

Enhanced Visualization of Low Probability Trajectories

Proceedings of the Human Factors and
Ergonomics Society Annual Meeting
1–6

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DOI: 10.1177/10711813261493611
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Abstract

Forecast paths for hurricanes are commonly communicated through Cone of Uncertainty (COU) visualizations. An alternative visualization, animated risk trajectories (ARTs), uses dynamic ensembles of instances to convey an array of possible future tracks. Four experiments with simplified scenarios explored how surprising or misleading each form of visualization was for outcomes beyond the most likely forecast path, using participants with little direct experience (Colorado-based participants) versus more familiarity with hurricane risk and forecasts (Florida-based participants). For subsequent landfalls at locations farther from the central projected path, all participant types felt less misled when viewing ARTs rather than COUs. While Colorado-based participants reported less surprise when viewing discrepant outcomes following ARTs, Florida-based participants found deviant outcomes surprising regardless of the visualization used. Results suggest ARTs may help people better understand uncertainty when singular “most likely path” forecasts are wrong, although those expected to have greater experience may benefit less.

Keywords

visualization, uncertainty, decision making

Introduction

Weather forecasts inherently incorporate some degree of uncertainty that needs to be conveyed. For hurricane forecasts, uncertain future forecast paths are most commonly communicated to the public via a product known as the Cone of Uncertainty (COU). Although iteratively updated over the years, the general COU design leads to some well-known misperceptions (see, Boone et al., 2018; Broad et al. 2007; Ruginski et al., 2016; Witt & Clegg, 2022) and specifically, a bias called the containment effect (see Padilla et al., 2018). The containment effect is the bias that creates a tendency to perceive that only areas within the cone as being at risk and areas beyond the cone as not being at risk. The containment effect suggests people will not expect hurricane paths to occur outside the cone, even though the cone only illustrates two thirds of likely future paths and relies on historical error data without considering the level of uncertainty in the projection of the current storm's trajectory. Although there is a reasonable possibility of variations from the predicted path, the use of visualizations like the COU might imply to viewers that there is very little chance of that happening.

Accentuating this effect, people can be inclined to systematically underestimate the likelihood and impact of low probability events (Taleb, 2008). Indeed, while so-called black swan events might be regarded as essentially impossible,

real-world situations with fat-tailed distributions rather than Gaussian distributions may make such situations less improbable. One additional factor that influences the impact of our sense of low probability events is our reliance on experiences versus the description of probabilities provided (see, e.g., Hertwig et al., 2004). However, in the case of hurricane forecasts, those with more experience in real-world settings may have encountered situations in which storm paths went outside an earlier forecasted cone. Hence, the interpretation of the cone for those more familiar with hurricane forecasts may differ from the likelihood suggested by the properties of the visualization alone.

We developed a new hurricane forecast visualization, called animated risk trajectories (ARTs; see Witt & Clegg, 2022; Witt et al., 2023), which has shown that in-the-moment decisions for an incoming hurricane are not biased by the containment effect. Decisions about whether to evacuate

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follow a more gradual decrease as a function of distance to the predicted storm path, rather than a steep drop-off at the boundary of 2/3 predicted storm paths (which corresponds the edge of the cone). More nuanced decisions, such as whether to evacuate or engage in preparations such as boarding windows and storing goods like water, also become better calibrated decisions according to proximity to the projected path of the storm. These studies show ARTs lead to better in-the-moment decisions.

Another issue with the COU is that the high expectation that the storm will make landfall in an area within the cone means a higher rate of false alarms (or the cry wolf effect). This could lead to higher levels of distrust of future forecasts, which then could lead to people not using the forecasts to make appropriate decisions such as to evacuate or prepare for hurricanes (e.g., LeClerc & Joslyn, 2015). Thus, to complement our prior work on in-the-moment decisions, we extend the comparison of COU to ARTs by testing whether people have better understanding of incorrect forecasts with the ARTs compared to COUs. If so, they should be less surprised and judge forecasts as being less misleading than when hurricanes make landfall outside the boundaries of the COU. Additionally, we compared two populations with different levels of probable hurricane forecast exposure to evaluate whether familiarity impacts comprehension of hurricane tracks. Across four experiments, we measured reactions to storm forecasts and storm outcomes. In doing so, we tested the impact of ARTs on after-the-fact reactions.

General Method

A similar method was used across all four experiments. The details are described here. Note that stimuli, data, analysis scripts, and a link to experience what it was like for a participant can be found here: <https://osf.io/n5ua3/overview>

Participants

Participants were recruited from universities in Colorado (Experiments 1 and 3) and Florida (Experiments 2 and 4). They received course credit in exchange for their participation.

Stimuli

The stimuli were visual displays of hypothetical hurricane forecasts. The display was presented as a Cone of Uncertainty (COU) or as animated risk trajectories (ARTs; see Figure 1). The hypothetical forecasts were created by manipulating the storm angle (70, 90, or 110°), the level of uncertainty (low or high), and the location of a town, which had an angular deviation from the storm angle between 21 and 148°. The storm angles were chosen so the storm would hit along the visible coastline, which was in the Gulf region. The level of

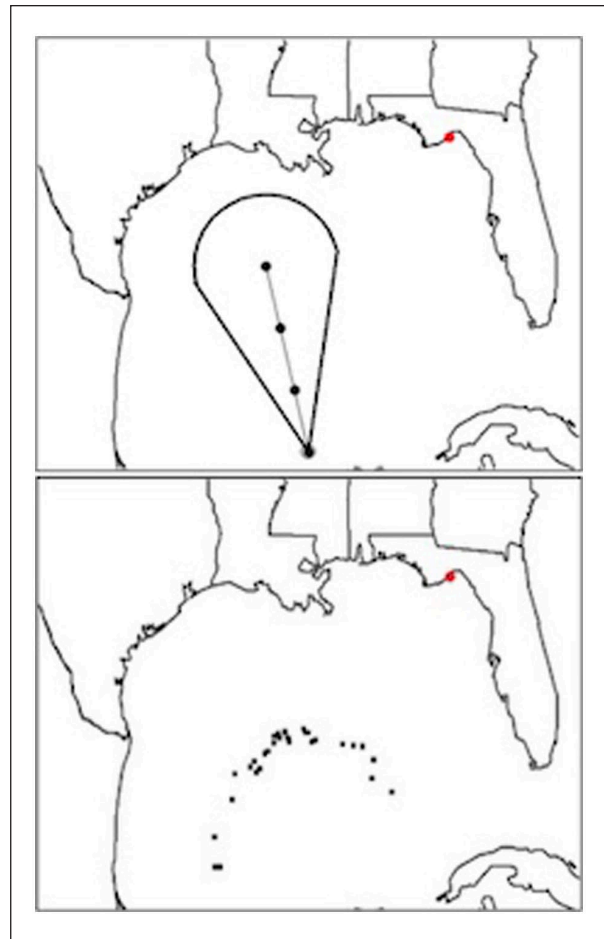


Figure 1. COUs (top) versus a static image from the ARTs (bottom) stimuli (black circles). The cued location is shown as a red circle along the coast.

Note. This is a static image screenshot of the ARTs, which were presented as an animated GIF.

uncertainty dictated the width of the COU, which is normally set based on historical errors in forecasts averaged over the past 5 years, but in our hypothetical scenarios, was instead set to be narrow (low uncertainty) or wide (high uncertainty). The ARTs were created by having 30 icons traveling along 30 angles. This animation was played on repeat until participants made their rating. The angles were sampled from a normal distribution with the mean set to the storm angle and the standard deviation set to 20 or 30°. Altogether, there were 96 forecasts (3 town angles $\times$ 2 levels of uncertainty $\times$ 16 town positions). Each forecast was paired with each of 3 possible outcomes of the damage (none, minor, catastrophic) for a total of 288 possible stimuli.

Procedure

Participants completed the survey online via Qualtrics. They were given these instructions:

- Imagine it's hurricane season (June–November).
- You will be shown a town along the Gulf region that will be marked as a red circle.
- You will be told the outcome of a hurricane event. The possible outcomes are:
 1. The hurricane did not pass over the town so there was **no damage**.
 2. A Category 1 hurricane hit the town and caused some damage, which may have included **minor damage** to roofs, shingles, vinyl siding, and gutters for well-constructed frame homes
 3. A Category 4 hurricane hit the town and **catastrophic damage** occurred in the town, which may have included severe damage to roof structures and exterior walls for well-built framed homes
- You will then see a weather forecast showing the projected path of the hurricane from 3 days ago.
- Your task is to rate the forecast.

Prior to the block of trials that showed the COUs, participants were given these instructions that included the standard warning provided with such visualizations:

The forecast will display a cone that shows the predictions of the hurricane's path. The cone shows the probable path of the storm center but does not show the size of the storm. Hazardous conditions can occur outside of the cone.

Prior to the block of trials that showed the ARTs, participants were given these instructions:

You will see several predicted hurricane paths, each presented as a dot. These dots show the probable path of the storm center. Hazardous conditions can occur outside of these paths.

On each trial, participants were shown a forecast and told that forecast was from 3 days ago. They were also told the outcome of the storm. We presented three possible outcomes indicated above: *none*, *minor*, or *catastrophic*. Upon seeing the forecast and the outcome, participants rated their reaction depending on experiment of either 0 (not at all surprising) to 100 (very surprising) or 0 (not at all misleading) to 100 (very misleading) by moving a slider. Participants rated their surprise in Experiments 1 to 2 and how misleading they found the forecast in Experiments 3 to 4. The forecast was displayed until participants completed their rating.

Participants completed 120 trials with ARTs and 120 trials with COUs. Which condition was shown first was randomized. Presentation order was randomized.

Data Analysis

The experiment was done via an online survey, so there was no oversight to determine whether participants were focused on the task. Because there are no correct answers given our

dependent measure, we evaluated outliers based on the one objective measure we had: the time they spent on the task. Outliers were deemed as participants whose duration on the experiment was beyond 1.5 times the interquartile range. The main analysis was a linear mixed model. The dependent measure was their rating of surprise or misleading. The fixed effects were town location, condition (COU or ART), and their interaction. The random effect was participant ID. The key outcome was the interaction between the condition and town location because this highlights how distance from the center of the forecast impacts the perception of the outcome.

Results

Experiment 1: Colorado and Misleading

There were 89 participants, and 6 were identified as outliers. Participants were recruited from a university in Colorado, and this population has been shown previously to have little familiarity with hurricane forecasts (see Witt et al., 2021). We ran a linear mixed model. The dependent measure was the extent to which the forecast was rated as being misleading. The interaction was significant, estimate=0.07, $SE=0.02$, $t=3.37$, $p<.001$ (see Figure 2 top-right panel). When hurricanes made landfall at locations farther from the center of the forecast track, people found the forecast less misleading when the forecast was shown with ARTs than COU. The visualizations present the same information underlying the forecast, so objectively neither is more misleading. Yet participants found the presentation with ARTs to be less misleading.

Experiment 2: Florida and Misleading

Next, we tested whether a population more familiar with hurricanes (recruited from a university in Florida currently living in the Gulf region) would also have a better understanding of uncertainty in hurricane forecasts with ARTs than with COU. There were 61 participants recruited from a university in Florida for this study, and 9 were considered outliers. The interaction between town location and condition was significant, estimate=0.09, $SE=0.03$, $t=2.74$, $p<.001$ (see Figure 2, top-left panel). Participants again found forecasts to be less misleading with ARTs than COU when the hurricane made landfall at further locations.

Experiment 3: Colorado and Surprising

We then ran a near-identical experiment but instead of asking participants to rate their impression of how misleading the forecast was, we asked them to rate their surprise. There were 87 participants recruited from Colorado. We found and eliminated 5 outliers. The interaction between town location and condition was significant, estimate=0.04, $SE=0.02$, $t=2.1$, $p=.04$. When storms made landfall further from the central predicted location, people found forecasts to be less

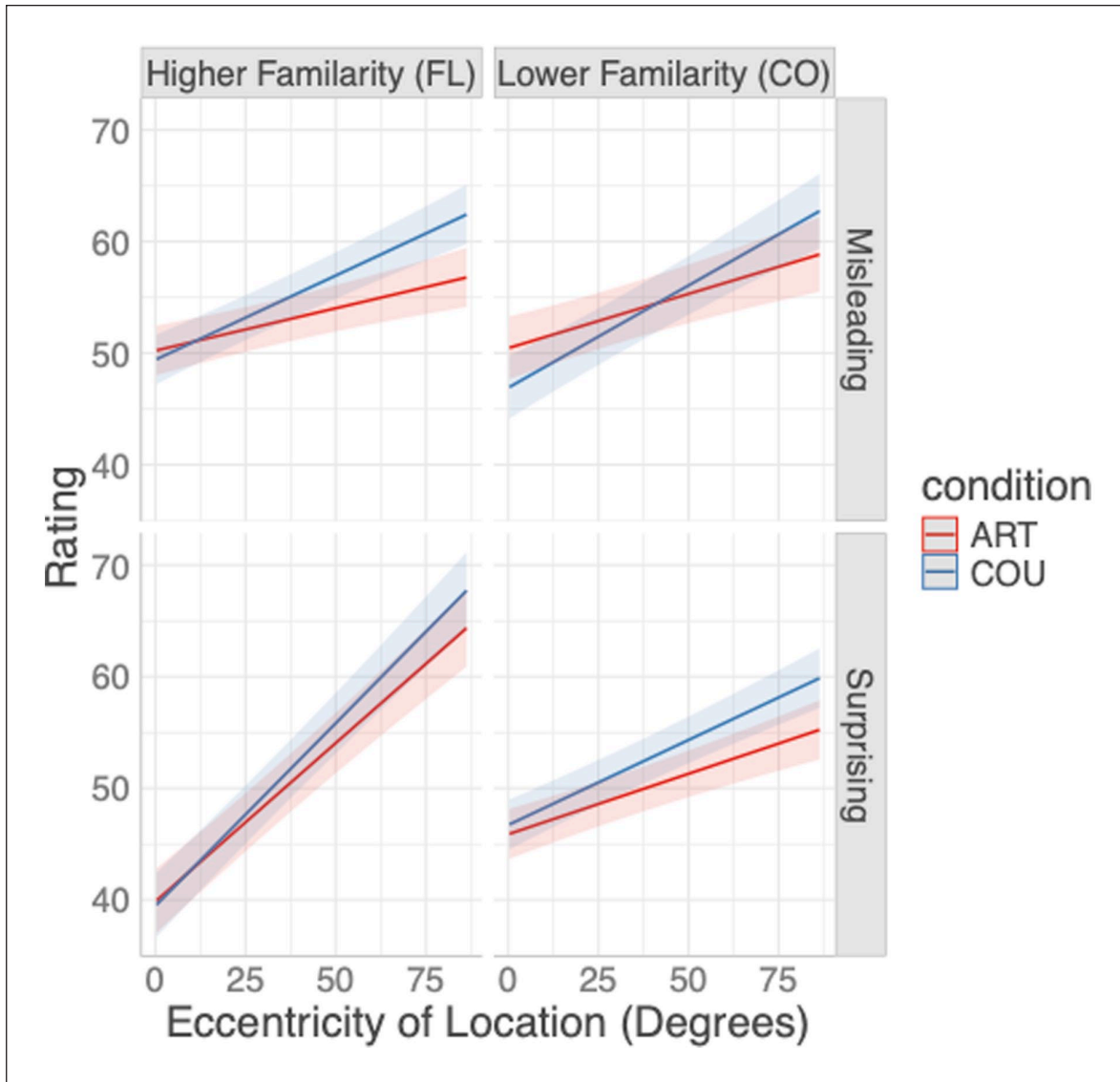


Figure 2. Ratings of level of “Misleading” (top row of figures) and “Surprising” (bottom row) outcomes as a function of eccentricity from the most likely forecast path (scored as 0 degrees) for Animated Risk Trajectory (ART; red) versus Cone of Uncertainty (COU; blue) visualizations.

Note. Ratings comprise individuals from those with likely lower familiarity with hurricanes and hurricane forecasts for participants from Colorado (right column) and higher familiarity with hurricanes and hurricane forecasts from Florida (left column). Shading represents 95% confidence intervals (CI).

surprising when the forecast was presented with ARTs than COU (see Figure 2, bottom-right panel).

Experiment 4: Florida and Surprising

We re-ran Experiment 3 but with 57 participants recruited from Florida. We found 8 outliers and removed them from analysis. In this experiment, the interaction between town location and condition was not significant, estimate=0.04, $SE=0.03$, $t=1.36$, $p=.18$ (see Figure 2, bottom-left panel).

Although there was a trend that participants found forecasts to be less surprising with ARTs than COU, it did not reach significance for these participants. Indeed, there is a strong tendency in participants expected to have more exposure to hurricanes and hurricane visualizations to believe that discordant instances farther from the most likely forecast path are increasingly surprising regardless of the representation used (as can be seen in the steeper slope gradients for Experiment 4 in Figure 2; and see Figure 3 for detailed information on the gradients across all four combinations of conditions).

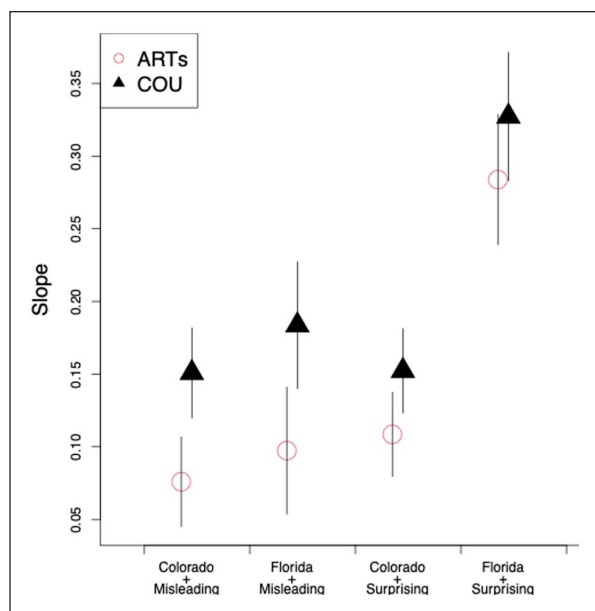


Figure 3. Gradients of regression lines for judgments by eccentricity for COUs (black triangles) versus ARTs (red circles) stimuli across the four experiments. Note. Error bars show 95% CI.

Conclusions

While forecast track errors have reduced substantially over time (see National Hurricane Center, 2025), the very nature of the COU visualizations aims to capture only two-thirds of future expected paths. Deviations outside the cone, while unlikely for a single storm, are a realistic possibility across any hurricane season of storm forecasts. Yet in the current study, we see high rates of surprise for landfalls that occur outside of the expected path, and beliefs that the visual representation in those cases is misleading. Our findings extend on previous findings that suggested ARTs provide advantages in improving decision making (e.g., Witt et al., 2023). This new evidence here implies they can also improve understanding of forecast uncertainty when storms may make landfall outside of the central predicted path.

Experience with hurricanes does change calibration for some judgment types. Florida participants were more likely to judge both visualization forms as increasingly surprising for aberrant instances at increasing eccentricities. However, they did feel more misled by such outcomes from cone-style visualizations. These findings imply they have adopted a different mental model of uncertainty around visualizations from their prior exposure. Our explanation would be based on their real-world experiences. The general tendency is that one does not frequently encounter future paths that deviate substantially. When variation from the predicted track does occur, iterative

forecasts update and reset the next forecast starting from the current position. Hence people in hurricane risk areas will largely encounter presentations that show storms moving within central bounds of the visualization. Within this context, these participants with higher familiarity may feel visualizations do not demonstrate the likelihood of such events at the rates encountered across the experiment. Although this trend may somewhat diminish some of the potential benefits of ARTs as a method of visualization, it is worth noting that the pattern is the same (and nominally stronger) for COUs. Importantly, therefore, nothing would be lost if a change in the visualization approach was adopted in the future.

Overall the results are congruent with ARTs offering an approach to avoid the containment effect found for COUs. ARTs can support improved uncertainty comprehension across populations, including those with lower and higher familiarity with hurricane risk. Our past research showed the advantage of ARTs for in-the-moment decisions (see above) and this work shows the advantage of ARTs for after-the-fact reactions.

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Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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