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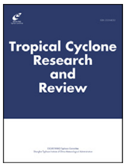

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Recommendations for improved tropical cyclone formation and position probabilistic Forecast products

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Abstract

Prediction of the potentially devastating impact of landfalling tropical cyclones (TCs) relies substantially on numerical prediction systems. Due to the limited predictability of TCs and the need to express forecast confidence and possible scenarios, it is vital to exploit the benefits of dynamic ensemble forecasts in operational TC forecasts and warnings. RSMCs, TCWCs, and other forecast centers value probabilistic guidance for TCs, but the International Workshop on Tropical Cyclones (IWTC-9) found that the "pull-through" of probabilistic information to operational warnings using those forecasts is slow. IWTC-9 recommendations led to the formation of the WMO/WWRP Tropical Cyclone-Probabilistic Forecast

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Products (TC-PFP) project, which is also endorsed as a WMO Seamless GDPFS Pilot Project. The main goal of TC-PFP is to coordinate across forecast centers to help identify best practice guidance for probabilistic TC forecasts. TC-PFP is being implemented in 3 phases: Phase 1 (TC formation and position); Phase 2 (TC intensity and structure); and Phase 3 (TC related rainfall and storm surge). This article provides a summary of Phase 1 and reviews the current state of the science of probabilistic forecasting of TC formation and position. There is considerable variability in the nature and interpretation of forecast products based on ensemble information, making it challenging to transfer knowledge of best practices across forecast centers. Communication among forecast centers regarding the effectiveness of different approaches would be helpful for conveying best practices. Close collaboration with experts experienced in communicating complex probabilistic TC information and sharing of best practices between centers would help to ensure effective decisions can be made based on TC forecasts. Finally, forecast centers need timely access to ensemble information that has consistent, user-friendly ensemble information. Greater consistency across forecast centers in data accessibility, probabilistic forecast products, and warnings and their communication to users will produce more reliable information and support improved outcomes.

Keywords: Tropical cyclone; Probabilistic; Formation; Position

1. Introduction

The need to express tropical cyclone (TC) forecast confidence, and in ways that are correctly interpreted by a wide variety of stakeholders, makes the use of ensemble forecast information and products derived from it of central importance to Regional Specialized Meteorological Centers (RSMCs), Tropical Cyclone Warning Centers (TCWCs), and other forecast centers (hereafter all referred to as forecast centers). The 2018 International Workshop on Tropical Cyclones (IWTC-9) recognized the need for improved probabilistic guidance for TCs globally and proposed several recommendations to streamline the use of ensemble probabilistic guidance and uncertainty information in operational forecast warnings and products (Titley et al., 2019). These IWTC-9 recommendations were the impetus for undertaking a project dedicated to improving the pull-through of ensemble forecast data into operational TC forecasts and warnings. In response to these recommendations, the World Meteorological Organization (WMO)/World Weather Research Programme (WWRP) Tropical Cyclone-Probabilistic Forecast Products (TC-PFP) project was launched in 2020., TC-PFP is being implemented in 3 phases: Phase 1 (TC formation and position) began in 2020; Phase 2 (TC intensity and structure) will begin in 2023; and Phase 3 (rainfall and storm surge) will start in 2024. The project has engaged forecast centers to learn about how ensemble-based products are currently generated, where limitations occur regarding use of that information, and gaps that prevent more consistent construction of ensemble-based products for effective decision making. The TC-PFP project is implemented as a five-year effort that is endorsed as a WMO Seamless Global Data Processing and Forecast System (GDPFS) Pilot Project, whose goal is providing an efficient and accessible platform for sharing data produced by operational centers.

Phase 1 of TC-PFP has focused on ensemble forecasts of TC formation and position. TC-PFP organized a 3-day WMO-sponsored workshop in June 2021 that focused on identifying best practices for conveying ensemble-based TC position guidance within the context of 3 overarching topic areas: 1) *current & planned probabilistic forecast products*; 2) *understanding & communicating probabilistic forecasts*; and 3) *resources for producing probabilistic forecasts*. The present article largely synthesizes presentations and discussions from the workshop and is thus not intended to provide a comprehensive review of ensemble prediction of TCs. While focused on forecasts of TC formation and position, outcomes from TC-PFP Phase 1 will be incorporated into later phases of TC-PFP, including ensemble-based products that convey TC intensity and structure in Phase 2, and as attendant hazards associated with TC rainfall and storm surge in Phase 3. A summary of the Phase 1 efforts was presented at IWTC-10 in Bali, Indonesia in December 2022.

Uncertainty (or confidence) in forecasts of TC position is traditionally communicated to the public using “cones of uncertainty”, which until recent years have mainly been sized based on historical forecast errors, and these ‘static’ cones do not contain information about the flow-dependent confidence in a forecast. Many centers are now experimenting with ensemble-based versions of these products, and there has been an encouraging acceleration of this work since IWTC-9. The underlying ensembles that are being used may derive from the control forecasts from different forecast centers (multi-model deterministic ensemble), an ensemble built around one center's modeling system (single-model ensemble), or a multi-model ensemble combining several ensemble forecast models (a super-ensemble).

While the spread from a multi-model deterministic ensemble provides useful information (Goerss 2000, 2007), research has shown that single-model ensemble prediction systems from perturbed initial conditions could provide improvements in TC track forecast uncertainty (Majumdar and Finocchio 2010) as well as in the spread-skill relationships for forecasts in the western North Pacific (Yamaguchi et al., 2009). These dynamical ensemble systems have been used to capture situation-dependent uncertainty and can be more skillful for predicting track uncertainty than static climatology-based approaches (Dupont et al., 2011; Zhang and Yu 2017;

Leonardo and Colle 2017). Combining the dynamical ensembles into a multi-model super ensemble also shows further improved skill over any single ensemble modeling system (Titley et al., 2020; Yamaguchi et al., 2012). JMA/RSMC Tokyo implemented a multi-model super ensemble-based probability circle in 2019 (Fukuda and Yamaguchi 2019) and demonstrated, on a research basis, the effectiveness of oval-shaped areas of uncertainty instead of circular areas of uncertainty (Kawabata and Yamaguchi 2020).

Prediction of TC formation carries additional uncertainty owing to challenges in identification as well as location. Identification of a TC depends on details of the tracker used as well as the fidelity of numerical representation of weak cyclonic disturbances. Ensemble outputs have shown skill in various TC formation metrics (Majumdar and Finocchio 2010; Belanger et al., 2012; Majumdar and Torn 2014; Yamaguchi et al., 2015). In addition to ensemble probabilistic TC genesis tools, probabilistic genesis tools using multi-model deterministic forecasts are also available (Halperin et al., 2013; 2016) and could be expanded to utilize dynamical ensemble outputs. Aspects of current & planned probabilistic forecast products are discussed further in Sec. 1.

The improvement of numerical predictions of TCs is a necessary, but not sufficient, condition for improved decision-making based on advisory products. Most users require easily interpretable and localized information on TC risk that enables them to take appropriate action. Communicating the location and path of a storm is only the first step in effectively communicating TC threats. Compounding the challenge of designing geographically-based products, a large percentage of the world is spatially illiterate and can struggle to relate map size to the world around them (Clarke 2003). This can lead to confusion about the size of the "threat zone" of TC wind, rain, and storm surge hazards, and even where one is located relative to such zones. These concerns are further accentuated in the context of probabilistic TC forecasts and the users' ability to understand numerical uncertainty. Members of the public who understand a probabilistic product (i.e., hurricane force wind speed probabilities) are three times more likely to take protective action compared with people that do not correctly understand the product (Spiegelhalter 2017; Demuth and Eosco 2021; Bica et al., 2019; Millet et al., 2022). However, they also found that over half of study participants incorrectly interpreted probabilistic TC output. While the utility of probabilistic information rests on both the accuracy of the underlying ensemble forecasts as well as the translation of that information into readily interpretable products, poor availability and timeliness of information, and its uptake, can render advances in forecast quality and products moot. Despite improvements in forecast accuracy and lead time, Dookie and Spence-Hemmings (2022) found that in many cases, the average time from watch publication to storm impact was under 24 h. This is problematic because many recommended actions take much longer than 24 h to initiate (e.g., Litman 2006). Discussion regarding the understanding and communication of probabilistic forecasts is presented in Sec. 2.

The utility and reliability of ensemble-based products is dependent on having a spread in the ensemble that, statistically speaking, matches the forecast error. Multi-model ensembles comprising a set of deterministic forecasts from different models and operational centers may be more readily available in real time, but these are generally insufficient for generating reliable probabilities. Single-model ensembles, available from several centers often via special agreements, can be under-dispersive. Data from super-ensembles are probably the best to use, but their availability, timeliness, and formats are often inconsistent. This creates a global patchwork of data availability. This is further complicated by challenges related to having reliable access to probabilistic forecast data, a lack of uniformity in data format, and availability of decoding software. Aspects of resources for producing probabilistic forecasts are discussed in Sec. 3.

The TC-PFP project has worked to identify forecast center efforts and challenges related to producing and distributing probabilistic forecast products of TC formation and position. In subsequent sections, we examine various aspects of these efforts and challenges and recommend strategies for moving probabilistic TC forecasts onto a more consistent foundation worldwide. While we consider the three areas of numerical forecasting, product design and interpretation, and data dissemination separately, we note up front that there are significant interdependencies among the areas.

2. Current & planned probabilistic forecast products

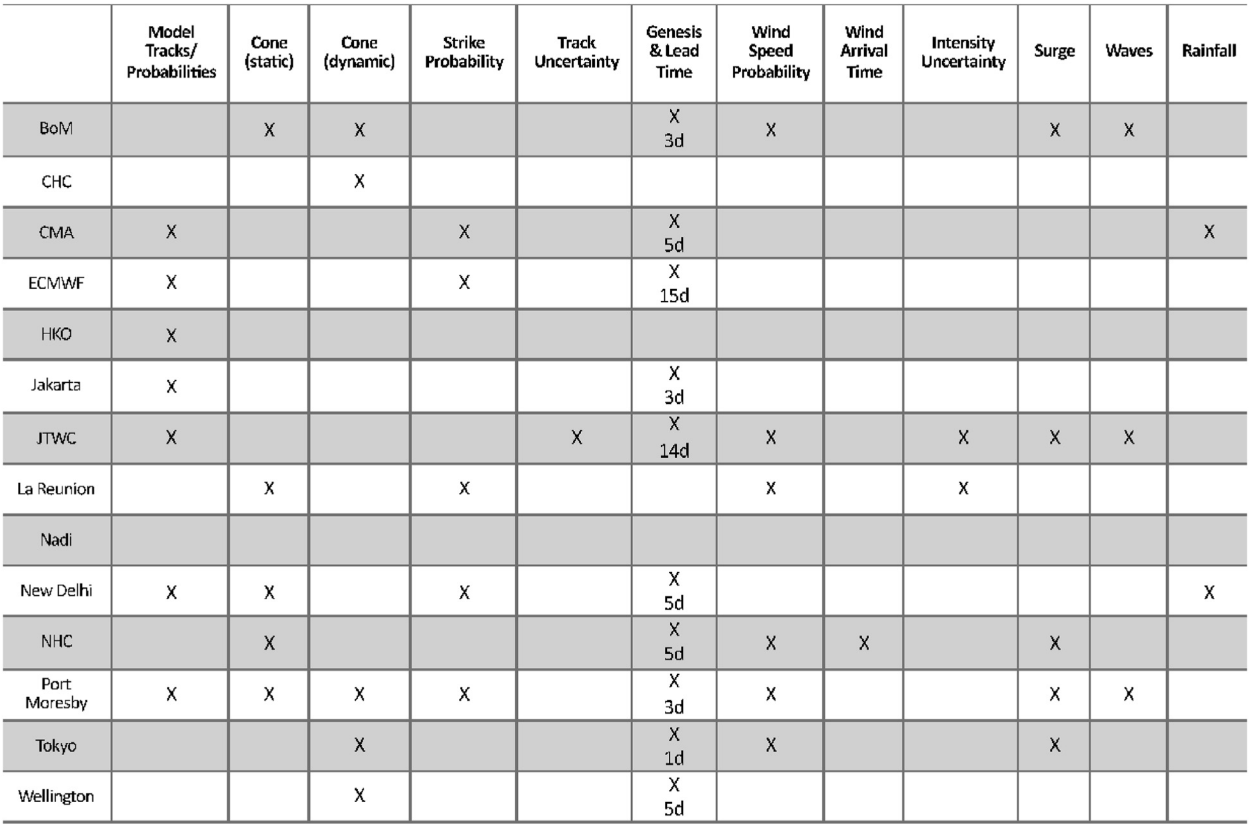
2.1. Current challenges and state of the science

2.1.1. Probabilistic TC formation (genesis) forecasting

Short-range and subseasonal TC formation outlooks generated by forecast centers vary widely in format and forecast period (Appendix A, Table 1). Most agencies provide graphical and/or text-based representations of the geographical location, timeframe, and likelihood of TC genesis. Some products depict areas of potential TC formation while others depict areas of TC occurrence to account for potential post-formation tracks. Forecast periods for publicly available products range from a minimum of 24 h (e.g., JTWC) to a maximum of three weeks (US Climate Prediction Center (CPC); Météo-France New Caledonia). Non-public outlooks available to approved customers cover forecast periods as long as four weeks (e.g., Bureau of Meteorology (BoM), Australia), and agencies report producing experimental outlooks (internally) with forecast periods that extend to as long as four weeks (e.g., TCWC Wellington). Some agencies base their TC genesis outlooks wholly on numerical model output, while others have forecasters fine-tuning the TC genesis forecast to set and adjust potential genesis locations, timeframes and probabilities, and draft text bulletins.

While TC genesis forecasting methods vary, operational forecasting centers increasingly rely on ensemble model forecasts and products, including derived pre-formation vortex trackers (see Sec. 3.1.1) and formation probabilities, statistical

Table 1
RSMC Operational probabilistic TC forecast products. This information was compiled via a 2021 TC-PFP project internal survey intended to complement findings and recommendations identified during the June 2021 TC-PFP Phase 1 workshop.



	Model Tracks/ Probabilities	Cone (static)	Cone (dynamic)	Strike Probability	Track Uncertainty	Genesis & Lead Time	Wind Speed Probability	Wind Arrival Time	Intensity Uncertainty	Surge	Waves	Rainfall
BoM		X	X			X 3d	X			X	X	
CHC			X									
CMA	X			X		X 5d						X
ECMWF	X			X		X 15d						
HKO	X											
Jakarta	X					X 3d						
JTWC	X				X	X 14d	X		X	X	X	
La Reunion		X		X			X		X			
Nadi												
New Delhi	X	X		X		X 5d						X
NHC		X				X 5d	X	X		X		
Port Moresby	X	X	X	X		X 3d	X			X	X	
Tokyo			X			X 1d	X			X		
Wellington			X			X 5d						

models, and statistical-dynamical methods to prepare TC genesis forecasts for all timescales. Some techniques account for ensemble and/or deterministic model biases by calibrating formation probabilities using statistical-dynamical approaches (e.g., Halperin et al., 2017). Additional details regarding techniques used by various forecast centers (e.g., unweighted consensus, weighted consensus, and ensemble positions) is further detailed in Conroy et al. (2023). Outlooks produced by climate experts, such as the US CPC's Global Tropics Hazards and Benefits Outlook, also inform and aid TC genesis forecasting efforts at the TC forecasting centers.

Various forecast centers are producing and developing probabilistic TC genesis outlooks that include more detailed information and cover longer forecast periods. The trend toward producing multi-week TC formation forecasts has accelerated since IWTC-9, aided by ongoing improvements in models and methods. The formats, styles and forecast periods of operational TC genesis forecasts are notably non-uniform, warranting consideration of best practices and possible data-driven standardization.

2.1.2. Probabilistic TC position (track) forecasting

Forecast centers primarily represent probabilistic TC forecast track data in the form of a swath or cone depicted in official, graphical forecast products. Some centers apply techniques that use historical forecast errors (climatological) to generate probabilistic representations of forecast tracks, hereafter referred to as "confidence areas" (Fig. 1). While these techniques are calibrated to produce statistically accurate representations of potential TC motion, they do not convey the situation-dependent probabilistic information that an increasingly skillful distribution of statistical, statistical-dynamical, and ensemble dynamical model forecasts provide. Therefore, many forecast centers are actively developing or implementing techniques that incorporate situation-dependent model output to generate confidence areas (Conroy et al., 2023). The India Meteorological Department (IMD) has historically used climatological forecast errors in their products and is now experimenting with ensemble-based products (Mohapatra et al., 2012). A few forecast centers (e.g., RSMCs La Reunion and Tokyo and TCWCs Jakarta, Melbourne, and Wellington) have already implemented dynamic uncertainty into their graphical products (Appendix A, Table 2). Additionally, some operational centers, including RSMC Miami, RSMC Honolulu (the Central Pacific Hurricane Center (CPHC)), and JTWC, use probabilistic forecast track data derived from a suite of high-resolution deterministic model solutions to generate complementary, dynamic TC strike and wind speed probability products for their customers (DeMaria et al., 2009). Others such as RSMC La Reunion are incorporating model ensembles

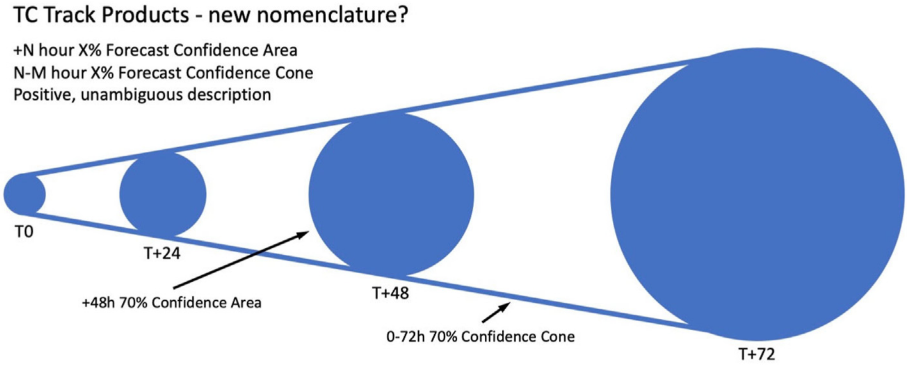


Fig. 1. Standardized nomenclature for the probabilistic representations of TC track forecasts proposed during the 2021 TC-PFP workshop. The term "confidence" is consistent with terminology from the field of statistics (confidence interval associated with a sample of data) and readily conveys the concept of "most probable outcomes."

to generate their wind speed probability products. A few forecast centers (e.g., RSMCs La Reunion and Tokyo and TCWCs Jakarta, Melbourne, and Wellington) have already integrated situation-dependent probabilistic track forecast data into their primary graphical TC track forecast products (see Appendix A, Table 2).

Multiple independent efforts to generate meaningful dynamic representations of confidence areas are currently underway. For example, Météo France's Système de Prévision des Inondations en contexte Cyclonique (SPICy) project has developed a method to generate 75 % forecast confidence areas (i.e., areas within which a TC center has a 75 % chance of tracking) around official, deterministic track forecasts by applying a Monte-Carlo approach to climatological data and European Centre for Medium-Range Weather Forecasts (ECMWF) ensemble forecasts (Bonnardot et al., 2019). This method has now been implemented to generate the confidence area in RSMC La Reunion's official TC forecast products. At RMSC Tokyo (Japan Meteorological Agency (JMA)) the uncertainty at each forecast timestep is expressed via a 70 % probability circle out to 120 h, the size of which have been determined solely by super ensemble spread using the ECMWF Ensemble (ENS), the NOAA National centers for Environmental Prediction (NCEP) Global Ensemble Forecast System (GEFS), the UK Met Office Global and Regional Ensemble Prediction System (MOGREPS-G) and the JMA Global Ensemble Prediction System (GEPS) since 2019 (Fukuda and Yamaguchi 2019). The Australian Bureau of Meteorology designed a technique that applies a Gaussian Mixture Model (GMM) to derive calibrated Forecast Confidence Areas from ensemble-based vortex tracker data. These model-based areas can be blended with forecaster-determined analysis uncertainty and climatological forecast errors "on-the-fly" to produce reasonable confidence areas for any percentage threshold. This methodology, described further in Conroy et al. (2023), was implemented operationally for the 2022–2023 season. The Naval Research Laboratory has also developed the capability for JTWC to adjust confidence areas (34-knot wind danger areas) on official forecast products using GPCE and wind speed probability data. These methods remain in testing and are not yet operational.

Additional detail on all the methods currently utilized at operational TC forecast centers to characterize track uncertainty can be found in Conroy et al. (2023), which is summarized by the IWTC-10 subgroup on "Track forecast: operational capability and new techniques" to which the TC-PFP project was linked.

2.1.3. Challenges and key issues

The production of probabilistic TC forecasts presents both operational and meteorological challenges. Operationally, since forecasts must be prepared on specific schedules, the delayed arrival of some ensemble data means that it sometimes cannot be incorporated into the current forecast cycle. The value of older ensemble forecast information must often be weighed alongside the value of newer deterministic forecast information. This is particularly challenging around the time of TC extratropical transition when the forecast is especially sensitive to the initial analysis, and there may be large variations from run to run. There is considerable discussion of the use of time-lagged ensemble approaches to mitigate run-to-run jumpiness.

Some current ensembles are under-dispersive, which can lead to overconfidence in the track prediction (Leonardo and Colle 2017; Titley et al., 2020) and large changes in the ensemble mean from one forecast cycle to the next. This behavior lessens forecast confidence and can be a significant challenge to forecast centers but can be overcome by utilizing well-calibrated multi-model ensembles.

Since deterministic model guidance underpins much official forecast track information, (e.g., a weighted consensus), maintaining consistency with ensemble forecasts becomes difficult when the ensemble mean and deterministic outlooks vary considerably (i.e., when the deterministic tracks are outliers in the ensemble spread). It is particularly challenging to evaluate forecast uncertainty when ensemble outlooks are clustered around multiple, significantly different outcomes, for example in the situation of competing, or bifurcating, steering flows that lead to diverging TC tracks.

At long lead times, it may be necessary to depict a very large cone of uncertainty, which may undermine the attempt to provide a probabilistic forecast by making it look like the TC could be anywhere. However, if this is a true reflection of the dynamic uncertainty in a particular case, then this may lead to more reliable warnings than those where uncertainty estimates are purely based on historical errors. Current depictions in terms of a "cone of uncertainty" emphasize the across-track error, but do not give an adequate account of along-track error or translation speed, so a key challenge is how to communicate ensemble-based along-track uncertainty information. Some forecast centers (e.g., the National Centre for Medium Range Weather Forecasting (NCMRWF) – India) have moved towards displaying an ensemble average track for their TC forecast tracks. The ensemble mean positions are calculated from the NEPS-G ensemble (the global ensemble prediction system of NCMRWF, Conroy et al., 2023).

There is still a need for localized forecast information, but any forecasts given in terms of probabilities can also be misunderstood depending on the numeracy of the end user. Simplification into categories such as "low", "moderate" and "high" can be a useful way to communicate risk, but definitions vary across forecast centers, and the interpretation of different levels will vary across different user communities (See Sec. 2). While we expect different forecast centers will develop different products, in part because of the different constituencies they serve, all products must have quantitative verification metrics, preferably with a common baseline so that at least some measure of performance can be compared across forecast centers.

2.2. Vision of the future

A vision for TC probabilistic formation and position products includes implementation of best practice approaches that incorporate the state of the science while also delivering clear, actionable messages to end users. The formats, styles, and forecast periods of operational ensemble-based TC formation and TC position forecasts are notably non-uniform, warranting consideration of best practices and possible data-driven standardization. These streamlined best practices will reflect synergy between the science, understanding and communication, and resources required for producing and distributing probabilistic TC formation and TC position forecasts.

2.3. Recommendations and paths forward

TC-PFP surveys indicated that RSMCs, TCWCs, and forecast centers are often unaware of the efforts, advancements, and best practices related to probabilistic forecasts of TC formation and TC position at other centers. It is recommended that WMO continue to promote communication and collaboration between various RSMCs, TCWCs, and forecast centers regarding the sharing of best practice approaches to ensemble-based probabilistic TC formation and TC position forecasts. Recommendations for current & planned probabilistic TC forecast products include:

- Promote opportunities for collaboration and sharing of knowledge between forecast centers. It is recommended that WMO facilitate workshops that provide centers with venues to exchange information and ideas related to advancing probabilistic TC forecasts.
- Forecast centers should develop best practices that weigh the utility of older ensemble forecast information against the value of relatively newer deterministic forecast information. Since operational forecasts adhere to specific schedules, the availability of ensemble data should be as timely as possible so that it can be incorporated into the current operational forecast cycle (see Sec. 3).
- Develop best practices that identify and address circumstances when current model ensemble TC formation or position forecasts are under-dispersive, as otherwise this could lead to jumpiness between runs and could lessen stakeholder confidence. Methodologies could include incorporating some static or climatological measure of uncertainty, or using several ensemble forecast models in a super-ensemble to provide greater spread.
- Develop best practices that effectively communicate forecast uncertainty when ensemble outlooks of TC formation or position are clustered around multiple, significantly different outcomes. For example, in the situation of competing, or bifurcating, steering flows that lead to diverging TC position forecasts.
- Forecast centers should assess the pros and cons of TC formation and position forecasts at long lead times (e.g., 5+ days) that may result in very large cones of uncertainty for both types of forecasts. While providing the most accurate representation of forecast uncertainty, these forecasts could also encompass extensive geographical areas, posing a challenge for communicating understandable and actionable probabilistic forecasts to stakeholders.
- Forecast centers should explore the tendency for current depictions of "cones of uncertainty" to emphasize the across-track error, while not always adequately conveying the uncertainty associated with along-track error or translation speed. It is important to explore the development and use of a "dynamic cone of uncertainty" based on model hindcast or Reforecasts data.
- Develop best practices regarding the definition and evaluation of TC formation (i.e., TC genesis) with a goal to reduce the uncertainty of event identification.
- Increase awareness of end user numeracy and avoid the use of vernacular language for communication to help alleviate misunderstandings by stakeholders (see Sec. 2 recommendations).

Given the increased skill of model forecasts, forecast centers are actively developing or implementing techniques that incorporate situation-dependent model output to generate confidence areas. Better collaboration and exchange of ideas between forecast centers could result in a semi-standardized set of best practices for publicly-available probabilistic TC formation and TC position forecasts (i.e., optimal forecast periods (e.g., days to weeks) that realistically reflect the state of the science and forecast model skill, classification scales (e.g., “low”, “medium”, and “high” with associated probabilities), and messaging style (e.g., graphical only, text-based only, graphical + text, etc.)). This could, in turn, significantly accelerate the effectiveness of probabilistic TC forecasts and promote a value-cycle approach to the forecast challenge of TC formation and TC position. Any efforts to enhance product uniformity amongst centers should be balanced against the need for forecast centers to develop their own tailored products for customers. This customization is necessary to maximize responsiveness to customer needs, while also providing an environment that advances product innovation and advancement.

3. Understanding and communicating probabilistic forecasts

3.1. Current challenges and state of the science

TC track products were first formally produced in the mid 1980s to communicate the probability of a storm coming within approximately 60 n mi of a given location (DeMaria et al., 2009). Its intended audience was expert users, government officials, and other decision-makers, but the data was made public to assure that as many possible users as practicable would have access to the data. In 2002, the now widely known “cone of uncertainty” was released by RSMC Miami. By 2021, TC-PFP's pre-workshop preliminary survey of forecast centers showed that a large range of probabilistic forecasts were available, covering both the spatial structure of a TC (i.e., formation and position) and its associated sub-hazards (e.g., storm surge, wind, and waves, Table 1).

3.1.1. Expert products available to the public

There are many publicly available products on forecast center websites that aim to reach as many interested users as possible. For example, most forecast centers provide a “tropical weather outlook” or similarly named product, highlighting areas with the potential for TC formation over the next 3–5 days. These products are typically available on forecast center websites as either regularly published bulletins or map based graphics (Fig. 2). They are also typically designed for expert users and bulletins often use complex meteorological jargon that can make them hard for a non-expert to understand. For the casual viewer, many TC formation graphics also bear a strong resemblance to “cone of uncertainty” plots, which could lead to misleading conclusions, especially if a user misinterprets the title ‘tropical weather outlook’. If these or other similar “research-level” products are freely accessible online, we suggest forecast centers also include clear language to explain what the outputs are designed for and links to educational materials. See (Santoalla 2023) for an example of a guide to the creation and interpretation of expert-level TC graphics at ECMWF.

3.1.2. Communicating TC position via written bulletins

Written bulletins about TC position are in use by the majority of forecast centers and are a valuable way to provide nuance or the forecaster's interpretation of events. Like tropical weather outlooks, many of these TC position bulletins are written directly by forecasters for expert interpretation, assuming knowledge of TC meteorology, TC lifecycle/properties and some aspects of statistics and probability. However, TC position bulletins are also accessed by a range of users with different levels of subject literacy, which could lead to misinterpretation. For example, meteorological jargon such as ‘weakening’ is often taken to mean that overall risk of impact is lessening, rather than a reference to a change in a storm's maximum surface wind speed.

To address this, many forecast centers now release a large range of written bulletins, with designs often backed up by extensive user research. For example, RSMC Miami releases public specific bulletins and detailed forecast discussions alongside several other tailored products to meet user requirements. Outcomes from the 2021 TC-PFP workshop and

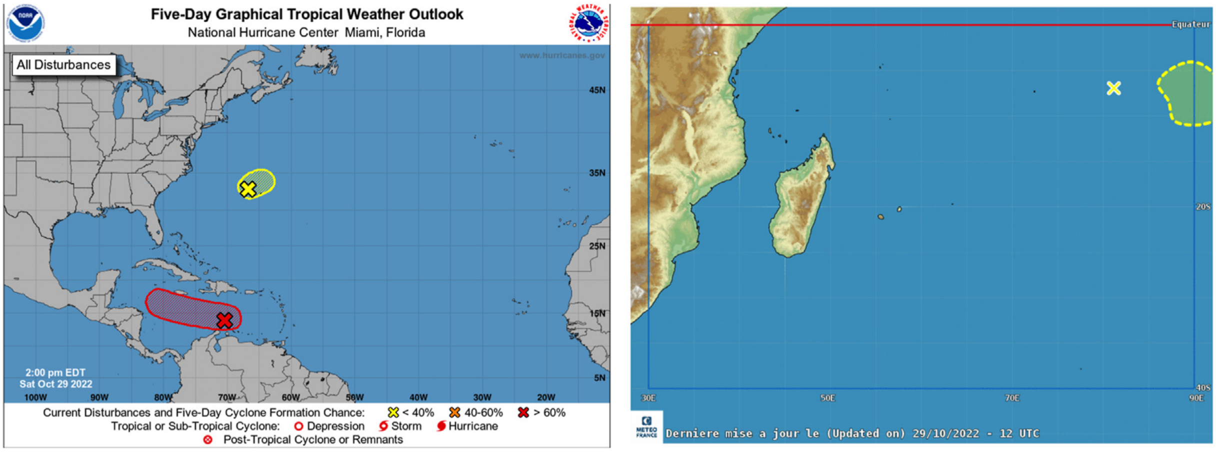


Fig. 2. Examples of TC formation graphics on October 29, 2022. (Left) RSMC Miami Graphical Tropical Weather Outlook depicting the 5-day probability of TC formation for a tropical disturbance in the Caribbean (70 % or “high” chance) and a disturbance northwest of Bermuda (10 % or “low” chance). (Right) RSMC La Réunion 5-day probability of TC formation for a disturbance near ~7°S, 81°E (10–30 % or “low risk”). For both graphics, the “x” denotes the current location of the disturbance and shaded areas show where TC formation could occur.

current peer reviewed literature suggest that utilizing the following resources could promote more effective communication of probabilistic forecasts of TC formation and position: there is now an expert field of science writers and press officers specifically trained in communicating complex and uncertain information. Most large journalistic centers also run data-labs, publishing a number of innovative free communication tools, from automatically translating stories into multiple languages, to building "explainers" or testing different written formats for comprehension. It is important for users to quickly find the level of TC forecast detail that they need. One proven way to mitigate this is to create 'nested' versions of a single TC formation or position forecasts at different complexity levels, similar to journalistic formats such as "short, medium and long stories" (BBC News 2020) or, "*What is happening? Who does it affect? What should I do next?*".

Probabilistic forecasts of TC formation and position should also be designed to maximize use and understanding by the general public, especially more vulnerable groups who are not fluent in English or local languages and who may not have easy access to forecast information. TC formation or position forecasts that are exclusively released in either English or the dominant local language, could exclude large swaths of the population and many vulnerable groups. This also leaves these TC forecasts open to misinterpretation by someone unfamiliar with TC meteorology. Similarly, if experimental TC forecast products are only published in one language (especially in English online) and feedback is requested, the final result will be fundamentally skewed towards the demographics able to access and interpret them. For example, many formats are tested by university students, who represent a small subset of the population. Forecast centers should work with expert translators to ensure that probabilistic TC formation and position products are tested and released in multiple languages to accommodate diversity of constituents. These efforts have the potential to transform TC response. For example, the aim of the recent "HURAKAN" project is to contribute to the design of an information provision system that communicates the minimal critical pieces of information to the maximum number of people from diverse backgrounds (Millet et al., 2020a; Lemos et al., 2012; Enenkel and Kruczkiewicz, 2022). Forecast centers should design websites with probabilistic TC formation and position forecast information that optimize public access by maximizing the visual accessibility of the information. Also, a confusing or text heavy website accessed using a smartphone might mean that a user never finds the forecast product or cannot access it if it is included as an embedded Portable Document Format (PDF). Within the development of these types of tools, identifying various users and their specific needs could help with different users understanding the degree to which certain websites, tools, etc. could be useful (or not) for their decision making context. This type of framing would be useful and would speak to the importance of the user-skill of understanding the appropriateness of using information rather than the current common approach of trying to access whatever they can find or trust what is perceived to be the 'best designed'.

Finally, given that many now access news via social media, video or social-media posts can be invaluable tools to complement written material. These communication channels provide reach to populations who may not routinely access written forecast material. For example, a 2 min video explaining forecaster reasoning with a 10 min moderated Q&A session via comment might reach many more people than written material alone. Similar to other fast moving fields such as spaceflight, pre-arranged daily press-briefings with Q&A have been shown to allow nuance to be explained or misconceptions to be dispelled. Soden et al. (2022) and Ma and Millet (2020) discuss examples and guidelines for social media TC forecasts.

3.1.3. Graphics: static and dynamic "cones of uncertainty"

The TC track forecast cone, or "cone of uncertainty" that was released by RSMC Miami in 2002 transformed TC position communication. The cone shows the probable TC position for five days, at 12-h intervals and incorporates historical forecast uncertainty. The radius of the cone is fixed so that two-thirds of 5-year historical track error falls inside the cone. Modern cone graphics also show many additional features such as initial intensity and motion and watch and warning areas (Fig. 3).

The "cone of uncertainty" is popular with the public and has been extensively studied. Unfortunately, it has been found that it is easy to misinterpret and rarely leads the public to adequately evacuate or prepare. Common biases include:

1. Many users assume that the cone suggests storm size is growing over time and conflate TC size and intensity. That is, they perceive that as the cone gets wider, the storm is getting larger and more intense. Although most forecasts contain warnings or directions, eye tracking software has shown that most viewers do not read map annotations or warnings (Millet et al., 2022), especially when viewing on a small screen such as a mobile device.
2. The symmetrical nature of the cone forecast downplays the fact that TC hazards are often oriented asymmetrically around the TC center. Also, the smooth shape of the forecast "cone of uncertainty" suggests there will be no sudden changes in TC direction or speed. Symmetry and smoothness of the cone can lead users to not fully understanding the nuances of track forecasts and associated storm hazards.
3. An assumption that the "cone of uncertainty" portrays the "threat/hazard zone" and uncertainty associated with the forecasted positions rather than the forecast storm path. This is increasingly problematic as forecast skill improves. In many TC scenarios dangerous weather is more likely to occur outside the ever-narrower cone's boundaries and perversely less clarity in communication is an unintended consequence of more accurate forecasts (Norcross 2019).
4. Misinterpretation of the "cone of uncertainty" as a proxy for risk is especially problematic because of the containment fallacy; when humans see a fixed line on a map, they typically assume a binary "in/out" perspective (Boone

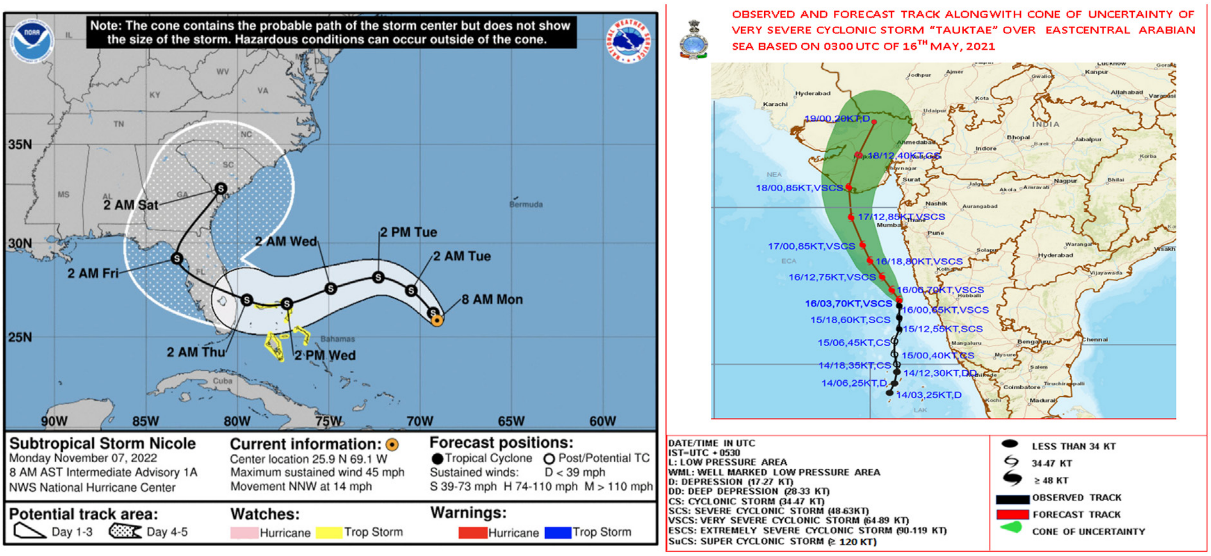


Fig. 3. Static "cones of uncertainty" examples from RSMC Miami and RSMC New Delhi.

et al., 2018). This means it is common for non-experts to assume if they are outside the cone, they are "not at risk".

5. A further problem is that users who correctly interpret the "cone of uncertainty" as a measure of uncertainty, often understand it to be the product of a variety of models or model runs when it actually represents the climatological uncertainty of the forecast track. This leaves little room to effectively communicate to the general public complex forecasts such as bifurcating ensemble tracks.

There has been a significant amount of research on improving the "cone of uncertainty" alongside several large operationally linked research programs (Demuth and Eosco 2021; Eosco and Sprague-Hilderbrand 2020; Millet et al., 2020b). We recommend that forecast designers utilize the available guidelines as a core part of the design process for probabilistic forecasts of TC formation and position (Bica et al., 2020; Franconeri et al., 2021; Ma and Millet 2022; Millet et al., 2020a; Prestley et al., 2021; Support for the Cone of Uncertainty Social and Behavioral Science Research Project, 2020).

RSMC Miami's website identifies five key points to consider while using and interpreting their "cone graphic". These points describe the cone's associated forecast uncertainty and its irrelevance to TC size and radial extent of potentially damaging winds. The overriding recommendation is that small tweaks to the cone design do not aid comprehension and that graphics centered around hazard or risk are more useful for risk communication (Millet et al., 2022).

Because of the issues of interpretation many forecast centers are experimenting with the arrival time of hurricane force winds, storm surge, or precipitation rather than the cone of uncertainty. These products will be examined more closely during TC-PFP Phase 2 (TC intensity and structure) and Phase 3 (rainfall and storm surge).

3.2. Vision of the future

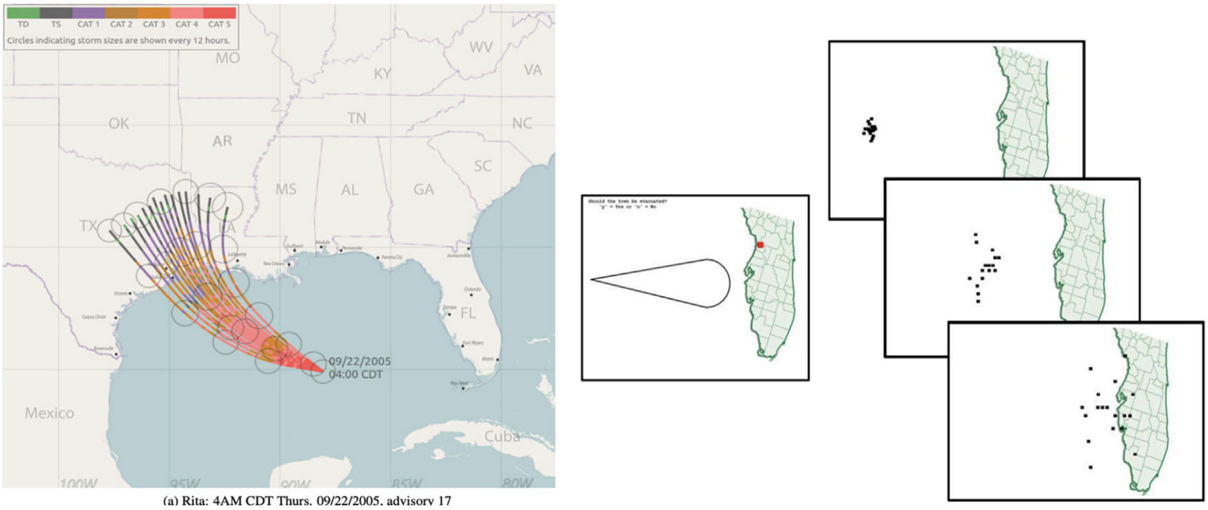
3.2.1. Co-design is key

Products have been shown to better meet the needs of users' when they are co-designed with communication experts and forecasters. Long term relationships allow for transparent feedback, tailored output, and help ensure that whatever is designed and disseminated is both interpreted correctly and is useful. Many forecast centers have partnerships with universities, broadcast centers, or "expert translator organizations" such as the Red Cross Climate Centre. They are also choosing to employ 'in-house' communication teams. For example, the Argentinian National Met service has created a Meteorology & Society Department that advises on the entire process of the production/improvement of weather services, alongside supporting the development of new products.

3.2.2. Experimental cone replacements: Dynamic cones and ensemble/spaghetti plots

Experimental ensemble outputs and dynamic forecast cones seek to separate TC size and model uncertainty. For example, Fig. 4 (left) shows how a carefully designed ensemble "spaghetti" plot helped study participants to better quantify the threat zone to a fictional oil rig and to understand size versus track uncertainty (Liu et al., 2018). They also found that users did not need training or any detailed information on how the plots were made.

These experimental products are still not perfect. For example, the number of model ensemble members shown impacts on the perceived risk and tracks that cross each other can cause confusion. Padilla et al. (2020) also found that testers estimated more risk for a location that was directly overlaid by an ensemble track although the effect could be reduced by manipulating the number of ensemble tracks that were displayed. Similar results were found by Bica et al. (2020) who



(a) Rita: 4AM CDT Thurs. 09/22/2005, advisory 17

Fig. 4. (Left) experimental ensemble plot published in Witt et al. (2022). The size of the cyclones is marked, alongside a range of potential model ensemble tracks and intensities. (Right), an example of dynamical model ensembles published in Witt et al. (2020). The panel on the left shows a cone trial with the town for which the evacuation decision must be made depicted to the right of the upper edge of the cone. The 3 panels on the right show the progression of "zoomies" with a trial, with each instance in the dynamic ensemble moving smoothly and continuously across the screen. View an example gif of zoomies here: https://col.st/TbdQ1.

analyzed communication of model ensemble spaghetti plots between members of the public and authoritative weather sources within the US during the 2017 Atlantic hurricane season. Even with training on what the ensembles mean, people tend to personalize the risk and overreact when they see one line projected to hit their town.

Several RSMCs have used dynamic "cones of uncertainty" and ensemble forecasts to overcome the challenges with the use of forecast cones. In the case of Witt et al. (2020, 2022), both the cone and small storms nicknamed "zoomies" were allowed to move towards a fictional town (Fig. 4). When trial participants assessed TC risk using the zoomies, they suggested a gradual decrease in evacuation rates rather than the sharp cutoff they had reported when given the cone.

3.2.3. Expert users

During the 2021 TC-PFP Phase 1 workshop, weather sensitive organizations and industries such as reinsurance, broadcast agencies and energy/off-shore oil, stated a preference for TC information to be provided in pre-determined formats tailored to their particular risk profiles and actions. This tailoring could be delivered by in-house meteorologists using raw model data rather than derived outputs. Organizations expressed a willingness to pay for access to the raw data. Creating these long term partnerships takes meaningful time and trust, but commonly leads to new forecast innovation, alongside additional funding for forecast development.

3.3. Recommendations and paths forward

Understanding and communicating probabilistic forecasts pose a significant challenge to forecast centers around the world. The following recommendations for understanding and communicating probabilistic forecasts are intended to address some of these challenges:

- Forecast centers should develop probabilistic TC forecast products in close collaboration with users and experts experienced in communicating complex probabilistic information (e.g., press-officers, broadcasters, science writers, social media experts, sociologists, disaster geographers, economists, and community leaders). This collaboration is especially important for supporting overlooked and/or underserved demographics.
- Design graphical forecast products that incorporate expertise from cartographic geographers, psychologists, statistics communicators, data visualization experts and cognitive neuroscientists, who use tools such as eye-tracking software to explore how a forecast product is interpreted.
- Design future forecast products that emphasize hazards and risk, rather than just the possible paths of the TC center.
- Emphasize, rather than obscure, uncertainty or alternative outcomes in visualizations to support better decision-making by users.
- Emphasize approaches that effectively communicate more than one forecast and watch/warning scenario, especially in medium-range and longer lead-time TC forecasts, where ensemble prediction indicates several distinct outcomes. For example, when the model ensemble of positions split into two clusters each affecting very different regions with risks of impacts.
- Forecast centers should strive to build long-term relationships with local communities to help ensure that forecast products (including graphics labels) are easily translatable and delivered through relevant channels. TC forecasts of formation and position are inaccessible to many stakeholders (e.g., due to lack of internet accessibility, mobile-unfriendly websites, or users not speaking the language).
- Incorporate the use of social media to increase reach however consistent messaging across platforms is important. Develop TC forecast products that meet accessibility

design principles. Particular consideration should be given to overcoming issues with map illiteracy, containment bias, and challenges related to the spatial overestimation of odds. Insights should be shared forecast centers alongside an "accessibility checklist" before product roll-out.

- Establish a central repository of operational and experimental forecast product designs, including examples of different 'use-cases' (public, disaster response, etc.) to assist forecast centers to share knowledge and implement best practices.

4. Resources for producing probabilistic forecasts

4.1. Current challenges and state of the science

4.1.1. Exchange of ensemble forecast data and forecast TC tracks

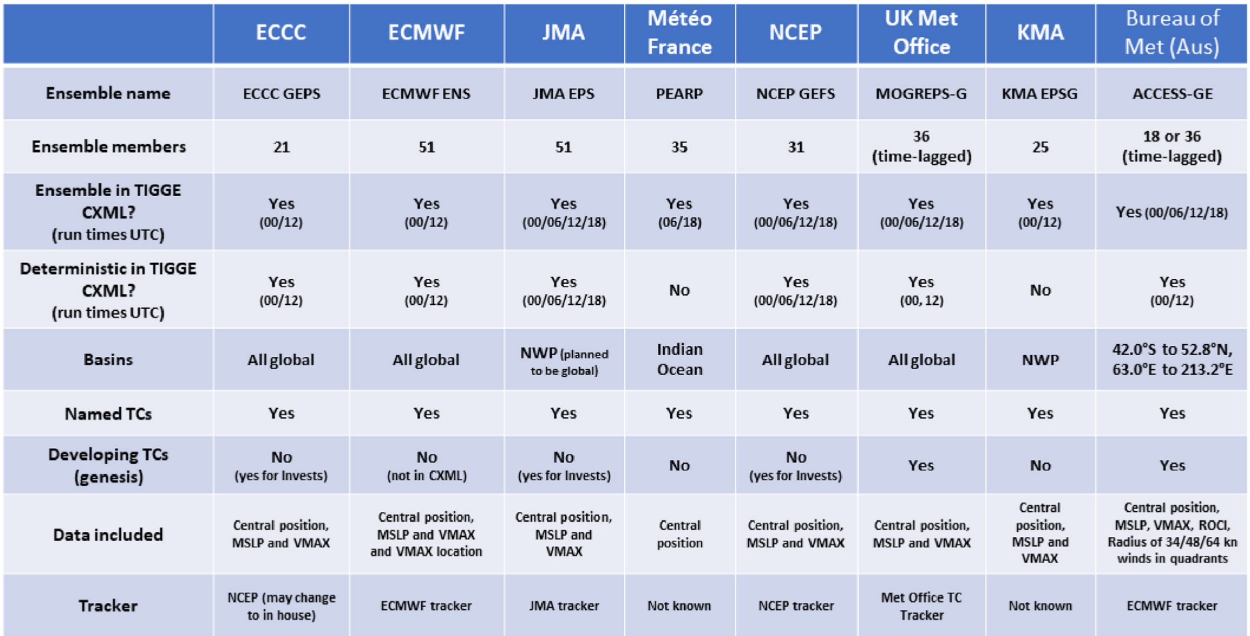
The sharing of TC-attribute data has been largely accomplished through The International Grand Global Ensemble (TIGGE; Bougealt et al., 2010; Swinbank et al., 2016) and the Global Telecommunications System (GTS). Beginning in 2006 as part of the WMO THORPEX project, gridded data from multiple global ensemble forecast models were made available for scientific research via data archive portal at ECMWF (https://confluence.ecmwf.int/display/TIGGE). Several TIGGE partners also exchange TC track predictions from their global ensemble forecast models in near–real time, using an XML-based format that was developed for the purpose (Cyclone XML (CXML)). These data mainly consist of TC position and intensity information, with intensity usually represented by a maximum wind value and a minimum sea-level pressure. The current list of contributors to TIGGE CXML are listed in Table 2. TC track data are available via the National Center for Atmospheric Research (NCAR) research data archive (https://rda.ucar.edu/datasets/ds330.3/), where there are 50–60 unique users of the dataset (National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce, and Coauthors, 2008).

Several challenges for forecast centers in using the current CXML ensemble TC track data were identified from the presenters and breakout groups at the 2021 TC-PFP Phase 1 workshop. First, TIGGE and TIGGE CXML are designed for research rather than operational use. This affects both latency and reliability. Second, there is inconsistency among contributions from different forecast centers because of the use of different trackers used to determine TC position (see Section 3.1.2). There is also inconsistent information about storm structure conveyed, meaning some of the contributing model ensembles do not provide wind radii or estimates of the radius of maximum wind. Moreover, the decision to add such information will require concerted coordination efforts across forecast centers, including devoted human resources, to include consistent structural information computed in a consistent manner. Note that, while TC structure is the subject of Phase 2 of TC-PFP, it is clear that the lack of consistent and reliable TC structural information will be substantial.

A third overall challenge identified by TC-PFP related to the mechanisms of data exchange between forecast centers. As a follow-up of the 2021 TC-PFP Phase 1 workshop, the project circulated questionnaires to understand the status of the access to and use of deterministic/ensemble TC tracking data for operations at numerous forecast centers. The questionnaire results

Table 2

TIGGE CXML contributors in 2022: Environment and Climate Change Canada (ECCC), ECMWF, JMA, Météo-France, UK Met Office, Korean Meteorological Administration (KMA), and BoM. Data include minimum sea level pressure (MSLP), maximum sustained surface winds (VMAX), center location, radius of outermost closed isobar (ROCI), and radius of 34, 48, and 64 kt winds (defined for each storm quadrant). Thanks to Doug Schuster (UCAR) for confirming the current contributors to the NCAR research data archive.



	ECCC	ECMWF	JMA	Météo France	NCEP	UK Met Office	KMA	Bureau of Met (Aus)
Ensemble name	ECCC GEPS	ECMWF ENS	JMA EPS	PEARP	NCEP GEFS	MOGREPS-G	KMA EPSG	ACCESS-GE
Ensemble members	21	51	51	35	31	36 (time-lagged)	25	18 or 36 (time-lagged)
Ensemble in TIGGE CXML? (run times UTC)	Yes (00/12)	Yes (00/12)	Yes (00/06/12/18)	Yes (06/18)	Yes (00/06/12/18)	Yes (00/06/12/18)	Yes (00/12)	Yes (00/06/12/18)
Deterministic in TIGGE CXML? (run times UTC)	Yes (00/12)	Yes (00/12)	Yes (00/06/12/18)	No	Yes (00/06/12/18)	Yes (00, 12)	No	Yes (00/12)
Basins	All global	All global	NWP (planned to be global)	Indian Ocean	All global	All global	NWP	42.0°S to 52.8°N, 63.0°E to 213.2°E
Named TCs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Developing TCs (genesis)	No (yes for Invests)	No (not in CXML)	No (yes for Invests)	No	No (yes for Invests)	Yes	No	Yes
Data included	Central position, MSLP and VMAX	Central position, MSLP and VMAX and VMAX location	Central position, MSLP and VMAX	Central position	Central position, MSLP and VMAX	Central position, MSLP and VMAX	Central position, MSLP and VMAX	Central position, MSLP, VMAX, ROCI, Radius of 34/48/64 kn winds in quadrants
Tracker	NCEP (may change to in house)	ECMWF tracker	JMA tracker	Not known	NCEP tracker	Met Office TC Tracker	Not known	ECMWF tracker

showed three main findings. First, it has become clear that forecast centers rely heavily on bilateral agreements, the internet, and other agencies for data acquisition, rather than on the GTS. Second, there are significant differences in the data being acquired, or potentially acquired, by each center. Such a situation may lead to large differences in the quality and quantity of services from one center to another. Third, different centers have different acquisition times for the same data. The challenge has become clear that TC forecast centers need to be able to access TC track and parameter data in a stable and timely manner to improve their operational and research activities. The desire by forecast centers for standardized data formats and TC tracking algorithms, as well as the need for information on pre-genesis tropical disturbances, also became clear from the questionnaires. Currently there are multiple data formats including ASCII formats, CXML and BUFR/GRIB. The heterogeneous landscape makes it difficult to ensure both transferability and reliability of products produced from the data.

A fourth challenge involves the quality of the operational forecasts themselves. TCs in global ensembles tend to be under-resolved and suffer from a low bias of intensity. This affects confidence in the predicted distribution of TC intensity but can also inhibit a realistic depiction of track spread in cases of weaker storms, or storms that are near the time of formation because some model ensemble members may not track a storm at all. Re-forecast datasets could help offset the TC intensity bias through post-processing techniques, but the size of these datasets makes them difficult to transmit, and their use requires someone at the forecast center to perform the calibration.

An additional fifth challenge, which affects the assessment of the quality of products, is the lack of appropriate verification datasets. While IBTrACS is the recognized international standard for TC position and intensity information, there are still inconsistencies of the information coming from different forecast centers, especially near the time of TC formation. There are also different definitions used for the maximum surface wind speed, with US agencies (RSMCs Miami and Honolulu and JTWC) reporting a 1-min averaging time for sustained winds, compared with the 10-min averaging time used by much of the rest of the world. Moreover, there is a relative absence of other TC attributes in verification data. Information on TC structure (e.g., significant wind radii) is produced and transmitted by some forecast centers, but not all, and data related to TC impacts such as precipitation or coastal inundation are essentially absent.

4.1.2. Uncertainty in TC identification and position associated with vortex trackers

Several vortex trackers are available and used internationally to identify and track TCs, which output vortex parameters and forecast track data at centers (e.g., Marchok 2021; Heming 2017; Vitart et al., 2012). Pre-genesis trackers produce data prior to the formation of a tropical disturbance and can be used to produce pre-formation forecasts of position, genesis, and outlook products. Post-genesis trackers only track vortices if they are initiated with an initial position, usually by means of a manual analysis, and therefore only produce data once the tropical disturbance has formed. Several TC trackers combine the tracking of both pre-genesis and post-genesis TC positions, with the option of applying different thresholds for each, and are the preferred type. The choice of TC vortex trackers can influence the characteristics and useability of the data for operations as well as in verification.

The 2021 TC-PFP Phase 1 workshop identified a gap in knowledge associated with the impact of tracker algorithms on TC track positions. TC-PFP funded research to make quantitative comparisons of four different tracking methods (Heming, 2017; Marchok, 2021; Vitart et al., 2012; Hodges et al., 2017) using the same ECMWF EPS ensemble forecast data for western North Pacific TCs during the 2020 season. The study found that differences in the variables and thresholds used for feature identification in the various trackers led to a significant difference in the number of track points that were identified, even for named TCs. Forecasts for ensemble spread were shown to be relatively insensitive to the vortex tracker used, with a slightly larger variation found between the trackers for the error of the ensemble mean. The differences in the error between the trackers may be related to differences in how the trackers calculate position, but it will also be impacted by the sample size differences, as trackers with lower thresholds will more readily track weaker systems which could introduce larger errors. (See Conroy et al. (2023) for more detailed results from this study)).

The differences between how tropical disturbances are tracked is an issue that needs to be overcome when developing probabilistic TC guidance that incorporates multiple ensemble systems (Conroy et al., 2023). Although ideally all ensemble forecast models would be tracked with the same tracker, or with multiple trackers to better capture the uncertainty related to the tracker, this will be difficult to achieve in the short to medium term as the tracker is often embedded into complex operational processes at NWP centers. Greater clarity for users on which tracker and thresholds were used to create the TC position and vortex parameter datasets from each ensemble, along with any known tracker issues or rules, would be useful.

4.2. Vision of the future

There should be a concerted and coordinated effort to produce consistent TC vortex parameter data in a given format that is accessible in real time by all forecast centers. In addition, the same data should be made accessible to researchers via the TIGGE TC database in a format that enables greater utilization in research, enhancing the pull-through from research into operational forecasting.

In an ideal future, ensemble forecasts of TCs would be well calibrated with reliable landfall probabilities. TC attributes beyond position and intensity, verified using appropriate metrics, would also be included in the transmitted data.

4.3. Recommendations and paths forward

We suggest that WMO coordinate a mechanism that makes TC information from ensemble forecast models available in a stable and timely manner. Challenges with data availability should be partly addressed by the Global Data-processing and Forecasting System (GDPFS), and bolstered by the new WMO Unified Data Policy, Resolution 1, adopted on October 18, 2021, which states:

> "Members shall provide on a free and unrestricted basis the core data that are necessary for the provision of services in support of the protection of life and property and for the well-being of all nations …"

Among the core data referred to are global analysis and prediction fields provided by global numerical weather prediction (NWP) systems of designated producing centers of the GDPFS (WMO 2022). By virtue of TC-related data being produced from analysis and forecast fields from producing centers of the GDPFS, and the intended use of TC-related products for public safety, the sharing of TC attributes derived from operational ensembles is consistent with the agreement stated under WMO Resolution 1. However, as noted by Titley et al. (2019), a key limitation of data sharing results from the lack of an agreed-upon format for the data, both content and file format. As a result, access to TC-related parameters from ensemble forecasts is inconsistent. Making the problem even more challenging is that tracking software differs across operational centers, such that running different trackers on the same data produces different results, especially for TC genesis. Overcoming such inconsistencies in TC parameter calculation and information dissemination is possible, and essential to make systematic progress in all regions.

The following recommendations are offered to optimize the use of resources and accelerate the development of ensemble-based probabilistic TC formation and TC position forecasts.

- TC-PFP and the WWRP Working Group on Predictability, Dynamics, and Ensemble Forecasting (PDEF) recommend that TC position information from ensemble forecast models should be encoded in a consistent format and disseminated to forecast centers in a stable and timely manner. The recommended path to meet this overarching goal is as follows:
    - o WMO requests that forecast centers transition to encode ASCII track and vortex parameter data output from their various vortex trackers into a consistent and standardized format. While the precise choice of data format will need to be agreed upon in consultation with stakeholders and other WMO committees including the Advisory Group on Tropical Cyclones (AG-TC) and the Expert Team on Operational Weather Forecasting System (ET-OWFS), one option is to use WMO standard BUFR format. ECMWF already encodes their TC forecast position and relevant gridded data using WMO standard BUFR and GRIB formats, and disseminates these in real-time on the GTS, and this could be promoted as best practice for all NWP centers. Training material on how to encode the standardized files (including a template detailing how to order and label TC positions and which vortex parameters to include) should be made available to forecast centers to facilitate this process.
    - o The standardized track/vortex parameter files should be disseminated in real-time via the GTS, facilitating their use by forecast centers. Training material on how to read in the standardized files should be made available to forecast centers, along with instructions on how to access the GTS for those centers who do not currently access data in this way.
- Once the standard format data is being transferred reliably for operational use, we recommend the data also be collected centrally for use in research, ideally at the NCAR Research Data Archive where the existing TIGGE CXML archive is hosted. If the selected format is not practical for the research community (e.g., BUFR format), the data could be decoded into format(s) that are familiar to the research community, such as netCDF, with software (including python code) made available to read in these tracks. Uptake of the CXML data has been hampered by inconsistent structure/labeling and a lack of python decoding software, so once in place, this new archive could replace the TIGGE CXML data.
- The standardized TC forecast track/vortex parameter data from forecast centers should include pre-genesis tracks in addition to post-genesis tracks. A consistent naming format for pre-genesis storms should be applied and will require coordination amongst forecast centers to agree on a standardized approach, ideally facilitated by WMO.

5. Summary

The WMO/WWRP Tropical Cyclone-Probabilistic Forecast Products (TC-PFP) effort is a WMO Seamless GDPFS Pilot Project established in response to recommendations from the 2018 IWTC-9 in Hawaii. The main goal of TC-PFP is to coordinate across RSMCs, TCWCs, and other forecast centers (i.e., forecast centers) to help identify best practice guidance for probabilistic tropical cyclone (TC) forecasts incorporating a value cycle approach. TC-PFP is being implemented in 3 phases: Phase 1 (TC formation and position) began in 2020; Phase 2 (TC intensity and structure) will begin in 2023; and Phase 3 (rainfall and storm surge) will start in 2024. Phase 1 included several efforts:

- A survey of RSMCs, TCWCs, and forecast centers to find out about their current efforts and future plans to produce probabilistic TC forecasts, and their various forecast challenges (March–May 2021).
- A WMO-sponsored 3-day virtual workshop focused on identifying best practice guidance for probabilistic forecasts of TC position (including TC formation). Over 100 participants from 16 countries and 14 different time zones attended from forecast centers, NWP centers, research centers, the private sector, and humanitarian organizations (June 15, 17–18, 2021).
- Creation of writing teams including workshop participants to write up the workshop findings and formulate

recommendations for how to improve probabilistic TC forecasts (Aug 2021–Oct 2022).

- A sub-project commissioned to fill a knowledge gap identified in the workshop by quantifying the uncertainty in track position associated with the tracking algorithm used (see Section 3.1.2).
- A specific questionnaire to TC RSMCs and TCWCs on the current status of their access to ensemble TC track data to support their operations (May–June 2022).
- Presenting a project summary of TC-PFP Phase 1 efforts at the 2022 IWTC-10 (Dec 2022).

The TC-PFP Phase 1 efforts described here reveal that many forecast centers are independently developing and advancing techniques for probabilistic forecasts of TC formation and position. Although each center has specific stakeholder needs, they share many common challenges, and there is a definite need to ensure more regular and specific communication between centers to pool their scientific research regarding optimal methods to exploit the benefits of ensemble forecasts in operational TC formation and position forecasts. Similarly, greater coordination of interdisciplinary research and approaches for interacting with end users to optimize product design and communication would be beneficial. This should be an ongoing process that WMO could help steward and would help alleviate the tendency for increasing divergence in approaches and techniques between centers over time. TC-PFP found that many forecast centers are not able to effectively utilize model ensemble information because they cannot access and use the data easily, with multiple data formats and delivery mechanisms hindering progress. Therefore, a clear need was identified for ensemble TC position data to be made available in a timely, stable, and consistent format to enable the pull-through of multi-model ensemble track forecasts into operational TC forecasts. The recommendations from Phase 1 of the TC-PFP project, presented at IWTC-10, include 3 main topic areas: 1) current and planned probabilistic forecast products (Sec. 1.3); 2) Understanding and communicating probabilistic forecasts (Sec. 2.3); and 3) Resources for producing probabilistic forecasts (Sec. 3.3). Phase 2 of the TC-PFP effort will build from the Phase 1 efforts with the goal of working with forecast centers to identify best practices of a value-cycle approach to probabilistic forecasts of TC intensity and structure.

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Appendix A.

Table 1
Probabilistic tropical cyclone formation (genesis) guidance produced by various operational centers. (Note: AOR is the Area of responsibility).

Probabilistic TC Formation Outlooks (Operational Centers)				
Agency	Short-range outlook (<1 week): Product type	Short-range outlook: Forecast period	Long-range outlook (≥1 week): Product type	Long-range outlook: Forecast period
RSMC Tokyo	AOR-scale graphical outlooks (maps) based on JMA, ECMWF, NCEP and UK Met Office ensembles Thresholds: Contours at 10 % intervals Not publicly available	2 and 5 days	N/A	N/A
TCWC Jakarta	Prospek Pertumbuhan Siklon Tropis bulletin (AOR-scale; text-based) Thresholds: <10 % Unlikely 20–50 % Medium >50 Likely Publicly available	3 days	N/A	N/A

(continued on next page)

Table 1 (*continued*)

Probabilistic TC Formation Outlooks (Operational Centers)

Agency	Short-range outlook (<1 week): Product type	Short-range outlook: Forecast period	Long-range outlook (≥1 week): Product type	Long-range outlook: Forecast period
Australia BoM TCWC	Regional TC outlook (AOR-scale; text- based) Thresholds: <5 % Very low 5–20 % Low 20–50 % Moderate >50 High Publicly available	3 days	TC 7 Day Outlook (graphic with text discussion accompanying each identified area) Thresholds: <5 % Very low 5–20 % Low 20–50 % Moderate >50 High Not publicly available	7 days
RSMC Miami **RSMC Honolulu**	Two-day and Five-day Tropical Weather Outlooks (AOR-scale; graphic and text with discussion of each identified area) Thresholds: <40 % Low 40–60 % Medium >60 % High Publicly available	2 days	N/A	N/A
RSMC New Delhi	Regional TC outlook for Bay of Bengal and Arabian Sea (AOR-scale; text-based with accompanying satellite graphic) Thresholds: Nil - 0 % Low - 1–33 % Moderate - 33–66 % High - 67–100 % Publicly available	5 days	North Indian Ocean Extended Range Outlook for Cyclogenesis (text- based with accompanying graphic) Thresholds: Low - 1–33 % Moderate - 33–67 % High - 68–100 % Publicly available	2 weeks
RSMC La Reunion	Bulletin for Cyclonic Activity and Significant Tropical Weather in the Southwest Indian Ocean (AOR-scale; text-based and map graphic) Text bulletin thresholds: Very low: <10 % Low: 10%–30 % Moderate: 30–60 % High: 60–90 % Very high: >90 % Graphic thresholds: Low - <33 % Moderate - 30–60 % High - >60 % Publicly available	2 and 5 days	N/A	N/A
RSMC Nadi	TC 5-Days Outlook (AOR-scale; text-based) Thresholds: Unknown Publicly available	5 days	N/A	N/A
TCWC Wellington	Tropical cyclone potential bulletin for Coral Sea/S. Pacific Text based, published on website and as a tailored briefing for clients Short discussion using thresholds for development (very low, low, mod, high) Longer technical discussion also disseminated locally. Verifications assessed internally	7 days (Day 1–5 published)	Long range TC potential outlook Text based, internal only, uses thresholds for development (very low, low, mod, high), with technical discussion Verifications and performance assessed internally Not publicly available	4 weeks
JTWC	Significant Tropical Weather Advisories (AOR-scale; text based with accompanying satellite graphic) Thresholds: Low Medium High (no percentage) Publicly available	24 h	2-week TC Formation Outlooks (graphical) Thresholds: <40 % Low 40–60 % Medium >60 % High Not publicly available	2 weeks

(*continued on next page*)

Table 1 (*continued*)

Probabilistic TC Formation Outlooks (Operational Centers)

Agency	Short-range outlook (<1 week): Product type	Short-range outlook: Forecast period	Long-range outlook (≥1 week): Product type	Long-range outlook: Forecast period
PAGASA	See long-range outlook info	See long-range outlook info	Tropical Cyclone (TC)-Threat Potential (AOR-scale combined text and map graphic) Thresholds: Low Moderate High Active TC (no percentage) Publicly available	Week 1 and Week 2
Météo-France New Caledonia	See long-range outlook info	See long-range outlook info	Statistical forecast of weekly cyclone activity in the Southern Hemisphere (hemisphere-wide; graphical maps) Thresholds: Shaded contours at 5 % intervals Publicly available	Week 1, Week 2, and Week 3
US Climate Prediction Center	N/A	N/A	Global Tropics Hazards Outlook (global; combined text and map graphic) Thresholds: Shaded contours at 20 % intervals: >20 % >40 % >60 % Publicly available	Week 2
CMA	Unknown	Unknown	Unknown	Unknown

Table 2
Techniques applied by operational forecast centers to generate probabilistic TC position forecast guidance.

AGENCY	FORECAST LENGTH -FREQUENCY	REPRESENTATION OF UNCERTAINTY (% of cases expected to stay within this)	SITUATION-DEPENDENT (SD) OR HISTORICAL ERROR BASED (HE)
RSMC Tokyo	5d - 3 hrly	Circle (70 %)	HE (0–72h), SD (96+hr)
RSMC Honolulu	5d - 6 hrly	Cone (67 %)	HE
RSMC La Reunion	5d - 6 hrly	Cone (75 %)	HE & SD
RSMC Miami	5d - 6 hrly (public) 7d - 6 hrly (internally) (more frequently if needed)	Cone (67 %)	HE
RSMC New Delhi	5d–6 hrly (more frequently if needed)	Cone (72 %)	HE
TCWC Jakarta	3d - 6 or 12 hrly	Cone (80 %)	SD
TCWC Perth	7d - 1, 3, or 6 hrly	Cone	SD
TCWC Wellington	1d–6 hrly 5d if threatening NZ	Cone (70 %)	SD
JTWC	5d - 6 hrly	Error Swath	HE & SD
PAGASA	5d - 6 hrly	Cone/Circle (70 %)	HE
Thai Met. Department	3d - 3, 6, or 12 hrly	Cone	HE
MetMalaysia	7d–3 hrly	Circle (80 %)	Not given
Météo-France New Caledonia	3d–6 hrly	Cone (75 %)	HE & SD
Météo-France Martinique	5d - 6 hrly	Cone (66 %)	HE
Hong Kong Observatory	5d - 24 hrly	Cone/Circle (70 %)	HE
CHC	5d - 6 hrly	Cone (70 %)	HE

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