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for the

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The National Hurricane Center did a good job with Hurricane Katrina. Hurricanes, by nature, are notoriously difficult to predict and Within 3 days of a northern Gulf coast landfall, the National Hurricane Center had refined the forecast landfall to the area that eventually was impacted by the storm.

Hurricane forecasting has come a long way over the last half century. The advent of weather satellites was probably one of the most revolutionary developments in hurricane tracking. No longer would a storm be un-detected over the vast expanse of tropical oceans and potentially strike an unsuspecting community without warning. Over the last several decades, reconnaissance and research aircraft have provided storm location and intensity information which was useful to hurricane forecasters. In addition, these aircraft, combined with coastal Doppler radars, have provided large amounts of data which has been useful in understanding the structure and evolution of the hurricane's severe inner core of winds and rainfall. The increased number of weather buoys deployed over the Gulf, Atlantic, and Caribbean Sea have helped to provide better coverage in a region where very few if any weather observations existed.

5-Day Forecast

As computer capabilities became larger and their speed faster, sophisticated weather forecast models have used much of this data to provide multi-day forecasts of tropical cyclones. Here is an example of the expansion of hurricane forecasting lead time which has occurred over the last quarter century for various storms which struck the north-central Gulf coast:

1979	Hurricane Frederic:	1-day forecast (only 18-20 hours lead time).
1985	Hurricane Elena:	3-day forecast
1998	Hurricane Georges:	3-day forecast
2005	Hurricane Katrina:	5-day forecast

Theoretically, with these longer-range forecasts, communities and the public have greater lead times in order to begin preparing. However, I am not so sure that the vast majority of the public has the confidence necessary in these forecasts to motivate them to begin early preparation.

With Katrina last month, the 3-day forecast was much more helpful in correctly portraying Katrina's landfall location than most of the 5-day forecasts. For example:

- From 5 pm Tuesday (23 Aug) – 11 am Wednesday (24 Aug): 5-day forecasts displayed some skill bringing the storm across Florida and into the eastern Gulf of Mexico (See Figure 1)

- After that, the 5-day forecast was generally not helpful in portraying the threat to New Orleans and the Mississippi Gulf Coast. Instead, the 5-day forecasts generally portrayed an incorrect threat to the Florida Big Bend and eastern portions of the Florida Panhandle (see Figure 2).
- By the time a serious threat to New Orleans became apparent, the storm was within 3 days of landfall. At 5 pm Friday (26 Aug), the storm is within 3 days of landfall and the 3-day forecast shows significant skill from this point forward with portraying a serious threat to the SE Louisiana, Mississippi, and Alabama coast. Thus, the 3-day, not the 5-day forecast, was useful in portraying Katrina's threat to the Louisiana/ Mississippi/ Alabama coastline (see Figure 3).

Starting in 2004, forecast outlooks were expanded from 3 days to 5 days. Having operationally produced numerous forecasts for industrial clients on all storms threatening the U.S. since 1997, I personally do not believe a 5-day forecast should be produced for <u>every</u> tropical cyclone (assuming 5 or more days of existence remain). There are some storms which are absolutely unpredictable at the 4 and/or 5 day point. Many of these are "difficult" storms are embedded within very weak steering currents, or within environments displaying moderate vertical wind shear.

Initially, Katrina's steering currents were fairly well defined, as evidenced by the general agreement (i.e., the general lack of scatter in the forecast tracks) between many models (see Figure 4). In this case, the 5-day forecast certainly indicated a possible future threat to the north-central Gulf coast area (see Figure 1). A couple of days later however, as scatter between model forecasts increased, the accuracy of Katrina's 5-day forecast went down as the northeast Gulf coast was now targeted (see Figure 5 and compare to Figure 2). Finally, after Katrina moved into the Gulf, the model forecast scatter once again began decreasing, and the threat shifted back to the north-central Gulf coast (see Figure 6 and compare to Figure 3). But by this time, the storm was within 3 days of landfall.

Hurricane Ophelia is an example of an unpredictable storm in which a forecast should be limited to only 3 days. Ophelia was embedded in weak steering currents and the scatter of the model forecast tracks was huge (Figure 7). The terribly large scatter of forecast tracks indicates that there should very little confidence in the storm's 5-day forecast; therefore, the public should only receive a 3-day forecast instead of the 5-day forecast as portrayed in Figure 8. Instead of striking South Carolina and moving well inland, the storm actually grazed the North Carolina coast before moving out to sea.

The National Hurricane Center's Tropical Cyclone Discussion from 5 am EDT, Friday, September 9 2005 indicates the forecaster's lack of confidence in the forecast track.

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THIS STORM...I HAVE ONLY MADE A MODEST WESTWARD ADJUSTMENT WITH
THE OFFICIAL FORECAST AT THIS TIME.  IT IS TOO EARLY TO BE
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SPECIFIC ABOUT WHICH AREAS MIGHT ULTIMATELY BE AFFECTED BY
OPHELIA...BUT THE PROXIMITY OF THIS CYCLONE TO THE COAST AND THE
WEAK STEERING CURRENTS DICTATES THAT INTERESTS FROM FLORIDA
THROUGH THE CAROLINAS WILL NEED TO MONITOR OPHELIA FOR THE NEXT
SEVERAL DAYS. …
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The graphic did not display this level of uncertainty any different than it would a more confident forecast, and most people see the graphic and not the Tropical Cyclone Discussion. Thus, a 4 and 5-day forecast track to South Carolina is misleading, even if there are huge margins of error depicted on the graphic. These margins of error (depicted by the white circular line surrounding the forecast track) are the same for every forecast, regardless of the true confidence of the forecast.

Yet, there are other storms in which the steering currents are well established and the storm is predictable with great accuracy out to 5 days. Hurricane Emily is an example of a storm with a highly predictable track (see Figures 9 and 10).

I believe that the 5-day forecast product contributes to public cynicism and too often tends to give the public the impression that "The 5-day forecast may have the storm pointed at my city today, but it always changes; I will wait until tomorrow or the next day before I begin to take any action. After all, I fully expect the track to be pointed somewhere else tomorrow, so why should I begin to prepare now?" I believe some of this mentality may have affected actions by both the public and public officials prior to Katrina's landfall.

I believe each storm should be forecast at least out to 3 days, regardless of the predictability. However, I believe that it would serve the public much better if the 4 and/or 5 day forecast were only issued when the confidence of the forecast is relatively high at that time range. A "confidence gauge" could be developed by calculating the "scatter" or "standard deviation" of the more reliable track models at the 4 and 5 day forecast points. If the "scatter" was within acceptable limits, then proceed with the 4 or 5 day forecast, but otherwise limit the forecast to only 3 days.

I have only discussed forecast tracks in the above paragraphs. The success with intensity forecasting is much less than with track forecasting. There is much more data collection and research that needs to be accomplished in order to better predict these storms.

Increasing the frequency of Mexican weather balloon launches (to 6 or 12 hour intervals, rather than the current 24 hour intervals) when hurricanes are present in the Atlantic would help increase the accuracy of measuring steering currents which later might impact the hurricane track.

<u>New Upgrade Needed for Saffir-Simpson Hurricane Scale</u>

A new hurricane intensity scale is needed in order to better relate the expected effects of a hurricane on the threatened population, thus better preparing them for the storm and their ability to evacuate.

Need a new scale to rate hurricane effects at landfall. Need alternative estimates of storm intensity which better define what a storm is capable of doing.

- Saffir-Simpson Scale is not representative of what hurricanes can do. Winds are only part of the story.

- Need a 4-pronged scale to rate the destructive potential of hurricanes which will include:
    - Wind
    - Storm surge
    - Rainfall and inland flooding.
    - Storm size

<u>Much More Storm Intensity Research Needed</u>

There need to be better ways to observe present storm intensity and predict changes in intensity.

- How strong are hurricanes? This is a very elusive question.
- Some storms appear as though they should have strong winds, but make landfall without doing much damage.
- Some storms produce wind damage which far surpasses their expected intensity.
- Some storms bring their strong winds to the ground and others don't. We cannot predict this. When it comes to wind damage and effects of the wind on the storm surge, it is the wind speeds which occur at the ground that count.

- New tools on board aircraft are being used to measure winds close to the surface of the ocean:

    - Global Positioning System Dropsondes have provided unparalleled views of vertical wind profiles in hurricanes, particularly near the surface.
    - Stepped frequency microwave radiometers (SFMR) have recently been placed on board NOAA research aircraft.
        - Presently need this type of equipment is needed on Air Force C-130 hurricane hunter aircraft.
        - SFMR provide surface wind speed estimates over the ocean.
        - Good calibration of these SFMR wind measurements only exists for low and moderate wind speed situations. Additional work needs to be done to calibrate this instrument for high wind speeds, typical of intense hurricanes. Rainfall estimates are also possible with the SFMR.
    - Important: The SFMR and other wind profiling instruments are critical to determining wave height out in the open ocean 1 or 2 days before landfall. In Katrina's case, waves generated while Katrina was a Category 5 over the central Gulf 1 or 2 days prior to landfall probably helped enhance the storm surge above what a weakening Katrina would have been capable of when it made landfall. In other words, the fact that Katrina was a large category 5 hurricane in the central Gulf probably led to a larger storm surge on the Gulf coast well above what

would probably have happened had Katrina never reached category 5. Assuming that Katrina crossed the Mississippi coast as a high category 3 or low category 4 storm, the storm surge was probably much higher with this storm because it had a recent history as a large category 5 storm. Had the storm not been so intense over the central Gulf 1-2 days before landfall, there probably would have been a smaller surge (everything else being equal). Thus, the ability to measure the size and strength of the storm is critical to storm surge prediction.

- UAVs (Unmanned Aerial Vehicles) offer great promise of long-term sampling of hurricanes, provided they are rugged enough to survive the hostile weather environment. Because of their small size and low speed, they may be better suited for remaining in the eye and measuring central pressure, rather than venturing into the rougher weather outside the eye to measure the maximum winds. Testing is ongoing.
- Storm winds near the ground in a landfalling hurricane are often difficult to asses.
    - The storms produce power outages and severe damage which often either renders wind equipment useless in the core of hurricanes, unless they are "hardened" to handle such extreme events. However, when observations are available, they are invaluable.
- Coastal and portable Doppler radars are extremely useful tools for assessing storm strength, but often cannot sample the atmosphere at low enough levels to determine the wind speed near the ground.
- Mesonets (mesoscale networks) consisting of a fairly dense array of low-cost weather stations are currently being set up by individual universities using grant money. Mesonets serve the dual purpose of operational and research benefits, particularly when hurricanes make landfall. In addition, they are good for public relations because the public likes to see local weather observations close to them. Dr. Kimball, at the University of South Alabama, is presently installing a mesonet along the north-central Gulf coast. She has had many requests from the public wanting access to her website which displays the observations taken by these instruments. Locating these instruments at schools also allows and educational component to be realized by teachers and students. During landfalling hurricane situations, these weather stations can provide extremely important wind and other weather information which can be used to determine the severity of the storm and later incorporated into research which furthers our understanding of these storms.
    - Ken Crawford has been appointed the COOP modernization person at NOAA, but that office needs to be expanded. They are often too busy to pursue collaboration efforts with universities in hurricane-prone regions.
    - These observations are critical to improving the accuracy of computer simulations attempting to re-create the structure, intensity, surge, and rainfall of actual storms which have made landfall.

    - Also, these mesonets need funding for infrastructure for long-term maintenance. After a university's mesonet grant expires, the stations may deteriorate, lose calibration, and eventually die.

Landfall Forecast Focus Needs to be Emphasized

- The accuracy of hurricane forecasts continues to slowly improve; however, the accuracy that really counts for most interests is the projected landfall location and intensity. This is where the most significant emphasis should continue to be placed. Much more research needs to be done to provide more accurate guidance to emergency managers and the public about what to expect as the hurricane approaches.
    - Obviously, accurate track and intensity forecasts are critical at landfall, but other less-obvious challenges are important too.
        - Better forecasting of size and structural changes in hurricanes which will allow for improved forecasts for the onset of tropical storm-force winds and early water rise at the coastline.
        - Onset of these winds effects evacuation efforts in the path of the storm (example: Often ferries and certain bridges used for evacuation may be closed early due to winds and/or tides exceeding limits., etc…)

Numerical Modeling

Much of the future of hurricane prediction lies in better observations and more powerful numerical computer modeling. Weather data is seriously lacking in the vicinity of tropical cyclones. These cyclones form over data-void regions of the tropical and sub-tropical oceans where weather observations are scarce. This weather data must be easily convertible into quantitative data compatible for use by weather forecast computers.

- Weather data is needed over vast regions surrounding the hurricane. The newly acquired NOAA Gulfstream jet performs some of this function, but it is not feasible to keep this aircraft continuously deployed. Satellite also can help, but most of this data alone cannot provide the quantitative accuracy or vertical detail needed by numerical models. There are some platforms, such as the QuikScat instrument deployed on low-flying polar orbiting satellites which provide good estimates of surface winds over the oceans; however, there are two major shortcomings which need to be overcome with more research:

    a. The polar-orbiting satellite only allows twice-a-day fly-overs at best, and large data-void swaths exist over tropical oceans in expansive regions between the successive orbital paths of the satellite. Often, a hurricane will fall within one of these data-void swaths and no wind data will be collected from the vicinity of the hurricane for maybe a day or two.
    Possible solutions:
        - Equip several polar-orbiting satellites with QuikScat
        - Place QuikScat on geostationary satellites, thus allowing continuous wind measurements from the same oceanic region.

b. The QuikScat wind measurements are degraded in areas of heavy rain. Since heavy rainfall is common in hurricanes, very limited information is available within the hurricane itself.

- The Tropical Rainfall Monitoring Mission (TRMM) satellite is a special satellite which has been in a low earth orbit which circles the tropical regions of the globe. This operational satellite was recently targeted for elimination, but some funds were found to extend its life. This type of satellite needs to continue operations in the future over hurricane-prone regions of the tropical and sub-tropical oceans.

- For more accurate forecasts of the inner-core structure of a hurricane, better techniques need to be developed for inserting (known as "bogusing") a hurricane vortex into numerical models. Better data incorporation and data assimilation of a representative hurricane vortex is needed in numerical models. However, in order to bogus a more accurate vortex into a model, better data quality and quantity is needed in the inner core of the hurricane.

- Better computer resources are needed to refine forecast models. Currently, the operational resolution and parameterizations of operational models are inadequate to provide routinely accurate hurricane forecasts, particularly with regards to structural changes and intensity forecasts. Faster computers and more complete numerical models are needed for more detailed and accurate hurricane forecasting.

- Observations are needed to refine model parameters. NOAA P-3 Orion research aircraft fly at a maximum altitude of 5 km, but observations of microphysical cloud structure (e.g., microphysics) above that level are needed due to their huge impacts on storm structure. The NOAA Gulfstream aircraft is capable of flying at some of these higher altitudes, but presently they only sample areas outside the immediate storm environment and not directly within the hurricane.

- Planetary boundary layer (PBL) parameters need to be refined for high wind regimes; exchange coefficients currently in use are for low winds. Plus, there is a need for quantitatively measuring and incorporating into models correct values of sea spray and wave roughness.

- Correct modeling of hurricane structure, size, and intensity is crucial if one ever expects to correctly predict flooding rainfall, storm surge and wind speed of landfalling hurricanes.

National Hurricane Center Public Relations

The Tropical Prediction Center National Hurricane Center (NHC) needs an experienced tropical meteorologist who is a professional public relations specialist. This person would be skilled at working with the media. Presently, this position is often filled by the NHC director himself (such as Mr. Mayfield). The NHC director needs to remain in the trenches with the hurricane forecasters. I do not believe that hurricane forecasts are improved by the NHC director having to devote so much time with the media when significant forecast challenges are always presented in landfalling hurricane situations. Public relations is extremely important in convincing the public that they should prepare for a hurricane, but it should not detract from the core NHC mission: accurate hurricane forecasts.

FIGURES

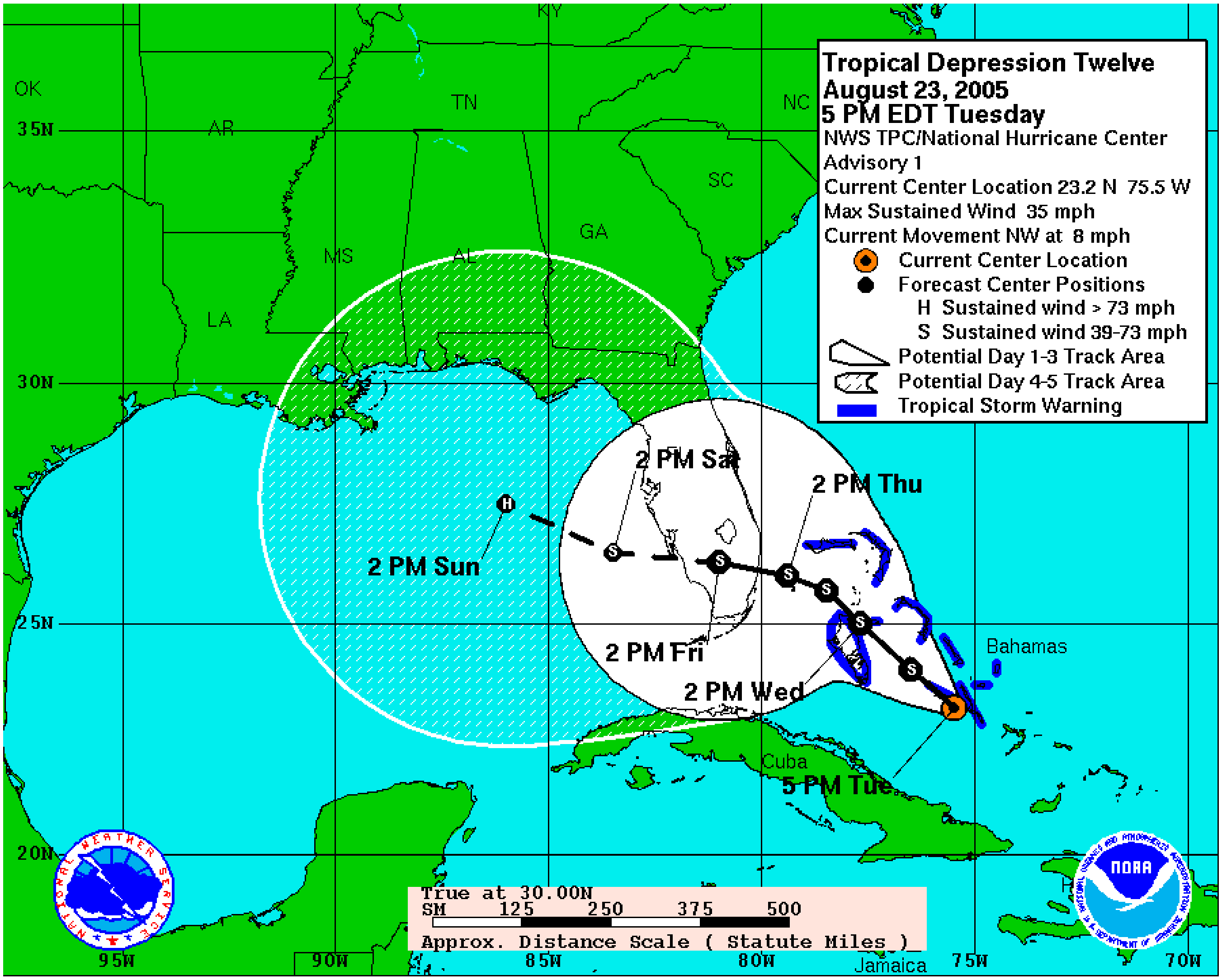

Figure 1. Hurricane Katrina 1 to 3-day forecast (solid line) and 4 to 5-day forecast (dashed line), issued 5 pm EDT Tuesday, 23 August 2005 by the National Hurricane Center. (Courtesy: Tropical Prediction Center/National Hurricane Center)

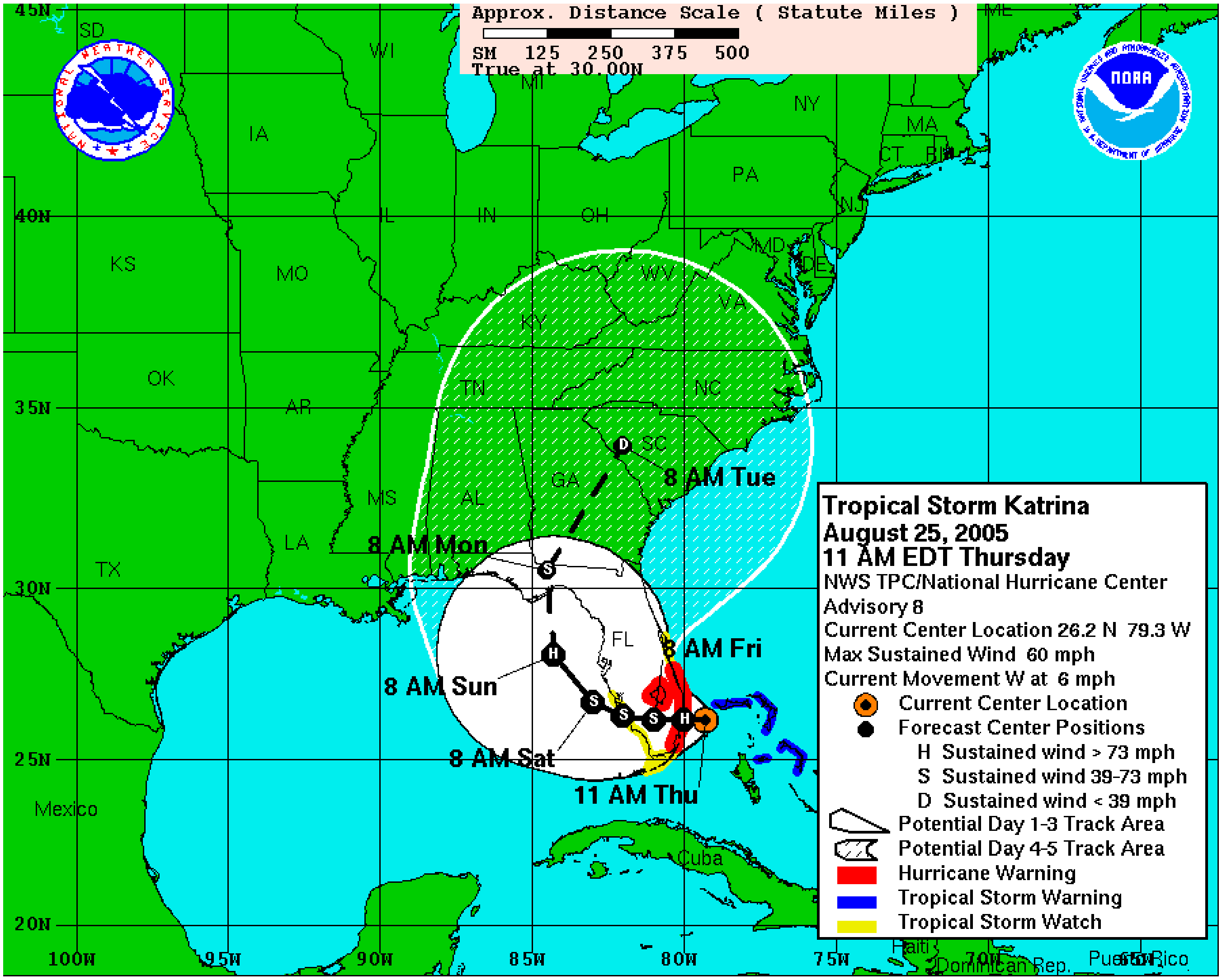

Figure 2. Hurricane Katrina 1 to 3-day forecast (solid line) and 4 to 5-day forecast (dashed line), issued 11 am EDT Thursday, 25 August 2005 by the National Hurricane Center. New Orleans, the actual landfall point, is not even within the cone of forecast uncertainty. (Courtesy: Tropical Prediction Center/National Hurricane Center)

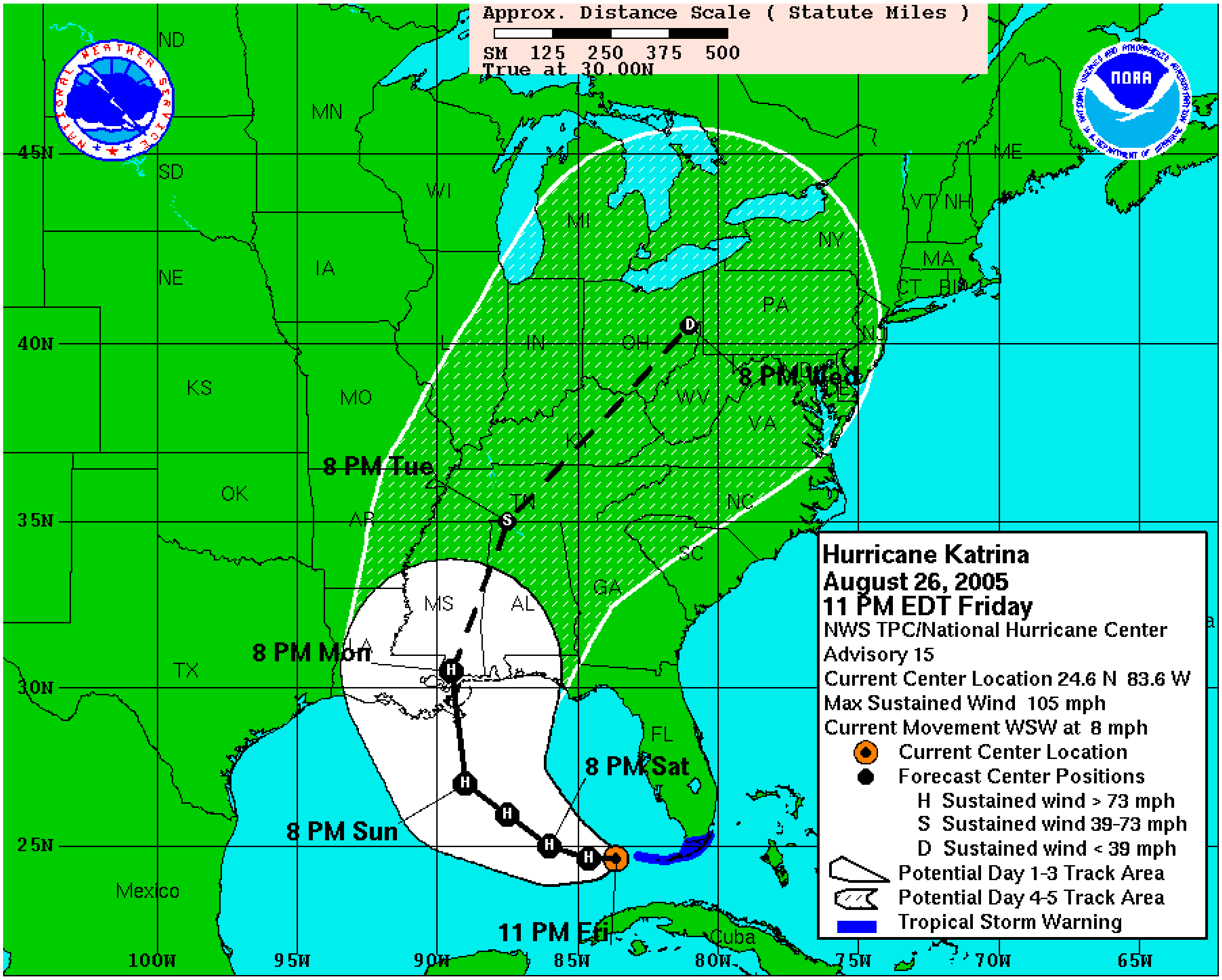

Figure 3. Hurricane Katrina 1 to 3-day forecast (solid line) and 4 to 5-day forecast (dashed line), issued 11 pm EDT Friday, 26 August 2005 by the National Hurricane Center. (Courtesy: Tropical Prediction Center/National Hurricane Center)

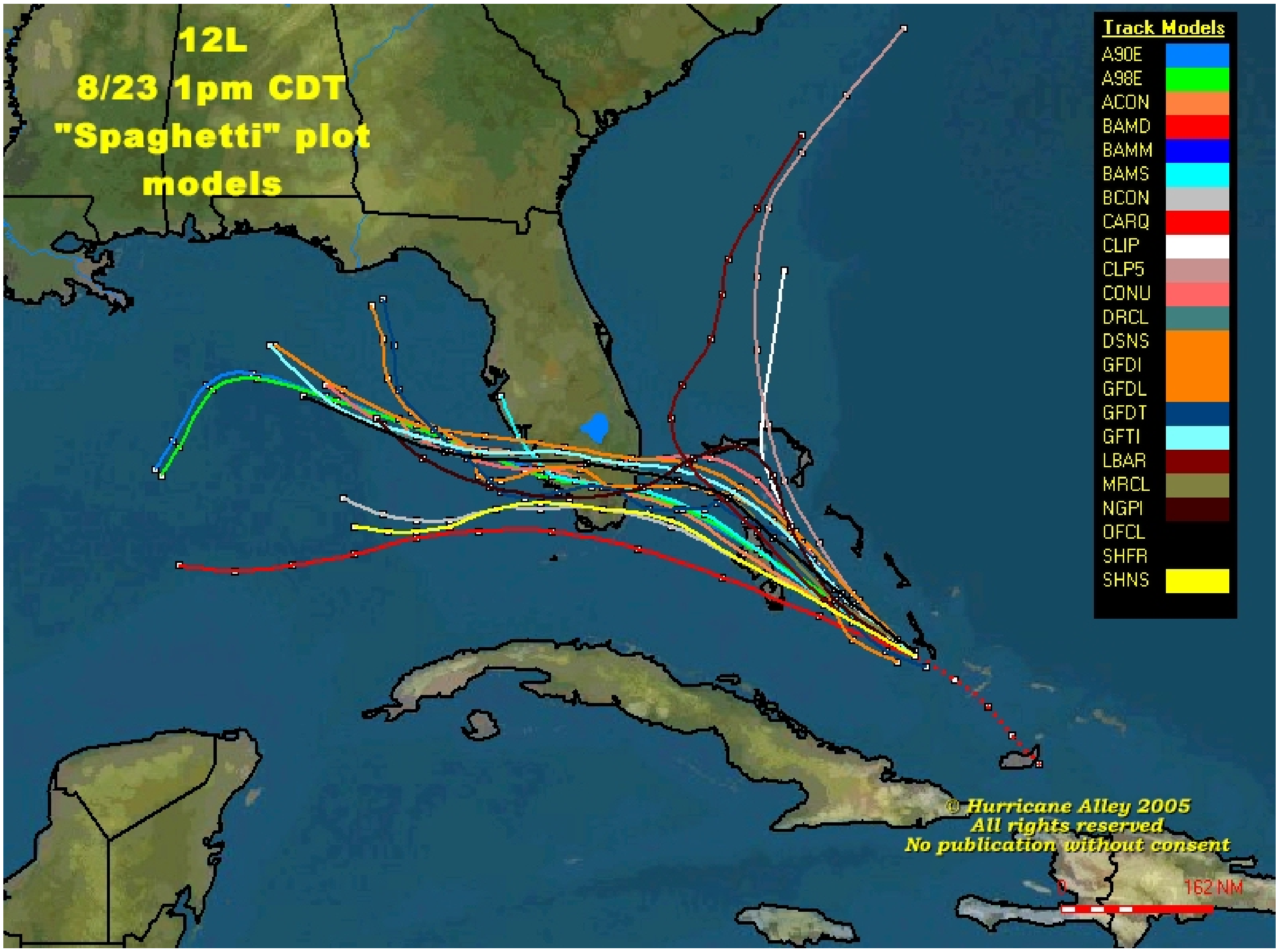

Figure 4. Hurricane Katrina forecast model tracks, issued 1 pm CDT Tuesday, 23 August 2005. Relatively good agreement between models indicates that there should be reasonable confidence in the 5-day forecast displayed in Figure 1. (Graphic used with permission from *Hurricane Alley*)

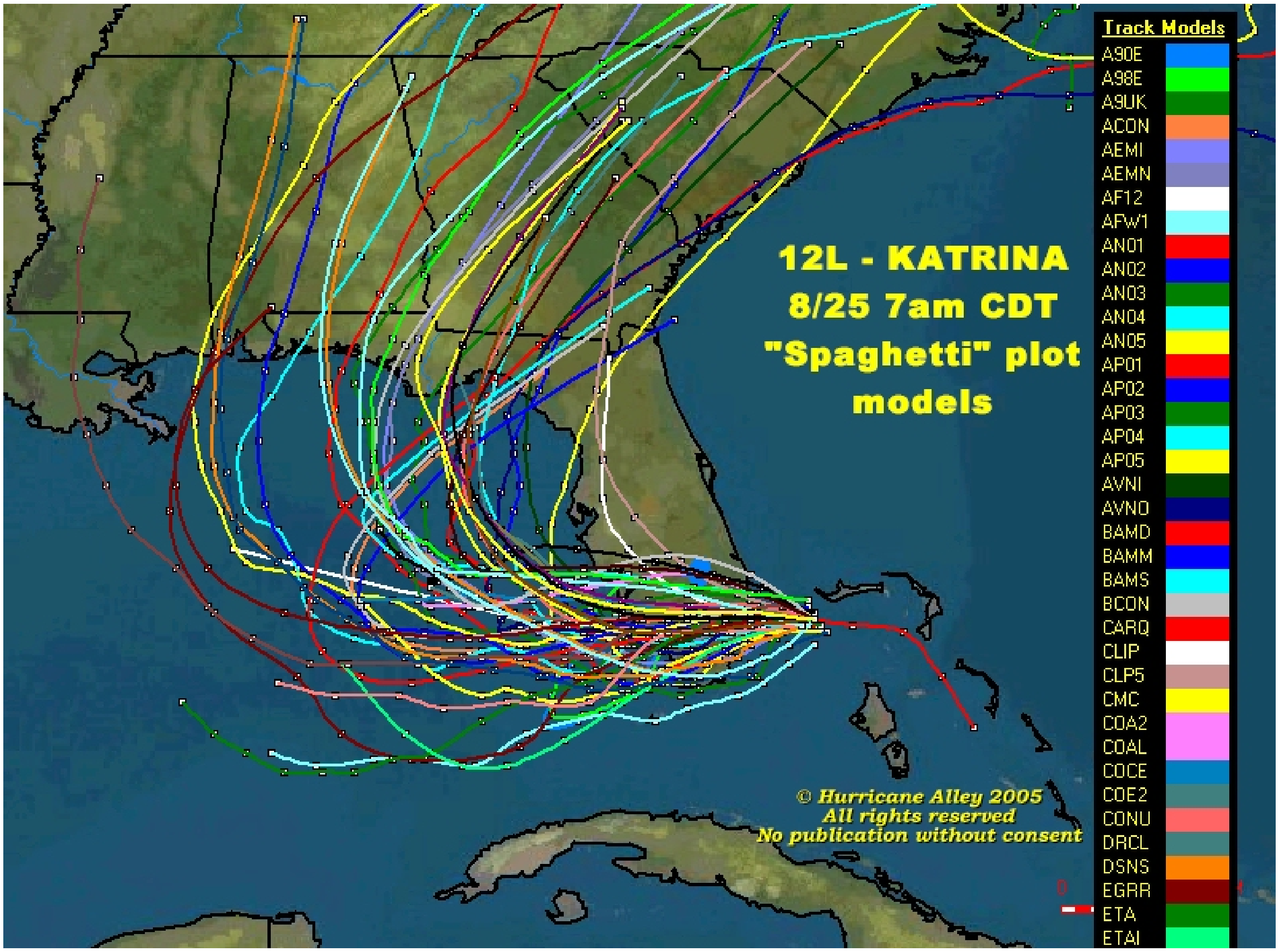

Figure 5. Hurricane Katrina forecast model tracks, issued 7 am CDT Thursday, 25 August 2005. Increasing scatter of forecast model tracks indicates that there should be less confidence in the 5-day forecast displayed in Figure 2. Maybe a 3 or 4 day forecast would be more useful than a 5-day forecast. Note that nearly all the models are much too far east and don't show a threat to New Orleans. (Graphic used with permission from *Hurricane Alley*)

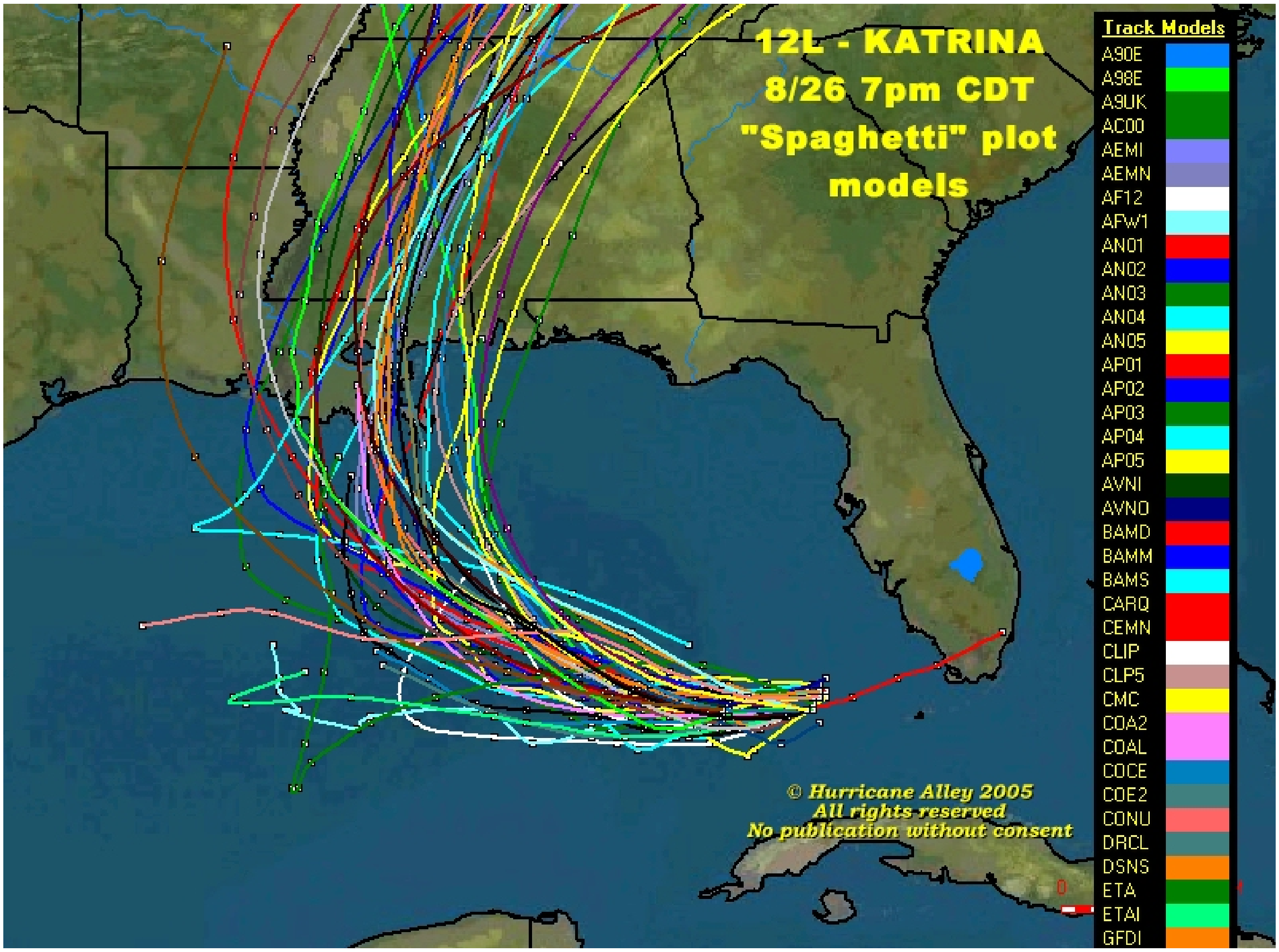

Figure 6. Hurricane Katrina forecast model tracks, issued 7 pm CDT Thursday, 26 August 2005. Decreased scatter of forecast model tracks indicates that there should again be greater confidence placed in the storm's 5-day forecast displayed in Figure 3 . A 5-day forecast is appropriate in this situation. (Graphic used with permission from *Hurricane Alley*)

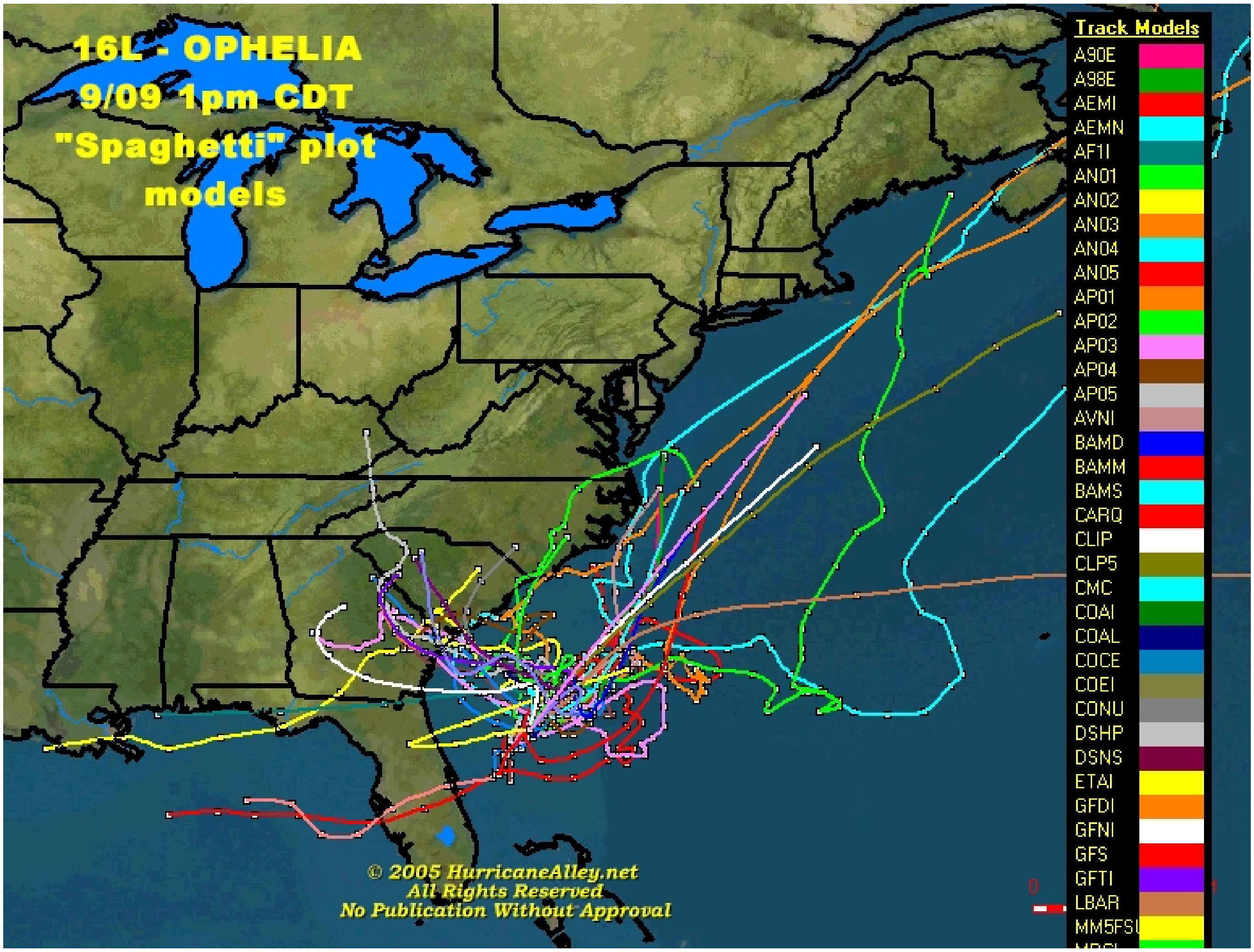

Figure 7. Tropical Storm Ophelia model forecast tracks, issued 1 pm CDT Friday, 9 September 2005. The terribly large scatter of forecast model tracks indicates that there should very little confidence in the storm's 5-day forecast; therefore, the public should only receive a 3-day forecast instead of a 5-day forecast as portrayed in Figure 8. (Graphic used with permission from *Hurricane Alley*)

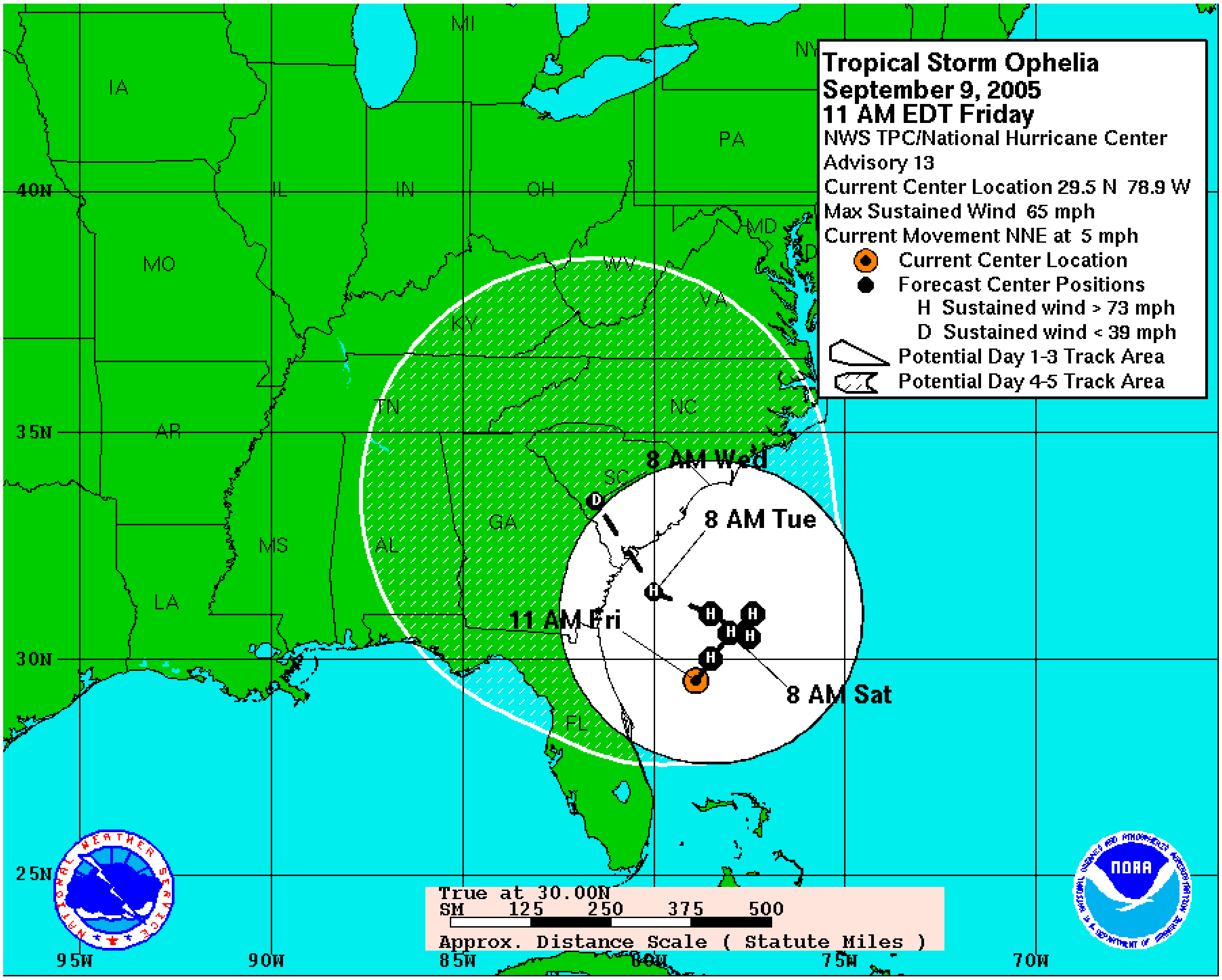

Figure 8. Tropical Storm Ophelia 1 to 3-day forecast (solid line) and 4 to 5-day forecast (dashed line), issued 11 am EDT Friday, 9 September 2005 by the National Hurricane Center. (Courtesy: Tropical Prediction Center/National Hurricane Center)

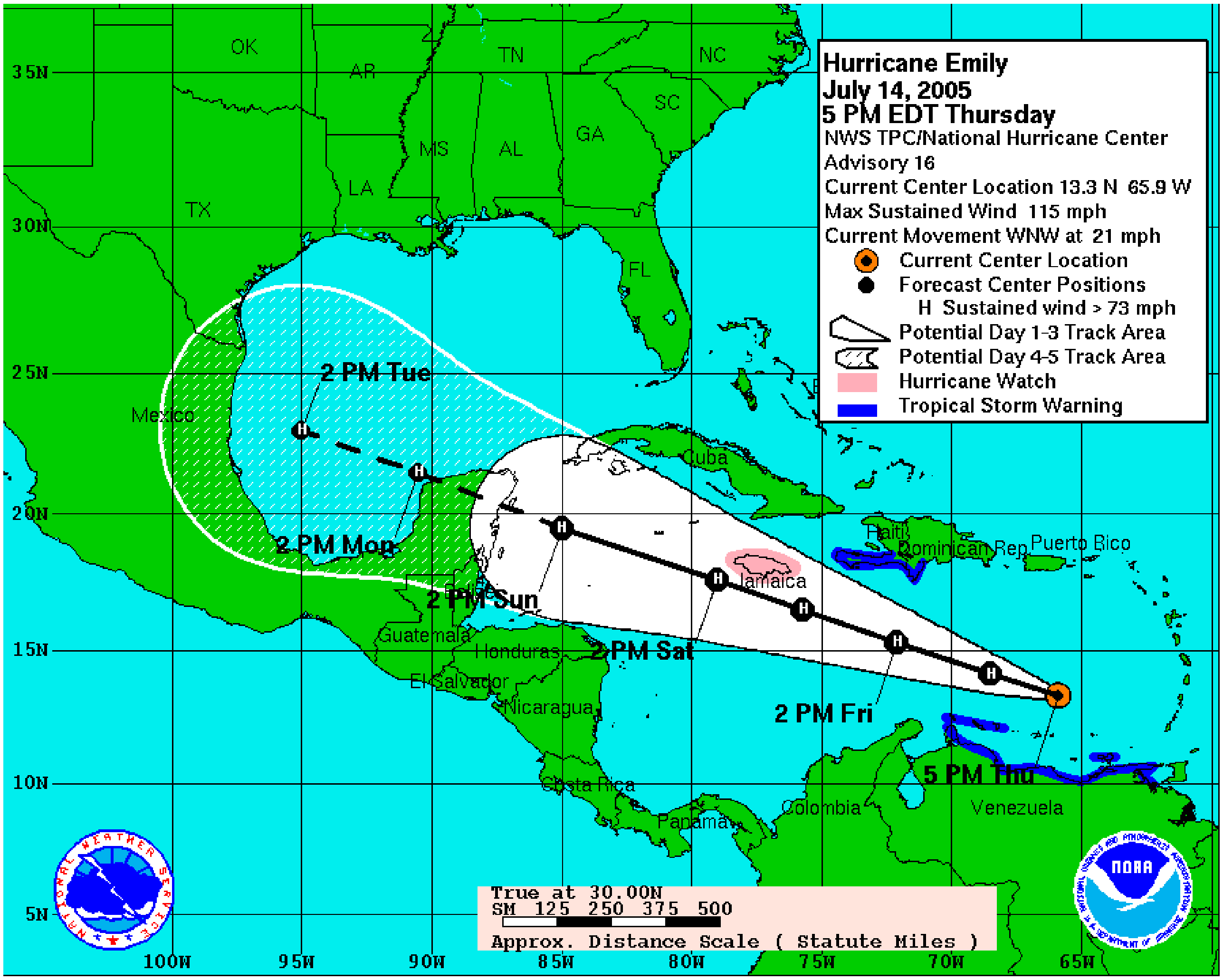

Figure 9. Hurricane Emily 1 to 3-day forecast (solid line) and 4 to 5-day forecast (dashed line), issued 5 pm EDT Thursday, 14 July 2005 by the National Hurricane Center. (Courtesy: Tropical Prediction Center/National Hurricane Center)

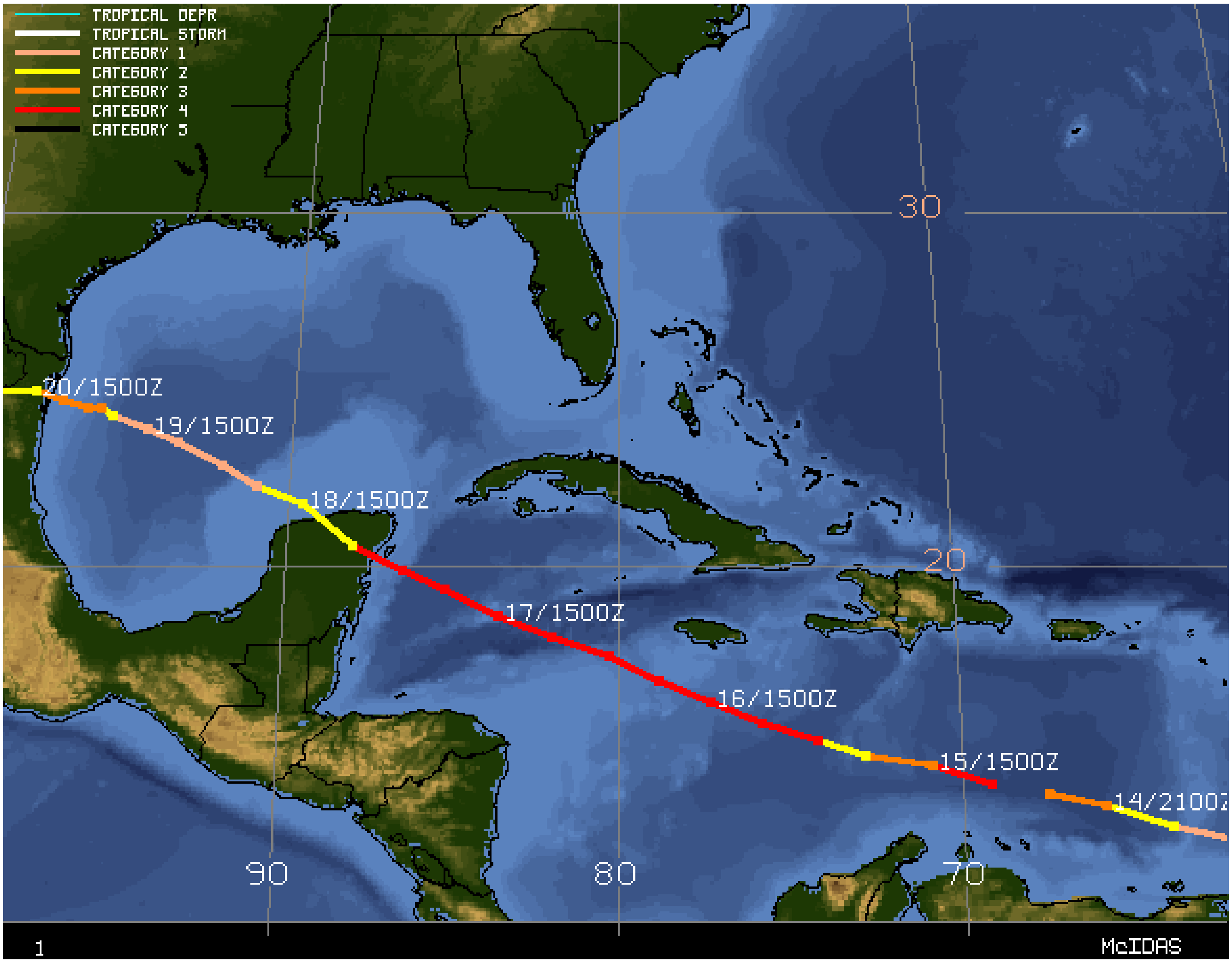

Figure 10. Hurricane Emily track. (Courtesy: Cooperative Institute for Meteorological Satellite Studies (CIMSS).