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Public Perceptions of Hurricane Modification

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If hurricane modification were to become a feasible strategy for potentially reducing hurricane damages, it would likely generate public discourse about whether to support its implementation. To facilitate an informed and constructive discourse, policymakers need to understand how people perceive hurricane modification. Here, we examine Florida residents' perceptions of hurricane modification techniques that aim to alter path and wind speed. Following the mental models approach, we conducted a survey study about public perceptions of hurricane modification that was guided by formative interviews on the topic. We report a set of four primary findings. First, hurricane modification was perceived as a relatively ineffective strategy for damage reduction, compared to other strategies for damage reduction. Second, hurricane modification was expected to lead to changes in projected hurricane path, but not necessarily to the successful reduction of projected hurricane strength. Third, more anger was evoked when a hurricane was described as having changed from the initially forecasted path or strength after an attempted modification. Fourth, unlike what we expected, participants who more strongly agreed with statements that recognized the uncertainty inherent in forecasts reported more rather than less anger at scientists across hurricane modification scenarios. If the efficacy of intensity-reduction techniques can be increased, people may be willing to support hurricane modification. However, such an effort would need to be combined with open and honest communications to members of the general public.

KEY WORDS: Forecast uncertainty; hurricane modification; public perception

1. INTRODUCTION

Intense land-falling hurricanes can cause great devastation. For example, Hurricane Katrina (2005) is estimated to have caused over 1,200 deaths[(1)] and losses of over 80 billion in 2006 U.S. dollars.[(2)] Residential damages range from broken windows and related rain-induced destruction of property to complete loss of residences. In the future, damages from hurricanes are expected to increase due to the growth of coastal populations and the possibility that intense hurricanes will become more common.[(3,4)]

Various mitigation strategies are available to reduce the likelihood that homes will be damaged in a hurricane. Such "hardening" includes installing storm shutters, strengthening roofs, improving roof to wall connections, assuring that structures have a negative load path to ground, and elevating buildings on pilings to avoid flood damage.[(5–7)] Once implemented, these mitigation techniques can remain in place for 30 years or more to provide protection against damages from hurricanes. Damages may also be reduced, and lives saved, through public awareness resulting from educational efforts, emergency planning for evacuation, and recovery planning.[(8–10)]

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One theorized strategy for reducing damages from tropical cyclones is hurricane modification, which attempts to reduce the intensity or change the direction of a storm. In the past cloud seeding was proposed to decrease a hurricane's intensity by injecting silver iodide into the hurricane eye wall to break its structure. In 1961 the U.S. government began cloud seeding experiments, but stopped in 1983 due to lack of results.[11] Recently, the Department of Homeland Security and the American Meteorological Society have devoted renewed attention to hurricane modification,[12,13] and the U.S. Department of Homeland Security has funded Project HURRMIT to study hurricane modification strategies.[14]

Although altering the initial conditions that foster hurricane formation[15] might potentially change the path of a subsequent hurricane, Project HURRMIT[14] and recent peer-reviewed literature[16–19] have focused on strategies that could reduce wind intensity but not change the path. One such proposal uses an array of wind-wave pumps, which involve a surface buoy connected to a long pipe reaching into the deep ocean. As waves move the apparatus up and down, cold water is gradually brought up from the deep ocean to reduce the sea surface temperature.[19,20] This temperature reduction should lead to a reduction in the wind speed of a hurricane without changing its path, perhaps also decreasing the risk of storm surge.[21] If successfully deployed, such a strategy could be more cost effective in reducing property damages[3] than standard hurricane mitigation efforts such as hardening homes, at least for very intense storms.[22]

As with any new technology, the feasibility of implementing hurricane modification will depend on how people respond to the technology. For example, public resistance to nuclear power plants has likely been a key factor in limiting its contribution to the U.S. electricity mix to about 20%.[23] Risk perception research has suggested that people respond more negatively to technologies that are perceived as novel and as having a large potential for catastrophes leading to a large number of deaths.[24] Moreover, initial negative reactions may influence subsequent evaluations of a technology, with stronger negative affect being related to the perception of greater risk and less benefit.[25] Especially with new technologies, people may lack sufficient understanding to evaluate their usefulness. In addition, hurricane modification raises serious questions about liability, ethics, and risk tolerance that do not arise in the absence of interventions to modify a storm.[11] Hence, to foster an informed public discourse about whether to support hurricane modification and, if so, how to deal with its consequences, policymakers need to effectively communicate the risks and benefits of hurricane modification.[26]

To date, relatively little is known about how people will respond to the possibility of experiencing damages from a modified hurricane compared to a hurricane that is left to run its natural course. Instead, most research to date has examined public perceptions of naturally occurring hurricanes, the associated emotions, and hurricane preparedness.[7,27–34] Recent work has reported that perceptions of hurricane risk are higher among Florida residents living in high-risk areas[7] and those who have previous experience with hurricanes.[35] Willingness to prepare for future hurricanes is greater among people who have experienced disastrous hurricanes in the recent past.[36–39] The implementation of hurricane preparedness strategies such as hardening homes, creating home disaster kits, and planning for evacuation has increased among residents of those Florida and the Gulf Coast areas that were threatened during the 2004 and 2005 seasons.[40]

The prospect of hurricane modification may evoke feelings of anger and blame, especially when it is easier for people to generate a counterfactual in which a different action would have led to a better outcome.[41] Indeed, social science research has suggested that counterfactual thoughts and related anger are more likely in unpleasant situations, such as accidents, that are caused by actions rather than inaction (a phenomenon known as omission bias),[42] and by actions that are nonroutine rather than routine.[43] Because hurricane modification involves nonroutine actions, residents who are affected by a hurricane after a hurricane modification attempt are likely to feel angry.

However, feelings of anger may be tempered if people perceive that chance played a role in producing the observed negative outcomes of, for example, a car accident.[44] Scientists agree that predicting the results of hurricane modification involves large uncertainty, both regarding the natural changes in hurricanes as well as the effect of the modification effort itself.[45] As a result, hurricane modification

[3]Hurricane modification also brings the promise of protecting lives, although these effects have not been quantified. Consequently, in line with earlier work, our focus here is on damage reduction.[22]

efforts may leave the projected path and intensity of a hurricane unchanged, or might be followed by damages that are worse than originally projected—but no worse than what might have been experienced without modification. If residents of hurricane-prone areas understand the scientific uncertainty inherent in hurricane forecasts, they might be less angry about any negative outcomes experienced after hurricane modification—especially if the experienced damages were worse than initially predicted. Decreased anger may, in turn, lead to a decreased tendency to initiate legal action.

To improve people's understanding of the uncertainty inherent in predictions about hurricanes, forecasters typically include a "cone of uncertainty," which shows the projected track of the center of a hurricane three to five days into the future, surrounded by a highlighted area reflecting a margin of error. This margin of error is chosen such that two-thirds of similar past hurricanes fall within the cone of uncertainty. Because the potential deviation from the projected track increases when forecasting further into the future, the display of the margin of error looks like a cone.[46] Based on archival research of Florida newspapers, responses to a National Weather Service request for comments on their cone of uncertainty graphic, and other survey research, it has been suggested that people underestimate the uncertainty presented in the cone-of-uncertainty graphics typically shown in hurricane forecasts, incorrectly assuming that they are safe if their area is not included.[47] Given this misunderstanding, they could be expected to respond with anger and accusations of blame if hurricane modification results in efforts that are different from those that they thought to have been predicted.

Here, we examine public perceptions of hurricanes and hurricane modification efforts to alter projected paths and wind speed. We used Carnegie Mellon's mental models methodology to examine public perceptions,[26] which has previously been used to examine people's beliefs about such diverse topics as sexually transmitted diseases,[48] carbon capture and sequestration,[49] radon in homes,[50] and climate change.[51–53] Developed to inform the design of risk communication materials, this method aims to improve researchers' understanding of people's beliefs or "mental models" about the topic under consideration. To this end, it begins with a small set of formative "mental models interviews." Research questions are derived from these interviews and subsequently tested in surveys with larger samples that provide statistical power. For example, interviews about climate change first revealed the perhaps surprising misconception that nuclear power plants are a cause of climate change, which was then confirmed in survey research.[51–54] Indeed, surveys that are based on formative interviews are more likely than conventional surveys to include questions about beliefs that are relevant to the target audience and use wording respondents understand.[55]

1.1. Research Questions Derived from Formative Interviews

To inform the design of our survey, we interviewed 10 Miami Florida residents who were recruited through online advertisements targeting their area. Following the mental models approach,[56] our semi-structured interview protocol included general, nondirective questions on topics relevant to hurricanes, damage reduction, and hurricane modification. We drew four key insights from the interviews, which we used to inform the design of the survey. First, none of the interviewees spontaneously mentioned hurricane modification as a strategy for damage reduction. When prompted, they questioned its effectiveness with comments such as "it will never be possible," and "hurricanes are too big and powerful to be changed." Second, most interviewees appeared to assume that hurricane modification would lead to changes in hurricane paths. None mentioned the possibility that it might reduce storm intensity or wind speed. Third, interviewees expressed anger when asked to discuss the possibility of a modified hurricane hitting their area, though, when prompted, classified strategies to reduce intensity as less negative than strategies for changing the path. Fourth, interviewees recognized the uncertainty inherent in hurricane forecasts when asked about it directly, but assumed that the path of a modified hurricane was determined by the modification.

Based on these interview findings, our subsequent survey was designed to examine the following research questions; (1) Are people aware of the idea of hurricane modification and do they perceive it to be an ineffective strategy for damage reduction? (2) Is hurricane modification expected to cause changes in the expected path and/or strength of hurricanes? (3) After modification has been attempted, does a change in the projected path or strength of a hurricane evoke anger? and (4) How is knowledge of forecast uncertainty related to anger about modification of the path and strength of hurricanes?

Table I. Mean (*SD*) Ratings of the Effectiveness of Different Strategies to Avoid, Prevent, or Reduce Damages Caused by Hurricanes

	M (*SD*) Effectiveness[a]	
Strategy	Category 5	Category 1
Having buildings up to code	5.59*** (0.89)	5.36*** (1.18)
Cutting old tree branches	5.40*** (1.14)	5.26*** (1.26)
Bringing in loose lawn items	5.39*** (1.17)	5.29*** (1.27)
Putting the car in the garage	5.30*** (1.20)	5.18*** (1.40)
Using hurricane shutters	5.27*** (1.32)	5.16*** (1.46)
Being prepared (with enough food, water, and batteries)	4.96*** (1.71)	4.59*** (1.93)
Using tie-downs to strengthen wall to roof connections in buildings	4.82*** (1.41)	4.82*** (1.66)
Raising coastal buildings above ground level by struts or some other method	4.69*** (1.42)	4.54*** (1.75)
Having better dikes (walls that keep out the ocean)	4.48*** (1.66)	4.19*** (1.90)
Evacuating everyone but emergency personnel	4.47*** (1.71)	3.16*** (2.21)
Using metal roofs	4.23*** (1.72)	4.42*** (1.77)
Hunkering down (sheltering in place) in a secure part of the house	4.21*** (1.96)	4.08*** (2.09)
Building new buildings farther from the coast	4.10*** (1.80)	3.85*** (2.15)
Using a spray to kill mold	3.09 (2.17)	3.10*** (2.18)
A government attempt to change a hurricane to reduce damage	2.70 (2.22)	2.18 (2.18)

[a]M = mean; *SD* = standard deviation.
Note: The response scale ranged from 0 (= not effective at all in reducing damages) to 6 (= extremely effective in reducing damages). Planned contrasts examined whether mean ratings were significantly different from hurricane modification within each hurricane category (***$p < 0.001$).

2. METHOD

2.1. Procedure

Using insights and word choices provided by our interviewees,[57,58] we developed a survey that was administered to a sample of 157 respondents in Florida. Below, we describe the survey questions, and discuss how they were designed to answer each research question.

2.1.1. *Are People Aware of the Idea of Hurricane Modification and Do They Perceive it to Be an Ineffective Strategy for Damage Reduction?*

To answer this research question, participants were first asked to generate damage reduction strategies: “Please list all of the ways that you can think of that could avoid, prevent, or reduce the damages (property damages, economic losses, and anything else you can put a dollar value on) caused by hurricanes.” Second, participants also rated how effective they perceived 15 specific techniques to be for “reducing damages (property damages, economic losses, and anything else you can put a dollar value on)” for both a category 5 and a category 1 hurricane forecasted to make landfall in Miami (see Table I). The response scale ranged from 0 (= not effective at all in reducing damages) to 6 (= extremely effective in reducing damages). Third, participants rated their agreement with four statements regarding the (in)effectiveness of hurricane modification, which were adapted from the interviews (see Table II). Responses were given on a scale ranging from 0 (= completely disagree) to 6 (= completely agree).

Table II. Agreement with Statements About the Ineffectiveness of Hurricane Modification

Statement	M (*SD*) Agreement[a]
Today, it is possible to change a hurricane to reduce its damage (R)	4.68*** (1.29)
It is a bad idea to change a hurricane because it might make things worse	3.59*** (1.80)
Hurricanes are too big and powerful to ever be changed by humans	3.49** (1.83)
At some point in the future, it will be possible to change a hurricane to reduce its damage (R)	3.15 (1.66)
We will never develop the technology to change a hurricane	2.76 (1.77)
Overall	3.54*** (1.18)

[a]M = mean; *SD* = standard deviation.
Note: (R) refers to statements that were reverse-coded to denote agreement with the ineffectiveness of hurricane modification. The response scale ranged from 0 (= completely disagree) to 6 (= completely agree). One-sample *t*-tests examined whether mean agreement with statements differed from the midpoint (= 3), indicating beliefs held with stronger conviction (***$p < 0.001$; **$p < 0.01$).

Fig. 1. Image presented with landfall location and wind speed questions.

2.1.2. *Is Hurricane Modification Expected to Cause Changes in the Projected Path and/or Strength of Hurricanes?*

To answer this research question, participants first received a description of an unmodified hurricane, with the news forecasting "that in 12 hours, a category 5 hurricane will make landfall at location 4 on the map" (see Fig. 1). To measure participants' expectations for the path of the hurricane, they were then asked to "check the boxes where you think the hurricane could make landfall. You may check one, several, or all boxes," with response options referring to 11 landfall locations along the Florida coast, to landfall being north or south of those locations, and the hurricane not making landfall at all. To measure participants' expectations for the strength of the hurricane, they were asked to "check the boxes which you think could describe the hurricane at landfall. You may check one, several, or all boxes," with response options ranging from "below category 1" to "category 5." These two questions were repeated for an unmodified hurricane that was projected to be of category 1. Both questions were also repeated while asking participants to assume that "scientists try to change that hurricane to reduce damages," and asking participants to "just indicate how the storm might change, not how you want the storm to change."

2.1.3. *After Modification Has Been Attempted, Does a Change in the Projected Path or Strength of a Hurricane Evoke Anger?*

Next, participants were asked to report their degree of anger at scientists who performed modification, in response to six different hurricane modification scenarios that systematically varied (a) whether the observed path was the same as what had been forecasted or differed from it, and (b) whether the damages due to storm intensity were the same, worse, or better than forecasted. The response scale for reported degree of anger ranged from 0 (= not at all) to 6 (= extremely).

2.1.4. *How Is Knowledge of Forecast Uncertainty Related to Anger About Modification of the Path and Strength of Hurricanes?*

The measure of the degree of anger triggered by the modification of the path and the strength of hurricanes is described in Section 3.3. To measure forecast uncertainty, participants were asked how much they agreed (0 = completely disagree; 6 = completely agree) with "The cone of uncertainty shows how uncertain forecasts are," and four statements claiming that "Hurricane forecasts are imperfect ..." followed by "... because scientists don't completely understand hurricanes," "... because technology is not advanced enough, ... because weather changes randomly," and "... because the media hypes up the possibility of a bad storm" (see Table V).

2.2. Sample

Participants responded to a newspaper advertisement or an online advertisement targeting the Miami, Florida area that read: "Researchers at Carnegie Mellon University are conducting 30–40 minutes online surveys to find out what people know about hurricanes. You will receive a $20 Amazon gift certificate for your participation. To qualify, you must: (a) currently live in Florida, (b) be available for a 30–40 minute survey, (c) be fluent in English, and (d) be at least 18 years old." They were directed to an online survey.

A total of 157 individual participants completed the survey after correctly answering two questions that examined whether they were paying attention (e.g., "Which is the largest number in this set: 10, 20, 500, or 1,000?") and received a gift certificate that was mailed to their Florida address. On average, their mean (M) age was 40.20, which showed a standard deviation (*SD*) of 14.88, and their median income was in the $50,000–$74,999 category, with 66.7% being women, and 54.5% having a college degree.[4] Almost all (91.7%) reported having been in a hurricane. When reporting on their type of dwelling, 57.3% reported living in a single-story home, 17.8% in a multiple-story home, 8.9% in a condo, 8.3% in an apartment on or above the 2nd story, 5.7% in a ground floor apartment, and 0.6% in a mobile home. When asked about the area in which they lived, 50.6% indicated it to be easily flooded, and 24.5% being less than a mile from the coast.

3. RESULTS

3.1. Are People Aware of the Idea of Hurricane Modification and Do They Perceive it to Be an Ineffective Strategy for Damage Reduction?

To answer this research question, we present three analyses to suggest that people do not readily think of using hurricane modification for damage reduction. Moreover, they perceive it as a relatively ineffective strategy for damage reduction.

First, as in the interviews, before the concept was introduced, none of our survey participants listed hurricane modification in response to the open-ended question asking for strategies to avoid, prevent, or reduce damages caused by hurricanes. Only two of the 157 participants suggested that "perhaps scientists could help" with 20 others citing large-scale civil engineering efforts such as burying electrical lines underground or building a dam. All other responses referred to disaster preparedness strategies individuals could implement, and followed the suggestions of the Florida Division of Emergency Management.[6]

Second, Table I shows mean ratings for perceived effectiveness of different strategies to reduce damages from hurricanes, including hurricane modification. Strategies are ordered by their mean perceived effectiveness for reducing damages from category 5 storms, with mean perceived effectiveness for reducing damages from category 1 storms following the same approximate order. To systematically examine planned comparisons between the ratings of perceived effectiveness (for hurricane modification vs. each other type of damage reduction) by hurricane category (5 vs. 1), we conducted a repeated measures multivariate analysis of variance (MANOVA) *F*-test.[5] As in the interviews, hurricane modification was rated as significantly less effective than each alternative, including "using spray to kill a mold," which is not actually a recommended strategy for reducing hurricane damages, with $F(1,135) > 13.16$, $p < 0.001$ for each planned comparison. A significant main effect of hurricane category showed that, overall, strategies were perceived as more effective against category 5 hurricanes than against category 1 hurricanes, $F(1,135) = 9.79$, $p<0.01$. There was a significant interaction of hurricane category with planned comparisons for the following techniques: using metal roofs, using tie-down to strengthen wall to roof connections in buildings, bringing in loose lawn items, evacuating everyone but emergency personnel, and using a spray to kill mold. That is, each was perceived as substantially more effective than hurricane modification for protecting against damages from a category 1 than from

[4]In 2010, the overall population of Florida had an average age of 38.7, median household income of $44,755, with 50.8% being women, and 25.6% having a college degree.[69] Hence, by comparison, our sample is wealthier and includes slightly more women and college-educated participants.

[5]Multivariate analysis of variance (MANOVA)[61] is used when there is more than one dependent variable, such as ratings of effectiveness for multiple damage reduction strategies. It examines the effect of one or more independent variables on the means of the dependent variables, as well as interaction effects between the levels of the independent and the dependent variables. Like univariate analysis of variance (ANOVA), it uses the *F*-test to examine these effects.

Table III. Participants' Expectations for the Landfall Location and Intensity of Modified and Unmodified Hurricanes

Type of Hurricane	Initially Projected Intensity	Percent Expecting Change from Initially Projected Landfall Location	Percent Expecting Reduction from Initially Projected Category
Modified	Category 5	16.4%***	40.5%**
Unmodified	Category 5	4.3%	25.9%
Modified	Category 1	16.4%*	.9%*
Unmodified	Category 1	6.0%	6.4%

Note: McNemar change tests[70] were used to examine whether hurricane modification significantly affected the percent of participants reporting specific outcomes (***$p < 0.001$; *$p < 0.05$).

a category 5 hurricane, with $F(1,135) > 4.86, p = 0.03$ for each.

Third, Table II shows participants' mean rating of agreement with five statements about the (in)effectiveness of hurricane modification, as adapted from our formative interviews. Positive statements about hurricane modification were reverse coded to reflect agreement with its ineffectiveness. To examine which beliefs were held with relatively strong conviction, we used one-sample *t*-tests to test the difference of the mean rating from the midpoint (= 3.0) of the scale, which ranged from 0 (= completely disagree) to 6 (= completely agree). As seen in Table II, the strongest agreement was with the reverse-coded statement "today, it is possible to change a hurricane to reduce its damage" as well as with "it is a bad idea to change a hurricane because it might make things worse" and "hurricanes are too big and powerful to ever be changed by humans." Cronbach's alpha across the five ratings was above 0.72, suggesting that their internal consistency was sufficient to conclude that they measured the same underlying construct, and to compute their overall mean.[6] Table II shows that the overall mean was significantly above the scale midpoint, suggesting that participants agreed that hurricane modification would be ineffective.

3.2. Is Hurricane Modification Expected to Cause Changes in the Projected Path and/or Strength of Hurricanes?

The results of our survey suggest that participants expected modification to lead to changes in hurricane paths, but not necessarily to the reduction of storm strength. We examined, for unmodified and modified hurricanes of categories 1 and 5, whether or not participants included the forecasted landfall location and the forecasted hurricane category among their responses. To determine whether participants were more likely to expect a change from what was forecasted after a modified hurricane than after an unmodified hurricane, we conducted a McNemar change test, a nonparametric version of the paired-sample *t*-test.[7] Table III shows that a significantly larger percent of participants expected that a modified hurricane rather than an unmodified hurricane would show diversion from the initially projected landfall location, whether the forecasted strengths were of category 5 or category 1. A significantly larger percent of participants expected the modified hurricane rather than the unmodified hurricane to show a reduction from the initially projected category 5 intensity. However, for hurricanes with a category 1 projection, more participants expected hurricane modification to increase rather than to decrease in intensity.

3.3. After Modification Has Been Attempted, Does a Change in the Projected Path or Strength of a Hurricane Evoke Anger?

Our results suggest that more anger is evoked when a hurricane's path or strength change from what was predicted before the modification attempt. Table IV shows participants' reported anger at scientists, as given in response to the six scenarios that described modified hurricanes hitting the participants' area, and that varied whether or not the path and

[6] Cronbach's alpha[59,60] is mathematically equivalent to the average value of all possible split-half correlations. A split-half correlation is the correlation between two mean ratings computed from two halves of the same set of items. Hence, it is an indicator of internal consistency reliability across items.

[7] McNemar change tests[70] are designed for use with 2 × 2 contingency tables of nominal data obtained in a repeated-measures design, for example, to compare whether expected change (yes vs. no) is more likely with different types of hurricanes (modified vs. unmodified).

Table IV. Reported Anger in Response to Scenarios in Which Scientists Had Tried to Modify a Hurricane that Hit Their Area

Hurricane Outcome, Compared to Prediction		
Path	Damage	M (*SD*) Anger at Scientists[a]
Same	More	2.89 (2.10)
Same	Same	1.75*** (1.86)
Same	Less	1.03*** (1.52)
Different	More	3.48** (2.08)
Different	Same	3.06 (2.10)
Different	Less	1.88*** (1.80)
Overall		2.36*** (1.46)

[a]M = mean; *SD* = standard deviation.
Note: The response scale for the degree of experienced anger ranged from 0 (= not at all) to 6 (= extremely). One-sample *t*-tests examined whether mean anger differed from the midpoint (= 3), indicating relative strength of the reported emotion (*** $p < 0.001$; ** $p < 0.01$).

direction differed from what was forecasted. As an initial indication of the relative strength of the reported anger, one-sample *t*-tests tested whether means were significantly different from the scale midpoint (= 3). Table IV shows that mean anger was significantly higher than the midpoint for only one scenario, in which the modified hurricane that hit participants' area was described having changed in path and increased in strength, compared to what was forecasted. Table IV also shows that mean anger was significantly below the scale midpoint for the one scenario in which both the path and the strength of the modified hurricane were the same as forecasted, and for the two in which the damages were less than expected. Across the six scenarios, reported anger showed sufficient internal consistency to allow for the computation of their overall mean, as seen in a Cronbach's alpha[59,60] of 0.85. The overall mean of anger was significantly below the scale midpoint, suggesting that participants experienced relatively limited anger when reading the hurricane modification scenarios.

To systematically examine the effects of changes from the initially forecasted path (yes or no) and from the initially forecasted damages (more, same, or less), we conducted a repeated measures MANOVA[61] on reported anger at scientists. We found a significant main effect of whether or not the forecast predicted that the hurricane would hit the participants' area, $F(1,152) = 67.38$, $p < 0.001$. Namely, participants reported significantly more anger at scientists when the modified hurricane hit their area but was not initially predicted to do so. There was also a main effect of damages, $F(2,151) = 101.63$, $p < 0.001$, suggesting that participants reported increasingly more anger when there were more damages than predicted due to increased hurricane intensity. A significant interaction between whether or not the forecast was predicted to hit the participants' area and the degree to which the damages were different than expected, $F(2,151) = 9.20$, $p < 0.001$) showed that the most anger was reported in response to the scenario in which both the path and the intensity of the hurricane changed in a way that was worse than initially expected.

3.4. How Is Knowledge of Forecast Uncertainty Related to Anger About Modification of the Path and Strength of Hurricanes?

To address this research question, we first examined the extent to which participants recognized the uncertainty inherent in hurricane forecasts. Table V shows their mean ratings of agreement with statements about the uncertainty inherent in hurricane forecasts, ordered by their degree of agreement. Overall, participants agreed with the statements that "hurricane forecasts are uncertain because weather changes randomly," "the cone of uncertainty shows how uncertain forecasts are," and "hurricane forecasts are uncertain because the media hypes up the possibility of a bad storm." Beliefs in these three statements were held with relatively strong conviction, with one-sample *t*-tests showing that mean ratings were significantly higher than the scale midpoint (= 3). Agreement was not significantly different from the scale midpoint for the two remaining statements (each $p > 0.05$), suggesting that participants were not as convinced that "hurricane forecasts are uncertain because technology is not advanced enough" or "because scientists don't completely understand hurricanes." Because Cronbach's alpha[59,60] showed relatively good internal consistency across these five statements ($\alpha = 0.69$), we computed the means to reflect overall agreement with reasons for why forecasts are uncertain.[59,60] That measure of overall recognition of forecast uncertainty was also significantly above the scale midpoint (= 3), thus suggesting that participants generally tended to agree

Table V. Agreement with Statements About the Uncertainty Inherent in Hurricane Forecasts.

Statement	M (*SD*) Agreement[a]	Relationship with Overall Anger Across Modification Scenarios
Hurricane forecasts are imperfect because weather changes randomly	4.66*** (1.52)	0.18*
The cone of uncertainty shows how uncertain forecasts are	4.31*** (1.59)	0.01
Hurricane forecasts are imperfect because the media hypes up the possibility of a bad storm	3.96*** (1.80)	0.18*
Hurricane forecasts are imperfect because technology is not advanced enough	3.06 (1.80)	0.22***
Hurricane forecasts are imperfect because scientists do not completely understand hurricanes	3.01 (1.88)	0.30***
Overall	3.80*** (1.15)	0.27**

[a]M = mean; *SD* = standard deviation.

Note: The response scale ranged from 0 (= completely disagree) to 6 (= completely agree). One-sample *t*-tests examined whether statements differed from the midpoint (= 3), indicating beliefs held with stronger conviction, and Pearson correlations to examine the relationship with overall anger (***$p < 0.001$; **$p < 0.01$; *$p < 0.05$).

that hurricane forecasts are uncertain, $t(156) = 8.71$, $p < 0.001$.

Unlike what we expected on the basis of the interviews, participants who more strongly agreed with statements that recognized the uncertainty inherent in forecasts reported more rather than less anger at scientists across hurricane modification scenarios. Indeed, Table V shows significant positive Pearson correlations between participants' overall recognition of forecast uncertainty measure with the mean anger reported across the hurricane modification scenarios and the overall uncertainty measure. The correlation was also significant for individual items, except for the one asking about the cone of uncertainty. Overall recognition of forecast uncertainty seemed differentially related to anger at scientists reported across hurricane modification scenarios. Specifically, it appeared that individuals who most recognized forecast uncertainty were especially angry when damages were unexpectedly worse, for when their own area was unexpectedly hit ($r = 0.22$, $p < 0.01$) and hit as predicted (r = 0.26, $p < 0.01$). The same pattern held when damages stayed the same ($r = 0.20$, $p = 0.01$ when unexpectedly hit; $r = 0.24$, $p < 0.01$ when hit as predicted). However, these correlations were not as strong when the damages were less than predicted ($r = 13$, $p = 0.12$ when unexpectedly hit; $r = 0.17$, $p = 0.04$ when hit as predicted).

Although overall perceptions of perceiving hurricane modification as ineffective were positively correlated to both overall anger about hurricane modification ($r = 0.21$, $p < 0.01$), and to recognizing forecast uncertainty ($r = 0.18$, $p = 0.03$), the observed relationship between anger and recognizing forecast uncertainty remained significant in partial correlations statistically controlling for perceptions of ineffectiveness ($r = 0.24$, $p < 0.01$). Additionally controlling for participants' age, gender, education, income, experience with hurricanes, area being prone to flooding, and distance being less than 1 mile from the coast had little to no effect on the reported correlation between overall anger across scenarios and overall recognition of forecast uncertainty ($r = 0.21$, $p = 0.03$). After adding all of these control variables, partial correlations of overall uncertainty with anger about individual hurricane modification scenarios also remained significant for those describing, compared to what was forecasted, an unchanged path with more damage ($r = 0.22$, $p = 0.03$), and a different path with more damage ($r = 0.19$, $p = 0.05$).

Moreover, our analyses suggest that recognizing forecast uncertainty mediated the effect of the degree to which damages were different from expected on reported anger at scientists. We added the overall agreement with statements recognizing uncertainty as a covariate to the MANOVA[61] that, as described above, examined the effect of whether or not the forecast was predicted to hit the participants' area (yes or no) and the effect of the amount of damages compared to prediction (more, same, or less) on anger at scientists. We then found a significant effect of recognizing uncertainty, $F(1,151) = 11.60$, $p < 0.01$, with the effect of predicted path showing reduced significance, $F(1,151) = 9.13$, $p < 0.01$, and the effect of increased damages and its interaction with the predicted path being no longer significant ($p > 0.05$). Even after controlling for perceptions of the ineffectiveness of hurricane modification and participant characteristics, uncertainty remained a significant predictor, $F(1, 104) = 4.78$, $p = 0.03$. None of the control variables showed significance ($p > 0.05$), suggesting that they did not drive the mediation.

4. DISCUSSION

In this article, we examined Florida residents' perceptions of hurricane modification techniques that aim to alter path and wind speed. Following the mental models approach,[26] we conducted a survey study about public perceptions of hurricane modification that was guided by formative interviews on the topic. Below, we report on our four main findings.

First, we found that hurricane modification was perceived as a relatively ineffective strategy for reducing damages. Unprompted, none of the respondents mentioned hurricane modification for reducing damages. When asked, they rated hurricane modification as significantly less effective than other damage reduction strategies such as home hardening. In fact, participants' ratings of the effectiveness of hurricane modification techniques were not statistically different from their ratings of the effectiveness of a fictional technique described as "using a spray to kill mold." Possibly, hurricane modification is perceived as relatively ineffective because people are much less familiar with it than with other damage reduction strategies. When a new technology is still relatively unfamiliar, people's perceptions of it may be especially negative and unstable.[62,63]

Second, while perceived as less effective than other strategies, hurricane modification was nevertheless expected to cause changes in storms. Participants expected that modified hurricanes would be more likely than unmodified hurricanes to divert from their initially projected landfall locations, and to show a reduction in intensity if the initial forecast predicted category 5. When the initial forecast predicted a category 1 storm, hurricane modification was expected to be counterproductive and increase storm intensity. Because the participants systematically expected changes from category 1 and category 5 projections to be larger for modified hurricanes than for unmodified hurricanes, we conclude that these results reflect actual effects of hurricane modification on reported expectations rather than just the mechanistic response bias referred to as regression toward the mean.[8]

Third, more anger was evoked when a hurricane was described as having changed from the initially forecasted path or strength after an attempted modification. Participants expressed increased anger both when their area was hit by a modified hurricane that had been projected to go elsewhere and when the modified hurricane produced more damage than forecasted. In contrast, reported anger was weaker when hurricane modification was described as leaving the projected track unaltered, and leading to the projected damages or less. Hence, hurricane modification efforts that aim to reduce damages without changing paths may be better received than hurricane modification efforts that focus on diverting paths. Indeed, techniques aiming to change the path of hurricanes have been identified to cause especially complex questions about liability and ethics.[45]

Fourth, unlike what we expected, participants who more strongly agreed with statements that recognized the uncertainty inherent in forecasts reported more anger toward scientists, across hurricane modification scenarios. Based on previous research about, for example, car accidents, we had expected that individuals who recognized the role of chance in forecasts of a hurricane's path and intensity would have shown less anger.[44] Indeed, when chance is seen as producing a negative outcome, it is more difficult to make attributions of causality and blame. Possibly, the discrepancy in findings is due to the context

[8] As a result of measurement error, initial observations of extreme values (e.g., very high blood pressure) tend to be less extreme in a subsequent observation,[71,72] thus showing regression toward the mean. Such observations may lead researchers to erroneously conclude that their treatment (e.g., blood pressure medication) may have led to the observed change. To separate actual treatment effects from the mechanistic effects of regression toward the mean, it has been recommended to compare changes in a treatment group to changes in a no-treatment control group (e.g., patients with high blood pressure who do or do not receive the medication). Because our response categories ranged from "less than category 1" to "category 5," participants had more ways to indicate that a projected category 1 storm would increase in strength rather than decrease in strength and that a projected category 5 storm would decrease in strength rather than increase in strength. As a result, responses may have been driven toward the middle of the response range. However, our conclusions are based on comparisons of participants' expectations for unmodified and modified hurricanes, which showed that participants systematically indicated that they expect larger changes with modified hurricanes than with unmodified hurricanes.

of hurricane modification being systematically different from the context of car accidents. For example, compared to cars, the risks related to hurricanes may be perceived as much less well-known, while triggering much more negative affect, feelings of lack of control, and fear of catastrophic outcomes. Risk perception research has suggested that each of these elements plays an important role in how people respond to risks—and, possibly, any related uncertainty.[24,25] Indeed, individuals who recognize the uncertainty inherent in hurricane prediction may have been less forgiving rather than more forgiving about the use of hurricane modification because they perceived hurricanes as too big and powerful to be reliably modified by humans.

However, while individuals' ability to recognize the uncertainty inherent in hurricane forecasts may have caused their increased feelings of anger toward scientists implementing hurricane modification, alternative explanations may apply. The correlation might also be explained by reverse causality, with individuals who feel more anger about hurricane modification possibly being more likely to question the certainty of hurricane forecasts. Additionally, even though we controlled for negative perceptions about the effectiveness of hurricane modification, demographic background, and experience with hurricanes, other unobserved variables may have affected the reported relationship between recognizing forecast uncertainty and anger about hurricane modification. For example, people who hold strong protective values related to nature and climate may be both more familiar with hurricane forecast uncertainty and more averse to hurricane modification. Indeed, research on the omission bias has suggested that protected values are related to being more negative about harmful acts of commission than about harmful acts of omission that produce the same negative results.[42]

To examine the causal effect of recognizing uncertainty on feelings of anger, follow-up research should randomly assign participants to receive detailed information about forecast uncertainty before asking how they feel about hurricane modification. Although our results suggest that it is incorrect to assume that hurricane modification will be more acceptable to individuals who recognize the role of uncertainty in forecasting hurricanes, it also seems premature to agree with those scientific experts who believe that providing members of the general public with information about uncertainty will increase distrust in science.[64] Indeed, risk communication efforts in other domains have suggested that communicating about the uncertainty surrounding risks does not necessarily reduce people's willingness to accept those risks, and have provided guidelines about how to communicate quantitative risks.[26,65–68]

One limitation of this study is that the sample was not randomly selected from residents of the state of Florida. Compared to the overall population of Florida, our sample is wealthier and more college educated.[69] While our relatively wealthy and college-educated participants may have been more familiar with hurricane modification than other Florida residents, they were clearly not well-informed. Thus, our results suggest that Florida residents likely need more information to make informed decisions about whether or not to support hurricane modification.

Any attempt to communicate the risks and benefits of hurricane modification should be designed to complement residents' mental models.[26] The survey presented here provides initial insights into people's knowledge and beliefs about hurricane modification, suggesting that they question its effectiveness, expect it to focus more on changing paths than on changing intensity, while also being angered more about changing paths than about changing intensity, especially when they recognize the uncertainty inherent in forecasts. If these results hold in follow-up research, policymakers who aim to facilitate informed public discourse about hurricane modification may specifically benefit from providing risk communications about hurricane modification techniques that bring the promise of reducing storm intensity without changing the projected path. It may be the case that effective risk communication about these hurricane modification techniques will increase acceptance of hurricane modification, even among individuals who recognize the inherent uncertainty.

Indeed, hurricane modification may be met with less public resistance if efforts focus on reducing storm intensity without changing the projected path. If the efficacy of those techniques can be increased, people may be willing to support hurricane modification. However, such an effort would need to be combined with open and honest communications to members of the general public. Lessons learned from the context of nuclear power[23] and other technologies associated with high risks suggest that dismissing the concerns of the general public will likely create a level of public distrust that will hamper any effort to successfully implement hurricane modification.

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