indicated in Figure 3, the Joint Typhoon Warning Center (JTWC) uses “Low,” “Medium,” and “High” development likelihood designations (Joint Typhoon Warning Center 2022). A “Low” likelihood indicates that development of a suspect area as a TC is unlikely within 24 hours. A “Medium” likelihood indicates that TC development is likely to occur, but not within 24 hours. A “High” likelihood indicates that TC development is likely within 24 hours and JTWC will issue a TC Formation Alert.

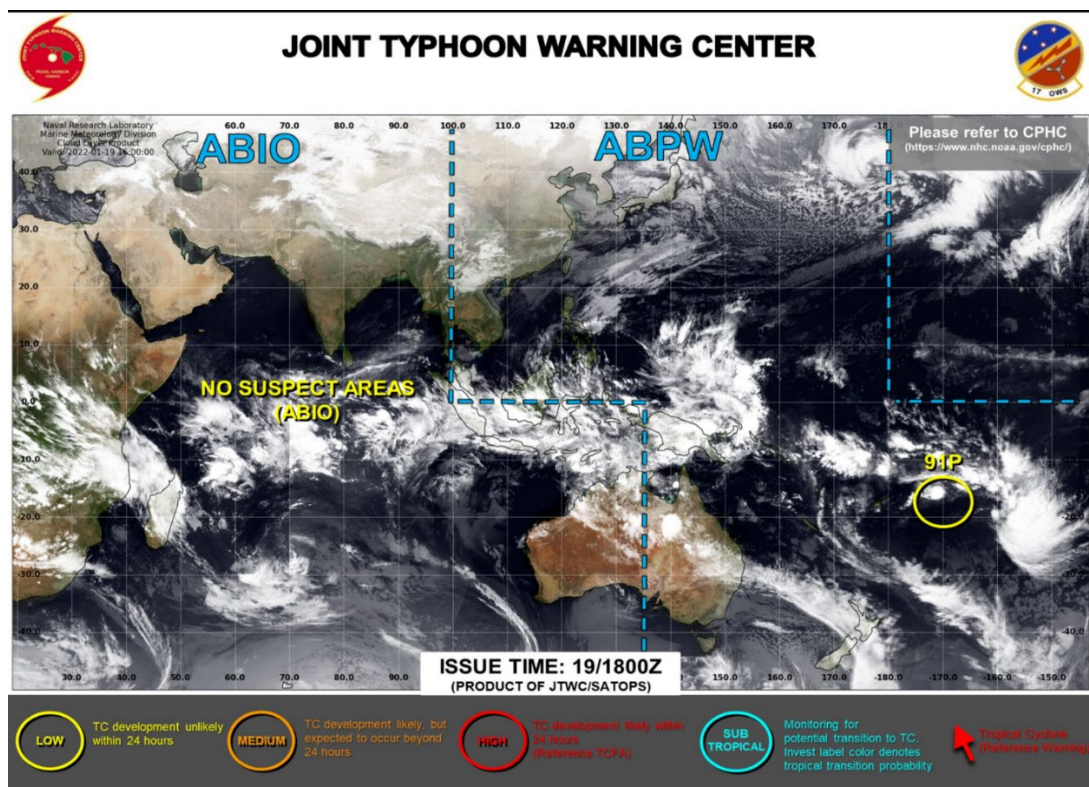


Figure 3. JTWC Significant Tropical Weather Advisory 91P,
Issued at 1800Z on January 19, 2022.
Source: Joint Typhoon Warning Center (2022).

The National Hurricane Center (NHC) in Miami, Florida, is responsible for TC Advisories in the ENP out to 140°W, and the Central Pacific Hurricane Center (CPHC) in Honolulu, Hawai'i, has responsibility for TCs west of 140°W. The advisories issued by the NHC and CPHC every six hours (0300, 0900, 1500, and 2100 UTC) provide information on all current tropical and subtropical cyclones including the following: associated watches and warnings, current latitude and longitude coordinates, intensity, motion, and forecasts of these criteria for 12, 24, 36, 48, 60, and 72 hours from the advisory time (National Hurricane Center 2021a). In addition to advisories, these two centers issue Tropical Weather Outlooks (TWOs) for two-day and five-day lead-times. They use “formation chance,” which is broken down into less than 40% chance, 40–60% chance, and greater than 60% chance categories (National Hurricane Center 2021b). See Figure 4 for an example of the large potential formation regions, and a rough indication of the track direction, that are forecast, at a maximum, five days in advance.

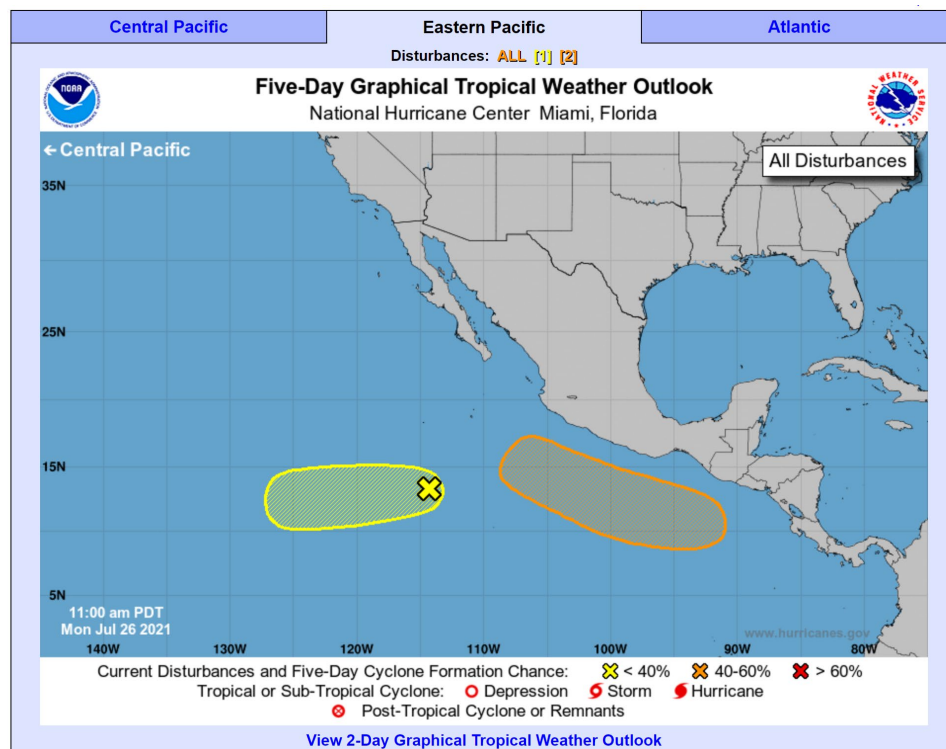


Figure 4. NHC Five-Day Graphical Tropical Weather Outlook, Issued at 11:00 am PDT on July 26, 2021. Source: National Hurricane Center (2021b).

These types of long-range products have the potential to be improved by more accurate and more comprehensive early detection forecasts that can articulate greater detail of the overall expected track direction and intensity evolution and final ending-stage during pre-formation and the early stages of development.

B. BACKGROUND

A recent survey by Titley et al. (2019) among 25 TC warning centers worldwide found that almost all of these warning centers utilize dynamic model ensemble forecasts for early TC formation detection. Typically, the dynamic model ensembles are a collection of multiple model members, each of which has been perturbed in unique ways to represent uncertainty in the initial conditions and uncertainty arising from imperfections in the model physics and parameterizations. The Titley et al. (2019) survey revealed that the most frequently used ensemble product was the simple ensemble mean. While dynamic ensembles are illustrative of the scope of possible outcomes, the simple ensemble mean that takes the basic average of all the members and values them equally implies that each ensemble member's forecast is equally likely. In contrast, Elsberry et al. (2020) utilized the Weighted-Mean Vector Motion (WMVM) track forecast technique that assigns a weighting factor that is proportional to the likely accuracy of each member's track forecast. That is, the 12-hour motion vector of each member is compared to the previous 12-hour WMVM vector, and greater (lesser) weight is assigned to those members tracks that are closest to (farthest from) that WMVM vector.

Elsberry et al. (2020) applied this WMVM technique to track forecasts from the European Centre for Medium-Range Weather Forecasts (ECMWF) ensemble prediction system (ECEPS), which are available from the Marchok vortex tracker files. The Marchok (2021) tracker is an advanced tracking method over the Marchok (2002) tracker that filtered digital numerical weather prediction (NWP) model data to create forecast guidance based on standard metrics including the predicted track, minimum sea level pressure (MSLP), maximum near-surface wind speed, and near-surface wind structure diagnostics for existing TCs (Elsberry et al. 2020). Thus, the Marchok (2021) vortex tracker algorithm extracts information on seven parameters: MSLP, 700 mb and 850 mb relative vorticity,

700 mb and 850 mb geopotential height, and the minimum average windspeed at 700 mb and 850 mb to create predicted track and intensity forecast outputs (Marchok 2021). In addition to calculating the WMVM track forecasts, Elsberry et al. (2020) used the Marchok vortex tracker files to calculate the ECEPS-predicted weighted-mean intensities along the WMVM track utilizing the same weighting factors the WMVM track was calculated.

Rather than also calculating the Time-to-Formation of 35 kt [T2F (35 kt)] directly from a weighted-mean ECEPS-predicted intensity as for the T2F (25 kt), Elsberry et al. (2020) used two of the Hart (2003) Cyclone Phase Space parameters also available from the Marchok vortex tracker to define a weighted-mean Warm Core Magnitude (WCM, in units of $\text{m s}^{-1} \text{mb}^{-1}$) along the WMVM track. Two layers determine the WCM: lower-layer (900-600 mb) warm core and upper-layer (600–300 mb) warm core. For a warm-core TC, these metrics are positive, and for a cold-core extratropical cyclone or a tropical upper-tropospheric trough, they are negative (Hart 2003). Elsberry et al. (2020) weighted the upper-layer (600–300 mb) warm core twice as heavily as that of the lower-layer (900-600 mb) in order to represent the $(1/p)$ component of the hypsometric relation. As a pre-TC circulation in the ECEPS enters a favorable environment for TC formation, the ECEPS-predicted WCM evolution will suddenly increase from near-zero values. Based on a 2019 season development sample of Joint Typhoon Warning Center (JTWC) Tropical Storm formations correlated with the ECEPS-predicted WCM evolutions, Elsberry et al. (2020) established the WCM threshold value for a Tropical Storm. Similarly, a WCM threshold for Typhoon intensity was defined, and thus the maximum WCM value along the WMVM track throughout the storm’s projected life cycle can be used to infer the Likely Storm Category (LSC) as either a Tropical Storm or as a Typhoon.

In summary, Elsberry et al. (2020) used Marchok vortex tracker outputs from 15-day ECEPS forecasts for early detection and forecasting of pre-TC circulation Time-to-Formation (T2F) and Time-to-Hurricane (T2H) timings and locations along the WMVM track forecasts. These ensemble-based guidance products developed by Elsberry et al. (2020) were validated for several Typhoons and Tropical Storms in the western North Pacific (WNP). In evaluating the forecasts for these T2F and T2H times and locations, Elsberry et al. (2020) ultimately found that if the timing errors are small, the position errors

will also be small. Elsberry et al. (2020) also provided an eastern North Pacific example of pre-Hurricane Kiko (2019), which had a type B₁ Track in Figure 2. An ECEPS pre-formation forecast initiated four days prior to formation correctly predicted the T2F (35) timing with a position that verified just 1.0° latitude to the south and 0.5° longitude to the west. Furthermore, the ECEPS-predicted WCM evolution was indicative of an LSC of Hurricane and the ECEPS 15-day WMVM track forecast indicated Hurricane Kiko would pass west of 140° into the area of responsibility (AOR) of the Central Pacific Hurricane Center (CPHC) and threaten Hawai'i.

Elsberry et al. (2021) extended these WNP techniques by using the ECEPS-predicted WCM evolutions to predict not only the T2F (35) but also the T2H timing and thereby infer rapid intensification (RI) events following formation. In that study, RI was defined as a maximum sustained windspeed increase of ≥ 30 kt occurring within 24 hours. It was documented that the predicted [T2H–T2F (35)] time difference was often very effective in indicating a RI event that occurred following formation in the western North Pacific (Elsberry et al. 2021).

C. OBJECTIVES

Elsberry et al. (2022), and this thesis have transitioned the WNP techniques to the ENP with adjustments to account for the uniqueness of this basin of interest. The original WCM thresholds assigned to T2F (35) and T2H based on extensive case studies using the Global Ensemble Forecast System (GEFS) forecasts for the 2017 WNP typhoon season were then recalibrated by Elsberry et al. (2020) during the 2019 WNP typhoon season. After similar testing, the WCM threshold for T2H in the WNP of 46.0 was adjusted to 37.0 for the ENP pre-TC circulation. Additionally, Elsberry et al. (2022) and this study for the first time implemented validations of ending-storm predictions, which are based on the hypothesis that these WCM thresholds, which successfully estimated pre-formation T2F (35) and T2H timings and positions, could correspond in the same way to the ending-T2H and ending-T2F (35) timings and positions along the WMVM during the decay stage of the TC.

As in Elsberry et al. (2022), this thesis utilizes Marchok vortex tracker output from the ECEPS to provide insights on the track and intensity through the forecast life cycle of pre-formation tropical disturbances in the ENP for up to 15 days. This thesis demonstrates ECEPS forecasts of T2F and T2H along WMVM track forecasts of up to 15 days and provides comparisons with National Hurricane Center (NHC) predictions to document the ECEPS capability for earlier T2F and T2H predictions. Elsberry et al. (2022), in conjunction with this thesis, explore the applications of these techniques to the developing and non-developing storms of the 2021 ENP hurricane season. Partial results have been submitted for publication by Elsberry et al. (2022). Additional results and implications to forecasters will be discussed in this paper.

The objective of this thesis is to develop a systematic scenario-based approach to interpreting and applying the ECEPS outputs to provide guidance for producing ensemble-based forecast guidance during the pre-formation stage of tropical disturbances. This thesis emphasizes the opportunity for early pre-formation TC detection and documents improvements in early pre-formation TC life cycle forecasts for forming and non-forming tropical disturbances. Of course, the decision to issue an advisory would not be based on these techniques and the resulting products alone. Many other resources must be consulted in real time by the forecasters, and a level of confidence in the forecast and temporal consistency must be reached before issuance of alerts, advisories, or warnings. This product is meant to supplement existing forecast tools such as the Dvorak technique, other deterministic and ensemble synoptic models, and dynamical and statistical schemes.

In the pre-formation stages of a potential TC, this process will help with initial detection of a potential disturbance and increase forecasters' confidence levels in the decision to issue or not to issue an advisory, or to include or not include them in long-range forecast products.

Another objective of this thesis is to explore the ways in which implementation would markedly improve forecasts and ultimately bring about longer lead-time forecasts of TCs. Utilizing the techniques detailed in Elsberry et al. (2022) and the findings from this thesis, intensity and track forecasts have the potential to be improved in pre-formation forecasts of potential TCs. This thesis includes validations of these techniques in the ENP

as a tool to facilitate the integration of these techniques and accompanying advancements of early TC detection and forecasting into operational centers such as the National Hurricane Center (NHC) and Joint Typhoon Warning Center (JTWC).

Chapter II details the methodology including datasets and ECEPS forecast processing. A decision flowchart, which was developed through analysis of this 2021 eastern North Pacific hurricane season by these methods, is presented in Chapter II for operational application. Chapter III demonstrates application of the decision flowchart to evaluate the Marchok vortex tracker output from the ECEPS to determine if the potential storms are valid and should be watched or issued upon, or if they are not likely to form and should not be issued upon. Chapter III also provides objective verifications of the resultant ECEPS forecasts for several categories of storms (hurricane, strong tropical storm, weak tropical storm, and non-developer) analyzed through their life cycles. Chapter III finally identifies the margin for potential improvement of advisories if this technique is implemented, based on these NHC advisories of tropical disturbances in the eastern North Pacific during 2021. A summary and the conclusions of the thesis are provided in Chapter IV, as well as recommendations for potential future work to be done to apply these methods and to improve this technique even further.

II. METHODOLOGY

A. DATASETS

As indicated in Figure 1, the eastern North Pacific (ENP) basin that extends westward from Central America and Mexico to 140°W falls under the National Hurricane Center’s (NHC) area of responsibility (AOR). Climatologically, the active period for TC activity in this basin is 15 May to 30 November (National Hurricane Center 2020). In 2021, there were 19 storms that developed in the eastern North Pacific basin, eight of which formed into hurricanes, and two of which were major hurricanes. One of the tropical storms was Marty that formed in mid-August from the remnants of Hurricane Grace that existed in the Atlantic. Therefore, the early formation detection techniques detailed in this study will not be used to evaluate Marty. These 19 storms represent an overall above-average number of named storms for the 2021 eastern North Pacific hurricane season, as well as an average number of hurricanes, but a below-average number of major hurricanes (Hurricane Specialist Unit 2021).

Historical TC tracks from the NHC working best track (WBT) database will be used, which is consistent with previous studies of similar interest. As will be described below in Section II.B, these eight hurricanes of the season were forecast in real time throughout the season, as well as the 10 tropical storms (all excluding Marty). Additionally, several cases of non-developing storms in the eastern North Pacific basin during the 2021 season were forecast and one will be documented in Chapter VI.

The ensemble model used is the 15-day European Centre for Medium-range Weather Forecasts (ECMWF) ensemble prediction system (ECEPS), which contains 51 ensemble members. Yamaguchi et al. (2015) evaluated the skill of several operational global medium-range ensembles in forecasting TC activity and established that the ECEPS is the most proficient single-model ensemble with skill extending into Week two. The ECEPS was used by Elsberry et al. (2020) for this reason, and it is used in this study with the same justification.

During 2021, there were no storms that formed in the Central Pacific Hurricane Center's (CPHC) AOR, which extends from 140°W westward to the International Date Line (Figure 1). The 2021 hurricane season outlook issued by the National Oceanic and Atmospheric Administration (NOAA) anticipated two to five tropical cyclones in the central North Pacific basin during the 2021 season (Bravender 2021). Three tropical cyclones that formed in the eastern North Pacific moved into the CPHC AOR during the season: Felicia as a Tropical Depression; Jimena as a Tropical Depression; and Linda as a Tropical Storm (Bravender 2021).

B. OPERATIONS DURING 2021 SEASON

As described in Section I.B, Elsberry et al. (2020) had focused on the western North Pacific TCs in developing and testing the T2F (25) and T2F (35) timings and positions along the 15-day ECEPS WMVM track forecasts. However, Elsberry et al. (2020) had also included the example of pre-Hurricane Kiko (2019) in the ENP primarily to demonstrate the capability of the ECEPS to predict not only the T2F (25) and T2F (35) in the far ENP, but also that the subsequent 15-day WMVM track forecast could approach Hawai'i. Although Elsberry et al. (2020) mention that the ECEPS-predicted WCM evolution indicated that Kiko might continue at hurricane intensity until two days before the end of the 15-day forecast, that was based on a WCM threshold for hurricanes that was revised after evaluating more ECEPS forecasts during the 2021 ENP season.

In May 2021, Professors Elsberry and Tsai were granted another Office of Naval Research (ONR) project entitled "Early guidance of tropical cyclone formation with accompanying track and seven-day intensity forecasts." The first-year objective of that new ONR project was to transition the western North Pacific (WNP) TC formation guidance product to the eastern North Pacific (ENP). Although that first work task anticipated that an ENP version of the WNP seven-day Weighted Analog Intensity Prediction (WAIP) technique would be developed, that intensity prediction transition is not part of this thesis. Rather, a near-real time demonstration of the ECEPS WMVM track forecasts and the T2F (25), T2F (35), and T2H for the ENP tropical cyclones was planned based on the success of the pre-Hurricane Kiko (2019) forecast in Elsberry et al. (2020). The data flow through

various agencies or groups, and the procedures, functions, and products contributing to them, that allowed such a near-real time demonstration for the ENP 2021 season TCs is summarized in Table 1.

Table 1. Dataflow for Near-real Time ECEPS Forecasts of T2F and T2H in ENP

Time	Agency/Group	Procedures, functions, and products
T+5	ECMWF ensemble prediction system	After assimilating all possible observations, the ECMWF deterministic model is integrated and that model is the control for the ECEPS, and that control is perturbed to create 50 separate ensemble member forecasts that are available each 12 hours on the ECMWF website.
T+8	National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory—Tim Marchok	Marchok vortex tracker is applied to the control and 50 other ECEPS ensemble member forecasts each 6 hours from T=0 to T+15 hours. In addition to the latitude and longitude positions of the initial and predicted variables, the intensity and other intensity-relevant variables such as the Hart (2003) parameters are provided on the Marchok website.
T+10	Tamkang University, New Taipei City, Taiwan—Prof Hsiao-Chung Tsai	Similar pre-TC circulations are combined and Weighted-Mean Vector Motion (WMVM) ensemble storm track forecasts are calculated and the weighted-mean Warm Core Magnitude (WCM) of each ensemble storm is calculated along the WMVM track forecasts. Plots of the WMVM tracks and WCMs are provided with digital values each six hours in tables. The T2F (25), T2F (35), and T2H are summarized for each ensemble storm that has at least three ensemble members and persists for at least three days.
T+12	Naval Postgraduate School—Capt Corie Capalbo and University of Colorado—Colorado Springs—Prof Russell Elsberry	ECEPS pre-TC circulation WMVM track forecast plots for 15 days, and the combined track and WCM plots and summary tables for each ensemble storm for the Day 0 to Day 7 period prepared by Hsiao-Chung Tsai are evaluated to select the most likely pre-TC circulation ensemble storms to become Tropical Storms and to discard (non-select) the likely non-developers and false alarms. Summary tables of the characteristics of these ensemble storms and their T2F and T2H timings and positions are prepared to simulate evaluation procedures for operational implementations.

A rough timeline of the preparation and availability of the ECEPS forecasts is given in the left column. Since the ECMWF ensemble is not run until after a high-resolution deterministic model forecast to 10 days is completed, and then the control and 50 separate ensemble model forecasts are run to 15 days, the ECEPS raw data sets are not available until at least five hours after the 00 UTC and 12 UTC synoptic times. Tim Marchok applies his vortex tracker not only to the ECEPS forecast files, he also applies his vortex tracker to the National Centers for Environmental Prediction (NCEP) Global Ensemble Forecast System (GEFS) 16-day forecast files. In addition to over-ocean TC and subtropical cyclones, the Marchok vortex track includes (over-land) extratropical cyclone developments. The additional calculations of vorticity, intensity, and the genesis parameters that are utilized to calculate the WCM along the track forecasts require a lot of time. Professor Hsiao-Chung Tsai's team at the Tamkang University in Taiwan then creates the WMVM track forecasts, the WCM evolutions, and calculates the T2F (25) and the T2F (35) along those WMVM track forecasts, and not just for the ENP, but also for the western North Pacific, central North Pacific, and the Atlantic. Finally at about 12 hours after the 00 UTC or 12 UTC synoptic times, the ECEPS pre-circulation WMVM 15-day track plot and the combined track plot and WCM plot (plus 7-day digital files) with the T2F (25) and the T2F (35) timings and positions arrive at the Naval Postgraduate School (NPS) and the University of Colorado—Colorado Springs (UCCS). Capt Corie Capalbo, USAF, at NPS and Prof Russell Elsberry at UCCS then alternate the evaluations of the ECEPS forecasts of the pre-TC circulations in the ENP, with Prof Elsberry evaluating the 00 UTC forecasts and Capt Capalbo evaluating the 12 UTC forecasts.

Elsberry et al. (2022) describe the original format ECEPS validation summary for pre-Hurricane Linda that is similar to the ECEPS validation summary for pre-Hurricane Kiko in Elsberry et al. (2020). Elsberry et al. (2022) note that after evaluating only the first few 2021 ENP Hurricanes, the original $WCM = 43.7$ threshold for the T2H was changed to 37.0. While a smaller $WCM = 20$ threshold [earlier achievement of T2F (35)] timing and associated position was retained in this thesis for some slower-developing Tropical Storms, a larger $WCM = 25.0$ threshold for T2F (35) will generally be utilized in this thesis. Thus, the Likely Storm Category (LSC) will be defined as: Tropical Depression maximum

WCM < 25.0; Tropical Storm $25.0 \leq \text{WCM} \leq 37.0$; and Hurricane maximum WCM > 37.0. It is with this maximum WCM threshold for an ENP Hurricane that the Time-to-Hurricane (T2H) will be calculated and following Elsberry et al. (2021) the time difference [T2H–T2F (35) ≤ 24 hours] will be defined as an indicator of a RI event following formation in the ENP.

C. PROVISION OF ENDING-STORM STAGE T2H AND T2F (35)

A major innovation in the Elsberry et al. (2022) study was providing for the first time the timing and position along the 15-day ECEPS WMVM track forecast at which hurricane-force winds, and later the 35 kt winds, will end for each hurricane. The Elsberry et al. (2022) hypothesis was that if the ECEPS-predicted weighted-mean WCM evolution could be utilized to accurately estimate the pre-formation T2F (35) and T2H timings and positions along the WMVM track forecast, then the same WCM thresholds could be applied to provide useful estimates of the ending-storm T2H and T2F (35) timings and positions at the end of the WMVM track forecast. Elsberry et al. (2022) emphasize that since these are 15-day ECEPS forecasts, and the life cycle of many eastern North Pacific TCs is often less than 15 days, these ECEPS forecasts have the potential for be life-cycle forecasts. While the focus of this thesis is on assisting forecasters in the selection of the pre-TC circulation in the ECEPS forecast that will become a Tropical Storm with the potential to later become a hurricane, these ending-storm stage T2H and T2F (35) along the 15-day WMVM track forecasts provide guidance as to what specific regions may be threatened by (or may escape) a hurricane. When the forecaster is making a decision as to whether/when to issue an alert, an advisory, or a warning regarding that pre-TC circulation, it will be helpful to know when and where hurricane-force winds will begin and will end. If there will be an early landfall, or an early threat to maritime activities, that forecaster may be well-advised to issue that early alert, advisory, or even a warning.

Elsberry et al. (2020) provide a comprehensive description of the ending-stage Hurricane Linda that the ECEPS predicted would threaten Hawai'i within the 15-day forecast periods. Although the early 15-day forecasts indicated that Linda would not continue to be a hurricane as it approached Hawai'i, the ECEPS forecasts initiated after

Linda became a Tropical Storm suddenly predicted the ending-T2H time would be much later. Thus, this was a nine day in advance prediction that Linda could still be a hurricane as it approached Hawai'i. Considering the potential damage to DOD assets throughout the Hawaiian Islands, the forecaster would likely want to issue an alert as soon as the ECEPS predicted such a WMVM track with an ending-stage storm with hurricane-force winds approaching Hawai'i.

D. DETECTION AND ELIMINATION OF CARIBBEAN FALSE ALARMS LEADING TO ENP TROPICAL CYCLONE FORMATIONS

Starting from the near-real time evaluations of pre-Hurricane Enrique, it became evident that the ECEPS was predicting questionable ensemble storms that would start very near the west coast of Central America and move to the northwest parallel to the coast. Except for some forecasts in which the ensemble storms made landfall or strongly interacted with land, the ECEPS was predicting that the storms would intensify to the hurricane stage, including a rapid intensification event immediately following formation. Consequently, these ECEPS-predicted storms would have posed a threat of substantial damaging winds and heavy rain to the coastal regions of Central America and Mexico, but time-after-time these ensemble storms did not verify.

An example of such a sequence of these false alarm ensemble storms is illustrated in figures 5 and 6. Note in the 12 UTC 3 August ECEPS forecast Storm 26 had a maximum of 13 members of which 10 member tracks were in the ENP with some very diverse tracks. The WMVM track (red dots) originated at 00 UTC 14 August with three members in the southern Caribbean Sea and these original three members cause the WMVM track forecast to move northwestward and make landfall in Central America on 16 August, although one ensemble storm continued northward into the central Gulf of Mexico. Because the weighted-mean WCM is calculated along that landfalling WMVM track, with the largest (smallest) weight given to those ensemble members with the closest (farthest) 12-hour vector motions aligned with the past 12-hour motion vector, the LSC for Storm 26 in the 12 UTC 3 August ECEPS forecast is only a Tropical Depression (not shown).

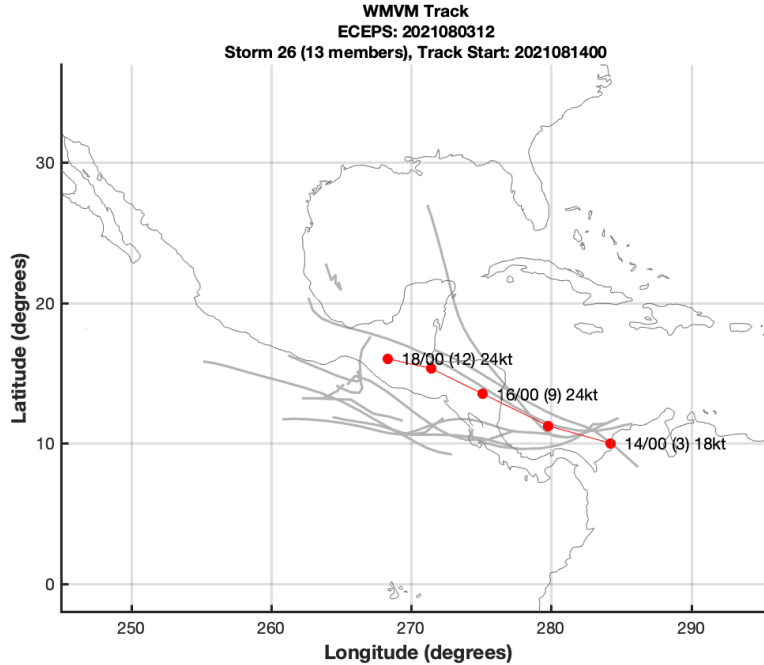


Figure 5. ECEPS WMVM Track Forecast 12 UTC 3 August Storm 26

Just 12 hours later (Figure 6), the 00 UTC 4 August ECEPS forecast Storm 12 starts in the extreme southern Caribbean Sea with only one ensemble member track that moves northwestward along the previous WMVM track forecast. Instead, two of the three initial WMVM ensemble member tracks are across the Central American peninsula into the ENP where the other ensemble member tracks join. Although the ECEPS-predicted WCM evolution does not indicate even a Tropical Depression (TD) until four days later, the ECEPS weighted-mean vortex intensity predicts a TD-stage within 24 hours after movement into the ENP (not shown).

Such Caribbean ensemble storm tracks were one of the four categories of Atlantic tropical cyclone events (formation plus track) studied by Elsberry, Tsai, and Jordan (2014). Specifically, not a single southern Caribbean event during the 2012 Atlantic hurricane season developed into a Tropical Storm. Therefore, those Caribbean events in the ECMWF 32-day ensemble predictions were considered to be false alarms (FAs) as far as Atlantic tropical cyclone formation events was concerned.

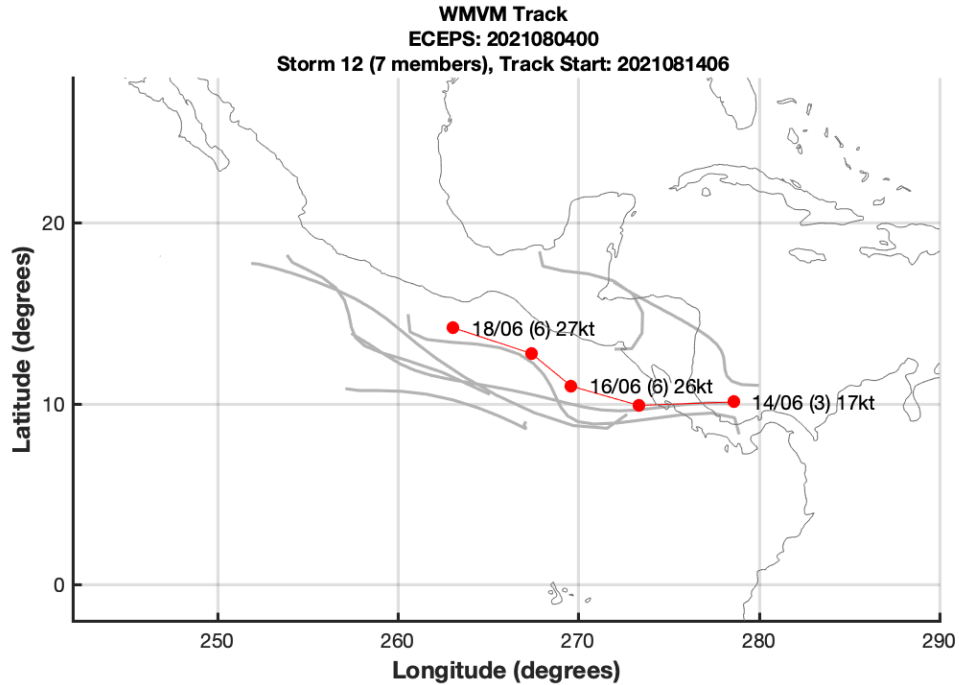


Figure 6. ECEPS WMVM Track Forecast 00 UTC 4 August Storm 12

It was on the basis of this and many other ECEPS ensemble member WMVM track forecasts that originated at low latitudes in the Caribbean and later appeared to initiate ensemble storms just offshore of the Central America west coast that Elsberry et al. (2022) assert that such initial conditions lead to FA tropical cyclone events in the eastern North Pacific. These Caribbean circulation systems act as a “seed” for eastern North Pacific ensemble storms in the ECEPS that begin too early just off the west coast of Central America (e.g., Figure 5), and intensify too quickly so that the T2F (35) and the T2H are too early. For those Caribbean circulations as in Figure 5 that have tracks farther north of the actual favorable formation area in the eastern North Pacific, the subsequent WMVM track forecasts tend to be parallel to the coastline. If the Caribbean circulation tracks are not as far north when they cross Central America, they may continue to move westward and trigger tropical cyclone developments farther to the west in the favorable formation area, and then have tracks to the west-northwest.

A fundamental question is then how to identify a false alarm ECEPS ensemble storm that co-exists with other ensemble storms whose development could provide early detections of a future Tropical Storm or a Hurricane in the eastern North Pacific. The user community of these ECEPS forecasts of course has no control over the ECEPS initial conditions or the ensemble model integrations that produce these false alarm tropical cyclones in the eastern North Pacific. Similarly, Tim Marchok at the NOAA Geophysical Fluid Dynamics Lab can only apply his vortex tracker to the ECMWF ensemble forecast output files as generated, as he has no inputs to the ECEPS initial conditions or control of the ensemble model predictions. One of the characteristics of these false alarm tropical cyclone developments in the ECEPS forecasts in the eastern North Pacific is that the number of ensemble members tends to be smaller (frequently less than 10 members, and seldom more than 15 members).

Elsberry et al. (2022) provide examples of two ECEPS forecasts for pre-Enrique in which there were two long-lived track forecasts that might reasonably represent the actual pre-Enrique track (Figure 7). In the first example, the 12 UTC 18 June forecast Storm 4 with a maximum of 24 ensemble members starts at 18 UTC 21 June near 10°N, 86°W and has a long (10 day) track along the west coast of Mexico (Figure 7 (a), red dots). Note that this Storm 4 WMVM track forecast does not “go down the middle” of those ensemble member tracks that start outside the small box in the lower right of Figure 7 (a). A minimum of three ensemble member tracks lasting at least 24 hours are required to start a WMVM ensemble storm. An early ensemble member track that turns poleward, makes landfall, and then persists for a long time over the Yucatan peninsula has a large impact on the early MWVM track within the small box, which results in the 18 UTC 23 June to 18 UTC 24 June motion vector to be toward the northwest parallel to the coast. Since almost all of the “late-joiner” member tracks to the southwest also have vector motions to the northwest, their joining the pre-Enrique WMVM track forecast does not change its northwestward pattern that continues outside the main cluster of tracks once pre-Enrique leaves the small box. In the Elsberry et al. (2022) second example of Storm 5 in that 12 UTC 18 June ECEPS forecast that has starting positions that are outside the small box, and the starting time for Storm 5 is 00 UTC 23 June rather than 18 UTC 21 June (Figure 7 (b)). While this later

starting time and more westward starting positions of the ensemble members results in them joining Storm 5 rather than Storm 4, the WMVM track forecast in Figure 7 (b) is a somewhat better representation of many of the ensemble member tracks that had joined Storm 4, because at their starting times they had positions closer to the Storm 4 WMVM track position.

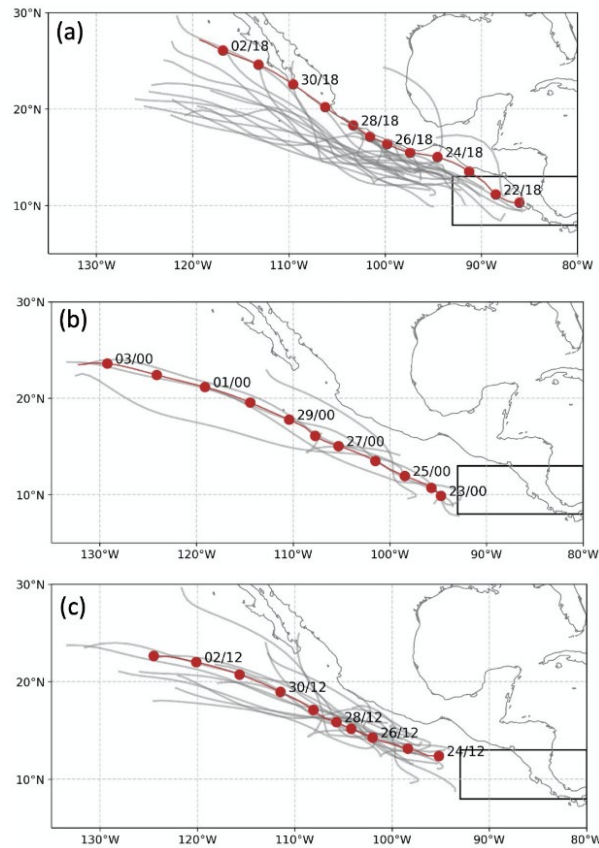


Figure 7. ECEPS 12 UTC 18 June 2021 forecasts of ensemble member tracks (gray lines) and the Weighted Mean Vector Motion (WMVM) tracks (red lines with dots labeled DD/MM) at 48 h intervals) with old procedure (a) Storm 4 and (b) Storm 5, and with new procedure (c) Storm 17 in which all ensemble member tracks within the small box in the lower right have been excluded (see text).

Source: Elsberry et al. (2022).

Elsberry et al. (2022) note that as soon as it became Tropical Storm Enrique at 00 UTC 25 June (6.75 days later), it was clear that Storm 5 in the 12 UTC 18 June ECEPS forecast (Figure 7 (b)) had the more accurate WMVM track forecast and more accurate

T2F (35) timing and position. Several other ECEPS forecasts for pre-Enrique were found to have two Storm options with one starting earlier near the Central American coast, and the second option that started later and farther west being more accurate.

For this thesis, the solution was to exclude any ensemble member tracks within the small box (8°N–13°N; western boundary at 93° west) in the lower right of each panel of Figure 7. With this new procedure (Figure 7 (c)), the Storm 12 WMVM track forecast starts later (12 UTC 24 June) and is nearly 10 degrees longitude to the west of Storm 4 in panel a, and to the north of Storm 5 in panel b. Although the new Caribbean FA procedure results in fewer ensemble member tracks in panel c due to the omission of the member tracks that originate within the small box in panel a, the track spread in panel c is smaller and the WMVM track “goes down the middle” of that track spread. Thus, the new procedure is applied to greatly reduce the number of ensemble storm tracks in the eastern North Pacific that originate from Caribbean FA circulations.

E. POST-SEASON REPROCESSING

As described above in Sections II.A and B, Elsberry et al. (2022) made several modifications of the western North Pacific version of the T2F and T2H code in its transition to the ENP version, and the dataflow modifications that were required for these near-real time evaluations of the 2021 season ECEPS forecasts of pre-TC circulations in the ENP. One of the important modifications in the code was to recalibrate the weighted-mean Warm Core Magnitude threshold for an ENP hurricane to 37.0, because that modification substantially decreases the time difference between the T2H and the T2F (35) that indicates a Rapid Intensification (RI) event if that time difference is ≤ 24 hours.

The major innovation by Elsberry et al. (2022) to provide the ending-storm stage T2H and T2F (35) timings and locations for ENP hurricanes described in Section II.B was initiated in the middle of the 2021 season after the Hurricane Linda evaluation. This modification required new coding and figures to be generated. However, the most challenging modification for Elsberry et al. (2022) was the detection and elimination of Caribbean false alarm (FA) pre-TC circulations that were leading to false tropical cyclones in the ENP. As described in Section II.D, these Caribbean FA precursors would start ENP

ensemble storms very near the west coast of Central America, move to the northwest parallel to the coast, and often would intensify to hurricane stage. It required several modifications before establishing the Caribbean FA box on August 24, 2021, within which any ensemble storm would be discarded.

Given all of the above modifications during the 2021 ENP season, it was necessary for Professor Hsiao-Chung Tsai and his research team at Tamkang University to reprocess the ECEPS forecasts for the entire season. Thus, the evaluation/analyses in the following sections of this thesis are based on this post-season reprocessing of the ECEPS forecasts.

III. DECISION FLOWCHART FOR STORM SELECTION

An outcome of evaluating the pre-formation ECEPS forecasts in real-time in the eastern North Pacific during the 2021 hurricane season was that a decision flowchart was created to select the most likely Tropical Storms to develop (Figure 8). The Marchok vortex tracker outputs from the ECEPS, which have been processed and assembled by Professor Hsiao-Chung Tsai for this forecast guidance product, must still be critically evaluated for validity and plausibility, and for general quality control. Many of these future disturbances are being forecast at very long lead times with the 15-day ECEPS. Because of the greater uncertainty/spread among these early disturbance initial positions, tracks, and WCM values, they must be examined with a forecaster's discerning eye. Furthermore, even if a potential disturbance is deemed reasonable, it must be matched with a similar disturbance in a previous forecast and must exhibit consistencies run-to-run within these forecasts in order to build confidence. This consistency is also identified through the decision flowchart.

In order to evaluate consistency in the forecasts over time, critical details from each likely ensemble storm forecast are compiled in a summary table for comparison and to keep track of how the pre-formation disturbance forecasts develop over time. The summary table for a given disturbance includes the forecast initial time, predicted T2F and T2H timings and positions, and in the post-storm analyses in this thesis, includes the calculated errors between the predicted timings and positions and the actual timings and positions from the working best tracks (WBTs).

The decision flowchart begins with the forecaster examining the first storm option in the list from that ECEPS forecast initial time, which is referred to as the shortest Tau storm. Forecast Tau is the estimated time (in hours) until the ensemble storm start. This flowchart is offered to be used as a guide to methodically evaluate each potential storm output each forecast run. For this reason, it begins with the shortest forecast Tau storm and progresses through the flowchart for that first storm. Because the shortest Tau potential storm is the first forecast, the shorter Tau storms generally have a higher likelihood of matching with a storm from a previous forecast run.

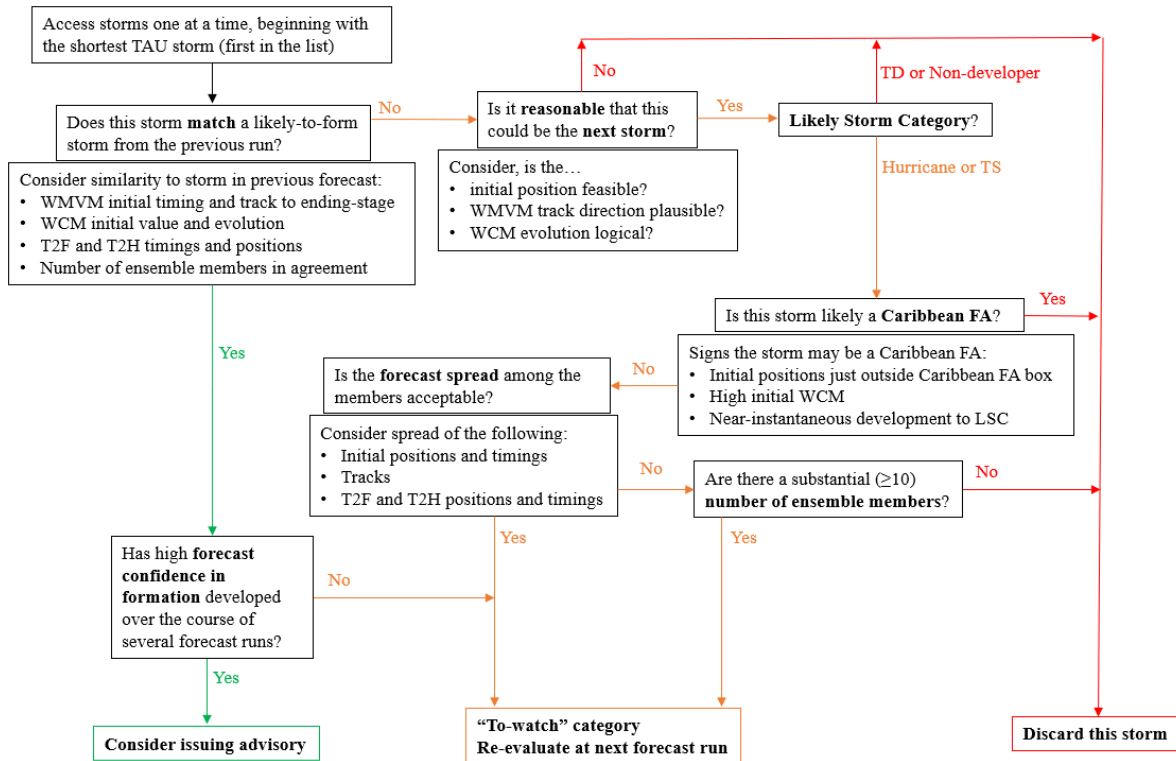


Figure 8. Decision Flowchart for Evaluating ECEPS Marchok Vortex Tracker Output Storms

In this first step, the forecaster evaluates this short Tau storm for consistency to storm variables from the previous forecast initial time based on the following items: WMVM initial timing and position and the general track agreement even to the ending-stage, T2F and T2H (if applicable) timings and positions, numbers of ensemble members in agreement, and the WCM evolution. If this new ensemble storm can be matched with an existing pre-formation ensemble storm predicted to form from the previous forecast, and there is fair consistency in the forecast development and TC formation, the forecaster can proceed through the decision flowchart to consider whether the confidence level is high enough to consider issuing an alert, advisory, or a warning. If the confidence in the series of storms has not reached this level, then the ensemble storm should be placed in the “To-watch” category. The storms in this category are documented and checked against in future ECEPS forecasts for potential matches in order to build forecast confidence.

If it cannot be matched with a storm from the previous forecast run, the forecaster then moves to the step of evaluating if the forecast reasonably indicates a new ensemble storm. That is, the forecaster evaluates the location within the basin, the season, and the synoptic background conditions when considering the validity of the pre-formation disturbance's forecast WMVM initial position and track direction, and the WCM evolution. If the forecast is not logical or feasible, the decision flowchart lands on the decision to discard the storm option. In this case, the storm may be a false alarm. If the forecast is reasonable, but the Likely Storm Category (LSC) is TD or N/A (i.e., the storm is forecast to not develop even to a TD), the decision flowchart again arrives at the decision to discard the storm option, as it is forecast to not be a threat. However, at the forecaster's discretion, if the storm track indicates it does pose an immediate threat, and there may be reason to believe the ECEPS is under-forecasting the intensity, the storm may be put in the "To-watch" category until the disturbance is either picked up by a later forecast as a developing TC or a final decision is made that it is a non-developer.

If the forecast is reasonable and the LSC is Hurricane or TS, the forecaster should immediately check whether the storm may be a Caribbean FA. The following are signs that an ensemble storm may be a Caribbean FA: the initial positions of most or all of the ensemble members are just outside the established Caribbean FA box; there is too high initial WCM to be reasonable for a new ensemble storm; and the WCM indicates near-instantaneous development to the LSC of Hurricane or TS. If these signs are present and the storm is strongly suspected to be a Caribbean FA, the decision is to discard the storm.

If there is not convincing evidence that this potentially intense ensemble storm is a Caribbean FA, the forecaster then evaluates the spreads among the members' initial positions and timings, subsequent tracks even to the ending-storm stage, and the T2F and T2H positions and timings. If the spreads of these critical forecast metrics are excessive such that the forecaster is unable to project an acceptable forecast with reasonable confidence, the storm may be placed in the "To-watch" category only if the number of ensemble members meets or exceeds 10. Through the analysis conducted in this thesis and previous studies by Elsberry et al. (2021, 2022), a substantial number of members has been defined as ≥ 10 . Otherwise, the storm should be discarded. If the ensemble members agree

to an acceptable level, then the forecaster puts the ensemble storm in the “To-watch” category.

All the storms selected for the “To-watch” category may be considered likely storms to form, although not necessarily the most likely to form. A summary table should be created for these “To-watch” category storms to follow the potential development in future ECEPS forecasts. If the new ensemble storm does closely match a storm from the prior forecast run, that new ensemble storm is considered the most likely storm to form. The forecaster must now evaluate the confidence level in the likelihood of the formation. If the confidence has developed over the course of several forecast runs (≥ 4), the forecaster may consider issuing an advisory for this storm. Of all the steps in the decision flowchart, this step particularly requires the forecaster’s judgement and expertise.

Following the decision on this first storm, the forecaster evaluates the second storm (next shortest Tau) in the list and repeats the process until a decision on the second storm is reached, and so on until all of the ensemble storm options from that ECEPS forecast initial time have been evaluated.

In summary, this Decision Flowchart in Figure 8 is to be used for each forecast in a repetitive manner until a decision is reached as to whether the ECEPS ensemble storm is: (i) discarded as a Caribbean false alarm (FA), or discarded because the WCM evolution is indicative of a cold-core disturbance or a non-developing disturbance; or (ii) it is considered to be at least a possible future threat “to-watch,” and possibly issued upon when a definite threat exists.

While in this study this decision flowchart is used as the sole guidance, forecaster judgements and experience could not be incorporated. The summary tables included in this thesis are based on raw model output and, while the storms are selected intentionally through the decision flowchart, no forecast adjustments have been attempted. In operational use, the decision flowchart is meant to be considered alongside existing procedures and used in conjunction with existing forecast tools. Decision flowcharts should be weaved into established confidence levels when internally tracking or deciding to publicly issue (or not) any sort of alert on potential storms. The methods to systematically

evaluate each storm must be efficient because of the forecasters' time constraints, and because the TC forecasts have to be posted on a tight schedule.

In the following three chapters, the decision flowchart introduced in Figure 8 is applied as a forecaster might do in real-time for storms of varying intensity. Developing storms (hurricane and tropical storm stage) will be evaluated as well as non-developing storms. Each of the examples provided is an in-depth demonstration of the recommended process for integrating these techniques into real-time forecasting. That is, these steps and recommendations are offered as guidance to a forecaster beginning to use this product and these techniques. The primary objective of the decision flowchart is to select the most likely pre-formation ensemble storm in each ECEPS forecast and determine if the confidence level is sufficiently high to issue an alert for that storm. For each of the examples, it will be demonstrated how to utilize the decision flowchart to identify and select the most likely Tropical Storm and evaluate the storm's entire life cycle starting from the pre-formation stage to the ending-stage, if applicable. To illustrate the benefits of the pre-formation ECEPS forecast guidance, a comparison is made with the presently available ENP guidance on formation timing and the five-day track forecasts in the NHC advisories.

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IV. HURRICANE CATEGORY EXAMPLES

A. HURRICANE ENRIQUE

1. Decision Flowchart Application to Pre-Enrique

Hurricane Enrique was the first hurricane of the eastern North Pacific 2021 season. The working best track (WBT) and intensity plots of Hurricane Enrique are presented in Figure 9. This storm is of particular interest as it was so close to the coast and yet it underwent rapid intensification (RI), which is defined as a maximum sustained wind speed increase of ≥ 30 kt within 24 hours. Although this RI phenomenon occurred following formation with almost every Hurricane in this basin during the 2021 season (Elsberry et al. 2022), these RI events are rarely forecast (Courtney et al. 2019). Indeed, the NHC advisories compared with these ECEPS forecasts rarely did include an RI following formation. As Enrique neared the southwestern coast of Mexico, it brought strong winds, widespread heavy rainfall, and subsequent flooding and landslides that ultimately caused two direct deaths in Guerrero and damage to over 390 homes in Guerrero and Coahuayutla (Latto 2021).

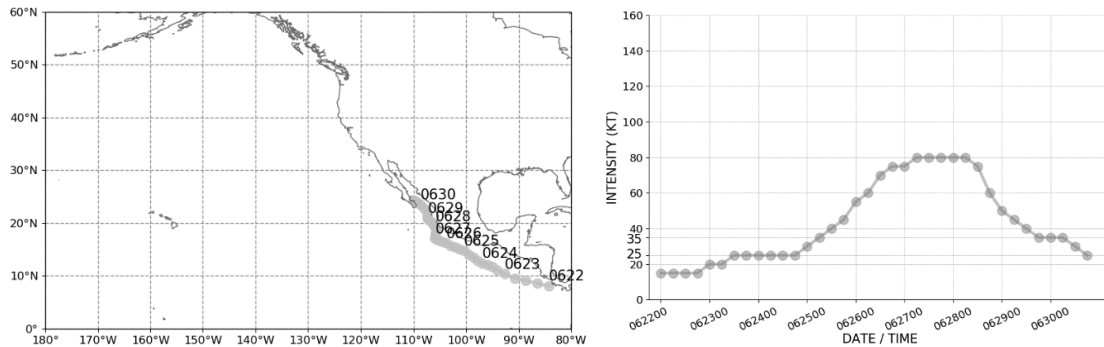


Figure 9. Hurricane Enrique (2021) Track and Intensity Plots.
Source: Elsberry et al. (2022).

Table 2 documents the first example of how pre-Enrique was selected as the most likely next storm in the 12 UTC 16 June ECEPS forecast among other pre-formation storm options by applying the Decision Flowchart in Figure 8. The Storm 13 option that has been

selected as the most likely pre-Enrique is entered in the first column, and the alternate storm options considered but not selected are in the last three columns. Note that these non-selected storms are listed from the smallest number to the largest number to be consistent with the ordering of smallest to largest forecast Tau in the Decision Flowchart. Normally, the selected ensemble storm number will be smaller than the numbers of non-selected ensemble storms, but that is not the case for the Caribbean FA category described earlier in Section II.D, in which the FA ensemble storm has the advantage of an earlier precursor circulation. For the 12 UTC 16 June ECEPS forecast (Table 2, row 1), the selected Storm 13 had 16 members and all three alternate storms options (Storm 9, Storm 11, and Storm 12) had lower numbers.

Table 2. Selection and Non-selection of the ECEPS Storms for Pre-Enrique from 12 UTC 16 June 2021 Forecast

ECEPS initial time (Selected storm)	T2F(35) Timing [error]	Alternate ECEPS Storm Options Considered [Scenario representing reason for non-selection]		
12 UTC 16 Jun (Storm 13)	062512 [Late 6h]	Storm 9 [cold-core system]	Storm 11 [8 members]	Storm 12 [Caribbean FA]

To help the reader visualize and understand the selection and non-selection procedures for this 12 UTC 16 June ECEPS forecast, Storm 13 in Figure 10 will be described first and then the non-selected Storms 9, 11, and 12 will be described in Figures 11, 12, and 13, respectively.

In the first step of the Decision Flowchart, Storm 13 could not be matched with an ensemble storm from a previous forecast. There were no likely-to-form storms selected previously which had similarities in WMVM initial timing and track, WCM initial value and evolution, T2F and T2H timings and positions, or number of ensemble members in agreement. Discussion of these items and potential matching will be covered in detail in this chapter and in Chapter V. Because the storm does not match a likely-to-form storm from the previous ECEPS initial time, the next step is to evaluate if it is reasonable that this could be the next storm. Storm 13 was ultimately determined to be reasonable based on the

instruction in the Decision Flowchart to evaluate the initial position and WMVM track direction, and WCM evolution. The digital values of the first seven days of the WMVM track forecast and the numbers of members each six hours are shown in the table in the upper-right of Figure 10. The digital values of the WCM that are used to determine the T2F (35), and the ECEPS storm intensity that is used to estimate the T2F (25) are shown in the table in the lower right of Figure 10. The WMVM Storm 13 starting time of 12 UTC 24 June and Storm 13 start location near 11.8°N, 95.3°W, which are found in the “Storm Start” section of the summary table at the bottom of Figure 10, are plausible for this time of year and this location of the eastern North Pacific basin. As listed in the summary table at the bottom of Figure 10, the predicted evolution from the T2F (25) at 00 UTC 25 June near 12.7°N, 96.4°W to T2F (35) WCM (25) at 12 UTC 25 June near 13.2°N, 97.9°W, and then to T2H at 12 UTC 26 June near 14.5°N, 100.6°W are certainly reasonable as is the northwestward WMVM track direction (Figure 10, red track in upper-left plot).

The forecaster then moves to the next step in the Decision Flowchart (Figure 8) of determining the Likely Storm Category (LSC) for Storm 13, which is provided in the “Likely Storm Cat.” center section of the summary table at the bottom of Figure 10. Because the Storm 13 LSC is Hurricane (HU), the forecaster then moves to the next step in the Decision Flowchart, which is to look for signs that Storm 13 may be a Caribbean FA. As discussed in detail in Section II.D and Chapter III, the signatures of a Caribbean FA are the following: (i) the initial positions of most or all of the ensemble members are just outside the established Caribbean FA box; (ii) there is too high initial WCM to be reasonable for a new ensemble storm; and (iii) the WCM evolution indicates near-instantaneous development to the LSC of Hurricane or TS. Whereas the initial position of Storm 13 is sufficiently far outside of the established Caribbean FA box indicated in Figure 7, the initial value of the WCM (14.0, lower right table) is not too high initially, and the LSC estimated from the maximum WCM value (61.3, bottom of Figure 10) is not achieved instantaneously. Therefore, there are no clear signatures of a Caribbean FA for Storm 13.

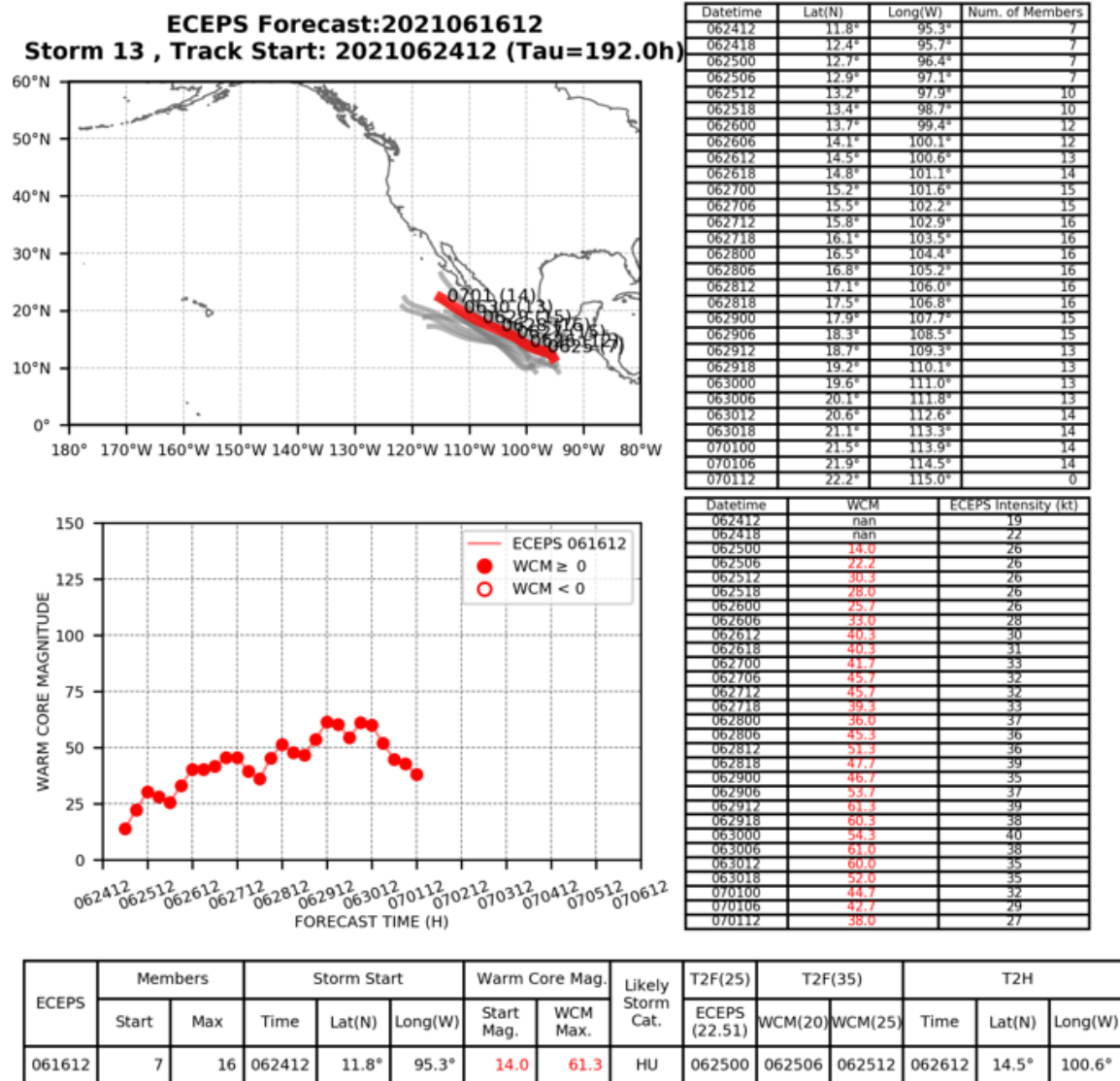


Figure 10. ECEPS Forecast 12 UTC 16 June Storm 13
 (Selected Storm for Pre-Enrique)

The forecaster then moves to the next step in the Decision Flowchart (Figure 8) of examining the spread among the ensemble member tracks, which are represented by the grey tracks in the upper-left map of Figure 10. While there is a fair amount of spread in initial positions and tracks, which should be expected at the long forecast Tau of 192 hours (indicated in the text at the top of Figure 10), the forecaster would note that the track spread decreases as the general northwestward track direction becomes well established. In this case, the Decision Flowchart concludes with the selection of Storm 13 for the “To-

watch” category with the instruction to re-evaluate the potential of this storm at the next forecast run.

Even if the forecast spread among the ensemble member tracks had been considered to be too large, the forecaster would have moved to the next step of checking the ensemble member count. The maximum ensemble member count for this storm is 16, which is indicated in the “Members Max” section in the summary table at the bottom of Figure 10. Consequently, Storm 13 has a substantial number of ensemble member tracks, which has been established as ≥ 10 . With this number of ensemble member tracks, even if the forecast spread had been questionable, Storm 13 would be placed in the “To-watch” category. Ultimately, this storm is selected as the most likely storm to form from this ECEPS forecast initial time and later becomes Hurricane Enrique.

Given the completion of the Decision Flowchart procedure for Storm 13, the forecaster would continue to evaluate the other ensemble storms for this ECEPS forecast initial time of 12 UTC 16 June. As indicated at the beginning of the Decision Flowchart (Figure 8), the order of this evaluation is according to the shortest Tau storm, which is Storm 9 (Table 2).

A similar WMVM track forecast and WCM evolution as in Figure 10 for Storm 13 is shown here for Storm 9 in Figure 11. In the first step of the Decision Flowchart (Figure 8), the forecaster would not find a TC in the previous forecast run with an initial position so far to the north with a quasi-stationary track. As the forecaster considers the second decision point, Storm 9 fails the “reasonable for a TC” check because it is a cold-core system as indicated by the $WCM < 0$ values, and Storm 9 is well outside of the tropics. Thus, the forecaster does not select Storm 9 as the likely next storm to form and can quickly eliminate that storm option. As noted above, the Marchok vortex tracker is applied to extratropical cyclones such as Storm 9. For operational application of this TC formation technique, such cold-core, extratropical cyclones should be excluded. This exclusion would simplify and speed-up the application of the Decision Flowchart as the forecaster is searching for the next most likely TC formation.

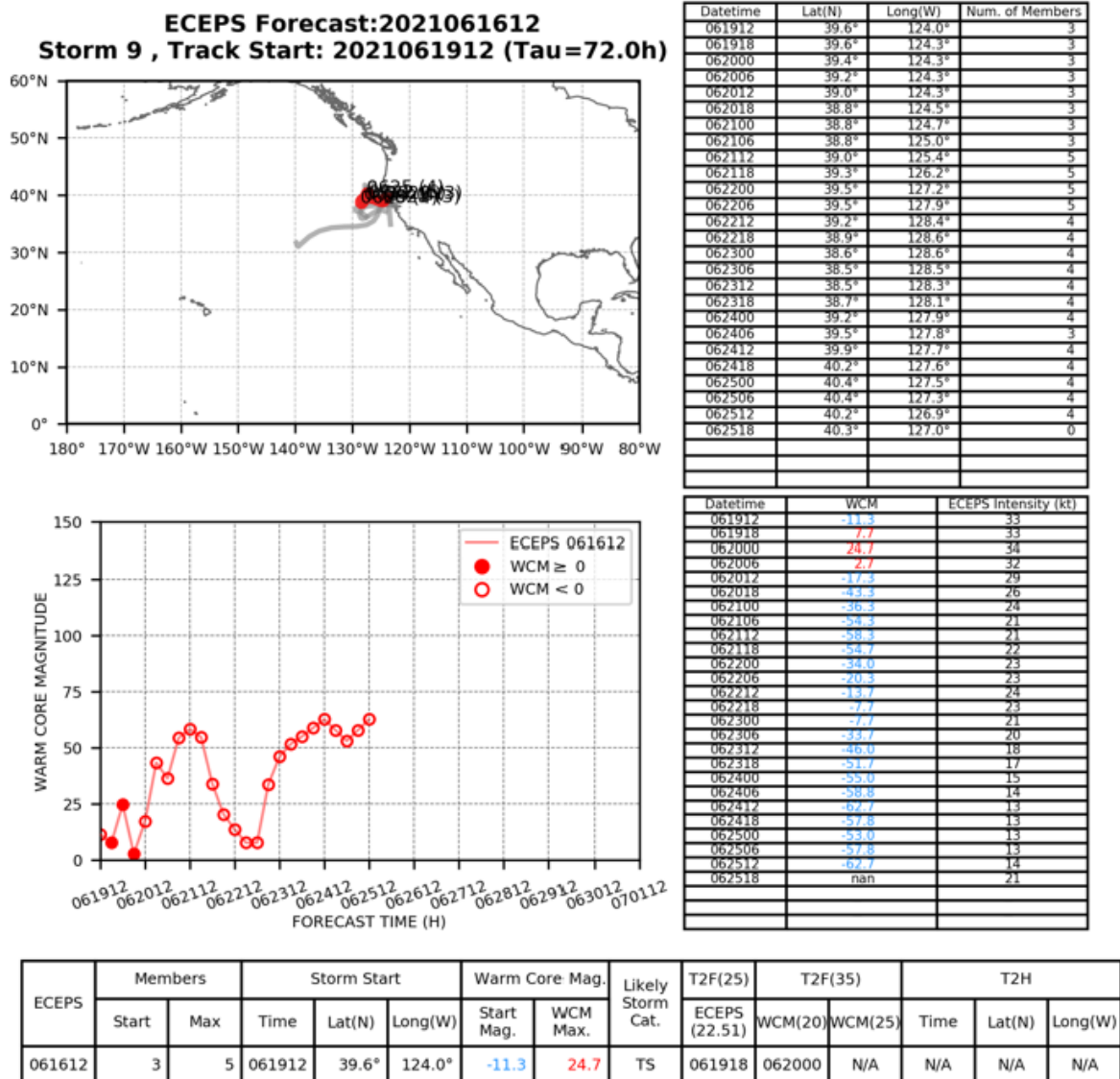


Figure 11. ECEPS Forecast 12 UTC 16 June Storm 9
(Non-selected Storm for Pre-Enrique)

Next, the forecaster applies the Decision Flowchart (Figure 8) to Storm 11, which is displayed here in Figure 12. After the first step is unable to match the storm with one from a previous forecast run, the second step is to examine whether Storm 11 is a reasonable representation of the next TC formation. Considering the WMVM initial position is in a favorable TC formation region, and the forecast track resembles Track C in

Figure 2, these Storm 11 track aspects are certainly reasonable. However, the WCM evolution in the lower-left panel of Figure 12 indicates only a brief increase to a maximum of 26, which indicates that Storm 11 is forecast to have a LSC of weak TS. Although the Storm 11 WMVM track starts at 00 UTC 22 June near 12.5°N, 99.4°W (upper-right table), there is suspicion that Storm 11 may be a Caribbean FA because a single ensemble storm track that starts near 6°N, 95°W (track plot in upper-left panel) appears to be the precursor track to start the Storm 11 WMVM track. Furthermore, the track spread among the members is somewhat high, and there is not a substantial (≥ 10) number of ensemble member tracks as there are just eight. While Storm 11 may not be the most likely next TC to form, it is still placed in the “To-watch” category because of the uncertainty as to whether it is a Caribbean FA.

The final storm option from Table 2 that the forecaster evaluates is Storm 12, which is shown here in Figure 13. Again, Storm 12 is not matched with a storm from the previous forecast run. As for Storm 11, the WMVM track forecast for Storm 12 is reasonable as it resembles Track C in Figure 2. A significant difference from Storm 11 is that the WCM evolution in the lower-left plot and lower-right table for Storm 12 indicate it has a LSC of Hurricane. Another similarity with Storm 11 is the possibility that Storm 12 is a Caribbean FA. Although Storm 12 WMVM track starts near 10.6°N, 100.6°W (track table in upper-right), there is a single ensemble member track that starts near 10°N, 95°W that is the likely precursor circulation to start the Storm 12 WMVM track forecast. Since that circulation is moving westward and its initial position is so close to the 93°W boundary of the Caribbean FA box, Storm 12 may be a Caribbean FA. Thus, Storm 12 is discarded based on the Decision Flowchart (Figure 8) and is not considered likely to form.

Once the forecaster has selected Storm 13 as the most likely storm to form and has evaluated the Storm 9, Storm 11, and Storm 12 options, the forecaster waits for the next ECEPS initial time at 00 UTC 17 June, which is the first entry in the second summary Table 3 for the other ECEPS forecasts for selecting the most likely pre-Enrique. The forecaster then repeats the Decision Flowchart, but the forecaster now has the most likely “To-watch” forecast from the previous forecast in Table 2 (Storm 13 from 12 UTC 16 June in Figure 10) to attempt to match. The selected storms and the non-selected storms and

their primary reason for non-selection are compiled in Table 3. The evaluation of the storm options for the 00 UTC 17 June forecast are provided in Figures 14, 15, 16, and 17, and in the discussions that accompany them.

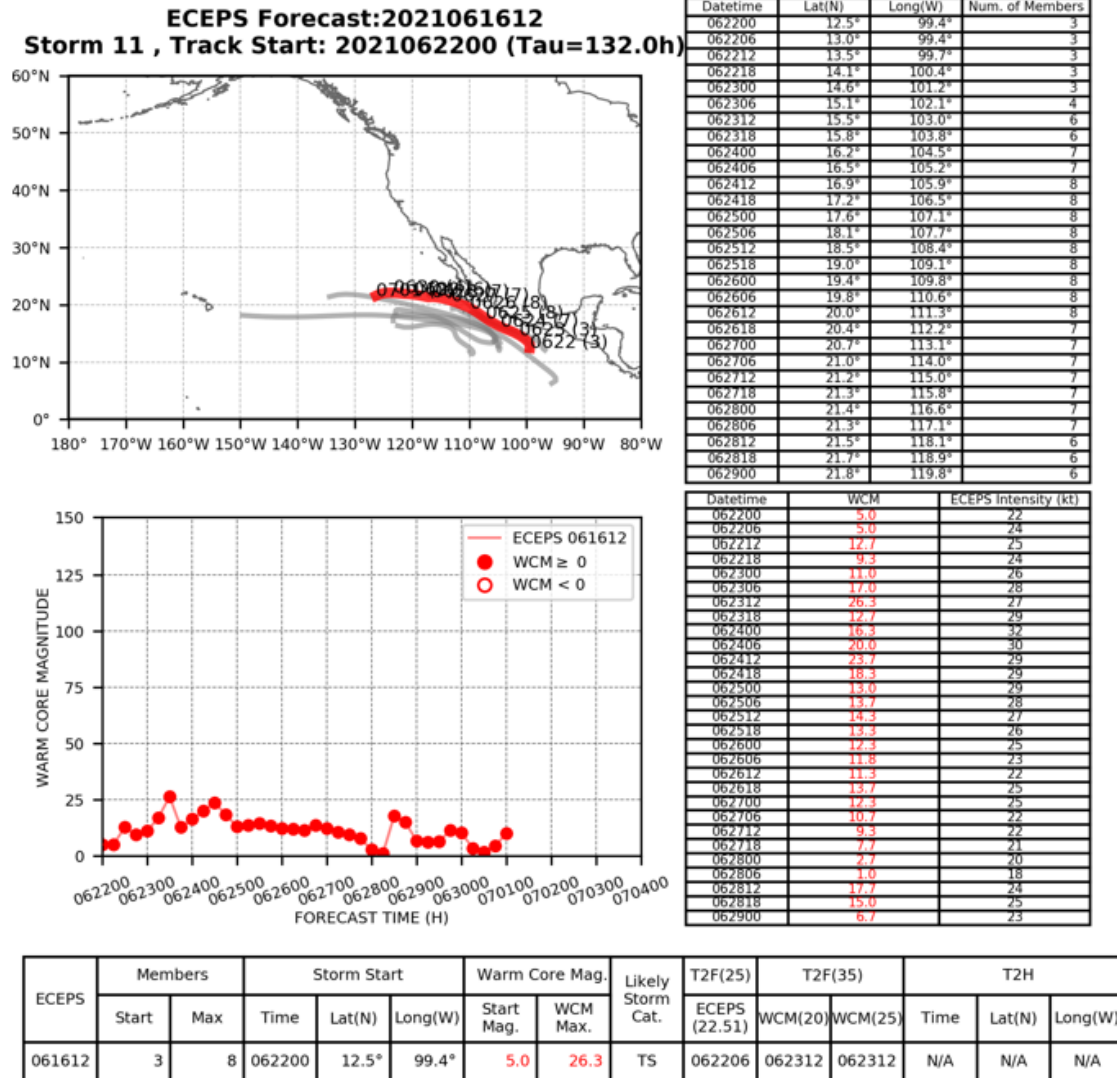


Figure 12. ECEPS Forecast 12 UTC 16 June Storm 11 (Non-selected Storm for Pre-Enrique)

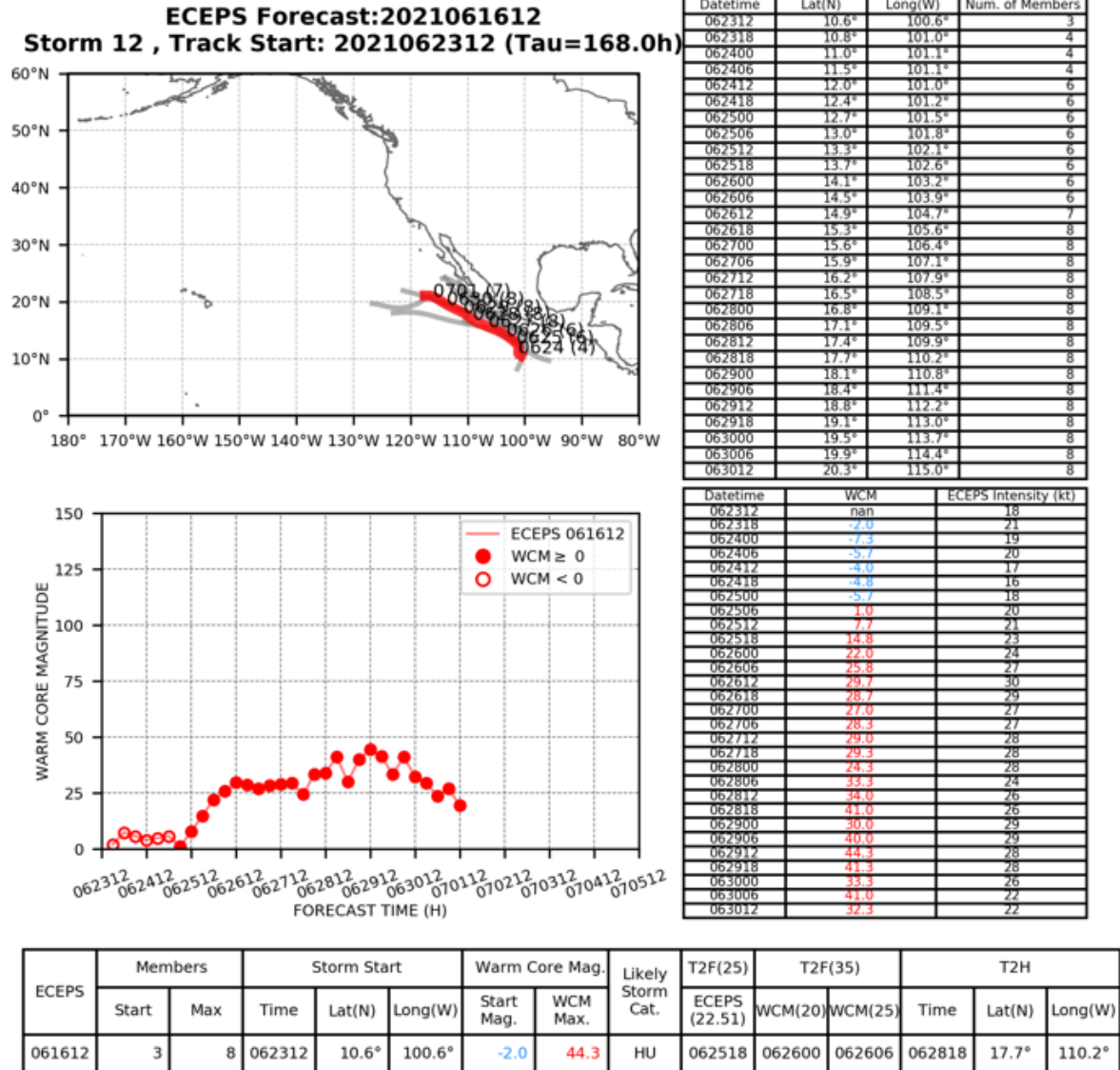


Figure 13. ECEPS Forecast 12 UTC 16 June Storm 12
 (Non-selected Storm for Pre-Enrique)

Table 3. Selection and Non-selection of the ECEPS Storms for Pre-Enrique after the 12 UTC 16 June 2021 Forecast

ECEPS initial time (Selected storm)	T2F(35) Timing [error]	Alternate ECEPS Storm Options Considered [Scenario representing reason for non-selection]		
00 UTC 17 Jun (Storm 14)	062512 [Late 6h]	Storm 11 [Caribbean FA]	Storm 12 [LSC TD]	Storm 17 [Caribbean FA]
12 UTC 17 Jun (Storm 10)	062512 [Late 6h]	Storm 7 [5 members]	Storm 11 [6 members]	Storm 12 [inconsistent WCM (high)]
00 UTC 18 Jun (Storm 8)	062600 [Late 18h]	Storm 2 [inconsistent T2F (early)]	Storm 5 [cold-core system]	Storm 11 [inconsistent T2F (late & west)]
12 UTC 18 Jun (Storm 12)	062600 [Late 18h]	Storm 8 [4 members]	Storm 11 [inconsistent WCM (low)]	Storm 13 [4 members]
00 UTC 19 Jun (Storm 11)	062606 [Late 24h]	Storm 7 [cold-core system]	Storm 8 [inconsistent WCM (low)]	Storm 13 [5 members]
12 UTC 19 Jun (Storm 9)	062612 [Late 30h]	Storm 7 [inconsistent T2H (late & west)]	Storm 11 [4 members]	Storm 14 [4 members]

ECEPS initial time (Selected storm)	T2F(35) Timing [error]	Alternate ECEPS Storm Options Considered [Scenario representing reason for non-selection]		
00 UTC 20 Jun (Storm 7)	062512 [Late 6h]	Storm 5 [inconsistent T2H (late & west)]	Storm 6 [Caribbean FA]	Storm 7 [inconsistent WCM (high)]
12 UTC 20 Jun (Storm 3)	062512 [Late 6h]	Storm 1 [cold-core system]	Storm 5 [inconsistent ending-stage (late)]	Storm 7 [cold-core system]
00 UTC 21 Jun Missing	Missing single forecast [Consider using last available]			
12 UTC 21 Jun (Storm 3)	062512 [Late 6h]	Storm 1 [cold-core system]	Storm 5 [cold-core system]	Storm 6 [cold-core system]
00 UTC 22 Jun (Storm 4)	062506 [Exact time]	Storm 1 [cold-core system]	Storm 2 [6 members]	Storm 5 [cold-core system]
12 UTC 22 Jun through 00 UTC 26 Jun	Missing forecasts for 3.5 days [Too many for extrapolation]			
12 UTC 26 Jun (Storm 2)	Already a TS since 06 UTC 25 Jun and Became a Hurricane 6h ago			

The forecaster first examines Storm 11 (shown in Figure 14) because it has the shortest Tau for this ECEPS initial time (Table 3, row 1). This Storm 11 would be matched with Storm 11 (Figure 12) from the previous ECEPS forecast because they have very similar starting positions near 12°N, 100°W and a similar WMVM track direction to the west-northwest. Both Storm 11s have a maximum number of ensemble members (only eight), and the initial positions of the precursor circulations are close to the western boundary (93°W) of the Caribbean FA box. Although the maximum WCM (37.7, which is barely a LSC of Hurricane) of the new ECEPS forecast is slightly larger than the value of 25 for the previous forecast, this factor is consistent with a matching of these two Storm 11s. If the forecaster had put the previous Storm 11 in the “To-watch” category, the question is whether this very similar Storm 11 should continue to be in the “To-watch” category (the conservative option) or should it now be discarded as a Caribbean FA storm (more aggressive option). Regardless, this Storm 11 is not a match for Storm 13, the most likely-to-form storm selected from the previous ECEPS initial time.

The forecaster then examines Storm 12 with the next larger Tau (Table 3, row 1), which is shown in Figure 15. This short Storm 12 WMVM track forecast could not be matched with any of the “To-watch” ensemble storms from the previous forecast. In the second step of the Decision Flowchart (Figure 8), this Storm 12 could not be considered to be a reasonable Tropical Storm option because the WCM evolution (lower-left panel) starts with negative values (cold-core rather than warm-core) and the later positive values correspond to a LSC of a Tropical Depression. Furthermore, the storm has a low ensemble member count (four) and poor ensemble member agreement, so is eliminated from being a likely storm altogether. Although this cold-core is within the tropics rather than in the extratropics for Storm 9 in Figure 11, in combination with the short (four-day) life cycle plus only four ensemble members, the question is whether this Storm 12 should not even be provided to the forecaster for evaluation as a likely next storm. That is, filtering out these cold-core storms before presentation to the forecaster would make the evaluation procedures more simple and more efficient.

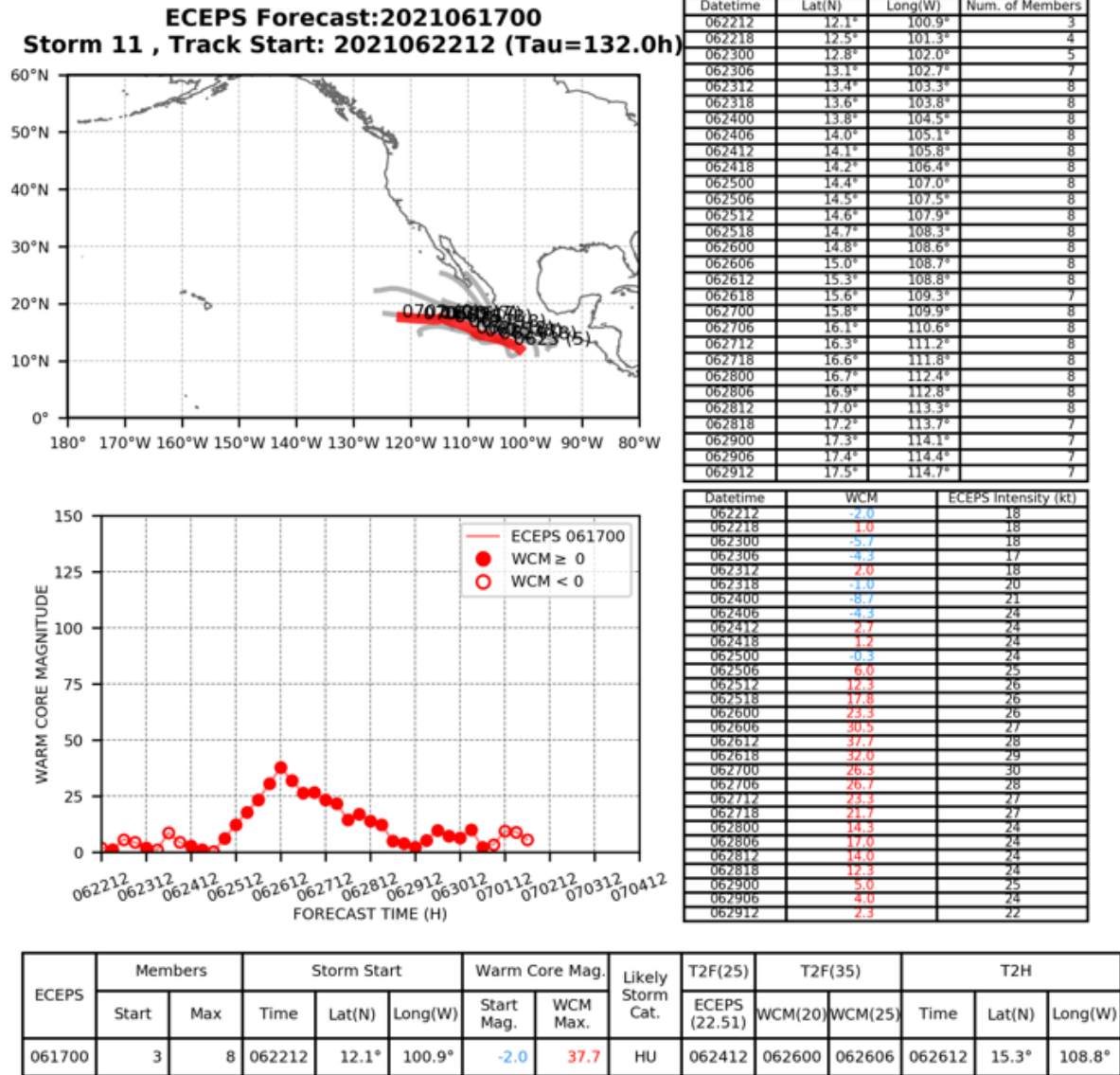


Figure 14. ECEPS Forecast 00 UTC 17 June Storm 11
(Non-selected Storm for Pre-Enrique)

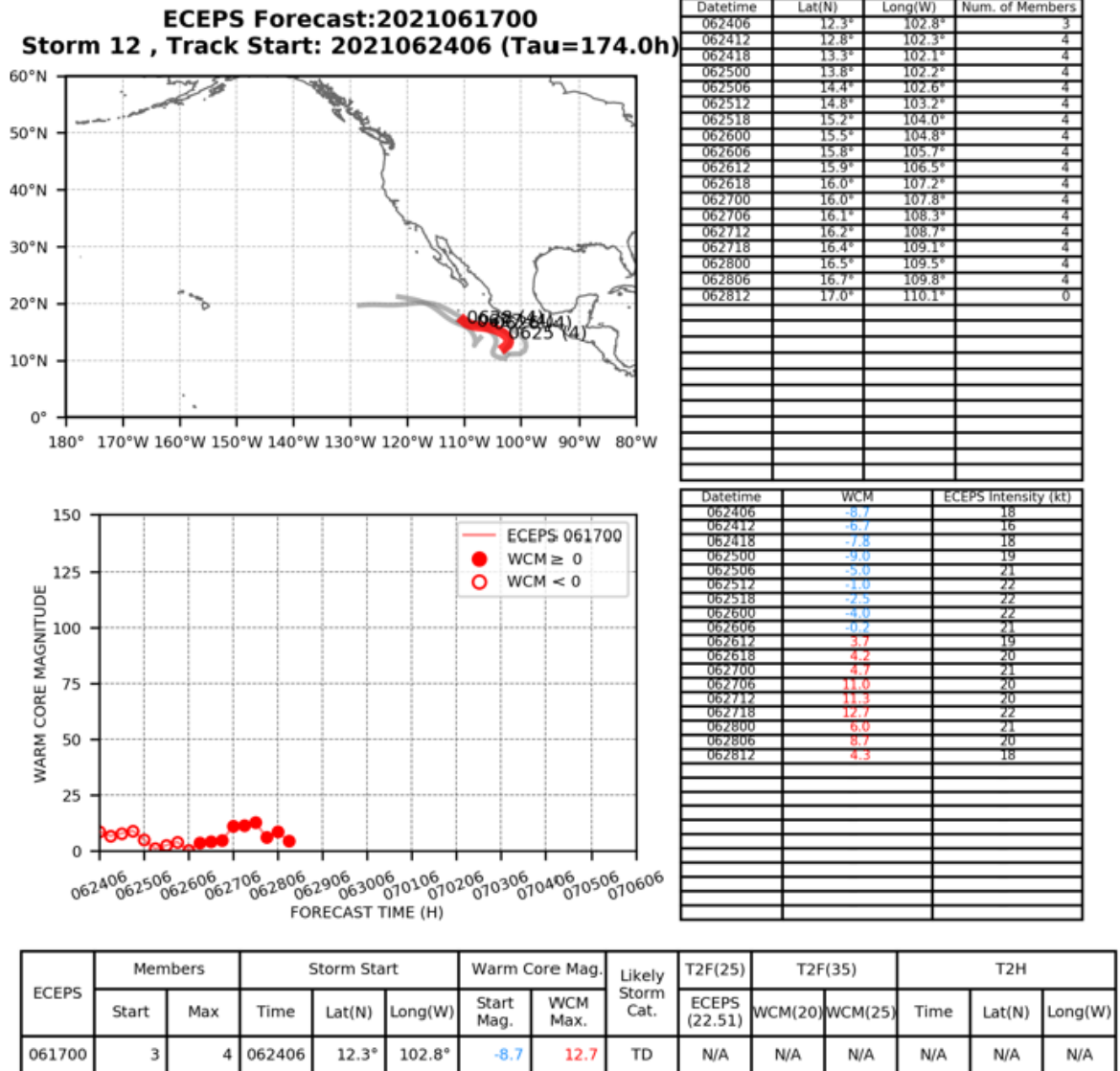


Figure 15. ECEPS Forecast 00 UTC 17 June Storm 12
(Non-selected Storm for Pre-Enrique)

The forecaster then would examine the next larger Tau Storm 14 (Table 3) of 00 UTC 17 June (Figure 16). In the first step of the Decision Flowchart (Figure 8), the forecaster would select Storm 14 as a match for Storm 13 of the 12 UTC 16 June forecast based on striking similarities. That is, the T2F (35) WCM (25) timing is exactly consistent at 062512, which ultimately verifies just six hours late of actual formation of Enrique. The Storm Start timings and positions are very similar, the LSC of Hurricane is consistent, and the maximum WCM is similar (61.3 of Storm 13 and 69.3 of Storm 14). After such a match from just two forecasts, the forecaster would normally not have developed high confidence in the predicted formation, which is described in the Decision Flowchart as being established over several consistent forecast runs. Thus, Storm 14 may be selected as one “To-watch.” Since Storm 14 is considered to be matched with Storm 13 of 12 UTC 16 June, it is added to the summary Table 5, which will be discussed later in Section IV.A.2. However, both of these storms are predicted to be hurricanes and pass close to the west coast of Mexico. This situation illustrates the critical role of the forecaster in the Decision Flowchart as an Alert may be already warranted in this situation.

The final storm option evaluated in Table 3 row 1 is Storm 17, which is shown in Figure 17. In the first step of the Decision Flowchart (Figure 8), the forecaster would have determined that Storm 17 was not a match for any “To-watch” storms from the previous ECEPS initial forecast time. In the second step of the Decision Flowchart, the forecaster would identify that the WMVM Storm 17 start near 13.4°N, 96.6°W is in a region favorable for TC formation, and the WMVM track direction toward the northwest is reasonable. The forecaster would certainly note that Storm 17 has a LSC of Hurricane with a WCM maximum of 55.7. The critical step is evaluating Storm 17 for signs of being a Caribbean FA. Although the WMVM track begins well outside of the Caribbean FA box, a single ensemble member track beginning near 12°N, 94°W is likely to be the precursor circulation for this Storm 17 WMVM track forecast. Thus, Storm 17 is discarded as a Caribbean FA storm.

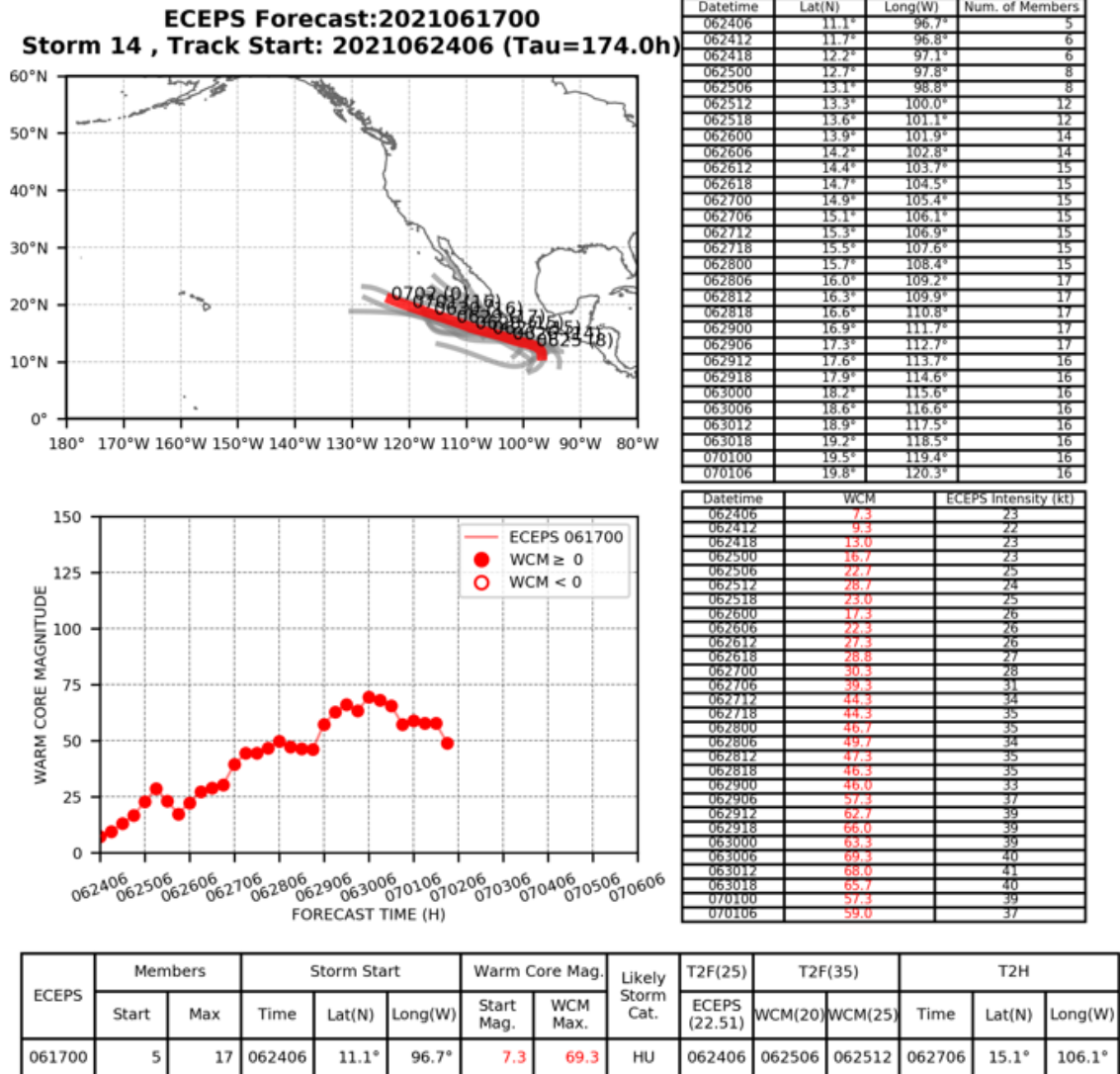
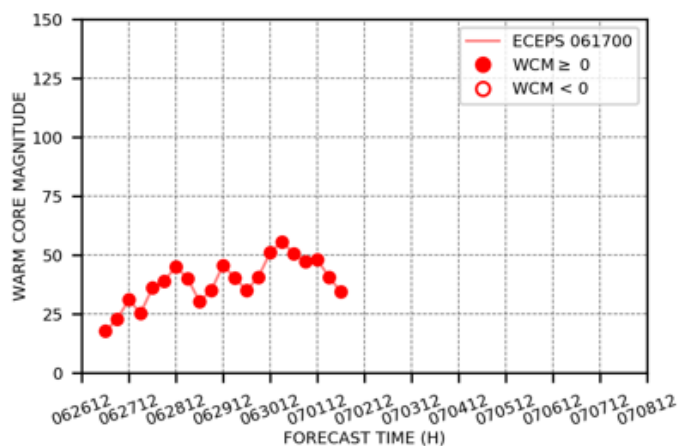
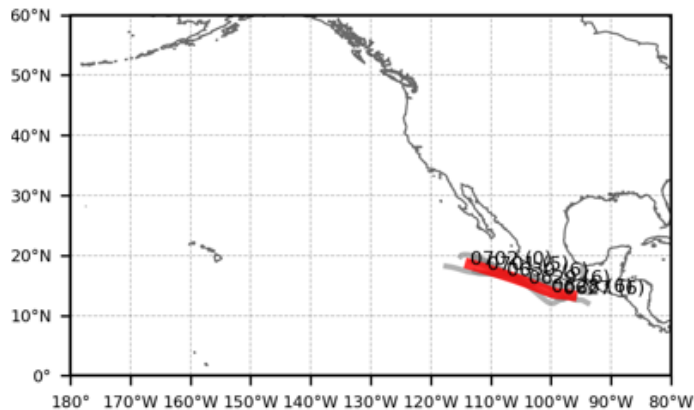


Figure 16. ECEPS Forecast 00 UTC 17 June Storm 14
 (Selected Storm for Pre-Enrique)

[illegible][illegible]

ECEPS	Members		Storm Start			Warm Core Mag.		Likely Storm Cat.	T2F(25)	T2F(35)		T2H		
	Start	Max	Time	Lat(N)	Long(W)	Start Mag.	WCM Max.		ECEPS (22.51)	WCM(20)	WCM(25)	Time	Lat(N)	Long(W)
061700	4	6	062612	13.4°	96.6°	17.7	55.7	HU	062706	062706	062712	062806	14.2°	100.7°

45

The clear choice from the 00 UTC 17 June ECEPS forecast for pre-Enrique in the summary Table 3 (row 1) is Storm 14. Selections of the ensemble storms that best represent the pre-Enrique storm in the remainder of ECEPS forecasts from 12 UTC 17 June through 00 UTC 22 June are listed in the first column of Table 3. Note how consistent in time were the T2F (35) times, and these times turned out to be clustered around the verifying T2F (35) time of 06 UTC 25 June. This consistent T2F (35) timing of 12 UTC 25 June (column 2) through the first three ECEPS forecasts in Tables 2 and 3 would build early confidence that this is the pre-Enrique disturbance. Several of the selected storms were placed in the “To-watch” category. For instance, between 12 UTC 16 June and 00 UTC 18 June, there was not enough confidence in the consistency of the forecasts to issue an advisory, but the forecasts showed evidence of a plausible future storm with a LSC of Hurricane. Thus, they were watched and added to the summary table. Progressing in time through the forecast runs, as the non-selected storms are ruled out for these various scenarios and the selected storms are chosen, a level of confidence in the selected matching storms must still be met in order to seriously consider issuing an advisory. It was determined through the course of this study that several (four or more) consecutive and high consistency storms should be selected to be placed in the “To-watch” category in order to move on to considering issuing an advisory. The final step in the Decision Flowchart in Figure 8 leading up to “Consider issuing advisory” illustrates this. However, if the pre-formation storm is expected to rapidly become a hurricane and be a threat, the forecaster may want to not wait for four consecutive forecasts (two days).

The non-selected ensemble storms in columns 3–5 in Table 3 either did not match a “To-watch” storm from the previous ECEPS forecast or were determined from the Decision Flowchart to not be reasonable or failed other selection factors. These non-selection categories include the following: cold-core system rather than a warm-core TC, which appears 10 times in Table 3; Caribbean FA, which appears only four times due to success of prior exclusions; too few members, which was tentatively defined as less than 10 and led to nine non-selections; and poor consistency with previous forecast run(s) in critical aspects such as the WCM evolution that indicates the LSC, which also appears nine times.

The characteristics of the long-Tau forecasts are low ensemble member counts and therefore substantial uncertainty in defining variables such as the initial position and timing, the general track direction and speed, the WCM evolution, and the pre-formation T2F (35) and T2H timings and positions. For example, it may be difficult to determine if the run-to-run T2F (35) timings and positions are so different because there are so few ensemble members, or simply that is a characteristic of extended-range forecasts. For a disturbance that does form, the ensemble member count generally increases as the forecast Tau becomes smaller, and the forecast variables will be more consistent run-to-run as the members come to better agreement.

Of course, the missing forecasts of 00 UTC 21 June and between 12 UTC 22 June and 00 UTC 26 June do interfere with the forecast process and would be of concern to the forecaster. However, if and when this technique becomes operational, such lengthy missing file incidents that occur here in a research study will not occur operationally.

2. Verification of NHC Advisories and ECEPS Summary Table for Pre-Enrique

The NHC's Five-Day Tropical Weather Outlook (TWO) included a disturbance for the first time with a $< 40\%$ chance of formation at 114 hours before the Enrique formation (Latto 2021). This chance was raised to 40–60% at 96 hours prior, then to $> 60\%$ at 78 hours prior (Latto 2021). The subsequent advisories issued by the NHC are summarized in Table 4.

It is noteworthy that the public advisories issued by the NHC did not begin until Enrique had already become a TS. That is, the first advisory (column 1, row 1) was issued when the maximum sustained wind speed was already 35 kt (i.e., it was at the T2F (35)). Just 24 hours after the first advisory was issued, Enrique met the threshold for a hurricane (column 3, row 5). The T2H timing was late in the first three advisories, although the error magnitudes did decrease in the later advisories. Position errors for the T2H (column 4) were very low during the 24-hour period (rows 3–4) preceding the T2H. Overall, the pre-Enrique NHC forecasts for T2H were highly accurate, which is in part because T2F (35) was already established before issuing the first advisory.

Table 4. re-Enrique NHC Timing and Position Predictions of T2F (35) and T2H based on NHC Advisories. Source: Elsberry et al. (2022).

NHC: T2F (35) Timing 06 UTC 25 June
Position: 15.0N, 101.7W

NHC: T2H Timing 06 UTC 26 June
Position: 16.7N, 104.5W

NHC initial time	T2F (35) Timing [error]	T2F (35) Position [error, S-South; E-East]	T2H (WCM 37) Timing [error]	T2H (WCM 37) Position [error, S-South; E-East]
06 UTC 25 June Advisory 1	Already a TS (35 kt)		062700 [Late 18 h]	16.6 N, 105.6 W [S 0.1 deg; W 1.1 deg]
12 UTC 25 June Advisory 2	Already a TS (40 kt)		062612 [Late 6 h]	16.4 N, 104.6 W [S 0.3 deg; W 0.1 deg]
18 UTC 25 June Advisory 3	Already a TS (45 kt)		062612 [Late 6 h]	16.5 N, 104.9 W [S 0.2 deg; W 0.4 deg]
00 UTC 26 June Advisory 4	Already a TS (55 kt)		062606 [Exact time]	16.5 N, 104.5 W [S 0.2 deg; W 0.0 deg]
06 UTC 26 June Advisory 5	Already a Hurricane		Already a Hurricane	

The ECEPS forecast guidance for pre-Enrique generated from the Marchok vortex tracker output (Elsberry et al. 2022) is similarly provided for comparison in Table 5. This validation of the ECEPS forecast guidance was done at the end of the season after the post-season reprocessing described in Section II.E was performed. The first ECEPS forecast that picked up the pre-Enrique disturbance was from 12 UTC 16 June (row 1, column 1), which is almost nine days in advance of the T2F, and the T2F (35) timing (column 2) and T2H timing (column 4) both erred by just six hours. There was a late bias in this first T2H timing forecast that persisted until the 12 UTC 21 June forecast, when the timing bias started to be slightly early. The T2H position errors are consistently around 2.5° south in latitude and between 1.6° west and 4.1° east in longitude. Neither the timing errors nor the position errors are egregious, and this guidance beginning 8 days, 18 hours in advance of the T2F (35) is considered a good early indicator of Enrique’s eventual formation. It is the objective of the Decision Flowchart to assist the forecaster in evaluating the ECEPS guidance to identify such early pre-Enrique forecasts.

Table 5. Pre-Enrique ECEPS Timing and Position Predictions of T2F (35) and T2H (WCM 37).
Source: Elsberry et al. (2022).

NHC: T2F (35) Timing 06 UTC 25 June
Position: 15.0N, 101.7W

NHC: T2H Timing 06 UTC 26 June
Position: 16.7N, 104.5W

ECEPS initial time	T2F(35) Timing [error]	T2F (35) Position [error, N-North, S- South; E-East, W- West]	T2H (WCM 37) Timing [error]	T2H (WCM 37) Position [error, N-North, S-South; E-East, W-West]
12 UTC 16 Jun (Storm 13)	062512 [Late 6h]	13.2N, 97.9 [S 1.8 deg; E 3.8 deg]	062612 [Late 6h]	14.5N, 100.6W [S 2.2 deg; E 3.9 deg]
00 UTC 17 Jun (Storm 14)	062512 [Late 6h]	13.3N, 100.0W [S 1.7 deg; E 1.7 deg]	062706 [Late 24h]	15.1N, 106.1W [S 1.6 deg; W 1.6 deg]
12 UTC 17 Jun (Storm 10)	062512 [Late 6h]	13.6N, 100.0W [S 1.4 deg; E 1.7 deg]	062806 [Late 48h]	16.4N, 104.8W [S 0.3 deg; W 0.3 deg]
00 UTC 18 Jun (Storm 8)	062600 [Late 18h]	14.0N, 102.2W [S 1.0 deg; W 0.5 deg]	062612 [Late 6h]	14.6N, 103.5W [S 2.1 deg; E 1.0 deg]
12 UTC 18 Jun (Storm 12)	062600 [Late 18h]	13.7N, 100.2W [S 1.3 deg; E 1.5 deg]	062612 [Late 6h]	14.3N, 102.0W [S 2.4 deg; E 2.5 deg]
00 UTC 19 Jun (Storm 11)	062606 [Late 24h]	15.0N, 101.9W [exact lat; W 0.2 deg]	062612 [Late 6h]	15.2N, 102.5W [S 1.5 deg; E 2.0 deg]
12 UTC 19 Jun (Storm 9)	062612 [Late 30h]	13.6N, 101.1W [S 1.4 deg; E 1.6 deg]	062712 [Late 30]	14.4N, 103.3W [S 2.3 deg; E 1.2 deg]

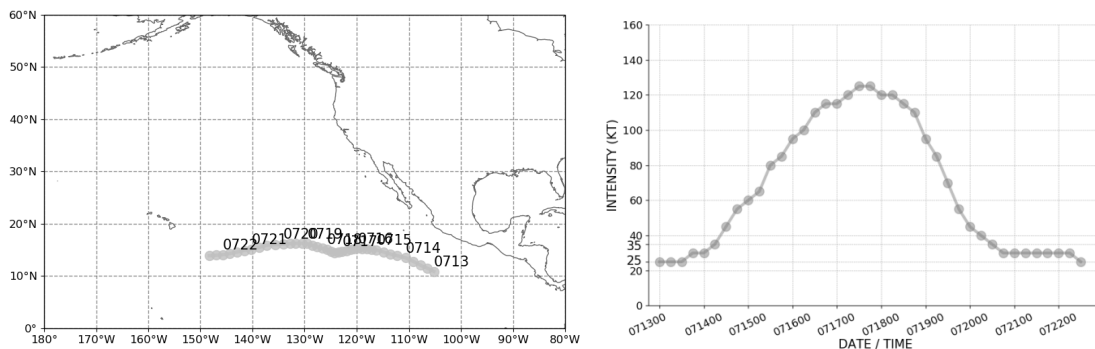
ECEPS initial time	T2F(35) Timing [error]	T2F (35) Position [error, N-North, S- South; E-East, W- West]	T2H (WCM 37) Timing [error]	T2H (WCM 37) Position [error, N-North, S-South; E-East, W-West]
00 UTC 20 Jun (Storm 7)	062512 [Late 6h]	13.3N, 97.8W [S 1.7 deg; E 3.9 deg]	062612 [Late 6h]	14.0N, 100.3W [S 2.7 deg; E 4.2 deg]
12 UTC 20 Jun (Storm 3)	062512 [Late 6h]	12.6N, 100.1W [S 2.4 deg; E 1.6 deg]	062706 [Late 24h]	13.8N, 103.4W [S 2.9 deg; E 1.1 deg]
00 UTC 21 Jun Missing	Missing single forecast [Consider using last available]			
12 UTC 21 Jun (Storm 3)	062512 [Late 6h]	13.2N, 100.0W [S 1.8 deg; E 1.7 deg]	062600 [Early 6h]	13.8N, 101.1W [S 2.9 deg; E 3.4 deg]
00 UTC 22 Jun (Storm 4)	062506 [Exact time]	13.4N, 99.5W [S 1.6 deg; E 2.2 deg]	062512 [Early 18h]	13.8N, 100.4W [S 2.9 deg; E 4.1 deg]
12 UTC 22 Jun through 00 UTC 26 Jun	Missing forecasts for 3.5 days [Too many for extrapolation]			
12 UTC 26 Jun (Storm 2)	Already a TS since 06 UTC 25 Jun		Became a Hurricane 6h ago	

All but three of these 11 pre-formation forecasts did also indicate a RI event (30 kt in ≤ 24 hours) following formation, with one such forecast as early as nine days prior to T2F (35) (Elsberry et al. 2022). This persistent messaging signals a level of confidence in the RI event forecast, which may prompt the forecasters to anticipate RI as a real possibility for this storm, even in a basin where it is seldom forecast (Courtney et al. 2019). The forecasters would of course consult their other forecast tools and resources to look for a sense of agreement and use this guidance product to back up a potential RI forecast.

B. HURRICANE FELICIA

1. Decision Flowchart Application to Pre-Felicia

Felicia formed in the far eastern North Pacific about three weeks after Enrique (Cangialosi 2021). Felicia also underwent RI and became a powerful Hurricane as it tracked mainly westward, as shown in Figure 18. While the early track indicated Felicia might have either a type A or type B₁ track defined in Figure 2, it ended up being closer to an A-type track. Although Felicia did cross the critical 140°W boundary into the central North Pacific basin, it did so as a remnant low. According to NHC advisories, the Felicia T2F (35) was 12 UTC 14 July with a position near 14.2°N, 113.4°W, and the T2H was 06 UTC 15 July with a position near 15.1°N, 117.1°W.

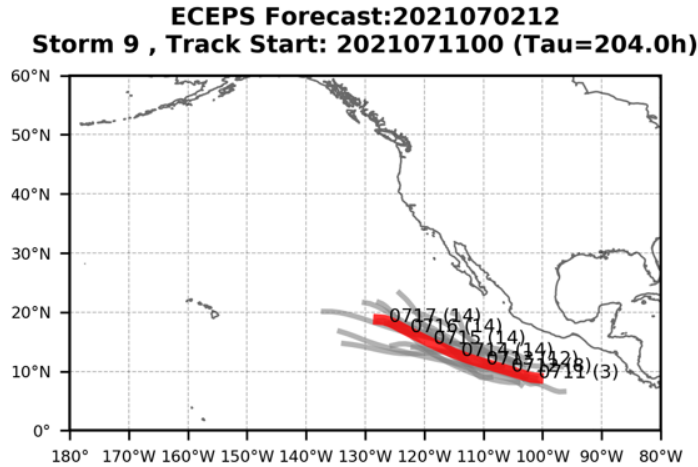


As in Tables 4 and 5 for Enrique, the ECEPS forecast ensemble storms that were selected to represent pre-Felicia are in the first column of Table 6, and the predicted T2F (35) and its timing errors are in column 2. Again, it is noteworthy that the first detection of pre-Felicia is 12 days in advance of the T2F (35), and yet that timing error is within 18 hours of the actual T2F (35). Even through the last forecast on 12 UTC 11 July, the largest T2F (35) timing error is 30 hours (at 12 UTC 4 July).

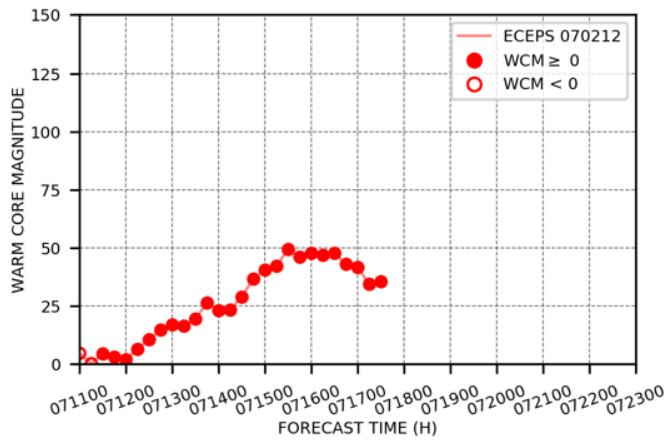
Beginning with Storm 9 (Figure 19) with 14 members in the 12 UTC 2 July ECEPS forecast (Table 6, row 1, column 1), a disturbance is identified as a realistic possible pre-Felicia and is placed in the “To-watch” category. In the first step of the Decision Flowchart (Figure 8), the forecaster determines that the Storm 9 does not match a likely-to-form ensemble storm selected in the previous ECEPS forecast. In the second step of the Decision Flowchart, the forecaster identifies that the WMVM initial position and the initial positions of the ensemble members are reasonable, the northwestward WMVM track is reasonable, and the WCM evolution to a LSC of Hurricane is logical. Although a single ensemble member track appears to begin near 7°N, 97°W, it is far enough outside of the Caribbean FA box and, with 14 ensemble members, Storm 9 is not likely to be a Caribbean FA. The forecast spread among the ensemble members is determined to be acceptable, especially considering the long forecast Tau of 204 hours. Thus, Storm 9 is selected as a storm “To-watch” which initiates its summary table (Table 8).

For this 02 UTC 2 July ECEPS forecast, the other storms evaluated by the forecaster in Table 6, row 1, columns 3–5 are non-selected and discarded as potential storms for the following reasons: poor member agreement in Storm 3, low number of members (four) in Storm 10, and that Storm 11 is likely a Caribbean FA.

Once the forecaster selected Storm 9 as the most likely pre-Felicia, identifying inconsistencies in the WCM evolution or storm start positions can be more straightforward and quick to conclude as reasons for non-selection. Examples of more difficult non-selections associated with the WCM evolution are Storm 9 in the 00 UTC 3 July forecast and Storm 5 in the 12 UTC 3 July forecast.



Datetime	Lat(N)	Long(W)	Num. of Members
071100	8.9°	100.7°	3
071106	9.0°	101.9°	3
071112	9.3°	102.9°	6
071118	9.6°	104.0°	6
071200	10.0°	105.2°	8
071206	10.3°	106.3°	8
071212	10.6°	107.4°	11
071218	11.0°	108.5°	12
071300	11.2°	109.5°	12
071306	11.5°	110.5°	12
071312	11.9°	111.6°	12
071318	12.2°	112.6°	13
071400	12.6°	113.8°	14
071406	13.1°	115.0°	14
071412	13.6°	116.2°	14
071418	14.1°	117.4°	14
071500	14.6°	118.5°	14
071506	15.2°	119.5°	14
071512	15.7°	120.5°	14
071518	16.1°	121.5°	14
071600	16.6°	122.4°	14
071606	17.1°	123.3°	14
071612	17.6°	124.2°	14
071618	18.0°	125.1°	14
071700	18.4°	125.9°	14
071706	18.7°	126.8°	14
071712	18.8°	127.8°	0



Datetime	WCM	ECEPS Intensity (kt)
071100	-4.7	21
071106	-0.2	22
071112	4.3	22
071118	3.2	22
071200	2.0	23
071206	6.3	23
071212	10.7	24
071218	14.7	24
071300	17.0	26
071306	16.3	26
071312	19.3	28
071318	26.3	27
071400	23.0	27
071406	23.3	28
071412	29.0	30
071418	36.7	31
071500	40.7	31
071506	42.3	33
071512	49.3	33
071518	46.0	34
071600	47.7	32
071606	47.0	32
071612	47.7	30
071618	43.0	29
071700	41.7	27
071706	34.3	28
071712	35.7	28

ECEPS	Members		Storm Start			Warm Core Mag.		Likely Storm Cat.	T2F(25)	T2F(35)		T2H		
	Start	Max	Time	Lat(N)	Long(W)	Start Mag.	WCM Max.		ECEPS (22.51)	WCM(20)	WCM(25)	Time	Lat(N)	Long(W)
070212	3	14	071100	8.9°	100.7°	-4.7	49.3	HU	071200	071318	071318	071500	14.6°	118.5°

Figure 19. ECEPS Forecast 12 UTC 02 July Storm 9
 (Selected Storm for Pre-Felica)

Table 6. Selection and Non-selection of ECEPS Storms for Pre-Felicia

ECEPS initial time (Selected storm)	T2F (35) Timing [error]	Alternate ECEPS Storm Options Considered [Scenario representing reason for non-selection]		
12 UTC 02 Jul (Storm 9)	071318 [Early 18h]	Storm 3 [poor member agreement]	Storm 10 [4 members]	Storm 11 [Caribbean FA]
00 UTC 03 Jul (Storm 7)	071406 [Early 6h]	Storm 2 [cold-core system]	Storm 8 [5 members]	Storm 9 [inconsistent WCM evolution]
12 UTC 03 Jul (Storm 4)	071406 [Early 6h]	Storm 5 [inconsistent WCM (high)]	Storm 8 [inconsistent storm start position]	Storm 11 [4 members]
00 UTC 04 Jul (Storm 6)	071312 [Early 24h]	Storm 5 [cold-core system]	Storm 7 [5 members]	Storm 8 [7 members]
12 UTC 04 Jul (Storm 8)	071306 [Early 30h]	Storm 6 [inconsistent storm start position]	Storm 9 [Caribbean FA]	Storm 10 [inconsistent storm start position]
00 UTC 05 Jul (Storm 8)	071318 [Early 18h]	Storm 7 [5 members]	Storm 9 [4 members]	Storm 10 [8 members]
12 UTC 05 Jul Missing	Missing single forecast [Consider using last available]			
00 UTC 06 Jul (Storm 7)	071406 [Early 6h]	Storm 6 [4 members]	Storm 11 [Caribbean FA]	Storm 16 [Caribbean FA]
12 UTC 06 Jul (Storm 9)	071412 [Exact time]	Storm 8 [inconsistent storm start position]	Storm 10 [inconsistent storm start position]	Storm 11 [4 members]
00 UTC 07 Jul (Storm 6)	071406 [Early 6h]	Storm 3 [cold-core system]	Storm 7 [8 members]	Storm 9 [inconsistent storm start position]
12 UTC 07 Jul (Storm 6)	071418 [Late 6h]	Storm 3 [inconsistent storm start]	Storm 8 [inconsistent storm start]	Storm 9 [Caribbean FA]

ECEPS initial time (Selected storm)	T2F (35) Timing [error]	Alternate ECEPS Storm Options Considered [Scenario representing reason for non-selection]		
00 UTC 08 Jul (Storm 7)	071500 [Late 12h]	Storm 5 [6 members]	Storm 8 [inconsistent T2H (late)]	Storm 9 [inconsistent WCM (low)]
12 UTC 08 Jul (Storm 8)	071418 [Late 6h]	Storm 5 [5 members]	Storm 7 [inconsistent WCM evolution]	Storm 11 [inconsistent WCM evolution]
00 UTC 09 Jul (Storm 5)	071412 [Exact time]	Storm 3 [4 members]	Storm 7 [inconsistent storm start position]	Storm 8 [7 members]
12 UTC 09 Jul (Storm 5)	071500 [Late 12h]	Storm 4 [cold-core system]	Storm 8 [inconsistent storm start position]	Storm 9 [inconsistent storm start time]
00 UTC 10 Jul Missing	Missing single forecast [Consider using last available]			
12 UTC 10 Jul (Storm 6)	071512 [Late 24h]	Storm 3 [inconsistent WCM (low)]	Storm 5 [cold-core system]	Storm 8 [inconsistent T2F (35) (early)]
00 UTC 11 Jul (Storm 7)	071506 [Late 18h]	Storm 5 [inconsistent storm start position]	Storm 8 [inconsistent storm start position]	Storm 12 [inconsistent storm start]
12 UTC 11 Jul (Storm 4)	071506 [Late 18h]	Storm 3 [cold-core system]	Storm 5 [5 members]	Storm 7 [inconsistent storm start]

The other storm options in columns 3–5 in Table 6 are not selected as the most likely storm to form if they fall into a category or multiple categories for non-selection. These non-selection categories include the following: poor consistency with previous forecast(s) in critical aspects such as the WCM evolution that indicates LSC, which appears 23 times; too few members, which was tentatively defined as less than 10, appears 16 times; cold-core system rather than a warm-core TC which appears six times in Table 6; Caribbean FA which appears five times; and poor track and/or WCM agreement among the members, although this factor appears only once. Because this series of ECEPS forecast

starts 12 days prior to the T2F (35), the forecaster would have to evaluate a large number of ensemble storms that were simply too inconsistent to be a match with the pre-Felicia selection in the previous forecast.

However, several of these storm options that were not matches could be placed in the “To-watch” category for identifying the next likely disturbance after pre-Felicia. Taking the forecaster’s storm selection process for the ECEPS initial time 12 UTC 7 July as an example, the previously selected Storm 6 of 00 UTC 7 July in Figure 20 is compared to the storm options from 12 UTC 7 July.

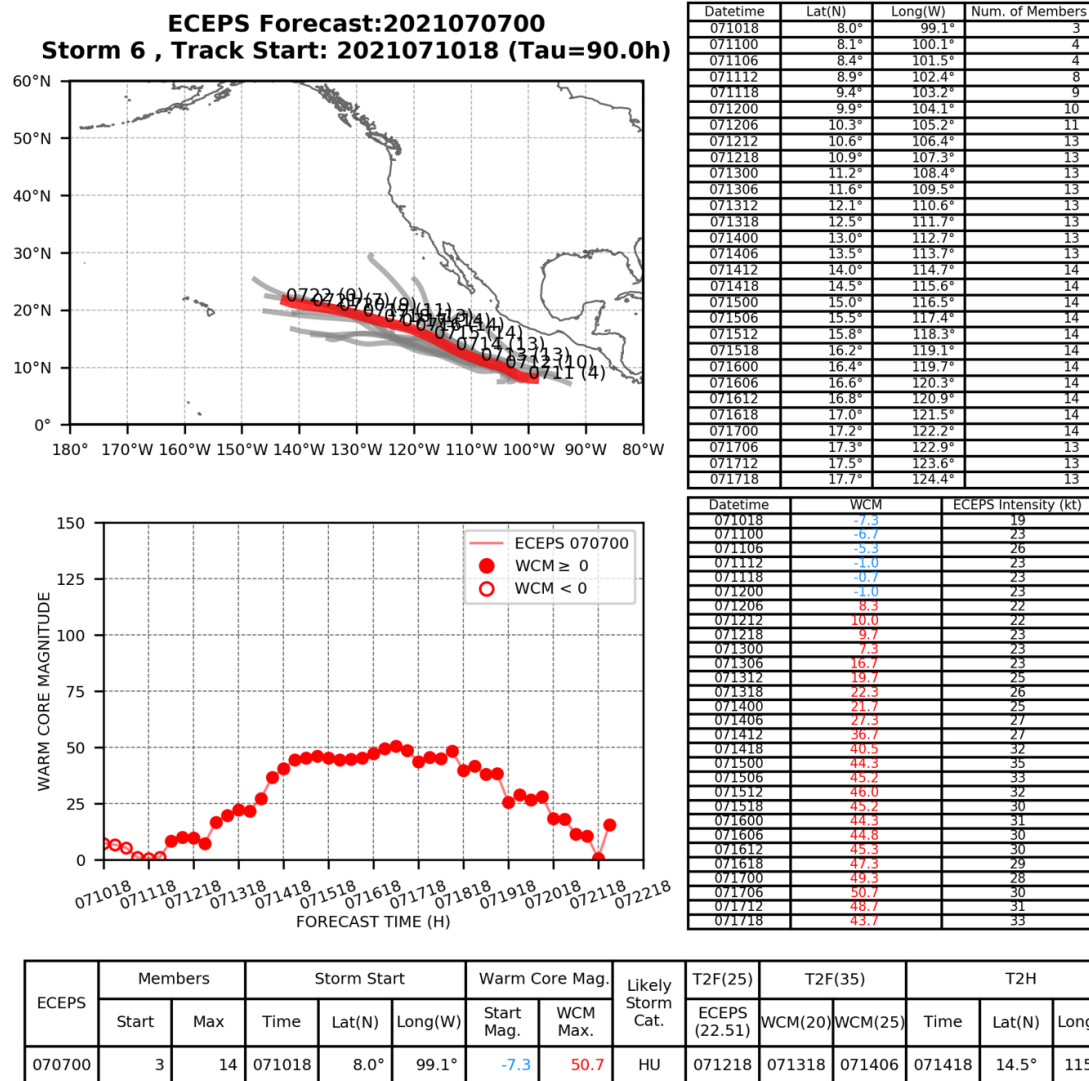


Figure 20. ECEPS Forecast 00 UTC 07 July Storm 6 (Selected Storm for Pre-Felicia)

The first storm option of the 12 UTC 7 July ECEPS initial time the forecaster evaluates through the Decision Flowchart is Storm 3, which is shown in Figure 21. In the first step of the Decision Flowchart, the forecaster compares the Storm 3 Storm Start near 9.3°N, 118.4°W at 00 UTC 8 July with the previously selected Storm 6 from 00 UTC 7 July near 8.0°N, 99.1°W at 18 UTC 10 July. Clearly, Storm 3 is a non-select for the disturbance associated with the previously selected Storm 6. However, Storm 3 has a reasonable ensemble storm initial position and track spread with no chance of being a Caribbean FA. Furthermore, Storm 3 has 10 members, the T2F (35) is reasonable, and the WCM evolution indicates a LSC of Hurricane. These are all of the characteristics of a likely next disturbance; therefore, Storm 3 may be placed in its own summary table with a “To-watch” category.

The forecaster next evaluates Storm 6 from the 12 UTC 7 July ECEPS forecast (Table 6, row 11, column 1), which is shown in Figure 22, and determines that the overall track as well as WCM evolution and maximum match reasonably well with the previously selected Storm 6 from the 00 UTC 7 July ECEPS forecast. That is, the new forecast T2F (35) position and timing of 13.5°N, 113.7°W at 06 UTC 14 July agrees very well with the previous 13.7°N, 115.2°W at 18 UTC 14 July, and the new T2H position and timing of 14.5°N, 115.6°W at 18 UTC 14 July to 15.1°N, 118.1°W at 12 UTC 15 July. It is noteworthy that the maximum number of ensemble members also increases significantly from 14 to 25 between the two forecast initialization times. Thus, Storm 6 of 12 UTC 7 July is accepted as the most likely pre-Felicia storm, and as the next storm in the forecast sequence for this potential disturbance, and confidence of the forecaster in Storm 6 would continue to build.

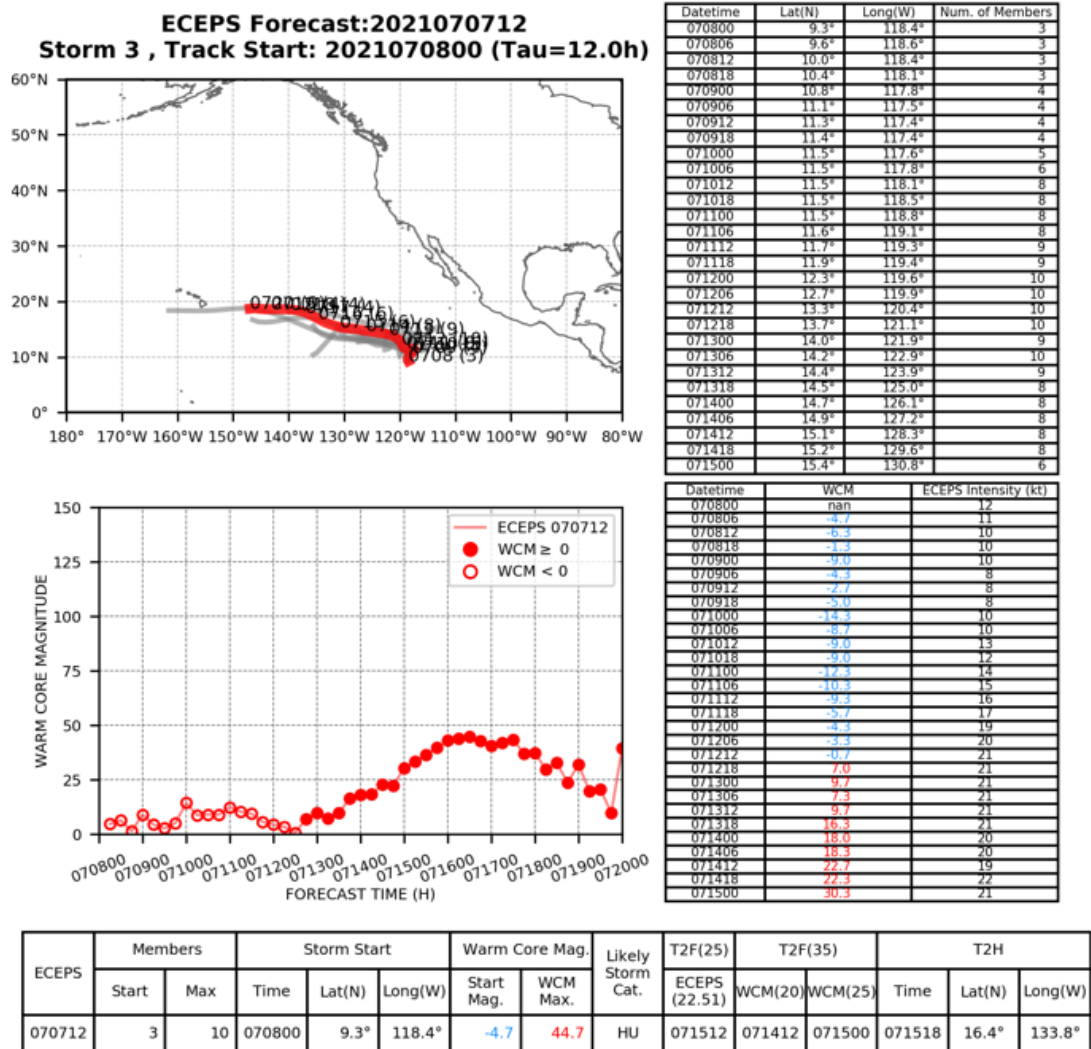


Figure 21. ECEPS Forecast 12 UTC 07 July Storm 3
 (Non-selected Storm for Pre-Felicia)

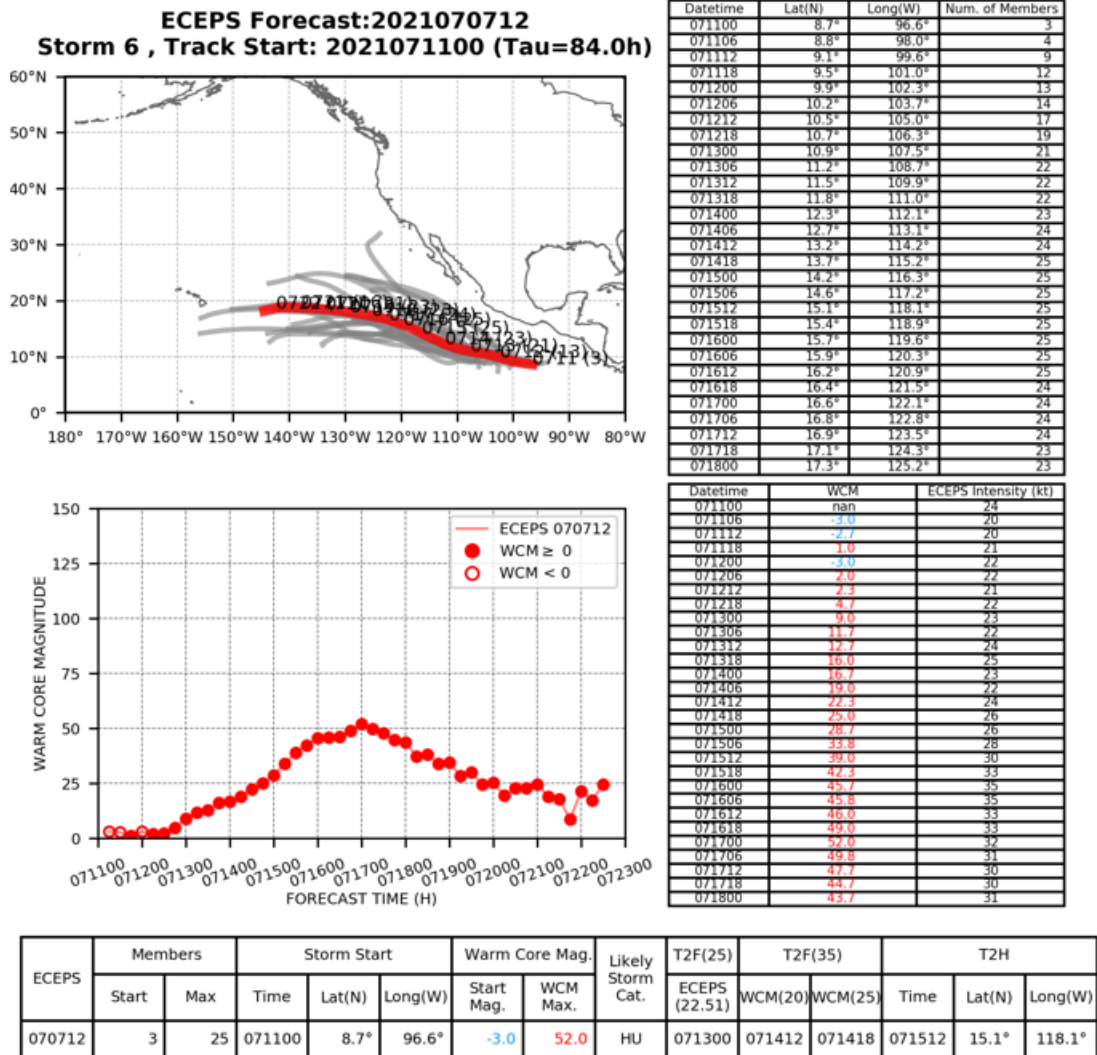


Figure 22. ECEPS Forecast 12 UTC 07 July Storm 6
(Selected Storm for Pre-Felicia)

The forecaster moves on to the next storm option in Table 6, row 11, column 4, which is Storm 8 in Figure 23. This Storm 8 WCM evolution, which is shown in the lower-left panel of Figure 23, may seem realistic and comparable to that of the previously selected Storm 6 of 00 UTC 7 July (Figure 20). In addition, the Storm 8 starting position near 10.6°N, 108.2°W at 06 UTC 12 July is inconsistent with that Storm 6 starting position near 8.0°N, 99.1°W at 18 UTC 10 July. Interestingly, the Storm 8 starting longitude is about midway between that Storm 6 position and the earlier described (Figure 21) Storm 3 position. As the forecaster evaluates Storm 8 through the decision flowchart, the Storm 8

track toward Hawai'i is of high interest, and the LSC is a Hurricane. Furthermore, there are no signs that Storm 8 might be a Caribbean FA, and the ensemble member spread is acceptable. Even though there are just eight ensemble members contributing to Storm 8, the forecaster labels Storm 8 as one "To-watch" with the potential to match in the following ECEPS forecasts, particularly due to the fact that its WMVM track is similar to a B₁ Track in Figure 2 and could potentially pose a threat to the Hawaiian Islands.

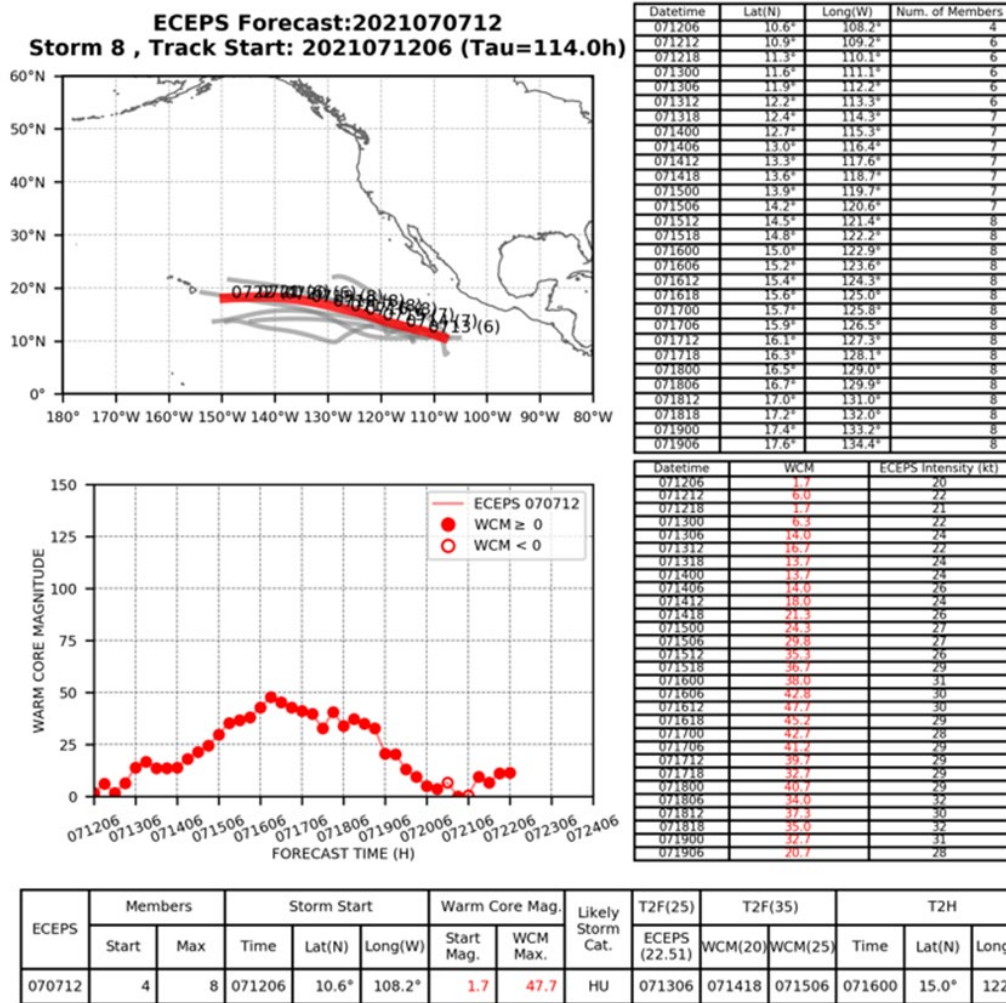


Figure 23. ECEPS Forecast 12 UTC 07 July Storm 8 (Non-selected Storm for Pre-Felicia)

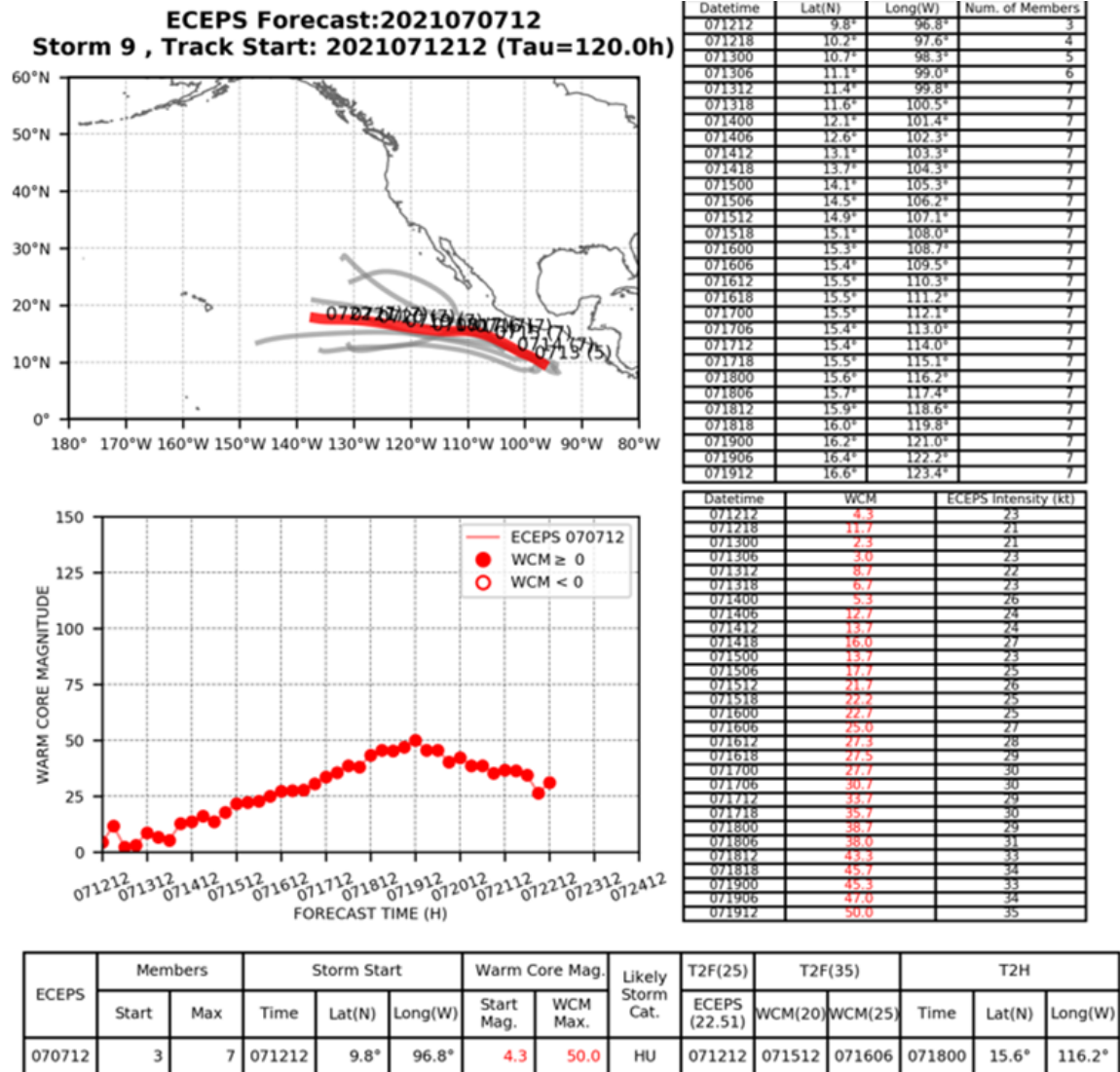


Figure 24. ECEPS Forecast 12 UTC 07 July Storm 9
(Non-selected Storm for Pre-Felicia)

Finally, the forecaster evaluates Storm 9 from the 12 UTC 7 July ECEPS forecast (Table 6, row 11, column 5), which is shown in Figure 24. In the first step of the Decision Flowchart, the forecaster identifies that the ensemble member tracks of Storm 9 are quite similar to those of the previously selected Storm 6 of 00 UTC 7 July. However, the Storm 9 starting position is different from that of Storm 6. Furthermore, this Storm 9 T2F (35) of 06 UTC 16 July near 15.4°N, 109.5°W compared to the previously selected Storm 6 T2F (35) of 06 UTC 14 July near 13.5°N, 113.7°W is an unreasonable change in just 12 hours. The forecaster continues to evaluate Storm 9 through the Decision Flowchart and identifies it to have a feasible B₁ type track and a LSC of Hurricane. In the next step of the Decision Flowchart of evaluating if Storm 9 is a likely Caribbean FA, the forecaster identifies several precursor ensemble member tracks (grey lines in the WMVM track plot in the upper-left of Figure 24) that begin close to the 93°W Caribbean FA boundary. This evidence suggests that Storm 9 is likely a Caribbean FA. Thus, the forecaster discards Storm 9 as it is not a likely-to-form ensemble storm.

All three of these non-selected storms (Storms 3, 8, and 9) for pre-Felicia for the ECEPS initial time 12 UTC 7 July would be first ruled out from being a continuation of the previously selected storm primarily due to their inconsistent storm start positions and timings. As discussed above, there were other factors for these storm options that prevented a match with the pre-Felicia disturbance. While these storms did not match the pre-Felicia disturbance, they proved to be reasonable forecasts thus candidates to become the next storm after pre-Felicia. Therefore, they were placed in the storms “To-watch” in the subsequent ECEPS forecasts in Table 6.

The Decision Flowchart is applied to each ECEPS initial time as the pre-Felicia storms are selected and compiled in the summary table. In real-time and operationally, once several storms for this specific disturbance have been placed consecutively into the “To-watch” category, confidence in the forecast will have increased and the forecaster would weigh the ECEPS forecast along with guidance from other forecast products to make the decision to issue an alert.

2. Verification of NHC Advisories and ECEPS Summary Table for Pre-Felicia

The NHC advisories for pre-Felicia are provided in Table 7 for comparison with the ECEPS summary table for pre-Felicia that is provided in Table 8. NHC's Five-Day TWO began at 12 UTC 9 July (120 hours prior to formation) to include a disturbance triangular area that could be associated with the ECEPS track forecast of pre-Felicia, but with only a 40% chance of formation (Cangialosi 2021). The TWO increased the chance of formation to 40–60% at 60 hours prior to formation, and then to 60% at 36 hours prior (Cangialosi 2021). However, NHC did not issue its first advisory of pre-Felicia until 06 UTC 14 July, which is just six hours prior to formation of Tropical Storm Felicia (Table 7, row 1, columns 1–2). Six hours later at the time of the second advisory, TS Felicia was already at 45 kt. Just 30 hours after the first advisory, Felicia had become a Hurricane (Table 7, row 5).

Table 7. Pre-Felicia NHC Timing and Position Predictions of T2F (35) and T2H based on NHC Advisories. Source: Elsberry et al. (2022).

NHC: T2F (35) Timing 12 UTC 14 July
Position: 14.2N, 113.4W

NHC: T2H Timing 06 UTC 15 July
Position: 15.1N, 117.1W

NHC initial time	T2F (35) Timing [error]	T2F (35) Position [error, S-South; E- East]	T2H (WCM 37) Timing [error]	T2H (WCM 37) Position [error, S-South; E- East]
06 UTC 14 Jul Advisory 1	071418 [Late 6 h]	14.9 N, 114.8 W [N 0.7 deg; W 1.4 deg]	071606 [Late 24 h]	15.7 N, 120.5 W [N 0.6 deg; W 3.4 deg]
12 UTC 14 Jul Advisory 2	Already a TS (45 kt)		071512 [Late 6 h]	15.4 N, 117.9 W [N 0.3 deg; W 0.8 deg]
18 UTC 14 Jul Advisory 3	Already a TS (55 kt)		071500 [Early 6 h]	14.9 N, 115.6 W [S 0.2 deg; E 1.5 deg]
00 UTC 15 Jul Advisory 4	Already a TS (60 kt)		071506 [Exact time]	15.2 N, 117.2 W [N 0.1 deg; W 0.1 deg]
06 UTC 15 Jul Advisory 5	Already a Hurricane		Already a Hurricane	

Recall from Table 6 that the first ECEPS forecast selected for pre-Felicia began at 12 UTC 2 July, which is an amazing 12 days prior to formation, and yet had high accuracy in T2F (35) and T2H timings and positions. The timing errors for the T2F (35) (Table 8, column 2) did not exceed 30 hours in any of the forecasts through 12 UTC 11 July, and frequently the T2F (35) timing was within 12 hours. These T2F (35) timings and positions (columns 2 and 3) tended to be early and eastward until after the 00 UTC 7 July forecast, when the errors then tended to be late and westward. The T2H errors (columns 4 and 5) followed similar trends and were also remarkably small. This guidance beginning 12 days in advance of the T2F is concluded to be an early and accurate indicator of Felicia's eventual formation. The objective use of the Decision Flowchart is to facilitate the forecaster's evaluation of the ECEPS guidance to identify early pre-formation forecasts such as these.

Table 8. Pre-Felicia ECEPS Timing and Position Predictions of T2F (35) and T2H.
Source: Elsberry et al. (2022).

NHC: T2F (35) Timing 12 UTC 14 July
Position: 14.2N, 113.4W

NHC: T2H Timing 06 UTC 15 July
Position: 15.1N, 117.1W

ECEPS initial time	T2F (35) Timing [error]	T2F (35) Position [error, N-North, S-South; E-East, W-West]	T2H (WCM 37) Timing [error]	T2H (WCM 37) Position [error, N-North, S- South; E-East, W-West]
12 UTC 02 Jul (Storm 9)	071318 [Early 18h]	12.2N, 112.6W [S 2.0 deg; E 0.8 deg]	071500 [Early 6h]	14.6N, 118.5W [S 0.5 deg; W 1.4 deg]
00 UTC 03 Jul (Storm 7)	071406 [Early 6h]	13.6N, 108.9W [S 0.6 deg; E 4.5 deg]	Peak forecast WCM 35.0 at 071800 [Not a Hurricane]	
12 UTC 03 Jul (Storm 4)	071406 [Early 6h]	12.9N, 109.9W [S 1.3 deg; E 3.5 deg]	071506 [Exact time]	15.0N, 114.1W [S 0.1 deg; E 3.0 deg]
00 UTC 04 Jul (Storm 6)	071312 [Early 24h]	11.1N, 112.1W [S 3.1 deg; E 1.3 deg]	071412 [Early 18h]	12.5N, 116.7W [S 2.6 deg; E 0.4 deg]
12 UTC 04 Jul (Storm 8)	071306 [Early 30h]	12.5N, 109.4W [S 1.7 deg; E 4.0 deg]	071406 [Early 24h]	13.5N, 113.7W [S 1.6 deg; E 3.4 deg]
00 UTC 05 Jul (Storm 8)	071318 [Early 18h]	12.2N, 113.2W [S 2.0 deg; E 0.2 deg]	071406 [Early 24 h]	13.0N, 115.2W [S 2.1 deg; E 1.9 deg]
12 UTC 05 Jul Missing	Missing single forecast [Consider using last available]			
00 UTC 06 Jul (Storm 7)	071406 [Early 6h]	13.2N, 112.7W [S 1.0 deg; E 0.7 deg]	071512 [Late 6h]	15.0N, 117.7W [S 0.1 deg; W 0.6 deg]
12 UTC 06 Jul (Storm 9)	071412 [Exact time]	15.0N, 112.1W [N 0.8 deg; E 1.3 deg]	071506 [Exact time]	16.4N, 114.7W [N 1.3 deg; E 2.4 deg]

ECEPS initial time	T2F (35) Timing [error]	T2F (35) Position [error, N-North, S-South; E-East, W-West]	T2H (WCM 37) Timing [error]	T2H (WCM 37) Position [error, N-North, S- South; E-East, W-West]
00 UTC 07 Jul (Storm 6)	071406 [Early 6h]	13.5N, 113.7W [S 0.7 deg; W 0.3 deg]	071418 [Early 12h]	14.5N, 115.6W [S 0.6 deg; E 1.5 deg]
12 UTC 07 Jul (Storm 6)	071418 [Late 6h]	13.7N, 115.2W [S 0.5 deg; W 1.8 deg]	071512 [Late 6h]	15.1N, 118.1W [Exact lat; W 1.0 deg]
00 UTC 08 Jul (Storm 7)	071500 [Late 12h]	14.7N, 115.0W [N 0.5 deg; W 1.6 deg]	071606 [Late 24h]	16.5N, 118.4W [N 1.4 deg; W 1.3 deg]
12 UTC 08 Jul (Storm 8)	071418 [Late 6h]	13.5N, 116.9W [S 0.7 deg; W 3.5 deg]	071518 [Late 12h]	15.1N, 120.4W [Exact lat; W 3.3 deg]
00 UTC 09 Jul (Storm 5)	071412 [Exact time]	13.4N, 115.4W [S 0.8 deg; W 2.0 deg]	071506 [Exact time]	15.0N, 118.5W [S 0.1 deg; W 1.4 deg]
12 UTC 09 Jul (Storm 5)	071500 [Late 12h]	13.8N, 116.3W [S 0.4 deg; W 2.9 deg]	071700 [Late 42h]	15.5N, 122.9W [N 0.4 deg; W 5.8 deg]
00 UTC 10 Jul Missing	Missing single forecast [Consider using last available]			
12 UTC 10 Jul (Storm 6)	071512 [Late 24h]	14.2N, 119.5W [N 0.0 deg; W 6.1 deg]	Peak forecast WCM 35.3 at 071618 [Not a Hurricane]	
00 UTC 11 Jul (Storm 7)	071506 [Late 18h]	14.9N, 117.1W [N 0.7 deg; W 3.7 deg]	071600 [Late 18h]	16.1N, 119.2W [N 1.0 deg; W 2.1 deg]
12 UTC 11 Jul (Storm 4)	071506 [Late 18h]	14.9N, 115.8W [N 0.7 deg; W 2.4 deg]	071612 [Late 30h]	16.2N, 119.4W [N 1.1 deg; W 2.3 deg]
Forecasts from 00 UTC 12 July through 12 UTC 15 July are omitted as the initial conditions for the ECEPS were clearly degrading the solution for the T2F (35) that occurred at 12 UTC 14 July.				

C. SUMMARY OF APPLICATION OF DECISION FLOWCHART FOR ENP HURRICANES

The application of the Decision Flowchart to process and interpret the ECEPS forecast guidance leads to the accurate selection of likely-to-form ensemble storms. This reliability and optimization have been demonstrated for Hurricanes Enrique and Felicia. The ECEPS forecast guidance for the remaining hurricanes (Hilda, Linda, Nora, Olaf, Pamela, and Rick) from the 2021 eastern North Pacific season were evaluated in the same manner. The detection timing in advance of T2F (35) and T2H by the NHC Advisories and ECEPS forecasts for all the hurricanes of the 2021 ENP season are provided in Table 9. The detections/warnings in the forecasts of T2F (35) by the NHC Advisories varied between 0 hours and 18 hours in advance (average of 7.5 hours in advance). In contrast, the detections/alerts in the ECEPS forecasts of T2F (35) were at least 5 days, 18 hours in advance for Hurricane Pamela and at most 12 days, 12 hours in advance for Hurricane Olaf and 12 days in advance for Hurricane Felicia with an average of 8 days, 18 hours in advance. The detections/warnings in the forecasts of T2H by the NHC Advisories were as short as 18 hours in advance of Hurricane Rick and at most 1 day, 18 hours in advance for Hurricanes Linda and Nora, with an average of about 1 day, 6 hours in advance. By contrast, the detections/alerts in the ECEPS forecasts of the T2H were at least 7 days, 2 hours in advance for Hurricane Rick and at most 13 days, 12 hours in advance for Hurricane Olaf with an average of about 10 days in advance. This thesis and the results from Elsberry et al. (2022) demonstrate that this early and accurate ECEPS forecast guidance would greatly advance pre-formation forecasts for hurricanes, if implemented and utilized in conjunction with the Decision Flowchart.

In conclusion, these techniques for evaluating Marchok vortex tracker outputs from the 15-day ECEPS forecasts prove to be early and accurate indicators of hurricane detection and life cycle and would be a valuable addition to a forecaster's resources at a TC warning center. However as also demonstrated in this section, the forecaster must have the capability to select the most likely ensemble storm that will become a long-lasting hurricane from among multiple potential ensemble storms during the pre-formation stage. Assisting the forecaster to achieve this capability to select that most likely ensemble storm

and/or the following ensemble storm is the objective of the Decision Flowchart (Figure 8), which has been extensively documented here for pre-Hurricanes Enrique and Felicia.

Table 9. NHC and ECEPS Early Detection of Eastern North Pacific Hurricanes. Source: Elsberry et al. (2022).

Hurricane	Detection in forecast in advance of T2F (35)		Detection in forecast in advance of T2H	
	NHC Advisory	ECEPS	NHC Advisory	ECEPS
Enrique (05E)	0 hours	8 days, 18 hours	1 day	9 days, 18 hours
Felicia (06E)	0 hours	12 days	1 day	12 days, 18 hours
Hilda (08E)	0 hours	8 days, 6 hours	1 day, 3 hours	9 days, 9 hours
Linda (12E)	12 hours	7 days, 18 hours	1 day, 18 hours	9 days, 12 hours
Nora (14E)	18 hours	9 days	1 day, 18 hours	10 days, 18 hours
Olaf (15E)	18 hours	12 days, 12 hours	1 day	13 days, 12 hours
Pamela (16E)	6 hours	5 days, 18 hours	1 day, 12 hours	7 days, 6 hours
Rick (17E)	6 hours	6 days, 6 hours	18 hours	7 days, 2 hours

V. TROPICAL STORM CATEGORY EXAMPLES

A. STRONG TROPICAL STORM EXAMPLE

Tropical Storm Guillermo formed in favorable conditions in mid-July about 275 n mi southwest of Manzanillo, Mexico (Berg 2021). The track and intensity plots for Guillermo are provided in Figure 25. Guillermo was a short-lived TS that took a track most similar to Track B₁ in Figure 2 but encountered higher wind shear and cooler waters and ultimately weakened and became a remnant low before crossing 140°W (Berg 2021). The maximum sustained wind speeds for tropical storms are 34 kt–63 kt, and Guillermo’s maximum sustained winds were estimated to be 50 kt, which is well within the bounds of TS intensity criteria (Berg 2021).

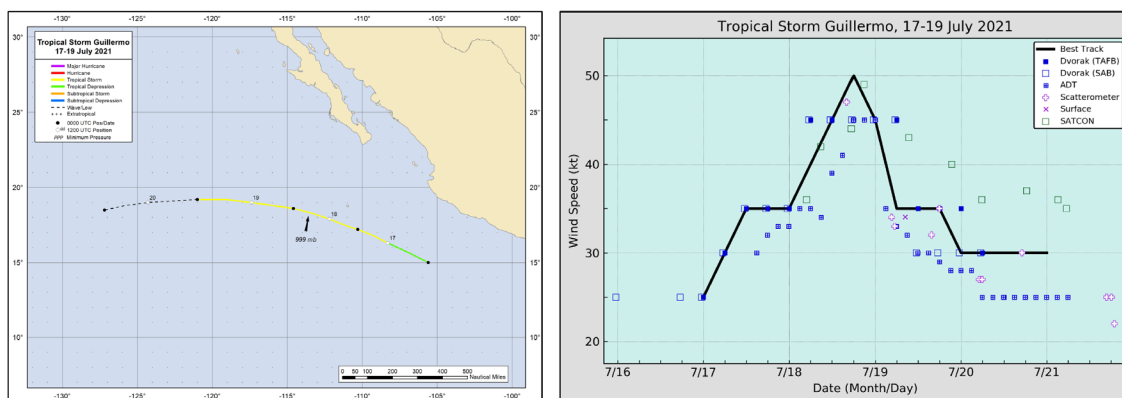


Figure 25. Tropical Storm Guillermo (2021) Track and Intensity Plots.
Source: Berg (2021).

The NHC included pre-Guillermo in their TWO leading up to issuing advisories. The 5-day outlooks first indicated a disturbance with < 40% chance of formation 192 hours prior to formation, then a 40–60% chance 162 hours prior, and > 60% chance 138 hours prior (Berg 2021). The 2-day outlooks indicated < 40% chance 54 hours prior, then 40–60% just 36 hours prior, and > 60% only 18 hours prior to formation. Note that these outlooks do not provide forecast details such as likely track or intensity evolution. The only advisory issued by the NHC ahead of formation is shown in Table 10.

Table 10. Pre-Guillermo NHC Timing and Position Predictions of T2F (35) and T2H

NHC: T2F (35) Timing 18 UTC 17 July NHC: T2H Did not make Hurricane
Position: 16.9N, 109.5W

NHC initial time	T2F (35) Timing [error]	T2F (35) Position [error, S-South; E- East]	T2H Timing [error]	T2H Position [error, S- South; E- East]
12 UTC 17 Jul Advisory 1	071718 [Exact time]	17.0 N, 110.0 W [N 0.1 deg; E 0.5 deg]	Peak forecast intensity 55 kt at 071912 Not a Hurricane	
18 UTC 17 Jul Advisory 2	Already a TS			

1. Decision Flowchart Application

During post-storm analyses of Guillermo and other tropical storms, it was determined that a disturbance achieving the WCM (20) threshold for the T2F (35) timing was more accurate than achieving the WCM (25) threshold. As noted in the Guillermo intensity plot in Figure 25, there can be considerable variability in the pre-formation intensity estimates among the various guidance products. For these ECEPS forecasts, this lower weighted-mean WCM threshold for the T2F (35) timing may be better addressing the variability among the members. For this reason, the WCM (20) threshold will be used for T2F (35) timing for TS Guillermo (Table 11, column 2 heading title).

A special consideration for this evaluation of the ECEPS pre-formation forecasts of TS Guillermo is that the Guillermo T2F (35) timing of 18 UTC 17 July near 16.9°N, 109.5°W (Table 10) closely followed (3.25 days) the Felicia T2F (35) timing of 12 UTC 14 July near 14.2°N, 113.4°W. The first ECEPS forecast in which a pre-formation circulation was detected that later (06 UTC 16 July) was predicted to become TS Guillermo was Storm 8 in the 00 UTC 9 July forecast (Table 11, rows 1–2). Although that T2F (35) forecast later was validated to be early by 36 hours, this ECEPS forecast was initiated almost nine days in advance of the Guillermo T2F (35), and more than five days in advance of the Felicia T2F (35) farther to the west. Thus, the ECEPS was simultaneously forecasting the pre-formation stages for both Felicia and Guillermo.

In the pre-Felicia discussion in section IV.B.1, there were three non-selected ensemble storm options in the ECEPS forecast from 12 UTC 7 July (Table 6, row 11, columns 3–5). That is, Storm 3 (Figure 21) and Storm 8 (Figure 23) are non-selected with the reason “inconsistent storm start,” which should be interpreted as inconsistent with the previously selected pre-Felicia storm initial positions. For example, Storm 3 starts at 00 UTC 8 July from 9.3°N, 118.4°W, which is far to the west of the selected pre-Felicia Storm 6 that starts at 18 UTC 10 July near 8.0°N, 99.1°W and has a T2F (35) at 12 UTC 14 July near 14.2°N, 113.4°W. Similarly, Storm 8 in the ECEPS forecast from 12 UTC 7 July starts at 06 UTC 12 July near 10.6°N, 108.2°W and has a T2F (35) at 06 UTC 15 July near 14.2°N, 120.6°W (Figure 23) that is again far to the west of the Felicia T2F (35) positions near 113.4°W.

However, Storm 9 in that same ECEPS forecast starts at 12 UTC 12 July near 9.8°N, 96.8°W and has a T2F (35) at 06 UTC 16 July near 15.4°N, 109.5°W (Figure 24), which is an excellent 10-day in advance T2F (35) position forecast for Guillermo that was near 16.9°N, 109.5°W. While that Storm 9 in the 12 UTC 7 July ECEPS forecast was categorized as a Caribbean FA for pre-Felicia (Table 6, row 11, column 5) because of its 96.8°W starting position, a five-day backward extrapolation of the Guillermo track in Figure 25 to 12 July would be consistent with a ~97°W starting position. In conclusion, during an active/favorable TC formation period in the ENP, indicated first by only a 3.25-day difference in the T2F (35) for Guillermo after the Felicia T2F (35) and secondly by all three of the non-selected storms had WCM evolutions indicating an LSC of Hurricane, a non-selected storm with a category of “inconsistent storm start position” to the east of an existing Hurricane may actually be an early precursor of the next TC.

Returning to the storm options from the 00 UTC 9 July ECEPS forecast in Table 11 row 1 that are evaluated via the Decision Flowchart as usual. The Storm 8 was selected as the most likely next storm once Storm 3 was discarded for having too few members, Storm 7 was then discarded for poor member track agreement. Finally, Storm 9 was also discarded for being a likely Caribbean FA. Thus, from an ECEPS forecast initiated almost nine days in advance of the T2F (35), Storm 8 is selected as a realistic disturbance that is likely to form and is put in the category “To-watch.”

Table 11. Selection and Non-selection of ECEPS Storms for Pre-Guillermo

ECEPS initial time	T2F (35) WCM (20) Timing [error]	Alternate ECEPS Storm Options Considered [Scenario representing reason for non-selection]		
00 UTC 09 Jul (Storm 8)	071606 [Early 36h]	Storm 3 [4 members]	Storm 7 [poor member track agreement]	Storm 9 [Caribbean FA]
12 UTC 09 Jul (Storm 9)	071612 [Early 30h]	Storm 4 [cold-core system]	Storm 5 [Caribbean FA]	Storm 8 [Caribbean FA]
00 UTC 10 Jul Missing	Missing single forecast [Consider using last available]			
12 UTC 10 Jul (Storm 9)	071706 [Early 12h]	Storm 5 [cold-core system]	Storm 8 [Caribbean FA]	Storm 11 [poor member track agreement]
00 UTC 11 Jul (Storm 8)	071712 [Early 6h]	Storm 5 [inconsistent WCM evolution]	Storm 7 [inconsistent storm start position and timing]	Storm 14 [4 members]
12 UTC 11 Jul (Storm 9)	071712 [Early 6h]	Storm 5 [5 members]	Storm 7 [inconsistent storm start position and timing]	Storm 10 [cold-core system]
00 UTC 12 Jul (Storm 9)	071712 [Early 6h]	Storm 8 [4 members]	Storm 10 [inconsistent storm start position]	Storm 12 [4 members]

ECEPS initial time	T2F (35) WCM (20) Timing [error]	Alternate ECEPS Storm Options Considered [Scenario representing reason for non-selection]		
12 UTC 12 Jul (Storm 7)	071706 [Early 12h]	Storm 5 [4 members]	Storm 9 [inconsistent storm start position]	Storm 13 [poor member track agreement]
00 UTC 13 Jul Missing	Missing single forecast [Consider using last available]			
12 UTC 13 Jul (Storm 4)	071712 [Early 6h]	Storm 1 [inconsistent max WCM (low)]	Storm 6 [8 members]	Storm 7 [9 members]
00 UTC 14 Jul (Storm 4)	071706 [Early 12h]	Storm 2 [4 members]	Storm 3 [7 members]	Storm 6 [inconsistent WCM evolution]
12 UTC 14 Jul (Storm 2)	071706 [Early 12h]	Storm 4 [5 members]	Storm 6 [cold-core system]	Storm 8 [inconsistent storm start timing and position]
00 UTC 15 Jul (Storm 1)	071612 [Early 30h]	Storm 2 [inconsistent WMVM track]	Storm 9 [cold-core system]	Storm 10 [8 members]
12 UTC 15 Jul (Storm 2)	071618 [Early 24h]	Storm 1 [inconsistent WMVM track]	Storm 6 [inconsistent WMVM track]	Storm 8 [cold-core system]
00 UTC 16 Jul (Storm 2)	071618 [Early 24h]	Storm 1 [inconsistent WMVM track]	Storm 6 [cold-core system]	Storm 8 [6 members]

ECEPS initial time	T2F (35) WCM (20) Timing [error]	Alternate ECEPS Storm Options Considered [Scenario representing reason for non-selection]		
12 UTC 16 Jul (Storm 2)	071618 [Early 24h]	Storm 1 [inconsistent WMVM track]	Storm 3 [inconsistent storm start position]	Storm 4 [cold-core system]
00 UTC 17 Jul (Storm 2)	071706 [Early 12h]	Storm 1 [inconsistent WMVM track]	Storm 4 [cold-core system]	Storm 6 [6 members]
12 UTC 17 Jul (Storm 2)	071718 [Exact time]	Storm 1 [inconsistent WMVM track]	Storm 4 [cold-core system]	Storm 5 [4 members]
00 UTC 18 Jul (Storm 2)	Already a TS			

The forecasts from the following ECEPS initial times are evaluated in the same way and the selected storms and the reasons for non-selection of alternate storm options are also provided in Table 11 in columns 3–5. Note after two T2F (35) timing error validations of early 30–36 hours, there are eight consecutive forecasts from 12 UTC 10 July through 00 UTC 14 July in which timing errors were only six hours to 12 hours early. As an example, Storm 4 from the ECEPS initial time 00 UTC 14 July (Table 11, row 11) was selected and is displayed in Figure 26. Not only is this Storm 4 evaluated as a disturbance likely to form, the WMVM track forecast (upper-left panel) indicates a possible direct hit on the Hawaiian Islands. Furthermore, the WCM (20) evolution is indicative of a T2F (35) at 06 UTC 17 July and a T2H at 12 UTC 18 July. Even though this pre-Guillermo disturbance is predicted to begin to decay from its peak intensity at 06 UTC 21 July near 17°N, 129°W, an alert regarding the potential hurricane may be considered by the forecasters.

Progressing in time through the ECEPS forecasts, as the forecaster non-selects ensemble storm options for the various scenarios documented in Table 11, a level of confidence in the selected ensemble storms develops and the forecaster would consider issuing an advisory. For pre-Guillermo, these non-selection scenarios included the following: poor consistency with the previous forecast run(s) in critical aspects such as the WMVM track or the WCM evolution that indicates the LSC, which appears 16 times in Table 11; insufficient ensemble members, which appears 15 times; cold-core system rather than a warm-core TC, which appears 10 times; Caribbean FA, which appears only four times; and poor ensemble member agreement in the WMVM track, which appears three times.

The breakdown of the non-selection scenarios for strong TS Guillermo are comparable to those of Hurricanes Enrique and Felicia, as discussed in Sections IV.A.1 and IV.B.1, respectively. Of note, the scenario that an alternate storm option is placed in “To-watch” category but is not selected as a match for the pre-Guillermo, pre-Enrique, or

pre-Felicia disturbances, is common to all three TCs. This speaks to the high number of ECEPS forecasts in advance of each T2F (35): 8 days, 18 hours ahead of Guillermo; 8 days, 18 hours ahead of Enrique; and 12 days ahead of Felicia. The scenario of a Caribbean FA is not frequently found to be a reason for non-selection in any of these three TCs, and this is likely due to the success of the Caribbean FA box in eliminating many of these FA circulations before they are presented to the forecaster for evaluation.

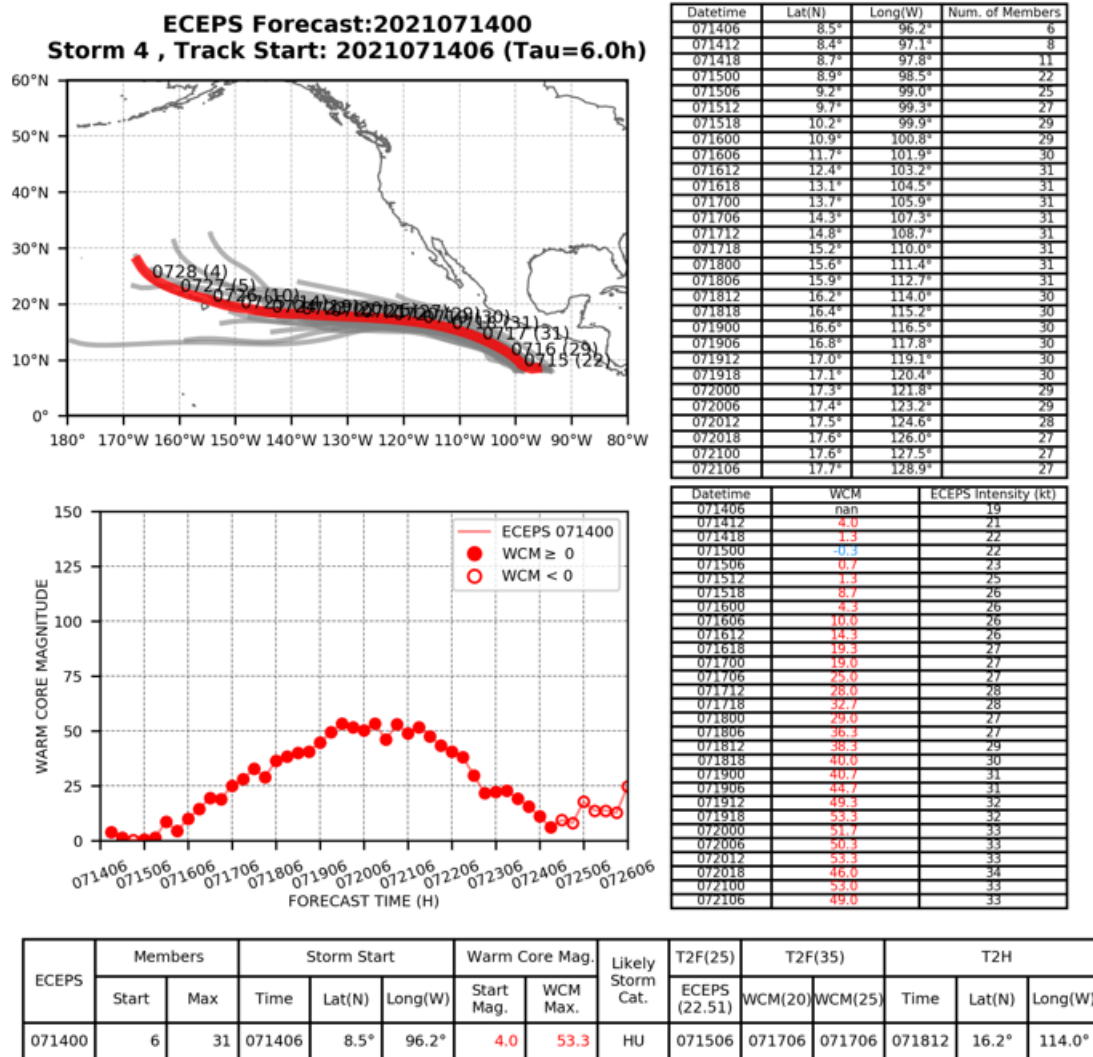


Figure 26. ECEPS Forecast 00 UTC 14 July Storm 4 (Selected Storm for Pre-Guillermo)

2. Verification of ECEPS Summary Table

Recall from Table 10 that just one advisory was issued by the NHC for pre-Guillermo, and just six hours prior to formation. While that Advisory 1 forecast of the T2F (35) timing and position accuracy was high, it was only for six hours. The validation summary table of the ECEPS forecasts of pre-Guillermo is provided in Table 12. As indicated in Section V.A.1, the first ECEPS forecast in which a pre-formation TS Guillermo circulation was detected was in the 00 UTC 9 July forecast, which is 8.75 days in advance of the NHC T2F (35) at 18 UTC 17 July (Table 12, row 1). Although this ECEPS-predicted T2F (35) was 36 hours early, its longitudinal position error was only 0.4° to the west. Even though these T2F (35) timing errors were only 6–12 hours early for the forecasts between 12 UTC 10 July and 12 UTC 14 July (Table 12, row 12), the longitudinal errors along this westward moving pre-Guillermo were larger. While Guillermo turned out to be a strong TS, the ECEPS-predicted maximum WCM consistently indicated a LSC of Hurricane from the first (00 UTC 9 July) forecast through the 12 UTC 15 July forecast (Table 12, row 14). Thus, it was only after the 00 UTC 16 July forecast [1.75 days prior to the T2F (35)] that the ECEPS-predicted maximum WCM indicated that Guillermo would only be a strong TS (Table 12, columns 4–5) instead of a Hurricane.

This strong TS Guillermo is an example of how ECEPS forecasts provide an opportunity for improved, earlier, pre-formation guidance. If the ECEPS forecast guidance is consulted and weighed by the forecaster along with their other forecast tools, a more full picture may be provided to DOD and the public of a formation well ahead of time with details of the disturbance's predicted progression in terms of both track and intensity.

Table 12. Pre-Guillermo ECEPS Timing and Position Predictions of T2F (35) WCM (20) and T2H

NHC: T2F (35) Timing 18 UTC 17 July
Position: 16.9N, 109.5W

NHC: T2H Did not make Hurricane

ECEPS initial time	T2F (35) WCM (20) Timing [error]	T2F (35) WCM (20) Position [error, N-North, S- South; E-East, W- West]	T2H (WCM 37) Timing [error]	T2H (WCM 37) Position [error, N-North, S-South; E-East, W-West]
00 UTC 09 Jul (Storm 8)	071606 [Early 36h]	14.8N, 109.9W [S 2.1 deg; W 0.4 deg]	071806 [Not a Hurricane]	16.2N, 116.9W [Not a Hurricane]
12 UTC 09 Jul (Storm 9)	071612 [Early 30h]	13.5N, 109.3W [S 3.4 deg; E 0.2 deg]	071900 [Not a Hurricane]	15.9N, 118.7W [Not a Hurricane]
00 UTC 10 Jul Missing	Missing single forecast [Consider using last available]			
12 UTC 10 Jul (Storm 9)	071706 [Early 12h]	11.5N, 104.7W [S 5.4 deg; E 4.8 deg]	071906 [Not a Hurricane]	14.2N, 113.9W [Not a Hurricane]
00 UTC 11 Jul (Storm 8)	071712 [Early 6h]	15.1N, 114.7W [S 1.8 deg; W 5.2 deg]	071900 [Not a Hurricane]	16.5N, 120.1W [Not a Hurricane]
12 UTC 11 Jul (Storm 9)	071712 [Early 6h]	12.6N, 108.1W [S 4.3 deg; E 1.4 deg]	071906 [Not a Hurricane]	14.5N, 116.6W [Not a Hurricane]
00 UTC 12 Jul (Storm 9)	071712 [Early 6h]	13.2N, 107.1W [S 3.7 deg; E 2.4 deg]	072100 [Not a Hurricane]	16.6N, 122.8W [Not a Hurricane]
12 UTC 12 Jul (Storm 7)	071706 [Early 12h]	14.1N, 105.3W [S 2.8 deg; E 4.2 deg]	072000 [Not a Hurricane]	16.2N, 117.1W [Not a Hurricane]
00 UTC 13 Jul Missing	Missing single forecast [Consider using last available]			

ECEPS initial time	T2F (35) WCM (20) Timing [error]	T2F (35) WCM (20) Position [error, N-North, S- South; E-East, W- West]	T2H (WCM 37) Timing [error]	T2H (WCM 37) Position [error, N-North, S-South; E-East, W-West]
12 UTC 13 Jul (Storm 4)	071712 [Early 6h]	15.3N, 108.4W [S 1.6 deg; E 1.1 deg]	072106 [Not a Hurricane]	17.6N, 126.3W [Not a Hurricane]
00 UTC 14 Jul (Storm 4)	071706 [Early 12h]	14.3N, 107.3W [S 2.6 deg; E 2.2 deg]	071812 [Not a Hurricane]	16.2N, 114.0W [Not a Hurricane]
12 UTC 14 Jul (Storm 2)	071706 [Early 12h]	15.1N, 107.4W [S 1.8 deg; E 2.1 deg]	071900 [Not a Hurricane]	17.3N, 116.5W [Not a Hurricane]
00 UTC 15 Jul (Storm 1)	071612 [Early 30h]	12.9N, 103.4W [S 4.0 deg; E 6.1 deg]	071712 [Not a Hurricane]	15.8N, 109.1W [Not a Hurricane]
12 UTC 15 Jul (Storm 2)	071618 [Early 24h]	14.5N, 104.0W [S 2.4 deg; E 5.5 deg]	071806 [Not a Hurricane]	18.0N, 112.9W [Not a Hurricane]
00 UTC 16 Jul (Storm 2)	071618 [Early 24h]	14.7N, 104.0W [S 2.2 deg; E 5.5 deg]	[Not a Hurricane -- Peak forecast WCM 33.3 at 071718 at 17.7N, 110.2W]	
12 UTC 16 Jul (Storm 2)	071618 [Early 24h]	14.5N, 102.9W [S 2.4 deg; E 6.6 deg]	[Not a Hurricane -- Peak forecast WCM 33.0 at 071812 at 18.9N, 113.0W]	
00 UTC 17 Jul (Storm 2)	071706 [Early 12h]	16.8N, 106.6W [S 0.1 deg; E 2.9 deg]	[Not a Hurricane -- Peak forecast WCM 28.0 at 071818 at 18.4N, 114.1W]	
12 UTC 17 Jul (Storm 2)	071718 [Exact time]	17.1N, 109.6W [N 0.2 deg; W 0.1 deg]	071912 [Not a Hurricane]	18.4N, 117.9W [Not a Hurricane]
00 UTC 18 Jul (Storm 2)	Already a TS		[Not a Hurricane -- Peak forecast WCM 34.7 at 071918 at 19.7N, 119.0W]	

B. WEAK TROPICAL STORM EXAMPLE

Tropical Storm Jimena began as a disturbance far south-southwest of the southern tip of Baja California, then developed into a weak Tropical Storm in early August. Jimena's track and intensity plots are provided in Figure 27. TS Jimena was one of the few storms during the 2021 ENP season that did not originate in the favored formation area south of the Gulf of Tehuantepec (Figure 2). Instead, pre-Jimena began near 15°N, 125°W and had a northwestward path that might have threatened Hawai'i if it had persisted (Figure 27). According to the NHC's Hurricane Specialist Unit (2021), Jimena's maximum sustained winds were 35 kt, and the range for tropical storms is 34 kt–63 kt (National Hurricane Center 2020), which qualifies Jimena as a very weak TS. Jimena entered the CPHC AOR on August 6 as a Tropical Depression and was shortly afterward declared a remnant low. Nevertheless, post-storm Jimena brought significant amounts of moisture and brief bouts of heavy rainfall over parts of Hawai'i, particularly to eastern Kaua'i and southern portions of the Big Island (Bravender 2021). Fortunately, there were no reports of damage or injuries associated with the heavy rainfall.

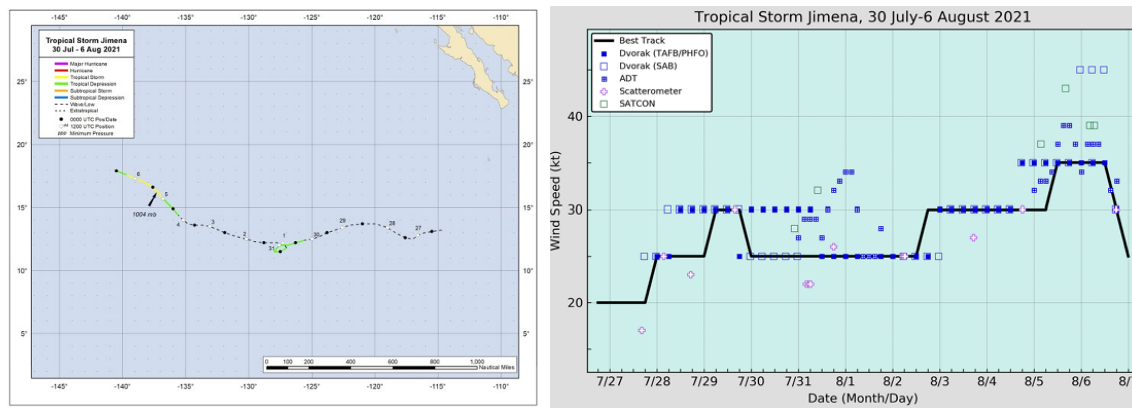


Figure 27. Tropical Storm Jimena (2021) Track and Intensity Plots. Source: Pasch (2022).

The NHC advisories issued for pre-Jimena are provided in Table 13. In contrast to the eight hurricanes summarized in Table 9 in which the average time-in-advance of NHC advisories prior to the T2F (35) was only 7.5 hours, there were nine NHC advisories for pre-Jimena, which included a period between 06 UTC 1 August and 18 UTC 4 August during which TS intensity was not predicted. The first advisory issued 18 UTC 30 July forecast a T2F (35) of 06 UTC 1 August, which turned out to be early by four days (Table 13, row 1, column 2). In addition, a peak intensity of 50 kt was forecast at 18 UTC 4 August (Table 13, row 1, columns 4–5), which was 12 hours before the actual T2F (35). NHC continued to be aggressive in forecasting an early T2F (35) and a peak intensity beyond 35 kt through Advisory 6 (Table 13, row 6). It was only in Advisory 8 after the four-day gap in forecasts, and only 12 hours in advance of the T2F (35), that very accurate T2F (35) timing and position forecasts became available.

Table 13. Pre-Jimena NHC Timing and Position Predictions of T2F (35) and T2H (WCM 37) based on NHC Advisories

NHC: T2F (35) Timing 06 UTC 5 August
Position: 15.3N, 136.4W

NHC: T2H Did not make Hurricane

NHC initial time	T2F (35) Timing [error]	T2F (35) Position [error, S-South; E-East]	T2H Timing [error]	T2H Position [error, S-South; E-East]
18 UTC 30 Jul Advisory 1	080106 [Early 4.0 d]	11.7N, 127.9W [S 3.6 deg; E 8.6 deg]	Peak forecast intensity 50 kt at 080418 Not a Hurricane	
00 UTC 31 Jul Advisory 2	080112 [Early 3.75 d]	12.4N, 128.4W [S 2.9 deg; E 8.0 deg]	Peak forecast intensity 50 kt at 080500 Not a Hurricane	
06 UTC 31 Jul Advisory 3	080206 [Early 3.0 d]	13.7N, 136.5W [S 1.6 deg; W 0.1 deg]	Peak forecast intensity 45 kt at 080406 Not a Hurricane	
12 UTC 31 Jul Advisory 4	080212 [Early 2.75 d]	12.5N, 132.3 W [S 2.8 deg; E 4.1 deg]	Peak forecast intensity 45 kt at 080512 Not a Hurricane	
18 UTC 31 Jul Advisory 5	080218 [Early 2.5 d]	12.2N, 133.5 W [S 3.1 deg; E 2.9 deg]	Peak forecast intensity 45 kt at 080518 Not a Hurricane	
00 UTC 1 Aug Advisory 6	080500 [Early 6 h]	14.5N, 138.0W [S 0.8 deg; W 1.4 deg]	Peak forecast intensity 40 kt at 080600 Not a Hurricane	
06 UTC 1 Aug Advisory 7	[Not forecast to be a TS]		Peak forecast intensity 25 kt at 080118 Not a Hurricane	

NHC initial time	T2F (35) Timing [error]	T2F (35) Position [error, S-South; E-East]	T2H Timing [error]	T2H Position [error, S-South; E-East]
[Not forecast to be a TS between 06 UTC 1 Aug and 18 UTC 4 Aug]				
18 UTC 4 Aug Advisory 8	080506 [Exact time]	15.6N, 136.1 W [N 0.3 deg; E 0.3 deg]	Peak forecast intensity 40 kt at 080518 Not a Hurricane	
00 UTC 5 Aug Advisory 9	080512 [Late 6 h]	16.0N, 136.6W [N 0.7 deg; W 0.2 deg]	Peak forecast intensity 40 kt at 080600 Not a Hurricane	
06 UTC 5 Aug Advisory 10	Already a TS			

1. Decision Flowchart Application

Applying the Decision Flowchart (Figure 8) to each of the storm options from the ECEPS forecasts, the selections of the ensemble storms that were most likely to become pre-Jimena are provided in Table 14, column 1. As for TS Guillermo, a WCM (20) threshold will be used for the T2F (35) timing (Table 14, column 2), as most of the early selected ensemble storm options forecast the pre-Jimena disturbance to be a TS.

Table 14. Selection and Non-selection of ECEPS Storms for Pre-Jimena

ECEPS initial time [Selected storm]	T2F (35) WCM (20) Timing [error]	Alternate ECEPS Storm Options Considered [Scenario representing reason for non-selection]		
00 UTC 31 Jul (Storm 2)	080306 [Early 72h]	Storm 5 [5 members]	Storm 6 [8 members]	Storm 7 [4 members]
12 UTC 31 Jul (Storm 2)	080100 [Early 102h]	Storm 3 [LSC TD]	Storm 4 [high initial position spread]	Storm 5 [high initial position spread]
00 UTC 01 Aug Missing	Missing single forecast [Consider using last available]			
12 UTC 01 Aug (Storm 4)	080312 [Early 42h]	Storm 2 [inconsistent initial position]	Storm 3 [inconsistent WCM (high)]	Storm 5 [inconsistent initial position]
00 UTC 02 Aug (Storm 2)	080418 [Early 12h]	Storm 1 [inconsistent WCM (high)]	Storm 3 [LSC TD]	Storm 4 [inconsistent initial position]
12 UTC 02 Aug (Storm 2)	080312 [Early 42h]	Storm 3 [inconsistent initial position]	Storm 4 [inconsistent initial position]	Storm 6 [LSC TD]
00 UTC 03 Aug (Storm 2)	080506 [Exact time]	Storm 3 [cold-core system]	Storm 5 [inconsistent initial position]	Storm 6 [inconsistent initial position]

ECEPS initial time [Selected storm]	T2F (35) WCM (20) Timing [error]	Alternate ECEPS Storm Options Considered [Scenario representing reason for non-selection]		
12 UTC 03 Aug (Storm 2)	080506 [Exact time]	Storm 1 [inconsistent WCM (high)]	Storm 3 [cold-core system]	Storm 4 [inconsistent initial position]
00 UTC 04 Aug (Storm 2)	080418 [Early 12h]	Storm 1 [inconsistent initial position]	Storm 4 [inconsistent initial position]	Storm 7 [inconsistent initial position and timing]
12 UTC 04 Aug (Storm 3)	080418 [Early 12h]	Storm 1 [inconsistent initial position]	Storm 2 [inconsistent WCM evolution]	Storm 4 [inconsistent initial position]
00 UTC 05 Aug (Storm 3)	080506 [Exact time]	Storm 2 [inconsistent WCM evolution]	Storm 4 [inconsistent initial position]	Storm 5 [inconsistent initial position]
12 UTC 05 Aug (Storm 2)	Already a TS			

As was the case for the NHC advisories in Table 13, the first ECEPS forecast in which a pre-Jimena circulation was detected at 00 UTC 31 July (Table 14, row 1) and the T2F (35) forecast timing of 06 UTC 3 August (column 2) was quite early (72 hours). Except for the 00 UTC 2 August forecast, the early T2F (35) forecasts continued through the 12 UTC 2 August forecast, and then the timing forecasts through 00 UTC 5 August were quite accurate (within 12 hours).

The initial selection of Storm 2 from the 00 UTC 31 July ECEPS forecast (Table 14, row 1) is a clear choice among the other storm options that all have very low ensemble member counts: Storm 5 with five members, Storm 6 with eight members, and Storm 7 with four members. By contrast, Storm 2 from this ECEPS forecast had all 51 ensemble members included and was a reasonable forecast with a LSC of Hurricane (not shown), although this LSC was correctly updated to TS in the following forecast (not shown).

Clearly, Storm 2 is the most promising as the next potential storm to develop and this particular disturbance is marked as one “To-watch,” and the summary table is begun.

Given this Storm 2 selection for the 00 UTC 31 July forecast, the other ECEPS forecasts of pre-Jimena are evaluated through the Decision Flowchart by comparing the critical forecast items including member count, storm start and T2F timings and positions, WCM evolution, and the WMVM track. For example, the ECEPS 12 UTC 1 August forecast Storm 4 is shown in Figure 28. Note again that all 51 ensemble members are included and the WMVM track-type B₁ forecast passes just to the south of the Hawaiian Islands. The T2F (35) based on the WCM = 20 threshold of 12 UTC 3 August is still early (Table 14, row 4, column 2). However, the maximum WCM is now only 27.0, which is indicative of a LSC of (weak) TS (bottom summary table in Figure 28).

The subsequent ECEPS forecasts of the ensemble storm options are repeatedly evaluated through the Decision Flowchart and thus the validation summary table (Table 15) is compiled in the same manner as they were for the hurricane examples and for pre-Guillermo. For pre-Jimena, the non-selection scenarios for the alternate storm options (Table 14, columns 3–5) included the following: inconsistencies with the previous forecast run(s), which appears 20 times in Table 14; insufficient number of ensemble members, which appears three times; LSC of TD, which also appears three times; cold-core system rather than a warm-core TC, which appears two times; and poor ensemble member agreement, which also appears two times.

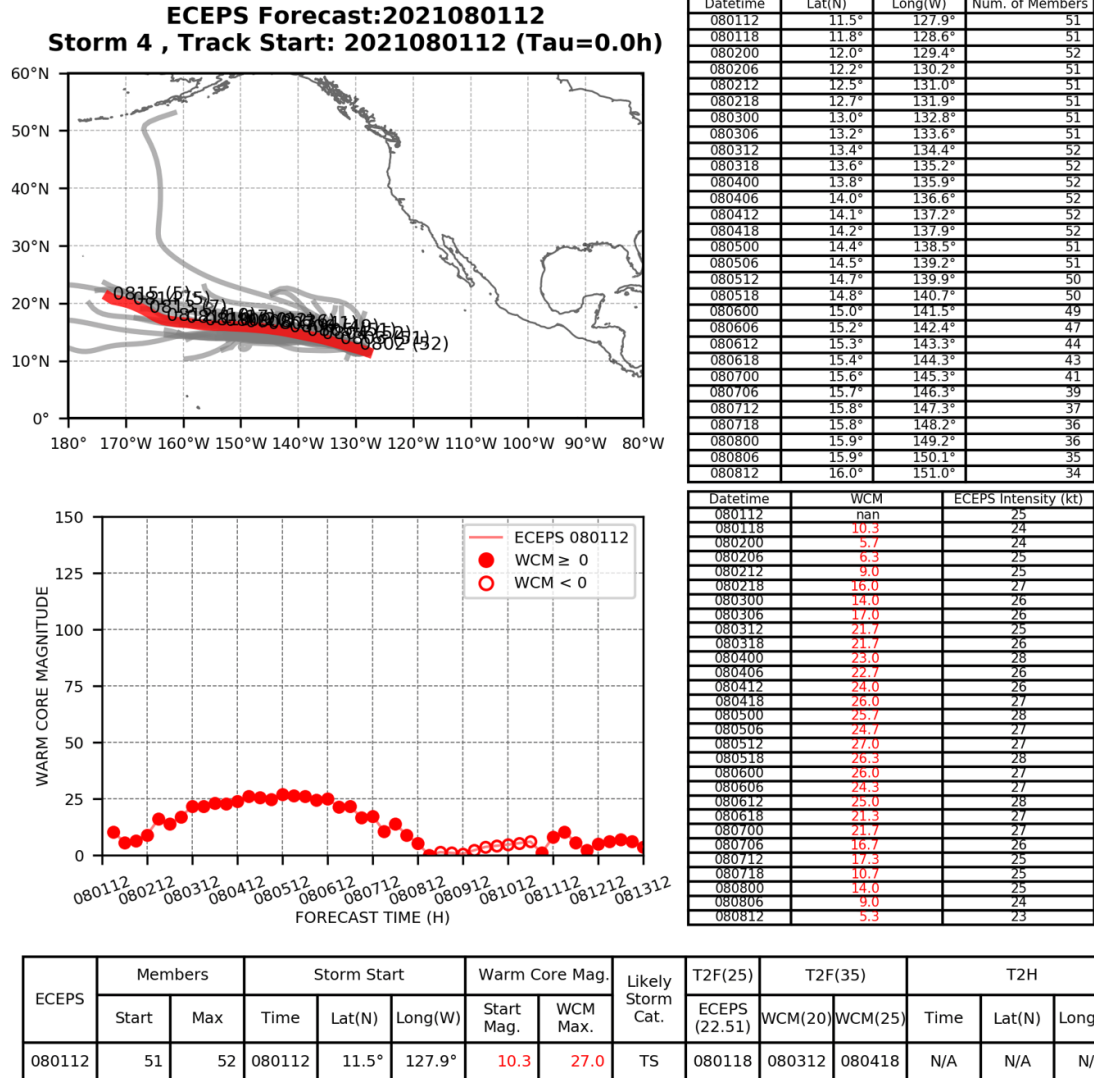


Figure 28. ECEPS Forecast 12 UTC 01 August Storm 4
(Selected Storm for Pre-Jimena)

2. Verification of ECEPS Summary Table

The summary validation table for the ECEPS forecasts of pre-Jimena is provided in Table 15. As indicated above, the initial ECEPS forecast from 00 UTC 31 July (Table 15, row 1) is almost the same time as the first NHC Advisory for Jimena (i.e., about six days in advance of the Jimena T2F (35) of 06 UTC 5 August). The two ECEPS forecasts on 31 July had very early predictions of the T2F (35) with timing errors of (early) 72 hours and 102 hours (Table 12, column 2). Whereas the first of these two forecasts incorrectly

predicted that pre-Jimena would become a Hurricane 30 hours after the T2F (35), the second forecast had only a peak WCM forecast of 32.7 (Table 15, row 2, columns 4–5), which corresponds to a strong TS. It is noteworthy that from the second ECEPS forecast until the last forecast at 12 UTC 5 August when Jimena became a TS, there was only one other forecast (12 UTC 2 August) that predicted a strong TS. Instead, three forecasts had peak forecast WCM values just over the larger WCM threshold of 25.0, and five were just over the lower WCM threshold of 20.0. Due to these highly accurate WCM predictions, the T2F (35) timing errors were also accurate with six of the seven forecasts from 00 UTC 2 August to 00 UTC 5 August having timing errors of either the exact time or early by 12 hours (Table 15, column 2). With these accurate T2F (35) timing errors, and accurate WMVM track forecasts, the T2F (35) position errors (Table 15, column 3) were very small for those six out of seven ECEPS forecasts from 00 UTC 2 August to 00 UTC 5 August, which was important since the WMVM track forecast was toward the Hawaiian Islands (Figure 28). Furthermore, the capability of the ECEPS-predicted WCM to indicate that pre-Jimena would remain a weak TS is important for avoiding unnecessary disaster preparedness activities in Hawai'i.

Table 15. Pre-Jimena ECEPS Timing and Position Predictions of T2F (35) (WCM 20) and T2H (WCM 37)

NHC: T2F (35) Timing 06 UTC 5 August
Position: 15.3N, 136.4W

NHC: T2H Did not make Hurricane

ECEPS initial time	T2F (35) WCM (20) Timing [error]	T2F (35) (WCM 20) Position [error, N-North, S- South; E-East, W- West]	T2H (WCM 37) Timing [error]	T2H (WCM 37) Position [error, N-North, S-South; E-East, W-West]
00 UTC 31 Jul (Storm 2)	080306 [Early 72h]	12.6N, 136.1W [S 2.7 deg; E 0.3 deg]	080412 [Not a Hurricane]	13.2N, 140.5W [Not a Hurricane]
12 UTC 31 Jul (Storm 2)	080100 [Early 102h]	11.7N, 127.6W [S 3.6 deg; E 8.8 deg]	[Not a Hurricane -- Peak forecast WCM 32.7 at 080600 at 14.9N, 145.0W]	
00 UTC 01 Aug Missing	Missing single forecast [Consider using last available]			
12 UTC 01 Aug (Storm 4)	080312 [Early 42h]	13.4N, 134.4W [S 1.9 deg; E 2.0 deg]	[Not a Hurricane -- Peak forecast WCM 27.0 at 080512 at 14.7N, 139.9W]	
00 UTC 02 Aug (Storm 2)	080418 [Early 12h]	14.4N, 136.7W [S 0.9 deg; W 0.3 deg]	[Not a Hurricane -- Peak forecast WCM 26.7 at 080600 at 15.5N, 140.6W]	
12 UTC 02 Aug (Storm 2)	080312 [Early 42h]	13.6N, 133.1W [S 1.7 deg; E 3.3 deg]	[Not a Hurricane -- Peak forecast WCM 33.0 at 080512 at 15.5N, 137.5W]	
00 UTC 03 Aug (Storm 2)	080506 [Exact time]	14.9N, 137.2W [S 0.4 deg; W 0.8 deg]	[Not a Hurricane -- Peak forecast WCM 21.3 at 080506 at 14.9N, 137.2W]	
12 UTC 03 Aug (Storm 2)	080506 [Exact time]	14.8N, 137.1W [S 0.5 deg; W 0.7 deg]	[Not a Hurricane -- Peak forecast WCM 22.0 at 080506 at 14.8N, 137.1W]	

ECEPS initial time	T2F (35) WCM (20) Timing [error]	T2F (35) (WCM 20) Position [error, N-North, S- South; E-East, W- West]	T2H (WCM 37) Timing [error]	T2H (WCM 37) Position [error, N-North, S-South; E-East, W-West]
00 UTC 04 Aug (Storm 2)	080418 [Early 12h]	14.6N, 135.5W [S 0.7 deg; E 0.9 deg]	[Not a Hurricane -- Peak forecast WCM 24.3 at 080512 at 15.6N, 136.7W]	
12 UTC 04 Aug (Storm 3)	080418 [Early 12h]	14.1N, 136.2W [S 1.2 deg; E 0.2 deg]	[Not a Hurricane -- Peak forecast WCM 25.3 at 080500 at 14.5N, 136.6W]	
00 UTC 05 Aug (Storm 3)	080506 [Exact time]	15.1N, 136.3W [S 0.2 deg; E 0.1 deg]	[Not a Hurricane -- Peak forecast WCM 21.7 at 080506 at 15.1N, 136.3W]	
12 UTC 05 Aug (Storm 2)	Already a TS		[Not a Hurricane -- Peak forecast WCM 23.7 at 080518 at 16.1N, 137.3W]	

C. SUMMARY OF APPLICATION OF DECISION FLOWCHART FOR ENP TROPICAL STORMS

The Decision Flowchart is critical to guide the forecaster to select the likely-to-form ensemble storms. The effectiveness of the Decision Flowchart has been demonstrated for Tropical Storms Guillermo and Jimena. The remaining tropical storms of the 2021 ENP season (Andres, Blanca Carlos, Delores, Ignacio, Kevin, Marty, Terry, and Sandra) were evaluated using the ECEPS forecast guidance and the Decision Flowchart. As discussed in Section II.A, since TS Marty formed from the remnants of Hurricane Grace in the Atlantic basin, these early detection techniques are not applicable and will not be shown for this TS.

The detection timing in advance of T2F (35) by the NHC Advisories and ECEPS forecasts for all the tropical storms (excluding Marty) is provided in Table 16. The detections/warnings in the forecasts of T2F (35) by the NHC varied between 6 hours in advance for several storms and 5 days, 12 hours in advance for TS Jimena, with an average of 1.2 days in advance. In contrast, the detections/alerts in the ECEPS forecasts for T2F (35) were at least 2 days, 6 hours in advance for TS Terry and at most 9 days, 18 hours in advance for TS Sandra with an average of 6 days, 18 hours in advance.

In conclusion, the ECEPS forecast guidance, processed through the Marchok vortex tracker and evaluated through the Decision Flowchart, is proven to be a reliable early and accurate indicator of tropical storms. If implemented at TC warning centers, and used in conjunction with the Decision Flowchart, this forecast guidance presents the opportunity for much earlier detection of disturbances and detailed intensity and track forecasts up to 15 days during the pre-formation stage.

Table 16. NHC and ECEPS Early Detection of Eastern North Pacific Tropical Storms. Source: Elsberry et al. (2022).

Tropical Storm	Detection in forecast in advance of T2F (35)	
	NHC Advisory	ECEPS
Andres (01E)	6 hours	8 days, 12 hours
Blanca (02E)	1 day	6 days, 6 hours
Carlos (03E)	6 hours	3 days, 12 hours
Dolores (04E)	6 hours	6 days, 12 hours
Guillermo (07E)	6 hours	8 days, 18 hours
Jimena (09E)	5 days, 12 hours	5 days, 6 hours
Ignacio (10E)	18 hours	8 days, 12 hours
Kevin (11E)	6 hours	8 days, 6 hours
Marty (13E)	Not evaluated—remnants of Hurricane Grace in Atlantic basin	
Terry (18E)	3 days, 6 hours	2 days, 6 hours
Sandra (19E)	6 hours	9 days, 18 hours

VI. NON-DEVELOPING DISTURBANCE CATEGORY EXAMPLE

In addition to hurricane and tropical storm extended range forecasts, these ECEPS products have application to non-forming disturbances. Over the 2021 season, there were several examples of the ECEPS guidance detecting a disturbance with fairly high confidence (i.e., consistent forecasts with high member agreement) in its non-development. One of these examples is detailed in this chapter.

A. DECISION FLOWCHART APPLICATION

The ECEPS guidance first identified a disturbance at 00 UTC 25 September with a forecast storm start time of 06 UTC 27 September. This Storm 4 was the first indication of this particular disturbance, which is shown in Figure 29. The forecaster evaluating Storm 4 would determine through the Decision Flowchart that this storm does not match a likely-to-form storm from a previous forecast. Furthermore, while the initial position and the WMVM track forecast are reasonable, the WCM values in the lower-left plot in Figure 29 are continually small with a maximum of 15.0 such that the LSC is only a TD. In addition, Storm 4 of ECEPS initial time 00 UTC 25 September only had a maximum of nine ensemble members, which is shown in the lower-left section of the summary table in the bottom of Figure 29. Consequently, this Storm 4 option would be discarded as a not-likely-to-form storm.

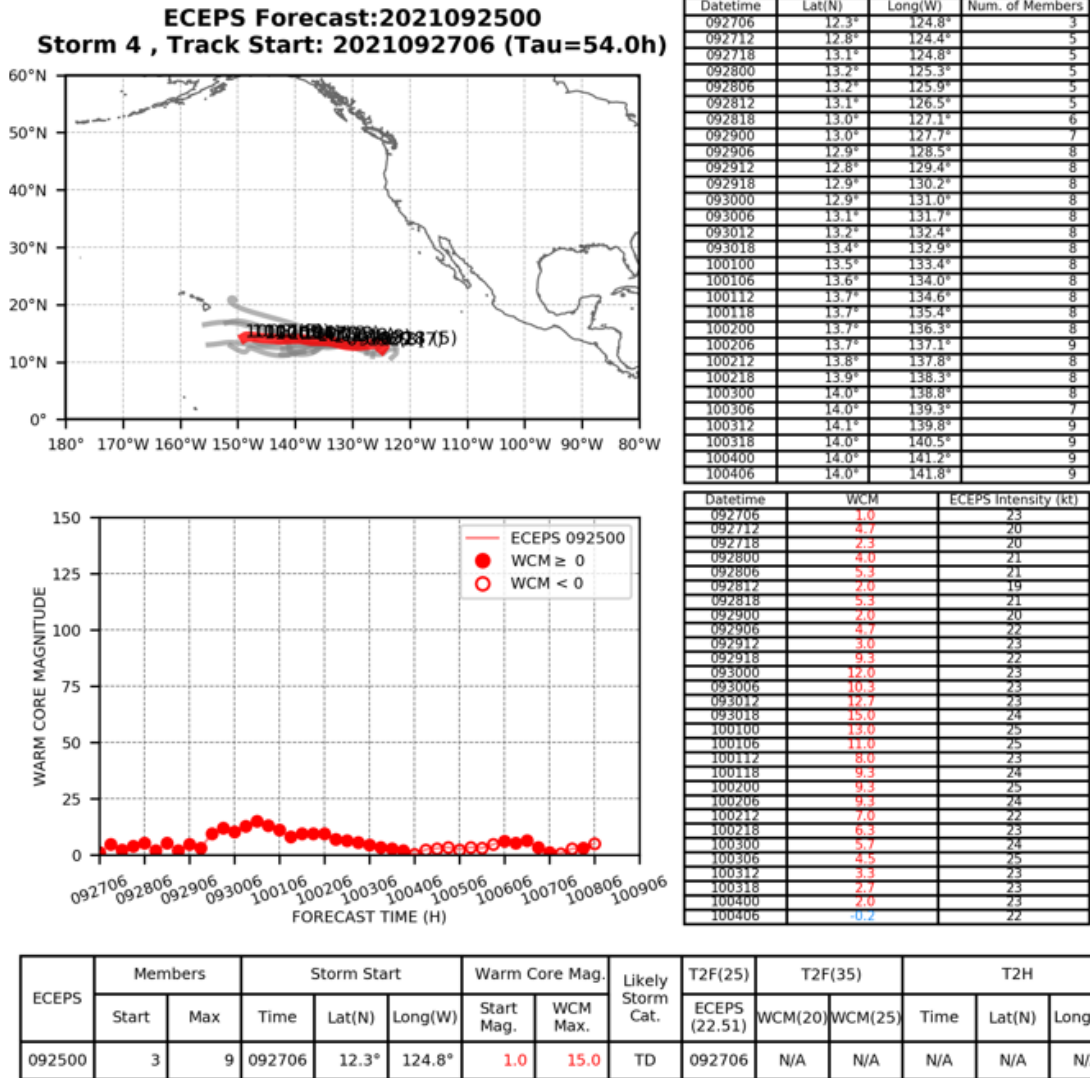


Figure 29. ECEPS Forecast 00 UTC 25 September Storm 4

Although the disturbance continued to be forecast by the ECEPS with increasing numbers of ensemble members, the WCM evolutions never surpassed the T2F (35) threshold (not shown). The forecasts were consistent in time and the storm options for this disturbance would be discarded by the forecaster at each ECEPS initial time according to the Decision Flowchart. Normally, a summary table would not be created by the forecaster for a disturbance forecast to not develop. However, for demonstration purposes, a summary table is compiled for the ECEPS forecasts of this disturbance (Table 17, columns 1–5). Ultimately, by the ECEPS guidance and the Decision Flowchart, this disturbance was

evaluated to be a non-developer for every ECEPS forecast between 00 UTC 25 September and 00 UTC 3 October, and results in the forecaster being prompted to “Discard this storm” per the Decision Flowchart each forecast run.

B. COMPARISON OF NHC TROPICAL WEATHER OUTLOOKS WITH ECEPS SUMMARY TABLE

It was not until 12 UTC 29 September that the NHC initiated a Tropical Weather Outlook (TWO) for a disturbance with a 0% formation chance within 48 hours and 20% formation chance within 120 hours (i.e., formation by 12 UTC 4 October) (Table 17, column 6–7). The first in this series of numbered disturbances had an initial position roughly near 12°N, 125°W, which is similar to the 12 UTC 29 September Storm 1 initial position in Table 17, column 2. However, those numbered disturbances were subsequently terminated at 06 UTC 3 October when the percentages were near zero chance of formation at both 48 hours and 120 hours. Table 17 documents the series of even earlier ECEPS forecasts that had predicted initial position and timing correlating with the NHC-predicted long-lived disturbances, but none of the ECEPS forecasts predicted the disturbance to meet the T2F (35) criteria. These early ECEPS ensemble storms are therefore considered to be correct predictions of the non-development of this NHC-predicted disturbance.

By the time the NHC began including this disturbance in their TWO, the ECEPS guidance had identified the disturbance as a definite non-developer (i.e., not reaching T2F (35) threshold) and with a high number of members in agreement during the ECEPS forecasts during the prior 4.5 days. The NHC carried the disturbance with 40% chance of formation from 00 UTC 30 September to 12 UTC 2 October. While no NHC advisories were issued for this disturbance, the ECEPS guidance would have provided early and high confidence guidance that the disturbance was very unlikely to form.

Early and high confidence forecasts in the non-development of tropical disturbances can prevent unnecessary resource protection measures from being initiated, which saves time and money. Particularly within the DOD, this allows the forces to continue to operate as usual, with minimal interruptions or distractions, and keep their focus on their primary missions.

Table 17. ECEPS Predictions of T2F (35) and NHC TWO Predictions of Eventual Non-developing Disturbance

ECEPS Initial Time	Initial Position	Maximum Members	ECEPS T2F (35) Timing	ECEPS T2F (35) Position	NHC 48h Disturbance Chance (%) and Lat/Long	NHC 120h Disturbance Chance (%) and Lat/Long
00 UTC 25 Sep (Storm 4)	12.3N, 124.8W	9	[Criteria not met]		[No disturbance associated]	
12 UTC 25 Sep (Storm 6)	12.2N, 121.0W	13				
00 UTC 26 Sep (Storm 3)	11.2N, 120.9W	15				
12 UTC 26 Sep (Storm 1)	11.0N, 121.7W	33				
00 UTC 27 Sep (Storm 3)	11.1N, 121.7W	27				
12 UTC 27 Sep (Storm 1)	11.2N, 121.5W	30				
00 UTC 28 Sep (Storm 1)	11.5N, 120.9W	21				
12 UTC 28 Sep (Storm 2)	11.4N, 122.5W	17				
00 UTC 29 Sep (Storm 1)	11.1N, 122.7W	23				

ECEPS Initial Time	Initial Position	Maximum Members	ECEPS T2F (35) Timing	ECEPS T2F (35) Position	NHC 48h Disturbance Chance (%) and Lat/Long	NHC 120h Disturbance Chance (%) and Lat/Long
12 UTC 29 Sep (Storm 1)	12.0N, 125.8W	37			0	20
					12N, 125W	
00 UTC 30 Sep (Storm 1)	12.2N, 127.6W	35			20	40
					12.5N, 128W	
12 UTC 30 Sep (Storm 4)	12.5N, 129.1W	34			20	40
					12.5N, 128W	
00 UTC 01 Oct (Storm 2)	13.2N, 129.9W	43			20	40
					12.5N, 128W	
12 UTC 01 Oct (Storm 2)	13.1N, 131.2W	50			20	40
					12.5N, 129W	
00 UTC 02 Oct (Storm 1)	13.7N, 131.8W	50			20	40
					13N, 132W	
12 UTC 02 Oct (Storm 4)	14.0N, 132.1W	28			20	40
					13N, 132W	
00 UTC 03 Oct (Storm 2)	13.4N, 134.1W	37			0	10
					13N, 133W	

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VII. CONCLUSIONS

A. SUMMARY AND DISCUSSION

As discussed in Section I.A, most TC warning centers provide probability-based early guidance in advance of possible TC formation. In almost every case examined in this thesis, it was only closer to formation, or even after formation, that the NHC included track and intensity forecasts in the associated advisories and warnings. In the eastern North Pacific, this is particularly disadvantageous when a pre-formation circulation appears to have the potential to impact the many DOD personnel and assets on and around the Hawaiian Islands. In either case of a forming or non-forming disturbance, the public, emergency management entities, and the DOD could greatly benefit from early and accurate intensity and track predictions.

The groundwork for this thesis, which is detailed in Chapter II, has been provided by Professors Elsberry and Tsai and their research team. They developed the framework and techniques to process the pre-formation Marchok vortex tracker outputs from the ECEPS by grouping similar pre-TC circulations, calculating the predicted Weighted-Mean Vector Motion (WMVM) track and weighted-mean Warm Core Magnitude (WCM) up to 15 days, and creating summary plots and tables of critical forecast information such as the Time-to-Formation (T2F of 25 kt and 35 kt) and the Time-to-Hurricane (T2H) timings and locations for predicted ensemble storms. In this thesis, these techniques have been transitioned to the TCs in the eastern North Pacific basin, with special adjustments to greatly reduce the number of false alarms (FAs).

The objective of this thesis is to highlight the validation of these methods for early and accurate predictions of forming and non-forming tropical disturbances in the eastern North Pacific basin during 2021, and to develop a comprehensive and systematic Decision Flowchart for forecasters to interpret and apply these methods to improve pre-formation forecasts. As explained in Chapter III, the Decision Flowchart created for evaluating ECEPS storms processed through the Marchok vortex tracker is presented as a tool to integrate these methods into operational TC warning centers. The forecasters must evaluate

the ensemble storm characteristics in each ECEPS forecast to make decisions as to whether there is high confidence that the predicted storm has the potential to form, and what the details of that formation might be. The criteria for making these decisions include: matching storms with previous forecasts, WMVM initial timing and tracks from the pre-formation stage through the ending-stage, WCM initial values and evolutions, T2F and T2H timings and positions, numbers of ensemble members in agreement, the ensemble member track forecast spread, the storm's possible immediate threat to DOD, etc. The objective of the Decision Flowchart is to guide the forecaster in selecting the storms most likely to form, and to develop confidence in the forecast.

This thesis approaches the ECEPS forecast evaluations from the perspective of a forecaster during the 2021 eastern North Pacific hurricane season. ECEPS forecast guidance for several examples of Hurricane strength, Tropical Storm strength, and non-developing storms are evaluated and compared to official NHC advisories. The Decision Flowchart is applied as a forecaster would, to portray the reality of these methods in action, and then to provide a validation of the forecasts.

In the example of Hurricane Enrique, which is described in Section IV.A, the first ECEPS forecast that predicted the pre-Enrique disturbance did so nearly nine days in advance of the T2F (35), and with just six hours of timing errors for both the T2F (35) and T2H (Elsberry et al. 2022). The timing and position errors were mostly consistently and remarkably low throughout the pre-formation forecast, and the occurrence of rapid intensification (RI) was also accurately forecast in the majority of the ECEPS forecasts, even as early as nine days prior to T2F (35) (Elsberry et al. 2022). In comparison, the earliest indication of pre-Enrique was included in the NHC's Five-Day Tropical Weather Outlook (TWO) at almost five days in advance of formation with a $< 40\%$ chance of formation (Latto 2021). No predicted track or intensity information is provided by NHC until an advisory is issued. The first NHC advisory for Enrique was issued when Enrique had already just become a Tropical Storm (TS).

In the similarly remarkable example of Hurricane Felicia, which is described in Section IV.B, the selected pre-Felicia storm from the ECEPS forecasts indicated a potential hurricane 12 days prior to formation, again with high accuracy in T2F (35) and T2H timings

and positions (Elsberry et al. 2022). By contrast, the NHC TWO identified an elliptical disturbance area at five days prior to formation with $< 40\%$ chance of formation during the following five days (Cangialosi 2021). The first NHC advisory was not issued until just six hours prior to the formation of Tropical Storm Felicia and just 30 hours prior to Felicia reaching Hurricane strength.

As discussed in Section IV.C, the ECEPS detection timing in advance of T2F (35) for all the ENP hurricanes of 2021 were at least 5 days, 18 hours in advance for Hurricane Pamela, and at most 12 days, 12 hours in advance for Hurricane Olaf and 12 days in advance for Hurricane Felicia. Averaged over the eight hurricanes during the 2021 season, the ECEPS guidance could have provided alerts of a hurricane 8 days, 18 hours in advance. By contrast, the detections/warnings in the forecasts of T2F (35) by the NHC Advisories varied between 0 hours and 18 hours in advance (average of 7.5 hours in advance). The detections/alerts in the ECEPS forecasts of the T2H were at least 7 days, 2 hours in advance for Hurricane Rick and at most 13 days, 12 hours in advance for Hurricane Olaf with an average of about 10 days in advance. In contrast, the detections/warnings in the forecasts of T2H by the NHC Advisories were as short as 18 hours in advance of Hurricane Rick, and at most 1 day, 18 hours in advance for Hurricanes Linda and Nora, with an average of about 1 day, 6 hours in advance. Thus, it was concluded in Section IV.C that the application of the Decision Flowchart to process and interpret the Marchok vortex tracker outputs from the 15-day ECEPS forecast guidance leads to the early and accurate selection of likely-to-form ensemble storms that made hurricane-strength, and this process would be a valuable addition to a forecaster's resources at a TC warning center.

Two examples of tropical storms, Guillermo and Jimena, are discussed in a similar manner in Chapter V: the Decision Flowchart is applied, and the forecast summary charts are provided and compared to the official forecasts from the NHC. TS Guillermo, which was a strong TS, is consistently over-forecast in intensity by the ECEPS guidance, except by four forecasts within 42 hours of formation which correctly predicted a strong TS (Elsberry et al. 2022). The pre-Guillermo disturbance was already indicated by the selected ensemble storms, with high position accuracy, nearly nine days ahead of formation (Elsberry et al. 2022). The NHC issued the first advisory for pre-Guillermo just six hours

ahead of formation, but with high position, timing, and intensity accuracy. Even accounting for the ECEPS too-high intensity errors, the forecast guidance would still be a valuable addition to the forecaster's resources and would contribute to earlier warnings to the public and DOD entities of a strong TS along with accurate WMVM track forecasts.

This forecast guidance applied to an example of a weak TS was explored in TS Jimena, which tracked northwestward across the eastern North Pacific and into the central North Pacific toward the end of its life cycle, and eventually brought some heavy rainfall to parts of eastern Kaua'i and southern portions of the Big Island, but ultimately no damaging TC impacts (Bravender 2021). For pre-Jimena, the ECEPS forecasts identified the disturbance over five days in advance, and all but the earliest ECEPS forecast correctly identified that the pre-Jimena disturbance would not reach hurricane strength. In addition, the ending-stage in the selected ensemble storms accurately indicated a maximum WCM corresponding to just a weak TS along the WMVM track toward the Hawaiian Islands. During a period of 3.5 days leading up to just 12 hours before formation, NHC did not issue advisories on this disturbance, as NHC did not forecast it would reach TS strength. Again, the ECEPS forecasts evaluated by these methods would provide very valuable guidance to a forecaster's resources for early detection, particularly in such a case where the disturbance turns out to be a weak TS.

As discussed in Section V.C, the NHC detection timing in advance of T2F (35) for all the ENP tropical storms during the 2021 season were at the least just 6 hours in advance for several storms (Andres, Carlos Dolores, Guillermo, Kevin, and Sandra) and at the most up to 5 days, 12 hours in advance for TS Jimena, with an average of 1.2 days in advance. In contrast, the detections/alerts in the ECEPS forecasts for T2F (35) were at least 2 days, 6 hours in advance for TS Terry and at most 9 days, 18 hours in advance for TS Sandra with an average of 6 days, 18 hours in advance. Thus, it was concluded in Section V.C that the 15-day ECEPS forecast guidance, processed through the Marchok vortex tracker and evaluated through the Decision Flowchart, could have resulted in the selection of likely-to-form ensemble storms during the pre-formation stage of TS-strength TCs.

An example of a non-developing disturbance is included to highlight the importance of early high confidence forecasts in the non-formation of predicted tropical

circulations. The disturbance discussed in Chapter VI was identified by the ECEPS guidance 4.5 days in advance of it being included in the NHC TWO. At no point did the ECEPS guidance indicate formation of this disturbance, and the confidence in this forecast was strong in terms of ensemble member agreement and temporal consistency. The NHC carried the disturbance with up to a 40% chance of formation for 3.5 days before dropping it from the TWO. While no advisories were issued for the disturbance, the ECEPS guidance would have provided the forecaster with early and high confidence forecasts that this disturbance was very unlikely to form. This type of guidance is very valuable to the public, emergency management, and the DOD, as it can be leveraged to prevent initiating unnecessary resource protection measures and spending on storm preparation, which saves time and money and, particularly in the case of the DOD, permits personnel uninterrupted attention on their primary missions.

In each example of forming and non-forming circulations, these methods of analyzing ECEPS forecast guidance, processed through the Marchok vortex tracker and evaluated through the Decision Flowchart, prove to be value-added to the official pre-formation forecasts. Furthermore, this approach would provide superior guidance to DOD in comparison to NHC Advisories alone. The results from Elsberry et al. (2022) and from this thesis demonstrate greatly improved guidance over the probabilistic formation forecasts, such as the JTWC pre-formation guidance and NHC/CPHC Tropical Weather Outlook (TWO). The ECEPS guidance analyzed through the Decision Flowchart provides more forecast details and higher confidence in the forecast earlier in the forecast timeline, in either a formation or a non-formation scenario.

In conclusion, this thesis highlights the opportunity to provide DOD interests and other stakeholders with early and accurate predictions of pre-formation TC detection and detailed intensity and track forecasts for up to 15 days, which in the eastern North Pacific frequently encompasses the whole TC life cycle.

B. RECOMMENDATIONS FOR FUTURE WORK

It is recommended that this technique be applied to interesting historical case studies of TCs that were particularly difficult to forecast or turned out to be extreme storms.

A study incorporating these may lend insight into the limitations and/or unique skills of the techniques or of the ECEPS forecasts. An ongoing global collaborative list of difficult and extreme TC cases contributed by operational forecast agencies is available on a website maintained by the Hong Kong Observatory on behalf of the WMO (World Meteorological Organization 2021). This website was constructed based on recommendations from the eighth International Workshop of Tropical Cyclones to have operational centers identify difficult cases and extreme events for the TC research community to analyze model performance and overall predictability (World Meteorological Organization 2021). The eastern North Pacific cases listed on the website include Hector (2018) and Pali (2015), both of which had particularly difficult intensifications to forecast. Ideally, these and other notoriously difficult-to-forecast storms will be reanalyzed to potentially glean further strengths and weaknesses of these techniques.

As determined by this thesis, many ensemble storm options were discarded as unlikely-to-form per the Decision Flowchart for having too few ensemble members, being a Caribbean FA, or being a cold-core system. Thus, it is recommended that these types of obvious non-select storm options be eliminated through the development and application of an automated Decision Flowchart. If these types of ensemble storm options are eliminated before they even reach the forecaster, the process of evaluating the remaining storm options will be more efficient. Furthermore, it is recommended that the matching process of storm options be automated as well. This will greatly reduce the time a forecaster must spend on manually applying the Decision Flowchart and will make the process of applying this ECEPS forecast guidance significantly more efficient.

It is also recommended that a statistical analysis be completed of the forecast performance for an additional season. False alarms, hits, misses should be calculated and compared in order to provide further evidence of the success of these techniques.

An additional recommendation is to experiment with more sophisticated solutions to reduce or eliminate Caribbean FAs. The present method of rejecting any storm that has its initial position within the Caribbean FA box is not all inclusive of Caribbean FAs, but also potentially discards legitimate TC disturbances that may actually originate in the region.

Ultimately, the essential recommendation of this thesis is for these techniques to be implemented into operational centers and utilized by forecasters to improve the clarity and accuracy of early forecasts of tropical cyclones in all basins.

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