6B.4 An Improved Methodology for Expressing and Communicating Tropical Cyclone Risk

Derek Ortt
StormGeo Inc, Houston, Texas

1. INTRODUCTION

Tropical cyclone (TC) forecasts are subject to uncertainty, despite decreasing errors in both the track and intensity forecasts during recent years (Cangialosi and Franklin 2016). One of the most important aspects in communicating a TC forecast is to communicate the level of uncertainty of that forecast. Understanding the level of uncertainty with regards to the TC forecast is essential for both offshore and onshore users of the forecast. Many actions need to be taken several days in advance. Knowing the level of risk for a given location is vital for making the proper preparation actions to protect life and property.

The most well-known way to communicate the forecast uncertainty is through the "cone of uncertainty", which is used for both National Hurricane Center and StormGeo TC forecasts. The cone is created by creating a circle around the forecast position. The radius of this circle is denoted by the 67th percentile of forecast errors for the given time period from all forecasts from the last 5 years. for the National Hurricane Center (Cangialosi and Franklin, 2016), while StormGeo uses the 75th percentile to create its cone.

There are several drawbacks to the "cone of uncertainty". The first is that many users of the cone do not understand what it is conveying (Broad et al. 2007). Users often believe that the cone is the area in which the models say the TC will move, or that is the area that the impacts will be confined to. A second drawback is that the cone is always the same size, implying that every forecast has the same amount of uncertainty. A third drawback is that it does not provide any quantitative information as to the increasing or decreasing threat to a location. A fourth drawback is that only one possible track can be depicted. There are occasions where the models indicate that a storm will move one way or another, with little chance of going between the possibilities. This bifurcation cannot be depicted by the current cone.

One method to estimate and communicate the TC forecast uncertainty is to use ensembles. Ensembles are variations of a model run with slightly different initial conditions (Lieth, 1974). Several runs of the same model with different initial conditions produces different forecast because the observations used to initialize the forecasts are subject to error (Lorenz, 1963). This is especially true over the open oceans where TCs reside. A second method of generating ensembles is to use different model physics paramaterizations (Stensrud et al. 2000) to represent sub grid scale processes. Probabilistic forecasts can be generated from the different ensemble forecasts. This is the case for TCs as different forecast tracks are generated by the different ensemble members.

Ortt et al (2017) created probabilistic forecasts from a limited set of storms from the 2016 Atlantic and East Pacific hurricane seasons using a multi-model ensemble consisting of the CMC, GFS, and ECMWF ensembles. In addition, a verification of the probabilistic forecasts was provided. That study verified the forecasts by determining the percentage of TCs that remained entirely within an area where the TC had at least a 5,

Corresponding author address: Derek Ortt, StormGeo Inc., 12650 N. Featherwood Dr. Ste. 140. Houston, TX 77034; e-mail: derek.ortt@stormgeo.com

10, 15, 20, and 25 percent chance of passing within 200km of a given point over the course of a 5-day forecast. It was shown that for the limited sample that the TCs remained entirely within the area having at least 20% chance of passing within 200km of a given location 71% of the time, which is slightly more than the 67% threshold used to create the NHC “cone of uncertainty”.

This study will further the results from Ortt et al. (2017) and will verify all TC forecasts from the same CMC/GFS/ECMWF multi-model ensemble from the 2017 Atlantic and East Pacific hurricane season. The aim is to confirm the preliminary results shown in Ortt et al (2017) to better determine if an ensemble based probability swath is a better method of communicating TC risk than the current “cone of uncertainty”. The study will also seek to address another of the short comings of the current cone, that being a lack of quantitative information regarding the increasing and decreasing threat to a given location. This study will evaluate site specific probabilities from the same multi-model ensemble previously used to determine if and how the ensembles can be used to quantify an increasing or decreasing risk at a given location.

2. DATA AND METHOD

This study closely follows the same method and uses the same data as did the Ortt et al. 2017 study. The ensemble data used for this study consists of ensembles from the National Center of Environmental Prediction (NCEP) Global Forecast System (GFS), the Canadian Meteorological Center (CMC) and European Center for Medium-Range Weather Forecasting (ECMWF) global models. The GFS global model is produced four times a day at 0000, 0600, 1200, and 1800 UTC synoptic times. The CMC and ECMWF ensembles are produced twice-daily at 0000 and 1200 UTC. The GFS and CMC ensembles each have 20 members plus the operational deterministic model. The ECMWF ensemble has 50 members, plus the operational deterministic model, as well as an ensemble control model. The ensemble control model is the same as the operational deterministic model except that it is run at the same lower horizontal resolution as are the ensemble members.

For this study, all ensemble members from the 3 ensembles were combined into a multi-model ensemble with 94 members. Each of the tracks from the 94 members is weighted equally. The ensemble TC tracks were mapped on to a horizontal grid that has a horizontal resolution of .25^{o} in both the longitudinal and latitudinal directions. Probabilities were then calculated for the TC passing within 200km of a given location. The 200km value was used as this often corresponds with a proximity to the center that will result in tropical storm-force winds. The probabilities were calculated four times daily. Because the ensembles arrived well after the synoptic times, hours 12 to 132 were used instead of hours 0 to 120. This is to allow for the ensembles to be used in forecast mode. Since the 0600 and 1800 UTC times only contain updated GFS ensemble tracks, hours 18 to 138 were used for the CMC and ECMWF ensemble members. Hours 12-132 were still used for the 0600 and 1800 UTC GFS ensembles. This is to allow for four estimations of the forecast uncertainty to be made daily. Times were excluded if all 3 ensembles were not available in real time. In addition, the TC had to be a TC continuously from the 0-132 hour time period to be included in this study.

The track forecast probabilities were then verified for all TCs that could be evaluated from the 2017 Atlantic and East Pacific hurricane seasons. There were 120 forecasts included for the Atlantic hurricane season and 54 for the East Pacific hurricane season. The probabilistic forecasts were verified by calculating the percentage of tracks that remained within certain probabilistic thresholds. This study evaluated the probability that the TC did not track outside of the 5, 10, 15, 20, and 25 percent regions. In addition to the 2017 Atlantic and East Pacific TCs, this study used the same ensemble set up for Typhoon Hagupit in 2014. Ensemble data from a forecast is used for demonstration purposes. However, the Hagupit forecast is not included in the verification.

To evaluate whether or not the multi-model ensemble can be used to quantitatively determine an increasing or decreasing threat at a given location, we will evaluate the site specific multi-model ensemble probabilities for various sites along the United States East Coast, including the Florida Peninsula, as well as the eastern Florida Panhandle from Hurricanes Irma and Maria. The probabilities will be evaluated over a period of 168 hours prior to the TCs making their closest approach to the given locations. Those sites that were within 200km of the center of the TC will be considered to have been hit by the TC, while those farther than 200km from the center will be considered to have been missed by the TC. Composite probabilities will be calculated for locations hit by the TC and those missed by the TC to determine if there is any quantitative information from the multi-model ensembles as to an increasing or decreasing threat for a given location.

3. RESULTS

a) 2017 Atlantic and East Pacific Hurricane Seasons

Probabilistic Multi-model ensemble forecasts from the 2017 Atlantic and East Pacific hurricanes were shown to depict the forecast uncertainty to at least a comparable level as is depicted by the "cone of uncertainty". This is demonstrated by the probabilistic forecasts issued during Hurricane Irma as it approached the Caribbean and Florida. Irma was a powerful category 5 hurricane that impacted the northeast Leeward and Virgin Islands before striking the Florida Keys as a category 4 hurricane (Cangialosi et al. 2018). The probabilistic forecast initialized with the 1200 UTC September 3 ensembles indicated that the most likely path of Irma was near or over the northeast Leeward and Virgin Islands, followed by a track into the southeast Bahamas, posing a threat to the Florida Peninsula. Irma generally moved along the southern edge of the 90 to 100% probability region until it reached the southeast Bahamas, when it moved along the southern edge of the probability swath, toward Cuba. The ensembles indicated as soon as September 3 that there was a chance of impacts to Cuba from Irma. As Irma approached the Leeward Islands, the ensemble probabilities initialized at 0600 UTC September 6 indicated a high chance of Irma moving near northern Cuba. They also indicated that the most likely area to be impacted in Florida would be the Florida Keys. Irma in fact impacted both of these areas directly. Figure 1 shows these two probabilistic forecasts for Hurricane Irma.

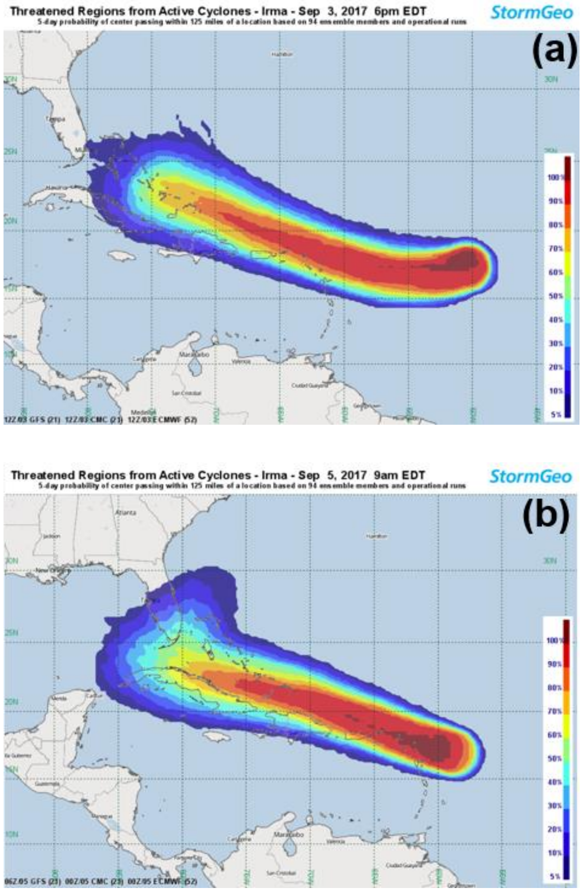

Figure 1: Probabilistic multi-model ensemble forecasts for Hurricane Irma initialized at 1200 UTC Sep 3 (a) and 0600 UTC Sep 6 (b).

Later in the month of September, the multi-model ensemble produced probabilistic forecasts for Hurricane Maria. As Maria was approaching the eastern Caribbean, the forecast initialized at 1800 UTC September 16 indicated a 90 to 100 percent chance that it would pass near Dominica and Puerto Rico, which verified. Thereafter, Maria moved a little north of the area containing the highest probabilities, but well within the probability swath. Several days later, Maria was approaching the East Coast of the United States. There was a high level of uncertainty as to if the system would directly impact or remain east of the Outer Banks of North Carolina. The multi-model ensemble forecast initialized at 0600 UTC September 22 indicated that the most likely path for Maria was to remain east of the Outer Banks of North Carolina. The ensemble also indicated that the forecast uncertainty was higher than when the system was located to the east of the Caribbean. That can be determined by the fact that the probability swath is larger when the system is north of Hispañiola than when it was east of the islands. Figure 2 shows these two probabilistic forecasts.

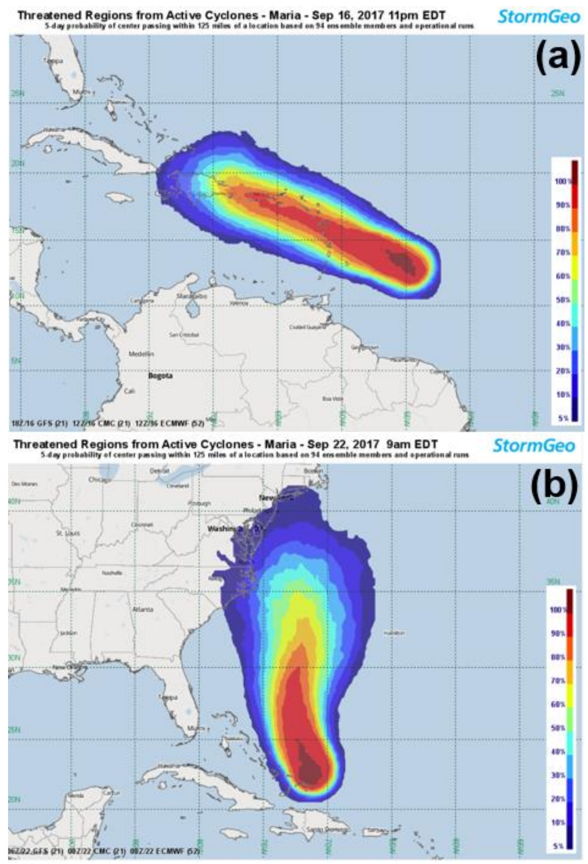

Figure 2: Probabilistic multi-model ensemble forecasts for Hurricane Maria initialized at 0600 UTC Sep 16 (a) and 0600 UTC Sep 22 (b).

To determine if this multi-model approach can work to supplement or even replace the "cone of uncertainty", verification of probabilistic forecasts over a much larger sample size is required. Therefore, all forecasts for the 2017 Atlantic and East Pacific hurricane seasons are verified. The results of this verification are shown in

Figure 3. For both the Atlantic and East Pacific, the TC remains within the 20 percent swath more than the 67 percent of the time depicted by the NHC "cone of uncertainty". These results are very similar to those from Ortt et al. 2017, suggesting that the 20 percent threshold from the multi-model ensemble can be used as a supplement, if not a replacement to the "cone of uncertainty.

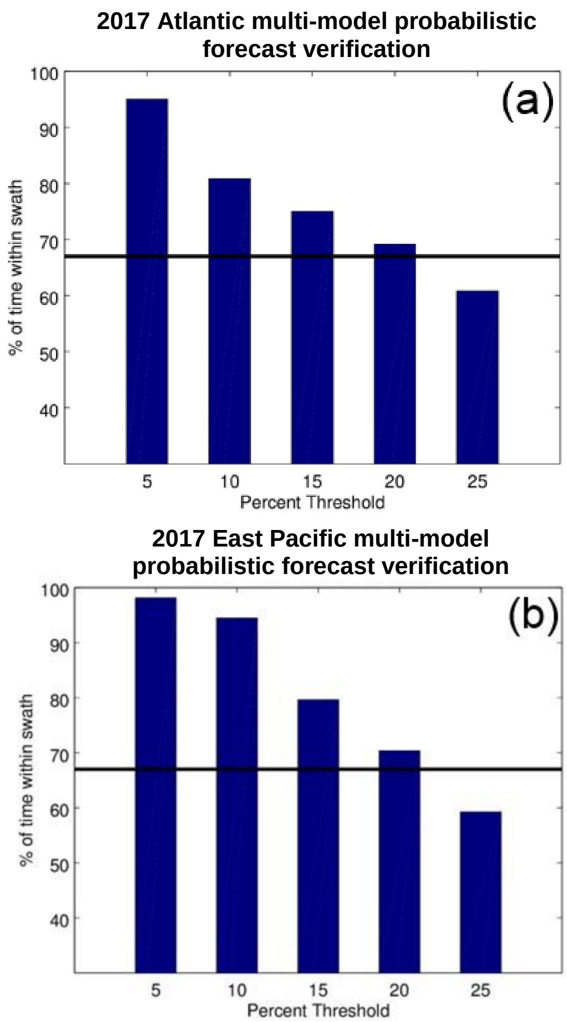

Figure 3: Verification of multi-model ensemble probabilistic forecasts for the 2017 Atlantic (a) and EPAC (b) hurricane seasons. The black line denotes the 67% level depicted by the "cone of uncertainty".

b) Typhoon Hagupit (2014)

Another benefit of a multi-model ensemble probability swath over the traditional cone is that multiple paths can be depicted. Typhoon Hagupit was one such case. Hagupit was a powerful typhoon that struck the Philippines in December of 2014. When it was east of the Philippines, models indicated two possible paths for the system. The first possibility was a track through the southern Philippines. The second was a turn to the northeast several hundred km east of the Philippines. Since the traditional cone is constructed by a circle around the deterministic forecast point, it cannot show multiple possible paths. Thus, it cannot depict the forecast uncertainty in the case where there are multiple possible tracks. Figure 4 demonstrates this using a forecast with a traditional cone from 0900 UTC, December 4, 2014 and a corresponding multi-model ensemble probabilistic forecast. The traditional cone was only able to depict a path toward the Philippines. The traditional cone includes the northern parts of Luzon. The probabilistic multi-model ensemble forecast indicates a very low chance of the system moving toward northern Luzon. Instead, there are the two likely paths previously mentioned. Hagupit followed the northern parts of the southern probability maxima into the southern Philippines. This example shows the second benefit of a probabilistic forecast compared to the traditional cone: the ability to depict multiple tracks, along with quantifying which of the tracks is more likely to occur. The same can be said for areas being at risk outside of the current cone. In 2012, Tropical Storm Debby was initially forecast both by StormGeo and the National Hurricane Center to move into Texas. However, there was always a chance that it could also move to the northeast toward Florida. The risk had to be conveyed in the text portion of the advisories. Debby ultimately did take the northeast option and move toward Florida. This would have been conveyed by a multi-model ensemble, while it was not conveyed by the operational cone.

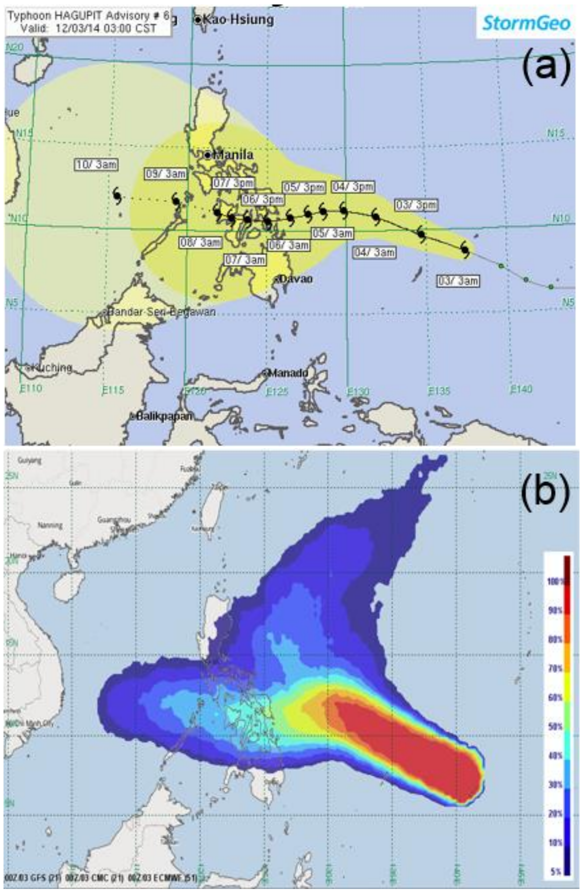

Figure 4: Traditional cone (a) and multi-model ensemble probabilistic forecast for Typhoon Hagupit from 0900 UTC, December 4, 2014.

c) Site Specific Probabilities

The third benefit of using ensemble probabilities to convey the TC risk instead of the current operational methods is that an objective estimate of the threat level can be provided for given locations. To demonstrate this, a comparison of site specific probabilities from the multi-model ensemble for Hurricane Irma from locations that were within 200 km of the center and those that remained more than 200km from the center will be presented. The probabilities from the following cities that were hit by Irma and were used for this example are: Melbourne, West Palm Beach, Miami, Key West, Ft. Myers, Clearwater, and Apalachicola. The probabilities from the cities used in this example were missed by Irma are: Savannah, Charleston, Myrtle Beach, Wilmington, and Cape Hatteras. These cities were selected as early on in Irma's evolution, some of the ensembles indicated a significant threat to these locations. The comparison is made for a period of 7 days prior to the closest approach. Composite time series of probability were created for the hits and misses respectively. These results are shown in Figure 5.

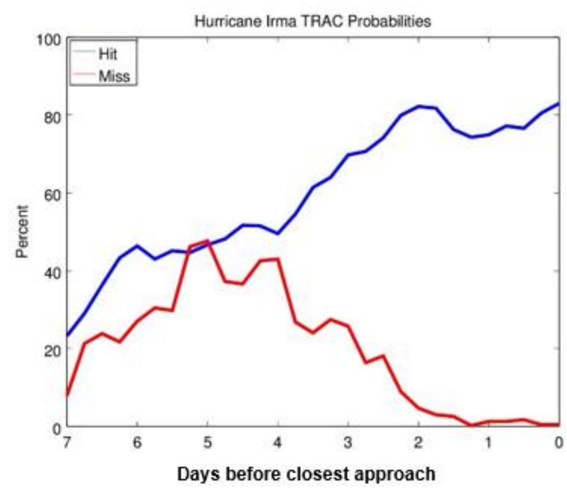

Figure 5: Composite probabilities for cities where Irma passed within 200km (red, hit) and those where Irma remained more than 200km away (blue, miss) for a period of 7 days prior to the closest approach to the given city.

While the multi-model ensemble probabilities for those cities that were ultimately hit by Irma were generally higher than those where Irma missed for the entire period, the probability of those that are hit is not more than about 10-15 percent higher. The difference begins to manifest itself inside of 96 hours. This is where the probability of passing within 200km continues to increase for those cities that were hit by Irma. The probability starts to decrease significantly for those cities that were missed by Irma. In the case of Maria, there was a similar probability signal for selected cities in the NE Bahamas and along the US East coast that Maria threatened but did not hit. Probabilities increased until about 72-96 hours prior to the closest approach. After this time, the multi-model ensemble probabilities decreased. These results suggest that 72-96 hours is the critical time in determining if an area experience a TC passing within 200km or if the TC will remain farther away.

4. DISCUSSION

A multi-model ensemble can be used to convey the risk posed by a TC to a given location. It overcomes some of the short comings of the current techniques, such as the “cone of uncertainty” in that it provides a range of solutions based upon the current atmospheric flow. In addition, it allows for multiple tracks to be depicted, better conveying the risk in cases where there is a bifurcation signal in the ensembles. This is important as areas that may be deemed at risk based upon the current methods, may have a very small risk, such was the case for northern Luzon in Typhoon Hagupit. In addition, areas that the current operational cone indicate are not at risk, may have a significant risk as was the case with Tropical Storm Debby. Verification from the 2017 Atlantic and EPAC verifications confirmed results from Ortt et al. (2017) that a multi-model ensemble accurately shows the range of possibilities as TCs remain entirely within the area with at least a 20 percent chance of the TC passing within 200km of a given point ~70 percent of the time, which is more than the 67% goal aimed for by the NHC operational cone.

In addition to replacing the cone, a multi-model ensemble can be used to determine if the threat from a TC is increasing or decreasing at a given location. Results from Irma and Maria from the 2017 Atlantic hurricane season indicated that it is 72-96 hours before the closest approach to a given location is key to determine if a TC will hit or miss a given location. The multi model ensemble probability of the TC passing within 200km starts to decrease for those sites that are ultimately missed 72-96 hours prior to the closest approach. The probabilities continue to increase for those sites that are hit by the TC.

5. ACKNOWLEDGEMENTS

The author would like to thank Devin Eyre for making many of the figures contained in this study, as well as providing the site-specific probability of passing within 200km data. The author would also like to thank Chris Hebert for many helpful discussions during the course of this study.

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