4.2 BETWEEN THE TROPICAL CYCLONE FORECAST AND THE PUBLIC RESPONSE: SCIENTIFIC PREREQUISITES TO COMPREHENSION

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1. INTRODUCTION

Warning the public about impending tropical cyclone-related threats to their communities necessarily involves the communication of forecast information, based in science, to audiences composed primarily of non-scientists. Successful implementation of the response therefore depends on the accuracy of comprehension and interpretation by non-scientists of the science-based information contained within the forecast, no less than on the accuracy of the forecast itself. While correct interpretations have the potential to elicit, though cannot guarantee, accurate assessments by non-scientist audiences of the levels and types of danger posed to them by any given storm event, incorrect interpretation of this information poses a fundamental impediment to a successful public response.

Inherent in the problem of communication of science-based forecast information to audiences of non-scientists is the necessity of translating or converting the forecast's scientific content - mathematical and statistical in its native structure - into restructured content that is comprehensible to populations not generally schooled in those disciplines. The forecast interpretation problem encompasses not only the forms in which the forecast information is presented or communicated (e.g., text vs. graphics), but even more so the complexity and transparency of the scientific content contained between those forms.

This study poses the question of whether and to what extent the forecast constructs, once the scientific information within them has been converted for public consumption, nevertheless still require certain types and levels of *a priori* scientific knowledge that may or may not exist among different members of the public, by virtue of such prerequisite knowledge remaining embedded within the content and structure of the forecast communications. Even more fundamental is the need to better understand how the substance of the official TC descriptions and forecasts, which are the source of the public forecast information and thereby define its structure and organization, fit within the context of existing levels of scientific understanding among the public, or more specifically, as juxtaposed against the prevailing levels of scientific literacy among those audiences.

2. RATIONALE

Although initially directed primarily toward technically trained user communities to help them elicit the desired actions by members the general public during tropical cyclone emergencies, the existing body of research suggests that some members of the general public are attempting to interpret the meteorological information provided by forecasters more directly. Across studies, respondents are consistently ranking meteorological factors, both current and projected storm attributes, as one of the primary factors in their decision (e.g., Howell, et. al., 2005; Zhang and Morss, et. al., 2007; Dow and Cutter, 1998, USACE, 2005a, 2005b, 2005c, 2005d). In some but not all cases, respondents are assigning the meteorological factors a higher importance ranking than the advice of emergency management officials. They are not merely relying on what public officials tell them, but are also looking directly at the scientific information presented in the storm descriptions and forecasts and drawing their own conclusions about the nature of the TC threat.

The full value of the tropical cyclone forecast, its associated products, and scientists' knowledge about a given storm is preserved so long as the knowledge received by the public is the same as the knowledge that was transmitted, with little to no loss of signal. To the extent that the information transmitted to users does not arrive intact, the transmission is compromised, resulting in some or all of the value of the scientific knowledge about a given tropical cyclone threat being lost to those members of society.

3. METHODOLOGY AND DATA

A spectrum of published academic research studies, public surveys, hurricane readiness questionnaires, and original documents going back through the past decade was collected. Data explicitly pertaining to public understanding of the scientific content of TC descriptions and forecasts were extracted, and a database created. The data were analyzed, both separately and together, in light of one another, for what they suggest about the public's ability to correctly interpret the scientific substance of the TC descriptions and forecasts, with particular emphasis on those pertaining to storm track, intensity, and size.

The database first includes results reported in published survey research from the last decade; it contains the distributions of answers to those survey questions, small in number, that point specifically to the state of respondents' comprehension of the scientific content of TC descriptions and forecasts. Among the studies examined for the relevant questions were post-storm and hypothetical storm surveys and polls conducted, sponsored, or commissioned by social scientists, meteorologists, universities, the National Weather Service, public service entities, and private corporations. In addition, the series of National Weather

Service post-storm service assessments was reviewed in its entirety, and the official observations and findings concerning interpretation difficulties by users that have occurred and/or interfered with the public response during specific storm events were extracted. US Army Corps of Engineers post-storm behavioral studies were reviewed for similar data and National Hurricane Center Tropical Cyclone Reports were consulted. Finally, the events that took place during the approach of Hurricanes Charley and Ike, as two conspicuous hurricane response failures by the general public during the past decade and pertaining to track and intensity forecast interpretation, respectively, were reviewed in their fine details.

4. RESULTS

While the data suggest that the information is partially understood, the study concludes that much of the scientific content contained in the most common types of TC descriptions and forecasts continues to be subjected to multiple interpretations. The public appears to require a greater degree of pre-existing scientific knowledge than they now have to be able to hone in on the single correct interpretations of the information they are seeing.

Understanding what a TC description or forecast means and being able to realize its full value is not just a problem of a lack of factual scientific knowledge on the surface, or in its literal sense. It is just as much a problem of being able to make the deeper connection that a certain fragment of general scientific knowledge is applicable to the new information for purposes of ascertaining its meaning, intent, and significance, comprehending its second-level implications and consequences, and relating it to a specific and unique real-world situation.

Misinterpretations of the TC descriptions and forecasts among the general public as evidenced in the source data were found to be present at multiple levels, starting from the bottom up:

1. Insufficient familiarity with basic physical and mathematical relationships, especially those concerning time, space, motion, and change, and with the broader meteorological context that frames the TC descriptions and forecasts.

2. Spatio-temporal distortions of the forecast data, including interpretations that contradict the natural arrow of time, that begin with incorrect spatial perspectives and priorities, and that reveal a lack of clarity with respect to time sequences and distinctions.

3. Insufficient ability to spark access to general knowledge of scientific and mathematical relevance that may have been previously learned, draw upon it, apply it to the meteorological information presented, and thereby be able to "see" the new knowledge contained within the specific TC description or forecast.

4. Difficulty in decoding the data packaging, whether text or graphics, beginning with incorrect identification of its constituent parts and extending to the whole, which for non-scientists often requires a multi-step process.

5. Failure to correctly discern the intent and purpose of the forecast products.

6. Insufficient ability to fully or correctly ascertain the implications or significance of the new knowledge, and apply it to a unique situation.

To what extent is the American public equipped to understand what they are looking at? The state of public scientific understanding is a moving target relative to the rest of the industrialized world, but the trend has been mostly downward (PISA, 2003; PISA, 2006; PISA, 2009). Presently the United States is 17th in scientific literacy and 25th in mathematical literacy, in the study of 34 industrialized countries. Part of literacy as defined in these studies is the ability to make decisions based on scientific information; the comprehension of uncertainty and probability falls under the category of mathematical literacy.

While forecasters are able to interpret and give meaning to their meteorological observations through the context of the collected knowledge of modern science and the operational models based on it to make their forecasts, members of the public do not have easy access to the complete body of knowledge: they have only the tapestry of their own knowledge to rely on in making sense of their meteorological observations, which for them are the TC descriptions and forecasts. To the extent that users' interpretive contexts are defective - inaccurate, absent, fragmentary, or inaccessible - or in whatever way inconsistent or incompatible with the collected knowledge of modern science, interpretation of the science-based information in the forecasts may not be as intended by forecasters, and judgements about the dangers they face may not be consonant with the objective physical realities.

a. Intensity

A specific focus was found to exist within several classes of users on the forecast for intensity at landfall, a forecast that technically does not exist. In a multiple choice poll question asking respondents which type of forecast they believed was least reliable, "storm intensity at landfall" was available as the correct answer (Mason-Dixon, 2010). Moreover, three-quarters of respondents did not choose that answer, opting instead for answers pertaining to the track forecast, demonstrating that they placed a great degree of confidence in this forecast for intensity at landfall as compared to different aspects of the track forecast.

Indications are that an expectation exists to be informed of a storm's intensity at landfall (NWS, 1996). This manner of interpreting the intensity forecast, specifically in those terms, is a problem of sequential logic. Holding out landfall as the main focal point effectively de-emphasizes the normal step progression of the sequential forecast lead times, which begins with the storm's current condition and looks forward through time. Instead, it jumps out to look at intensity at a single arbitrary forecast time in the future, when the storm is forecast to be approaching land. Following naturally from a perspective that pays attention to the intended time sequence, starting in the here in now and following the natural arrow of time, is an ability to notice whether the forecast trend is projecting intensification, de-intensification, or persistence of the storm's current intensity (figure 1, last pg.), together with the broadening of possibilities over time, which is the uncertainty.

Interpreting the intensity forecast simply as intensity or category at landfall takes the focus away from noticing which lead time that particular forecast pertains to, how many hours or days out it is from the storm's current intensity estimate, and how much uncertainty coincides with that lead time. Devoid of temporal context or sequence, this type of black-and-white interpretation may also encourage the declaration of a forecast near landfall as "right" or "wrong" - for instance, a TC was forecast to make landfall as a Category-2 but actually did so as a Category-4, and therefore the forecast was wrong - instead of seeing the forecast in a more fluid way, as a changing set of approximations about a changing storm within a changing atmosphere.

The tendency to focus on landfall, however understandable, reflects the population's location-centric perspective. Yet the intensity forecast itself, like the track forecast, contains within its structure the storm-centric perspective of the forecasters. The location-centric interpretation of the storm-centric forecast carries deep implications that may be logically inhibitory to the assimilation of uncertainty for both track and intensity forecasts, because of the way it handles time, space, and motion.

Difficulty assimilating the passage of time as context for a changing storm may allow uninitiated users to gloss over the distinction between the storm's present condition and its future condition. For example: "They [emergency management] apparently focused on an earlier description of Marilyn as a small Category 1 hurricane and were not prepared for a direct hit from an intensifying storm" (NWS, 1996). Those users had effectively frozen the storm in its current condition and adopted that description as their expectation for the future. While they could see the storm moving forward in space, toward their location, they had not accounted for it also changing through time. No sharp distinction was made between intensity in the present and in the future, with the TC's current description and its uncertain future all rolled up into one.

A second, intersecting problem lies in the interpretation of the Saffir-Simpson wind intensity categories as all-purpose danger/decision thresholds, as is suggested across studies (e.g., Whitehead, 2000; Whitehead and Smith, 2000; Howell, et. al., 2005; Morrow and Gladwin, 2006; Zhang and Morss, et. al., 2007; Morss and Hayden, 2010), as well as in past storm events. The major response failure by the general public in Hurricane Ike was largely attributed to its low Saffir-Simpson category, the intensity analogue to Hurricane Charley and the "skinny black line." As with Charley and the track forecast, the Saffir-Simpson categories were taken out of context during Ike's approach and subjected to grave misinterpretation by a significant segment of the public.

When the Saffir-Simpson categories are interpreted as all-in-one danger thresholds, if people believe they should evacuate for a storm of one category but not another - the distinction is almost never made as to whether the Saffir-Simpson category under consideration is the storm's current category, which is known, or its future category closer to land, which is unknowable at the time of decision, but for which there is a forecast. A TC's current intensity at the time of decision could be and often is different from that later experienced at the location. It could be dramatically different, because of the additional possibility of rapid intensification between the time of decision and the time of impact. This did not come up during Hurricane Ike, but had Ike rapidly re-intensified to a Category-4 storm, Texas coastal residents relying on descriptive communications about its then-current category and believing they were declining to evacuate from a Category-2 storm would have found out after the fact that they had instead declined to evacuate from a Category-4 storm.

The Saffir-Simpson scale is, in practice, being widely interpreted as a generalized hurricane danger scale, something the public obviously wants, but which does not now exist. The events of Hurricane Ike, in which storm size played a major role, demonstrated the inadequacy of the Saffir-Simpson scale as a substitute for the more general scale. The underlying meteorological context for correct interpretation of the Saffir-Simpson scale is that every storm is different, and that the scale alone cannot account for all storm effects. Of the four major TC effects - storm surge, wind, flooding rain, tornadoes - the scale is able to consistently communicate the danger posed by only one of those: wind.

Danger thresholds based on Saffir-Simpson categories have been found to vary by region, a result with little discernable relation to the actual TC threat in the different areas. The balance of perceived safety for coastal Louisiana respondents seemed to break at Category-4 (Howell, et. al., 2005), while in the greater Galveston area of coastal Texas the responses to the hypothetical evacuation-by-category question clearly flipped from "no" at Category-2 to "yes" at Category-3 (Zhang and Morss, et. al., 2007). Hurricane Ike was the next Category-2 storm to strike the area, and the study's finding effectively predicted the outcome, that a Category-2 storm would not meet the threshold of danger for a significant portion of these residents. A subsequent study conducted after the passage of Hurricane Ike found approximately 35 percent of respondents in that same area still saying categorically "no" to evacuation from a future Category-2 storm (Morss and Hayden, 2010).

b. Track

Documented misinterpretations of the official track forecast cone (Broad, et. al., 2007) have in common the problem of misidentification of the cone's core components. Some of the misinterpretations place the sequenced components of the product into an incorrect temporal context, for example, "this shows the past and forecasted path of the storm." Almost all of them share a fundamental inability to correctly identify the shaded area of the cone, to "see" its component circles both as uncertainties and as distinctly separate entities.

Some cone misinterpretations, documented not only formally but also known informally in weather forecast offices throughout the southeastern United States, identify the shaded area as representing something concrete, as a physical storm attribute or effect. These concrete interpretations tend to fall into two basic clusters: the size/wind field interpretations, e.g., "the area the entire storm is expected to cover," and the damage swath/danger zone interpretations, e.g., "the area that it [the storm] is effecting [sic]" (quotes cited in ibid). Even if people have the prerequisite knowledge that a one-day forecast is more reliable than a three-day forecast, as is reflected in the data (Morss, Demuth, and Lazo, 2008), this does not necessarily mean they are able to apply it to cone interpretation. Indeed, it would be unlikely, if not impossible, for them to do so without first being able to identify the cone's core components, and therefore ascertain the substance and intended meaning of the shaded area.

The practice of mapping and contouring abstract mathematical and statistical concepts, among them uncertainty and probability, is common within the scientific disciplines: among scientists, comprehension is automatic and second nature. For those unfamiliar with it, a conscious, two-step process may be required. Despite the cone's ubiquitous presence in the public arena, available evidence points to a persistent inability by many users to undertake the two-step process, to "unzip" the data packaging of the cone and reveal its contents.

Doing so enables a user to "see" in a typical three-day cone not a single, blended object, as in the documented misinterpretations, but a composite image consisting of six distinct objects: one current estimated storm position and five separate forecast objects. The passage of time itself is the second abstraction in the cone, reflecting the value scientists place on efficiency (compactness, non-repetitiveness) in the presentation of data. As a multiday forecast, it compresses multiple, sequential time frames, in which storm motion is forecast to occur, into a single still object. In most instances, the component circles are themselves overlapped to a lesser or greater extent, leading to even greater compression.

In some track forecasts, there may be significant to near-total overlap of the component circles: a respondent in the NHC's request for comments on its three different cone options referred collectively to those examples as "cluttered," (e.,g., option #3b, figure 2, last pg., right pane) and was unable to recognize them as alternate examples of the same three cone options (e.g., option #3a, left pane) (Broad, et. al., 2007). There is much evidence to indicate that non-scientist users do not necessarily have the ability to successfully uncompress the data.

Separating out the cone components and noticing their sequential arrangement may be obvious to the scientist, yet may not be automatic for a population that might be focused primarily on where the TC is forecast to intersect a particular landmass rather than what it may be doing out in ocean - the track analogue of the "intensity at landfall" interpretation. However, as with the intensity forecast and the progression of Saffir-Simpson categories of increasing uncertainty, proper time-sequencing means starting with the current storm, wherever it may be, and moving with it in a forward direction through time and space. A clear understanding almost requires the adoption of the forecasters' storm-centric perspective for purposes of interpretation, because that perspective is built into the structure and logic of the cone itself.

Seeing the cone as a time series that starts with the current estimated position of the storm, and moves through time and space into an increasingly distant and therefore uncertain future, gives meaning to the ballooning of possibilities across time, to the progressive enlargement of the circles with increasing forecast lead time. It is for this same reason that the current trend of doing away with the center-track line has had the effect of making the entire cone product more transparent, not less. The uncertainty is an abstract concept represented spatially and temporally by circles of increasing radii; the circles themselves are embedded and not directly visible in the cone. However, since they are the cone's component parts, the circles are the cone, and therefore the comprehension of the circles is necessary for the comprehension of the cone.

It is not only the data packaging, but also the origin and substance of the uncertainty, that appears to be insufficiently understood. The constantly changing, shifting, dynamic nature of the steering currents across time is an important part of track forecast uncertainty, and is part of the background context for short-term changes in the track forecast. The steering currents in which TCs are embedded, and the surrounding atmosphere in its more global sense, are changing all the time, with forecast model guidance being continuously updated to accommodate these changes.

There is evidence that the different classes of users may not have a sufficient pre-existing understanding of the continuously changing nature of the steering currents as background context for the track forecast. Emergency managers and the media alike were found to have been surprised by short-term changes in the track forecast, and confused by what they perceived to be a lack of explanation by forecasters for them (NWS, 1990). This is related to the well-known "forecasters can't make up their minds" problem: if people do not know why they should expect these changes, they may mistake their occurrence for evidence of the indecisiveness of forecasters.

A different manifestation of the same problem is contained within the non-linguistic aspects of the misunderstanding surrounding the "100-year storm" concept (NWS, 1996). In other words, this may not be solely a semantic problem about the misinterpretation of problematic language, though the language itself certainly complicates things. It suggests to some non-scientist users a predictable long-term periodicity where none exists, and it implicitly conflates TC attributes with TC effects: it is unclear whether the label "100 year storm" applies to attributes of the storm itself or to severity of the damage at a location. Equally important, however, is the fact that a TC might track in a certain direction and therefore strike one location as opposed to another because it is being steered that way in the moment, not because the location is itself on a pre-determined schedule to receive a catastrophic hurricane strike after the passage of a fixed interval of time (100 years).

Finally, evidence was found of some difficulty in understanding the significance of a decrease in the forward speed of a TC: a little more than half provided an incorrect answer to this question, whose correct answer was more rainfall due to more time spent by the storm over an area (Lindner, Cockcroft, and Brueske, 2004). Fewer people, only about one-third of that sample, failed to realize that errors in forecasting the forward speed would affect the time available for evacuation (ibid.), but that is an even more basic connection. Even if people had learned the relationship between time, speed, and distance in earlier school years, it does not necessarily mean they will be able to trigger access to that knowledge, apply it to the forward speed information, and draw the correct meteorological conclusions - or even understand that the forward speed information was relevant in the first place.

c. Size

There is a relative sparsity of data about the public's interpretation of statements about storm size, how the public conceives TC size or its significance, or even to suggest it is on the public radar. There is evidence, however, that size is not always separated from intensity, and is often tangled up with it. Not everyone understands that size and intensity are two different, independent storm attributes that may combine in different ways: "They [emergency management] apparently focused on an earlier description of Marilyn as a small Category 1 hurricane and were not prepared for a direct hit from an intensifying storm.... They [the media] also assumed that since Marilyn was a compact storm, much smaller than Hugo or Luis, it would be a fairly minor event" (NWS, 1996).

Size descriptors were found to be present in contexts pertaining to storm intensity. Terms such as "large" have been misapplied to TCs with high maximum sustained winds, which is intensity; "large" is actually a size descriptor denoting a TC with a wind field of great spatial extent, which is size. Similarly, terms such as "growth" have been misapplied to the transition of TCs from one status to another (e.g., tropical depression to tropical storm) or from lower to higher Saffir-Simpson categories, which is intensification; "growth" is actually a size change descriptor denoting the expansion of a TC's wind field (Merrill, 1984), which is size. Confusion of this type has been found to exist in the broadcast media as well as in some publicly available educational materials, e.g., "In particularly large storms (such as Hurricane Andrew), the force of the wind alone can cause tremendous devastation."

It became apparent after Hurricane Ike that clarity about the meaning of storm size is important in its own right because of its contribution to surge heights, and because of the connection of the 34-kt wind threshold to evacuation timing and deadlines. Pre-existing knowledge about the significance of Ike's extraordinarily large size - whether in relation to the potential surge heights or to the early arrival of the storm's 34-kt winds relative to its center - was not in evidence during the approach of that storm. On the timing issue, some residents in the Galveston area apparently believed they could wait another 12 hours, until the following morning, to confirm the threat as the social science research indicates people often do, and delayed their departure. By then it was too late, as storm surge had already begun to overtake the area (TWC, 2009).

5. CONCLUSION

Although the TC descriptions and forecasts are partially translated for the use of non-scientists, the study concludes that the material still retains components that are technical, which might be defined as "using terminology or treating subject manner in a manner peculiar to a particular field" (Random House, 1967). It still contains content that requires specialized knowledge and close ongoing familiarity with the subject matter and its background context to be understood as intended by forecasters.

From the user side, much of the meteorological context necessary to obtain better clarity in understanding the TC descriptions and forecasts may be found in the interrelationships, and in the making of distinctions, among the elements within four basic groupings:

1. TC attributes; e.g., direction, forward speed, intensity, size, others.
2. Framework attributes; e.g., time/change, space/distance, motion/steering, others.
3. Land attributes; e.g., bathymetry, topography, orientation/angle, latitude, others.
4. TC-land interactions; e.g., storm surge, rainfall/flooding, wind, tornadoes, others.

The realization that elements both within and among these basic groupings will combine in different and unique ways every time a TC approaches helps shed light on one of the most important elements of contextual knowledge: the knowledge that every storm, and every storm event, is different from every other. This knowledge could help members of the public to understand why they should not try to draw their own conclusions about these complexities by themselves, and why they should rely more heavily on those with expertise in the scientific subject matter to help them interpret the substance and significance of what they are seeing. The problem of TC descriptions and forecasts taken and interpreted out of context includes many of the interpretation errors found in the source data.

From the forecaster side, the problem of the communication of hurricane forecasts may not be in the first place so much about the procedural aspects of how to communicate (form), but more fundamentally, in the precedential sense, about the deeper substantive questions of which types of scientific content should be disseminated beyond the scientific community, and which content should be directed toward which audiences. The NWS concluded after Hurricane Charley that "[e]ducation on hurricane products needed improving, particularly with regard to the forecast track cone of uncertainty" (NWS, 2006). Yet this type of specialized education about forecast interpretation, which is not limited to the track forecasts, almost implies a form of training. In communicating with members of the general public, the problem ultimately becomes one of ascertaining what scientific content is most relevant to their purposes, and then, how to break down the selected content and make it completely transparent to audiences that may be unfamiliar with the scientific basics.

Emergency managers, who are mostly non-scientists, receive specialized training to show them how to interpret the TC descriptions and forecasts as intended by forecasters and convert it into knowledge with relevance in the physical world. Yet even they have still on occasion fallen into making the same types of interpretation errors as other non-scientists; even members of the media are not completely immune. Members of the general public, who do not receive this specialized training, may require the introduction of supplemental content that is even more transparent.

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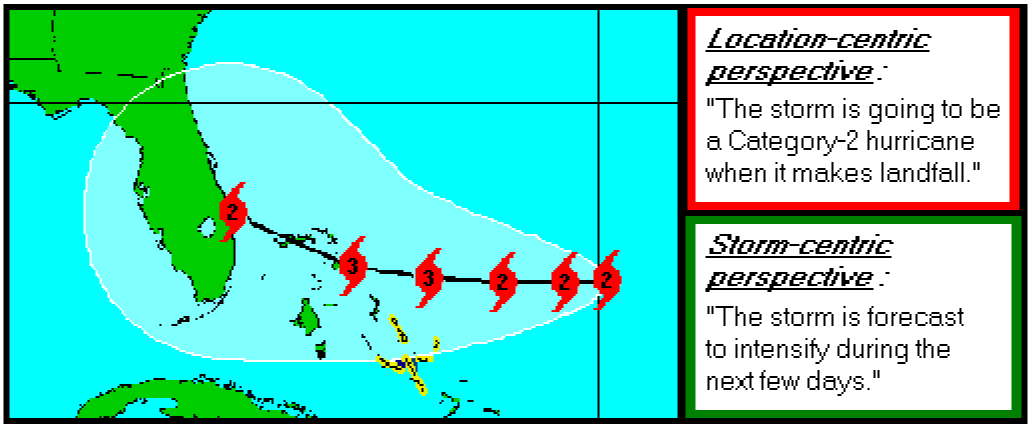
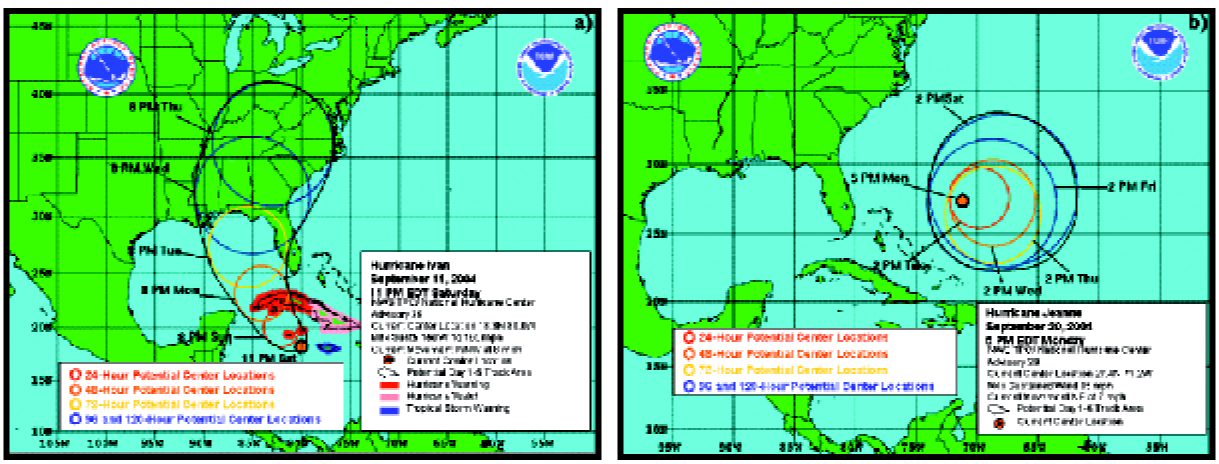
Figure 1
Interpretation of Media-Style Intensity Graphics



Adapted from NHC Hurricane Jeanne Advisory #40, 9/23/04, 1500Z.

Figure 2
Degrees of Overlap in Track Forecast Uncertainty Circles for Hurricanes Ivan and Jeanne (NHC Cone Option #3)



NHC Cone Option #3, depicting forecasts for Hurricanes Ivan and Jeanne, left and right respectively. Images re-printed from Broad, et. al., 2007.