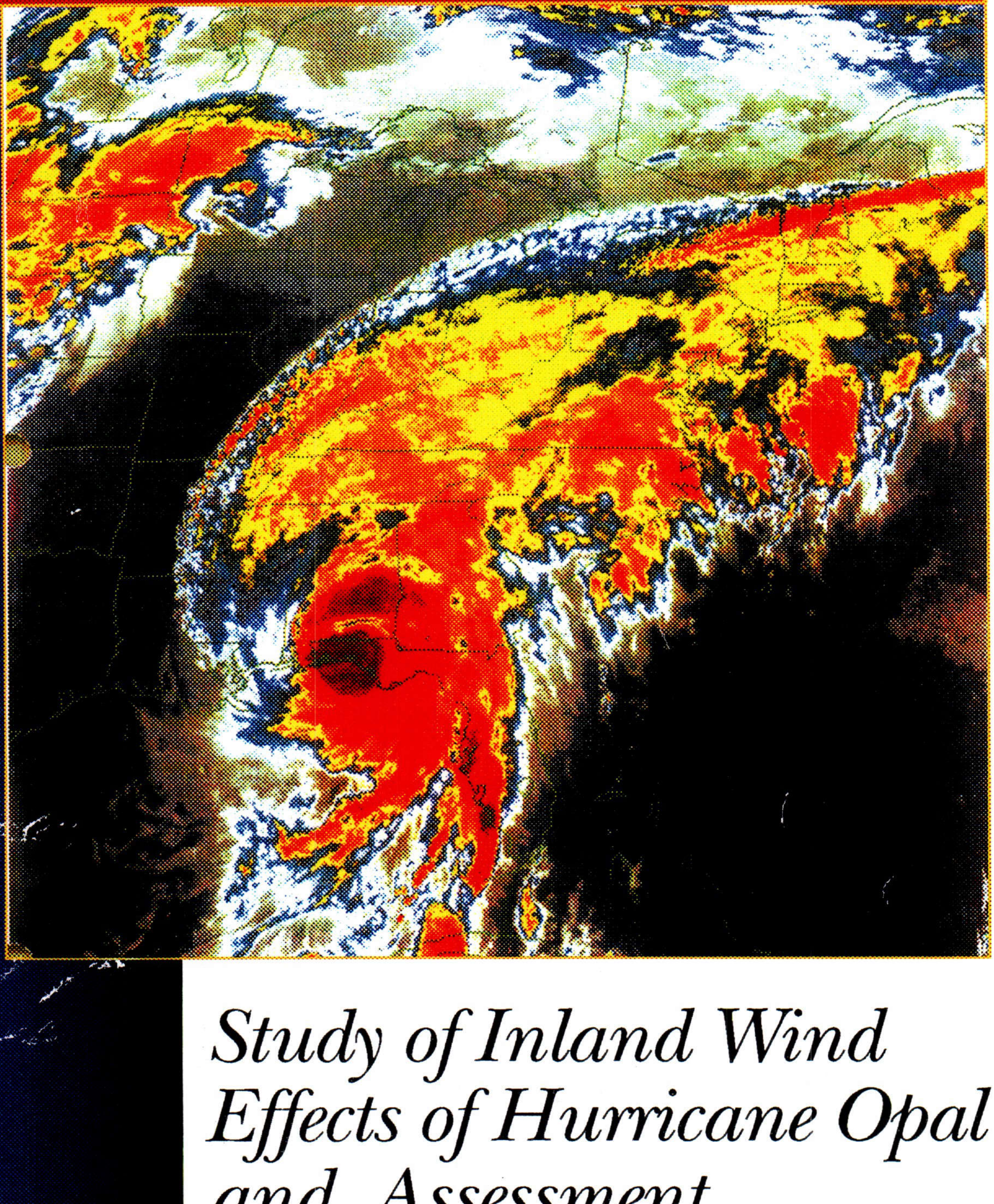
DRAFT REPORT **MAY 24, 1996**



Study of Inland Wind Effects of Hurricane Opal and Assessment of Inland Wind Model

FEDERAL EMERGENCY MANAGEMENT AGENCY
MITIGATION DIVISION R6 IV

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STUDY OF INLAND WIND EFFECTS OF HURRICANE OPAL AND ASSESSMENT OF INLAND WIND MODEL

DRAFT REPORT

Prepared for:

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1 INTRODUCTION

1.1 Background

Hurricane Opal made landfall just east of Pensacola, Florida, on October 4, 1995, at approximately 6:00 p.m. c.d.t. (central daylight time). The estimated maximum sustained wind speed at the time of landfall was reported to be 125 miles per hour (mph) and the forward speed of the storm was 22 mph. Six hours before landfall, the storm was classified a Category 4 storm on the Saffir-Simpson Scale; it was downgraded to a Category 3 storm at landfall. During October 4 and 5, the storm traveled approximately 500 miles inland, reaching as far north as the southeast portion of Kentucky.

Research performed after the storm by the Hurricane Research Division of the National Atmospheric and Oceanic Administration (NOAA) indicated that the maximum sustained winds were in the range of 100 to 115 mph at landfall and rapidly decayed to 86 to 92 mph just inland.

The effects of the storm were felt as far north as Huntsville, Alabama, and Asheville, North Carolina, and as far east as Atlanta, Georgia. Hurricane force winds (greater than 74 mph) were measured as far inland as Fort Rucker, Alabama, some 100 miles from Pensacola, Florida. High winds and tornadoes spawned by Opal occurred as far north as Maryland.

Total damages resulting from Hurricane Opal have been estimated to be as high as $3 billion. According to Federal Emergency Management Agency (FEMA) Disaster Survey Reports, damages to infrastructure in inland communities totaled over $157 million. Nine deaths were reported to have resulted from the hurricane -- one caused by a tornado and the others by trees falling on structures.

1.2 Purpose

Under contract to FEMA, Greenhorne & O'Mara, Inc., (G&O) conducted an investigation to evaluate the damages resulting from inland winds associated with Hurricane Opal, verify and standardize the recorded wind data for Hurricane Opal, compare wind information predicted by the Inland Wind Model with the recorded wind data, and ultimately assess the ability of the Model to predict wind speeds accurately and support the pre-storm estimation of expected damage levels. Section 5 of this report describes the development and purpose of the Inland Wind Model. Information about both wind and wind-induced damage was collected from many sources for the four-state area affected by Opal: Alabama, Florida, Georgia, and North Carolina. Although emphasis was placed on inland communities, wind information was also obtained from several sources along the coast of the Florida Panhandle.

The investigation included collecting wind speed and wind damage data, conducting site visits to assess storm damage over the four-state affected area, contacting a large number of people who had pertinent information, and analyzing the information to compare the effects of Hurricane Opal to those of other inland wind events. As a supplement to this technical report, a slide presentation was prepared that summarizes G&O's findings, conclusions, and recommendations. In addition, a descriptive reference guide was prepared (see Table 8.1) that categorizes the damages associated with various wind fields in inland communities.

types

FEMA expects that county emergency managers will be able to use the personal computer (PC) version of the Inland Wind Model to predict the ~~levels~~ of damage that may result from a particular inland wind event and to help organizations such as utilities, schools, churches, and the Red Cross ~~prepare for the~~ expected damages. ~~to~~ so that plans / SOP and/or procedures can be developed ~~to~~ in preparation for such events.

1.3 Organization of the Report

FEMA's DSP plays

This report presents an overview of Hurricane Opal, a description of the investigation, a discussion of ~~the~~ Inland Wind Model -- ~~both the PC version~~ and the ~~version~~ developed by the National Weather Service (NWS) National Hurricane Center (NHC) -- Predictive model and a detailed review of actual wind speeds and the predicted effects of various wind fields. A comparison of predicted and recorded wind data provides the basis for conclusions and recommendations concerning predicting wind speeds, estimating the expected damages, and undertaking mitigation measures that can enhance building performance under gale-force wind, storm-force wind, and hurricane conditions. A descriptive reference guide has been developed for use by emergency management personnel to help describe the effects of strong inland winds.

Supporting data, including site visit summaries, a list of persons contacted, sources of information and wind model output information, are provided in appendixes. Where applicable, photographs, charts, figures, and maps are used throughout this report to present findings and illustrate the conclusions and recommendations.

2 INVESTIGATION

2.1 Information Sources

Numerous sources of information pertaining to Hurricane Opal were contacted, including state and local governments, universities, newspapers, and television stations. A comprehensive list of the specific individuals and organizations contacted is provided in Appendix A, and the newspapers and other materials reviewed are listed in Section 9. The types of sources contacted are as follows:

- State Hurricane Program Managers
- County Emergency Managers
- Federal and state Forest Service personnel
- Meteorologists
- Regional and national newspapers
- Local television stations
- NWS Climate Data Centers
- The U. S. Census Bureau
- Military airports
- Regional airports
- Universities
- Utility companies
- The American Red Cross
- The Internet

Approximately 200 individuals were contacted by telephone, mail, or in person to obtain relevant information. Hurricane Program Managers and County Emergency Managers provided wind and damage data and identified other potential information sources. U.S. Forest Service personnel provided topographic maps, wind and anemometer data, and other data pertaining to the forest, such as types of trees, numbers of damaged trees, and specific areas of damage. Meteorologists at the NHC, television stations, and airfields were contacted regarding wind measurements taken during the storm.

Newspapers proved a valuable source of local coverage of damages sustained during Opal. Several videotapes were made available, including some taken from the air. The National Climatic Data Center and Southeast Regional Climate Data Center provided wind and station data for weather stations in each of the four states. The U.S. Census Bureau provided population information and a breakdown of residential structures by type. Universities, including forestry departments and agricultural extension services, were also contacted for information.

2.2 Site Visits

The investigation was begun 5 months after the occurrence of Hurricane Opal, and information about wind-induced damages had to be collected within a short period. It was determined that the best way to obtain the necessary information under these conditions was to conduct site visits in selected portions of the four-state area where hurricane damage was still visible or where other valuable information was available, including photographs or an anemometer that provided wind speed information which needed to be verified.

After an intensive information gathering effort, three travel routes were selected for the site visits. These routes were selected for one of the following reasons: anemometers used in the collection of recorded wind speeds were nearby, damage from Opal was still visible and accessible, photographs and/or videotapes of damages were available for review on-site, a significant event was reported to have occurred along the route (e.g., an unusual recorded wind speed), or the route approximated the actual storm track through the four states.

Three G&O employees conducted the site visits. Thirty seven sites were inspected, and over 1200 miles traveled within an area extending northeast from Pensacola, Florida, to Asheville, North Carolina, and southeast from Birmingham, Alabama, to Columbus, Georgia. Figure 2-1 shows the site visit locations and the travel routes. A summary of the site visits is provided in Appendix B.

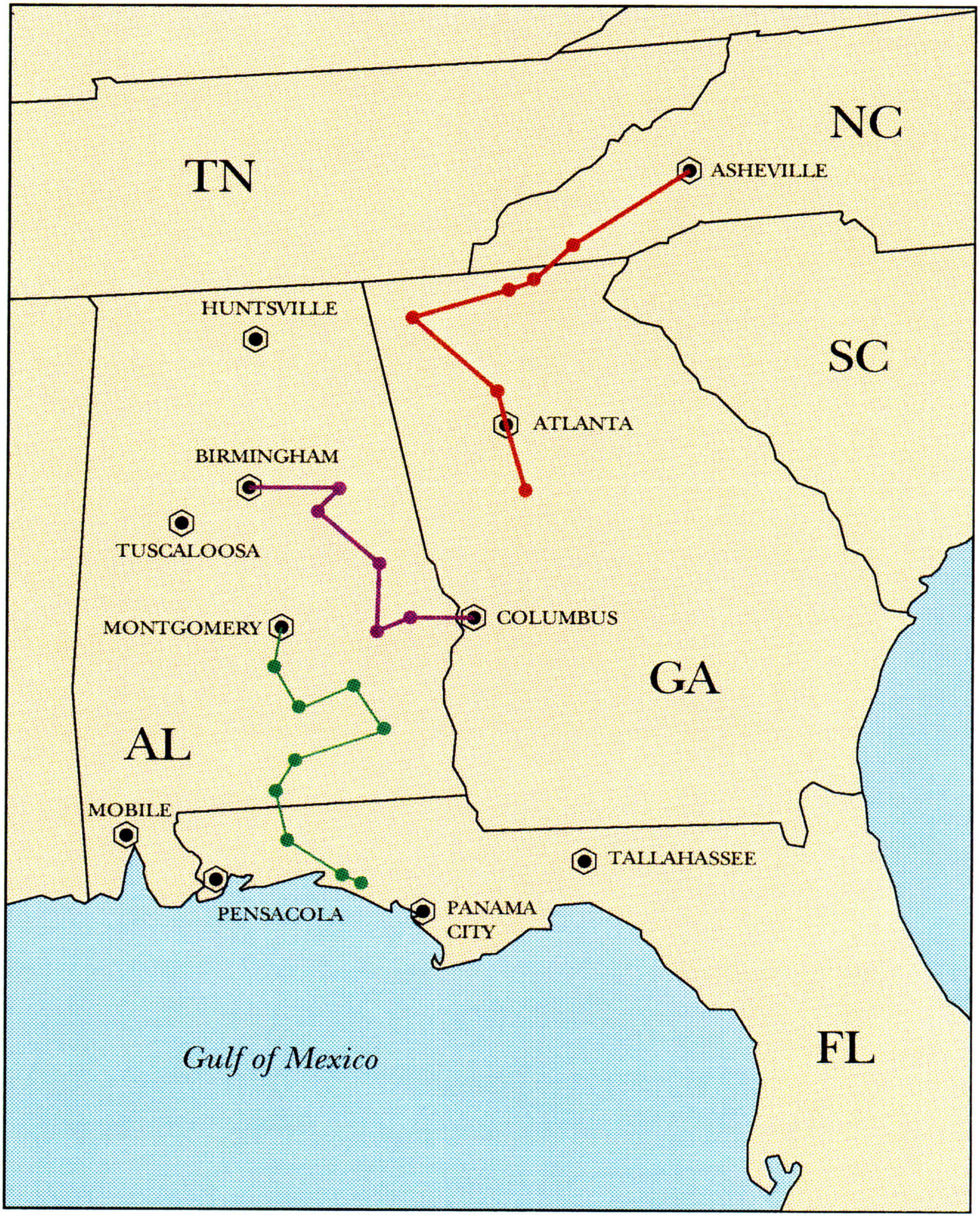

Figure 2-1. Site Visits and Travel Routes

3 WIND MEASUREMENTS

3.1 Wind Speed Measurements

In recent years, there has been considerable confusion and controversy about the estimation, measurement, and reporting of wind speeds in hurricanes. This confusion has been due to a lack of properly functioning anemometers, references in building codes to obsolete methods of wind-speed measurements, the use of inappropriate adjustments to account for wind speed variation in the atmosphere boundary layer, and failure to comply with international standards of measurement and reporting. All of these problems were apparent in the measurement and reporting of wind speeds associated with Hurricane Opal.

Before discussing the wind speed reports available for use in constructing Hurricane Opal's wind fields, it is worth considering the nature of typical "official" reports and their limitations. All official meteorological stations, whether operated by NWS, the Federal Aviation Administration (FAA), or the military, make hourly reports of wind conditions. At manned stations, the sustained wind speed is determined by averaging the wind speed over a 2-minute period, a few minutes before the end of each hour. If instruments are out of service, wind speed is estimated with the Beaufort Scale.

At stations that produce a continuous record of wind speed, the highest gust in the last 10 minutes is included in the report to indicate the character of the wind. If a higher gust occurred within the hour, that speed is reported in the remarks section as a peak wind and the time of its occurrence noted. At the end of the day, the highest gust of the day is reported, together with the highest observed 2-minute average. Both may be from hourly reports or some special observation. Until recently, the NWS has had no means of determining the true highest 2-minute (or 1-minute) average wind speed, i.e., the 2- minute or 1-minute "gust."

The introduction of the Automated Surface Observing System (ASOS) by NWS had the potential of providing wind measurements in the internationally agreed upon format recommended by the World Meteorological Organization (WMO). However, this potential has not quite been fulfilled. At ASOS stations, measurements are usually made at the standard height of 33 feet above the ground. (Prior to the introduction of ASOS, very few NWS, FAA, or military stations made measurements at the standard height.) The digital output from the wind sensors is processed to give a 2-minute average, updated every minute, and the highest 5-second gust in the most recent 10-minute period. Each hour, a standard report is made that provides the most recent 2-minute average, the highest 5-second gust in the last 10 minutes, and the peak 5-second gust in the hour. This reporting process is illustrated by the wind data recorded at Hurlburt Field in Fort Walton Beach, Florida (see Figure 3-1).

At the end of the day, the highest 2-minute average is recorded. This average is now called the maximum 2-minute wind. The maximum 5-second gust is also recorded. This is not referred to as the peak wind, as in earlier reports, but as the maximum 5-second wind.

The use of the 2-minute period to determine the average wind speed is a departure from international standards, and a 2-minute period is too short to filter out the effects of turbulence. The 10-minute averaging period recommended by the WMO provides a much more stable measure of the prevailing wind conditions with the turbulence removed. Figure 3-1 clearly illustrates this point.

An anemometer trace such as the one shown as Figure 3-2 provides a continuous record of the wind speed. Such traces are available from some stations. Figure 3-2 is the trace from Mobile, Alabama, recorded during Hurricane Opal. The peaks are easily read on this trace; however, the 2-minute and 10-minute averages are much more difficult to accurately assess.

It is worth noting that the NWS operational procedures for manned stations do require the operator to avoid gusts and lulls in assessing the average speed. This, to some extent, does filter out the effects of turbulence. The best that can be said for the hourly ASOS measurements is that, on average, they are within about 10 percent of the true 10-minute mean at the time of measurement. However, the maximum 2-minute wind recorded at the end of the day is a true maximum, unlike the one reported by manned stations. It should also be noted that the peak wind reported by manned stations is roughly a 2-second average and is likely to be slightly higher than the maximum 5-second wind reported by an ASOS station, if measured at the same height.

In general, the following information was available from which to construct the sustained and gust wind fields for Hurricane Opal:

(a) From NWS stations with ASOS equipment and fully commissioned non-ASOS stations that operated throughout the storm -- accurate measurements of the maximum 2-minute wind and maximum 5-second wind.

(b) From NWS stations without ASOS equipment but with strip-chart recorders -- accurate measurements of the maximum gust and an approximate indication of the maximum sustained speed. Adjustments to the standard anemometer height were usually necessary.

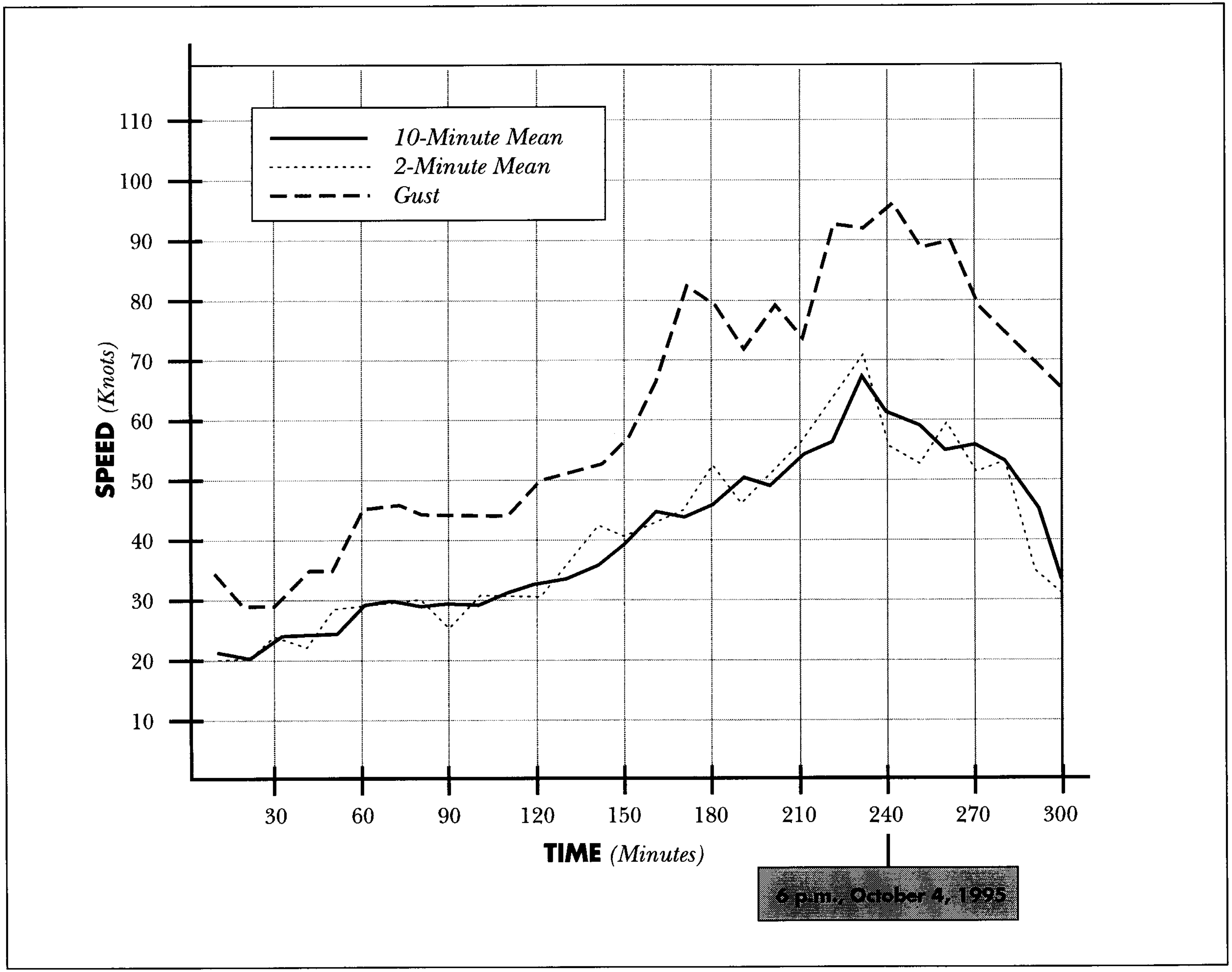

Figure 3-1. Hurlburt Field Wind Data, Fort Walton Beach, Florida

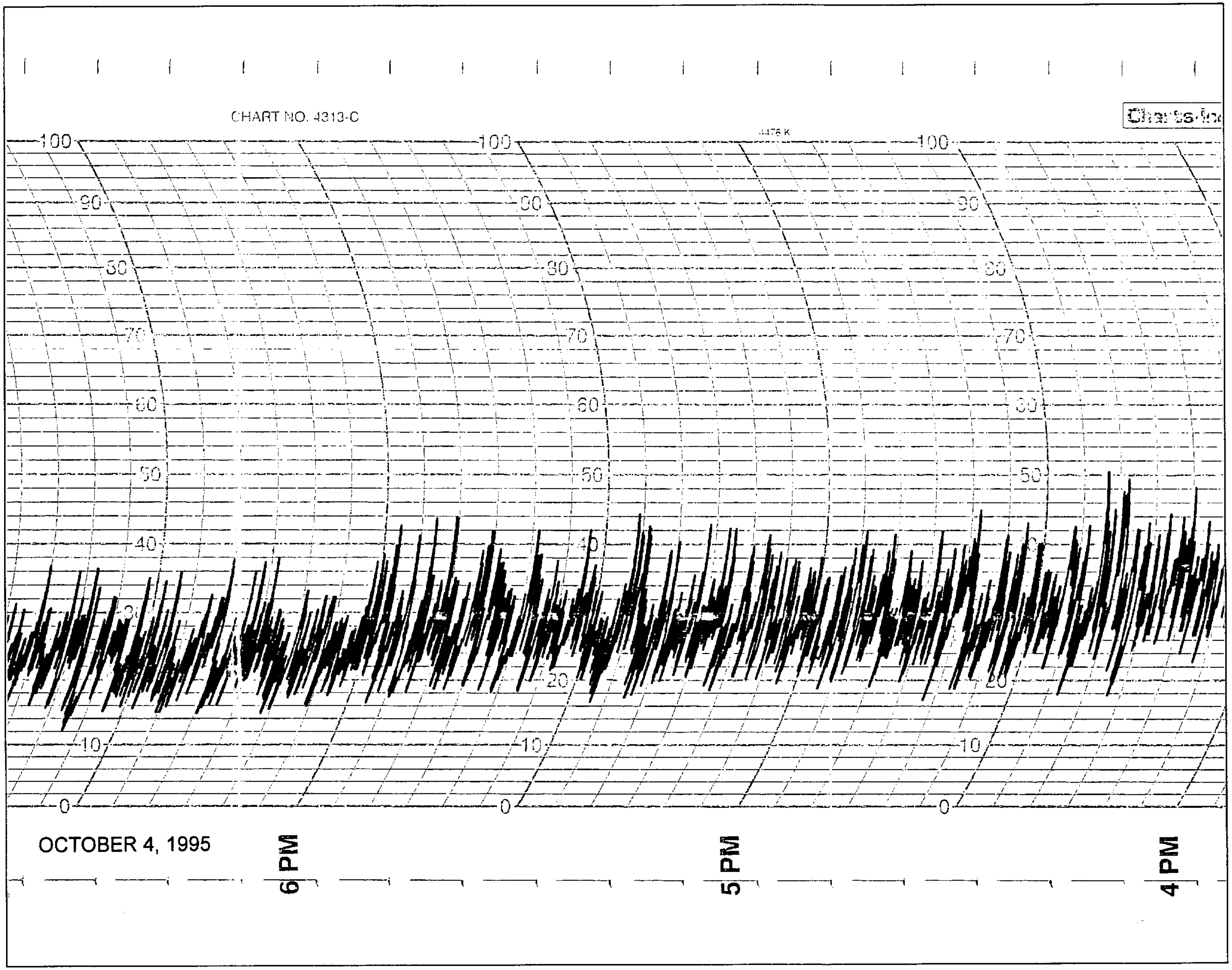

Figure 3-2. Mobile, Alabama, Anemometer Trace

(c) From military bases with "hot-wire" type anemometers that operated throughout the storm -- accurate measurements of the maximum 2-minute wind and the maximum 5-second wind. Adjustments to the standard anemometer height were necessary.

(d) From Ft. Rucker -- an approximate indication of the highest sustained wind speed and peak gust based on measurements by a hand-held anemometer.

(e) From other stations -- approximate indications of the possible maximum sustained winds and peak gusts. (Considerable uncertainty often existed concerning the height of the anemometer, the nature of the measurements, and whether the station was fully operational throughout the storm).

(f) From the Hurricane Research Division, NOAA -- a surface wind speed map for coastal areas based on aircraft measurements and surface observations.

It should be noted that northwestern Florida, Alabama, and Georgia have a large number of "official" anemometer sites that could have provided valuable information concerning the wind fields. Many failed to do so because they were deliberately shut down prior to the arrival of the storm or were forced to shut down because of power failures. Also, the data from 19 non-commissioned ASOS stations had been destroyed before this investigation took place. At the time of the investigation, these stations were still undergoing evaluation.

Facing the reality that the best data available were in the form of the maximum 2-minute winds and maximum 5-second winds, and that other data would approximate to those conditions, wind fields for Hurricane Opal were constructed for sustained winds (maximum 2-minute winds, or "sustained" reports) and peak gusts (maximum 5-second winds or peak gust reports) all adjusted to 33 feet at open airport sites. The original and adjusted data are shown in Table 4.1, in Section 4.

3.2 The Saffir-Simpson Scale and Damage Potential

The most widely used damage potential scale for hurricanes is the Saffir-Simpson Scale. A description of this scale, excerpted from the *National Hurricane Operations Plan* issued by the Office of the Federal Coordinator for Meteorological Services and Supporting Research, is provided in Appendix C. That document includes an interesting definition of a sustained wind, i.e., one that persists for the minimum time period to establish optimal dynamic forces on a nominal building structure. For a typical house, this period is only a few seconds. Indeed, Saffir, writing a report for the United Nations in 1975, clearly stated that his wind speeds refer to gusts of 2 to 3 seconds.

At some point, the meteorological sustained wind speed (taken by most of the world to be a 10-minute average wind speed) and the structural sustained wind speed (a 2- to 5- second average speed) got mixed up with the conventional way of measuring the sustained wind in the United States, i.e., observing a wind speed indicator for a minute. The net result was the Saffir-Simpson Scale in the form now used by the NHC to classify hurricanes. In the Saffir-Simpson Scale, a sustained wind is taken to be a 1-minute average. As can be seen from Figure 3-1, there is a considerable difference between a 1- or 2-minute average wind speed and a 5-second gust.

Because of the procedures used to convert wind speeds measured by reconnaissance aircraft to estimated speeds 33 feet above the earth's surface, the error in the Saffir-Simpson Scale has not become obvious from damage observations. Extensive comparisons between surface measurements and aircraft measurements by the Hurricane Research Division of NOAA have shown that, on average, the mean wind speed at 33 feet over the ocean is approximately 68 percent of the speed measured by the aircraft. Maximum 1- or 2- minute speeds are probably about 10 percent higher (75 percent of the aircraft-measured speeds). Only once, in Hurricane Andrew, has NHC used the figure of 75 percent to estimate surface speeds instead of the usual 85 percent. ?

Peak gusts near the surface over the ocean are typically about 95 percent of speeds measured by aircraft. They drop to about 80 percent a few miles inland. Thus the sustained winds estimated and forecast by NHC are approximately equal to the gust speeds where building damage occurs. Hence there is no obvious discrepancy between the observed damage and the estimated sustained speed.

NOAA's ~~The~~ Inland Wind Model uses NHC's estimate of maximum surface sustained wind speeds over the ocean as a starting point for the inland wind predictions. The authors of the model have noted that their estimates appear to match the observed peak gusts better than the observed sustained speeds. Under the circumstances, that is not surprising.

Within the next few years, the modernization of NWS will result in over 850 ASOS stations providing (if they have power) minute-by-minute updates of wind conditions. This information will be accessible by telephone and will be broadcast on aircraft communication channels. Hourly reports will be available on the Internet. Emergency managers will almost certainly make use of these data to check the inland wind forecasts and assess the potential for damage. If the Saffir-Simpson Scale is used with the "sustained" winds reported by the ASOS stations, the amount of damage will be dangerously underestimated. Until the Saffir-Simpson Scale is corrected, it should not be used at inland locations where accurate observations of wind speeds might be available. ?

The starting point for the proposed damage potential scale (see Table 7.2) is the Beaufort Scale used by NWS to estimate "sustained" wind speeds. Although the Beaufort Scale is intended to be used with 10-minute mean speeds, the assumption has been made that because it is an approximate scale, it can be applied to the 2-minute wind recorded by an ASOS station. The original scale was developed in Europe for storms with little convective activity and whose sustained and peaks gusts have a relatively fixed ratio.

Sometimes in hurricanes, and usually when mean wind speeds are quite low and thunderstorms are present, thermally induced convection will produce unusually high gusts. Very often these peak gusts are not associated with the highest mean speed in the storm. While such gusts may produce local damage, they are isolated events and not typical of general wind conditions.

To overcome this problem of extreme local gusts, the Beaufort Scale has been modified to include both the maximum 2-minute wind and the maximum 5-second wind. The 2-minute average probably gives a better indication of widespread effects. If the maximum 5-second wind exceeds the 2-minute wind by more the 30 percent, this is usually an indication of convective effects. Use of the 5-second wind in these cases will give an indication of potential damage, but the damage is likely to be localized. The more extreme the 5-second wind, the more localized the damage is likely to be. For example, the maximum 2-minute wind reported by the ASOS station at Montgomery was 52 mph, and the maximum 5-second wind was 63 mph. A few miles away at the Maxwell Air Force Base, the maximum 2-minute wind (adjusted to reflect the speed at 33 feet above the ground) was 51 mph, but the maximum 5-second wind was 90 mph. At the ASOS station, either the 2-minute wind or the 5-second wind could be used to assess the general wind conditions. At Maxwell Air Force Base, the 2-minute wind gives a reasonable indication of the prevailing wind conditions, but the 5-second wind (if it actually existed -- there is some concern that there may have been an instrumentation error) is an indicator of a very localized effect.

Since the Beaufort Scale is open-ended for hurricane conditions, the Saffir-Simpson Scale has been used to subdivide the hurricane category. It has been assumed that the nominal 1-minute sustained wind is equivalent to the maximum 2-minute wind. Since NHC uses the maximum sustained wind anywhere in the storm to categorize a hurricane, and the Beaufort Scale refers to wind conditions at a particular location, using the terms "Category 1," "Category 2," etc. Is considered unwise. Therefore, in this report the classes of hurricane have been given separate names.

The expected damage is based upon the original Beaufort Scale, the Saffir-Simpson Scale corrected to the form originally intended by Saffir, and observations of the effects of Hurricanes Frederic, Hugo, and Opal.

4 HURRICANE OPAL

4.1 Recorded Wind Speeds

The maximum sustained wind speeds and peak wind gusts associated with Hurricane Opal are shown in Table 4.1. The recorded speeds have been adjusted for height (to reflect speeds at 33 feet above the ground in open terrain). Only values from anemometers that were fully functioning throughout the storm have been used unless noted. See Sections 3.1 and 6.1 for additional discussion of the comparisons between wind speed measurements. It should be noted that the highest adjusted peak gust wind speed believed to have been associated with Hurricane Opal is 115 mph at Hurlburt Field, Florida, not 125 mph or 144 mph, both of which have been reported as the peak gust. Anemometer station data are included in Appendix D.

How Do we Know this?

Wind speeds higher than those in Table 4.1 were recorded; however, they appear to be very localized and associated with thunderstorms moving through a particular location. These anomalies cannot be used to assess widespread damage or to compare damage levels between locations. These anomalies are noted in Table 4.1.

An analysis of the storm indicates that its eye probably passed very near Montgomery, Alabama, which is further west than the official track. However, this small difference in storm direction does not alter the results of the study.

4.2 Structural Damage

Most of the structural damage resulting from Hurricane Opal occurred along the coast. The majority of the wind damage was confined to the coastal region and occurred primarily to roof systems. Structural damage inland was caused mainly by falling trees. Some of this damage was extensive. See Figures 4-1 through 4-5 for pictures of common structural failures observed during the site visits.

The most common inland residential construction type is a one-story wood-frame structure built on either a crawlspace or slab-on-grade foundation. The roof system is wood frame with an asphalt shingle covering. Roof styles for residential structures are typically gable or hip. Residential structures along the coast commonly have more than one story and are typically elevated above the Base Flood Elevation (elevation of the 100-year flood) on piles or by some other elevation technique.

There are many manufactured housing units in the four-state affected area. Little of the reported damage to these units was caused by the wind alone. Most of the reported damage was caused by falling trees. One manufactured home observed in Florida had been shifted from its foundation by the wind (see Figure 4-6).

Table 4.1 Recorded and Adjusted Wind Speeds

Station	Recorded Sustained Wind Speed (mph)	Recorded Peak Gust (mph)	Adjusted Sustained Wind Speed (mph)	Adjusted Peak Gust (mph)	Anemometer Height (feet)	Primary Wind Direction
Hurlburt Field, FL [1]	84	110	91	115	20	SE
Pensacola NAS, FL	52	77	44	71	87.75	NW
Tallahassee, FL	32	52	33	53	25	S
Eglin AFB, FL	75[E]	104[E]	87[E]	112[E]	13	E
Panama City, FL	14 (stopped recording)	--	--	--	35	SE
Apalachicola, FL	32	59	32	59	30	--
Gainesville, FL	--	--	14	--	Unknown	--
Jacksonville, FL	--	--	22	35	Unknown	--
Anniston/Calhoun Co., AL	29	40	31	42	20	NE
Auburn, AL	44[E]	57[E]	45	58	29	--
Birmingham Mun., AL	31	58	33	60	22	N
Cairns AAF / Ozark / Ft. Rucker, AL	58	75[2]	67	81	13	SE
Huntsville / Madison Co., AL	43	55	44	56	25	N
Montgomery / Dannelly, AL[1]	52	63	52	63	33	E
Montgomery, AL Maxwell AFB	47	64[3]	51	67	20	E
Tuscaloosa, AL	26	46	28	48	20	NW

Table 4.1 Recorded and Adjusted Wind Speeds (continued)

Station	Recorded Sustained Wind Speed (mph)	Recorded Peak Gust (mph)	Adjusted Sustained Wind Speed (mph)	Adjusted Peak Gust (mph)	Anemometer Height (feet)	Primary Wind Direction
Mobile, AL Bates Field[1]	38	59	38	59	33	N
Mobile, AL Brookley Airport	23	35	27	38	12	N
Atlanta, GA[1] International Airport	33	49	34	49	30	S-SE
Atlanta, GA[1] Dekalb	35	52	38	54	33	S
Atlanta, GA Fulton	26	48	28	50	21	SE
Augusta, GA[1]	32	44	32	44	33	S
Athens, GA	29	47	31	49	20	S
Columbus, GA[1]	40	52	40	52	32	SE
Lawson AAF, GA	41	61	44	64	20	E
Macon, GA[1]	33	45	33	45	33	S
Marietta, GA Dobbins AFB	43	69	47	72	20	SE
Asheville, NC	33	58	36	60	20	SE
Chattanooga, TN	31	37	31	37	30	NE-SE

Notes:

[1] ASOS Station: actual highest 2-minute average used.

[2] Hand-held anemometer recorded 98 mph.

[3] Thunderstorm present when peak wind was recorded at 90 mph.

[E] Estimated speed

Figure 4-1. Roof Failure -- Holiday Isle, Florida

Figure 4-2. Residence Damaged by Tree -- Okaloosa County, Florida

Figure 4-3. Residence Damaged by Tree -- Okaloosa County, Florida

Figure 4-4. Residence Destroyed by Tree -- Opp, Alabama

Figure 4-5. Roof Covering Damage -- Opp, Alabama

Figure 4-6. Manufactured Home Shifted by Wind

Commercial structures are frequently constructed similarly to residential structures or are built using metal framing with metal siding and roof material. The roofs of many commercial structures, including schools, are flat with either built-up asphalt or single-ply membrane roof surfaces. See Figures 4-7 through 4-9 for pictures of common structural failures sustained by commercial structures.

4.3 Utility System Damage

Damages to utility systems from Hurricane Opal's winds were extensive. Power outages from the Florida panhandle to the mountains of North Carolina were reported. Some outages lasted as long as a week. The primary causes of the extensive outages were trees falling across power lines and main distribution lines being blown down by the wind. Many distribution lines run through sparsely populated but densely forested areas, where gaining access to the power distribution system was difficult. It was reported that nearly 2 million people were without power immediately after the storm.

4.4 Tree Damage

Extensive tree damage was reported in the State and National Forests of all four states, from the Blackwater State Forest in Florida to the Nantahala National Forest in western North Carolina. Sustained wind speeds greater than 55 mph have pushed over shallow-rooted trees in other high-wind events, and the tree damage from hurricane Opal verified this wind damage threshold. Several visits were made to State and National Forests in Alabama, Georgia, and North Carolina to document damage in those areas. Figures 4-10 through 4-12 illustrate the extent of damage to trees along the 500-mile path of the storm.

Much of the wind-induced tree damage can be attributed to the topography of the forest, as well as the wind speed. In some instances, a change in the topography created a wind acceleration effect. Although there was evidence of some diseased trees, these did not appear to contribute significantly to the damage levels that occurred. Both pines and hardwoods were affected by the gale-force and storm-force winds. The hardwoods with shallow roots were uprooted and blown over; the pines with tall, sturdy trunks were bent over or broken above the base. The leaves on the hardwoods contributed to the tree damage because they increased the surface area exposed to the wind. The heavy rains saturated the soil and loosened the soil in the tree rooting zone. These conditions would not be uncommon in any hurricane event.

4.5 Rain Effects

Hurricane Opal created almost twice as much rainfall in the mountains of North Carolina as it did at Pensacola, Florida. Large amounts of rainfall were recorded at Hendersonville, North Carolina (10.48 inches), Birmingham, Alabama (9.8 inches), Marietta, Georgia (8.66 inches), and Mobile, Alabama (7.89 inches). This rain, which occurred over a 2-day period, caused serious flooding in northwest Georgia and some

Figure 4-7. Building Facade Damaged -- Clearview, Florida

Figure 4-8. Roof Canopy Damaged -- Troy, Alabama

Figure 4-9. Wind Damage to Warehouse -- Walker County, Georgia

Figure 4-10. Tree Damage -- Oklaloosa County, Florida

Figure 4-11. Tree Damage -- Blue Ridge, Georgia

Figure 4-12. Tree Damage -- Blue Ridge, Georgia

flooding in the North Carolina mountains. The amount of damage to structures would have been much greater if the inland winds had also been greater. The rain would then have entered the damaged structures, causing interior flooding and serious damage to contents. The effects of rain water will not be discussed in any detail in this report, however, since the purpose of this study is to compare the effects of Hurricane Opal's winds with expected levels of damage based on inland wind predictions.

5 INLAND WIND MODEL

5.1 Development and Purpose

FEMA's ~~The HURREVAC~~ Inland Wind~~s~~ Display Computer Model, Version 1.0 for use on a PC, was developed to provide emergency managers with a predictive tool that would help them in their evacuation decision making processes. The PC version graphically displays in color the inland progress of wind fields that are greater than 40 mph, greater than 58 mph, and greater than hurricane-force winds of 75 mph. The wind speeds used in the model are maximum sustained winds and are intended to represent the upper bound of these sustained winds.

The model is intended to be used only in the last hours of a landfalling hurricane, when the forecast errors are relatively low. The input to the model includes the NHC's Tropical Cyclone Forecast, which provides the storm's location in latitude and longitude and the radius of sustained winds at 34 knots (39 mph), 50 knots (58 mph), and 64 knots (74 mph). In addition, the forecast positions for the storm are inputs to the model because the forward speed and direction of the storm are crucial to the decision-making process for local emergency managers.

The development of this program for use with a PC makes this tool available to most emergency managers and enables them to make the forecast for an inland wind swath quickly, to consider many possible scenarios, and to develop "what if" decision trees.

The NHC has ~~the~~ A model that predicts the decay rate of landfalling Hurricanes. It is the intent that this model will be used by NHC forecasters as another tool to predict storm intensities and direction. Enhanced forecasting will improve the accuracy of the PC version of the model used by emergency managers because the starting point, the tropical cyclone forecast, will ~~be~~ improved, over time.

It is not the intent of this report to cover the details of the many program options; however, it is important to note that many possible program outputs are available to emergency managers. These options include, but are not limited to, a forecast storm plot, a forecast wind swath, forecast error options, a closeup of a state map, the timing of the predicted storm and its effects on a particular selected region, and a maximum envelope of winds (MEOW). These program options for Hurricane Opal Advisory Numbers 28 and 29 are included in Appendix E.

5.2 Hurricane Opal Predictions Using the Inland Wind Model

A comparison of the storm information for Hurricane Advisory Numbers 28 and 29 demonstrates the importance of using the Inland Wind Model when the tropical cyclone is almost at landfall, the forecast errors are smaller, and the storm impact can be more accurately forecast for the residents of the affected areas. If the wind swaths generated by the PC version can be further improved with improved forecasts from the NHC model, the accuracy of the storm impact will become progressively better.

Hurricane Advisory Number 28 was issued when the storm was approximately 175 miles south-southwest of Pensacola, Florida. The storm was classified a Category IV hurricane with maximum sustained winds of 150 mph, and it was moving toward the north-northeast at 23 mph. Hurricane-force winds extended outward from the center of the storm for 145 miles, and tropical-storm-force winds extended outward 260 miles from the center.

The inland wind prediction based on this forecast with the PC version was that hurricane-force winds could be expected all the way into Georgia, or some 285 miles inland, and tropical-storm-force winds could be expected to extend into North Carolina and Tennessee. See Figure 5-1 for this inland wind forecast at the time of Advisory Number 28.

Six ~~Five~~ hours later, Hurricane Advisory Number 29 was issued, when the storm was approximately 45 miles South of Pensacola. At that time, the storm was classified a Category III hurricane with maximum sustained winds of 125 mph and a forward speed of 22 mph. Hurricane-force and tropical-storm-force winds were still 145 miles and 260 miles, respectively, from the center of the storm.

The inland wind prediction based on this forecast with the PC version was that hurricane-force winds could be expected north of Montgomery, Alabama, or approximately 175 miles inland, and that tropical-storm-force winds could still be expected in western North Carolina and Tennessee. See Figure 5-2 for the inland wind forecast at the time of Advisory Number 29.

? The NHC model prediction run after the storm but using the landfall location and intensity as the starting point indicated that hurricane-force winds (shown as 65 knots) could be expected approximately 136 miles inland. See Figure 5-3 for the NHC model developed from the "best track" information. ?

The NHC has determined that the actual wind speeds were within the bounds the model predicted using Advisory Number 29, in that all of the sustained wind speeds were under the model-predicted values at all distances inland. In addition, the gust speeds were under the model-predicted values for sustained

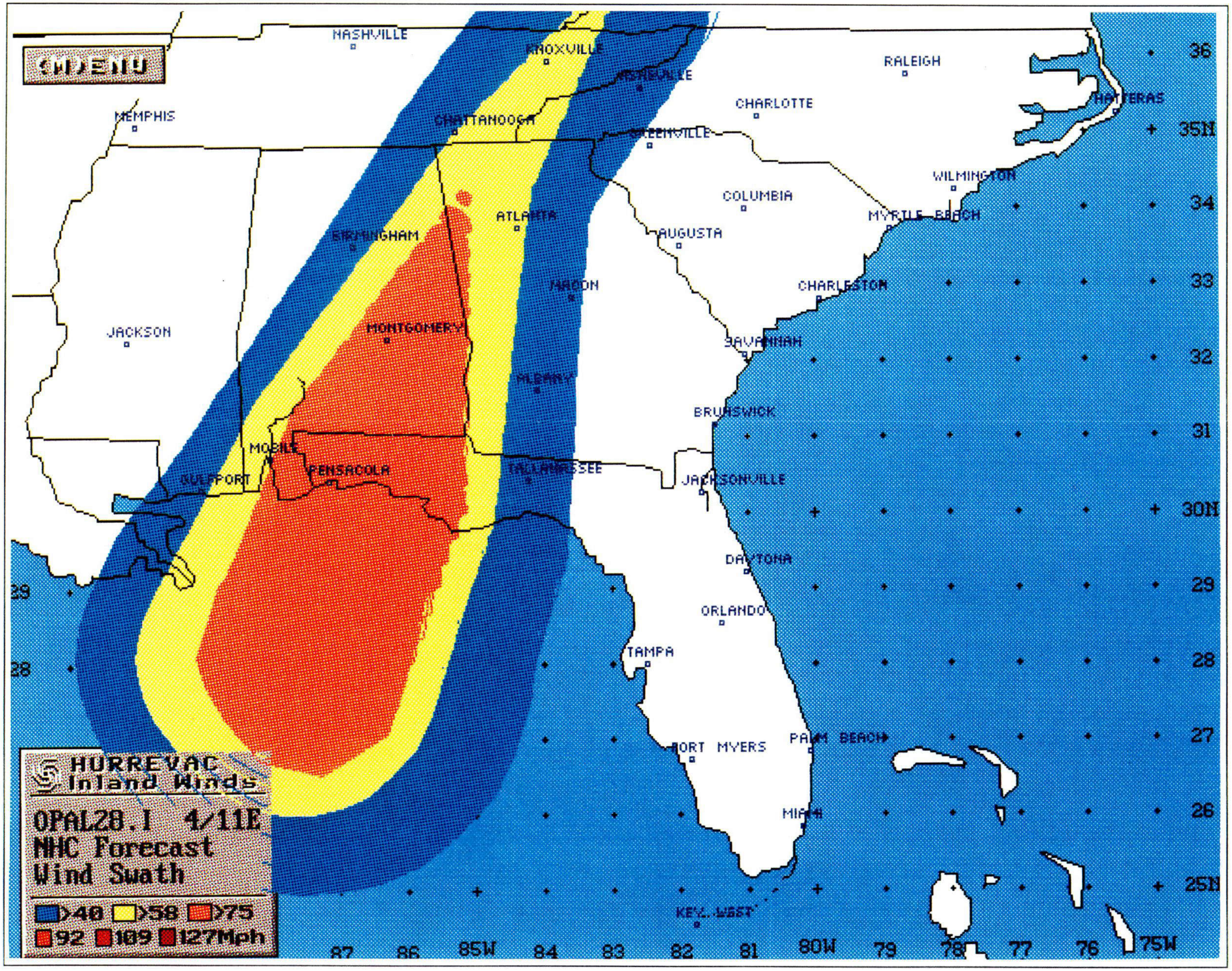

Figure 5-1. Inland Wind Forecast (at Hurricane Advisory Number 28).

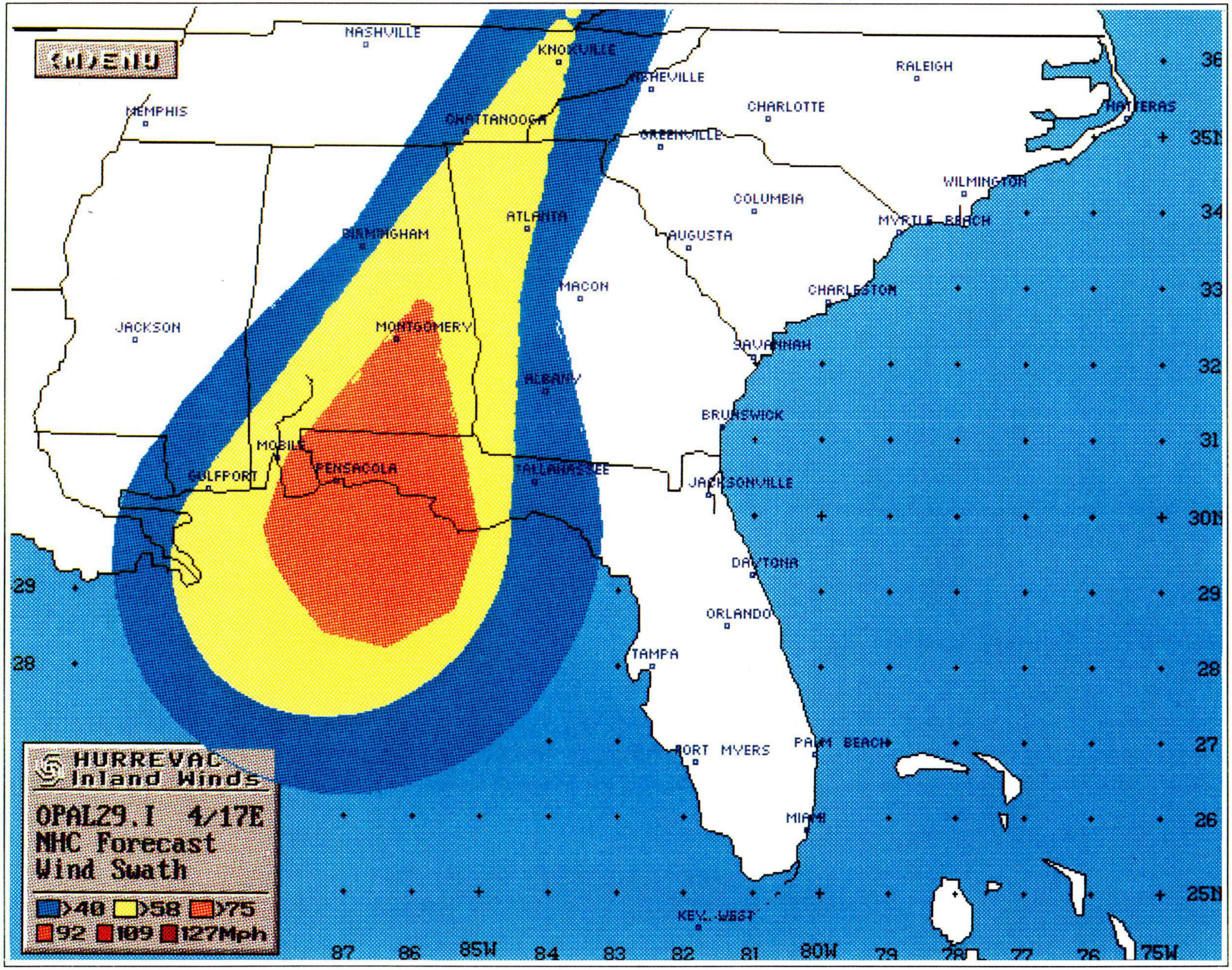

Figure 5-2. Inland Wind Forecast (at Hurricane Advisory Number 29).

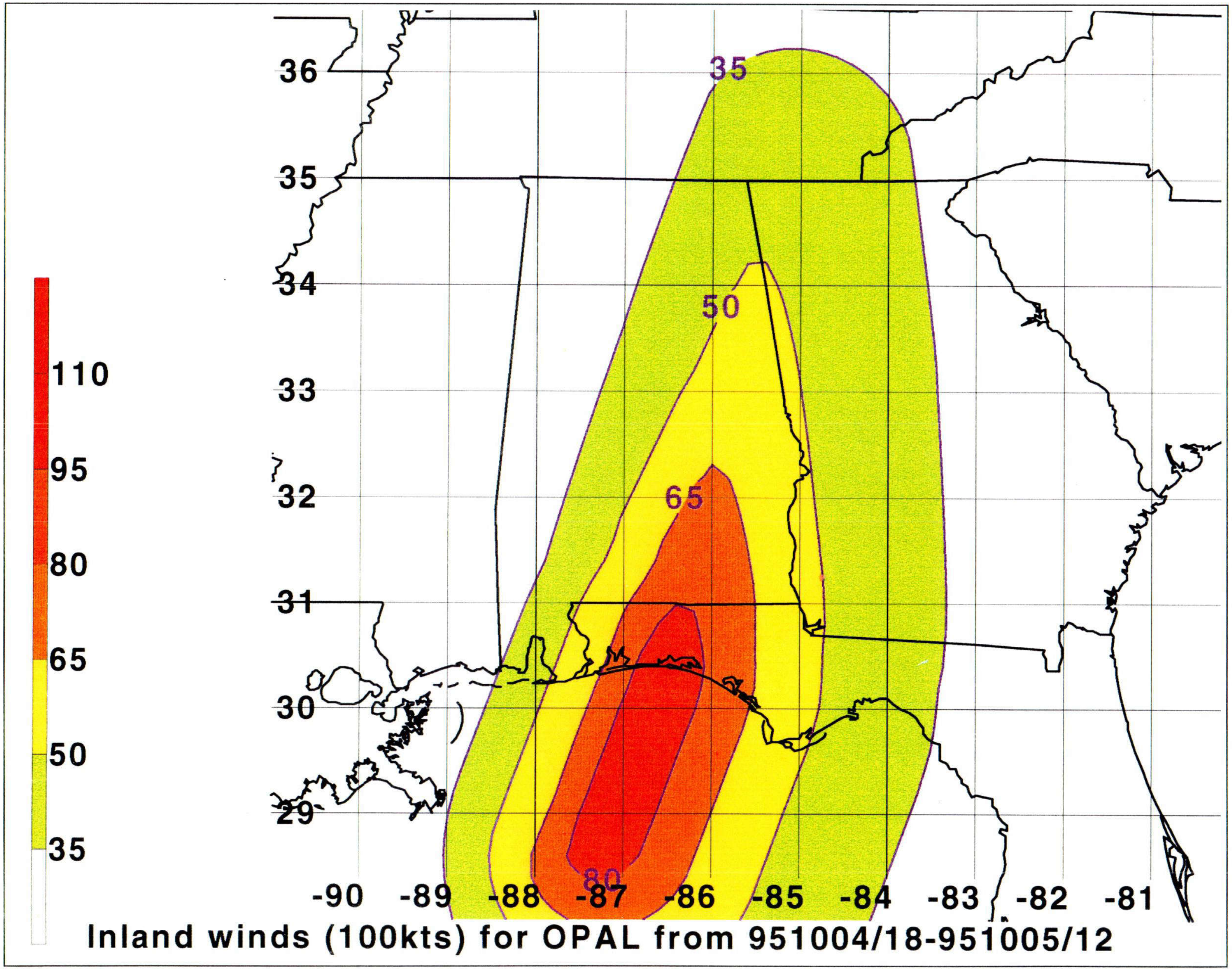

Figure 5-3. NHC Model Developed from "Best Track" Information.

SCALE: 1" = 95 Miles

winds at all except 10 locations. The NHC graphs of predicted versus actual speeds (in knots) are provided in Appendix F (1 knot = 1.15 mph).

5.3 Wind Effects from Hurricane Hugo vs. Model Predictions

In order to validate the inland wind model predictions with data from at least one additional storm, the inland wind effects from Hurricane Hugo were reviewed. Figure 5-4, which presents the inland winds predicted with the PC version, shows hurricane-force winds extending 230 miles inland to approximately Hickory, North Carolina, and storm-force winds as far inland as Virginia.

The peak gust wind speeds experienced during Hurricane Hugo were actually greater than 75 mph and extended as far inland as Hickory, North Carolina; storm-force winds of 60 mph extended as far inland as southwest Virginia, or 310 miles. It should be noted that Hurricane Opal was rapidly decaying before landfall, ~~and~~ the onset ~~of a cold front~~ of converging with a cold front over Louisiana, and this caused the storm to weaken very fast. ~~this~~ Therefore, additional landfalling storms will need to be studied before final conclusions can be made.

5.4 Critique of the Inland Wind Model

The Inland Wind Model has the potential for providing valuable wind speed forecasts to inland areas. However, in its present form, it appears to seriously overestimate the actual wind conditions. The reasons for this are fairly clear and easily correctable.

All evidence to date suggests that mean wind speeds at the surface in hurricanes can be determined, with reasonable accuracy, by the application of conventional atmospheric boundary layer theory to reconnaissance aircraft measurements. From aircraft measurements prior to landfall and a knowledge of the forward speed of the storm, a gradient wind field can be established. At that level, the full effect of the forward speed is seen in the asymmetry of the wind field. After the hurricane has made landfall, it begins to decay. This process appears to be virtually independent of the roughness of the ground. It is this decay process that the Inland Wind Model attempts to predict.

Given that the hurricane boundary layer is almost identical to the non-hurricane boundary layer, the gradient wind field over land can be used to predict the over-land surface wind speeds. The conversion of gradient wind speeds to surface speeds is well established because it is the essence of forecasting surface winds from pressure gradients.

Extensive studies of extratropical storms have indicated that mean hourly wind speeds at inland airports are approximately 45-50 percent of the gradient wind speed and peak gusts are on average 70-80 percent of the gradient speed. Assuming normal gust factors, maximum 2-minute wind speeds could be expected to be 55-60 percent of the gradient speed.

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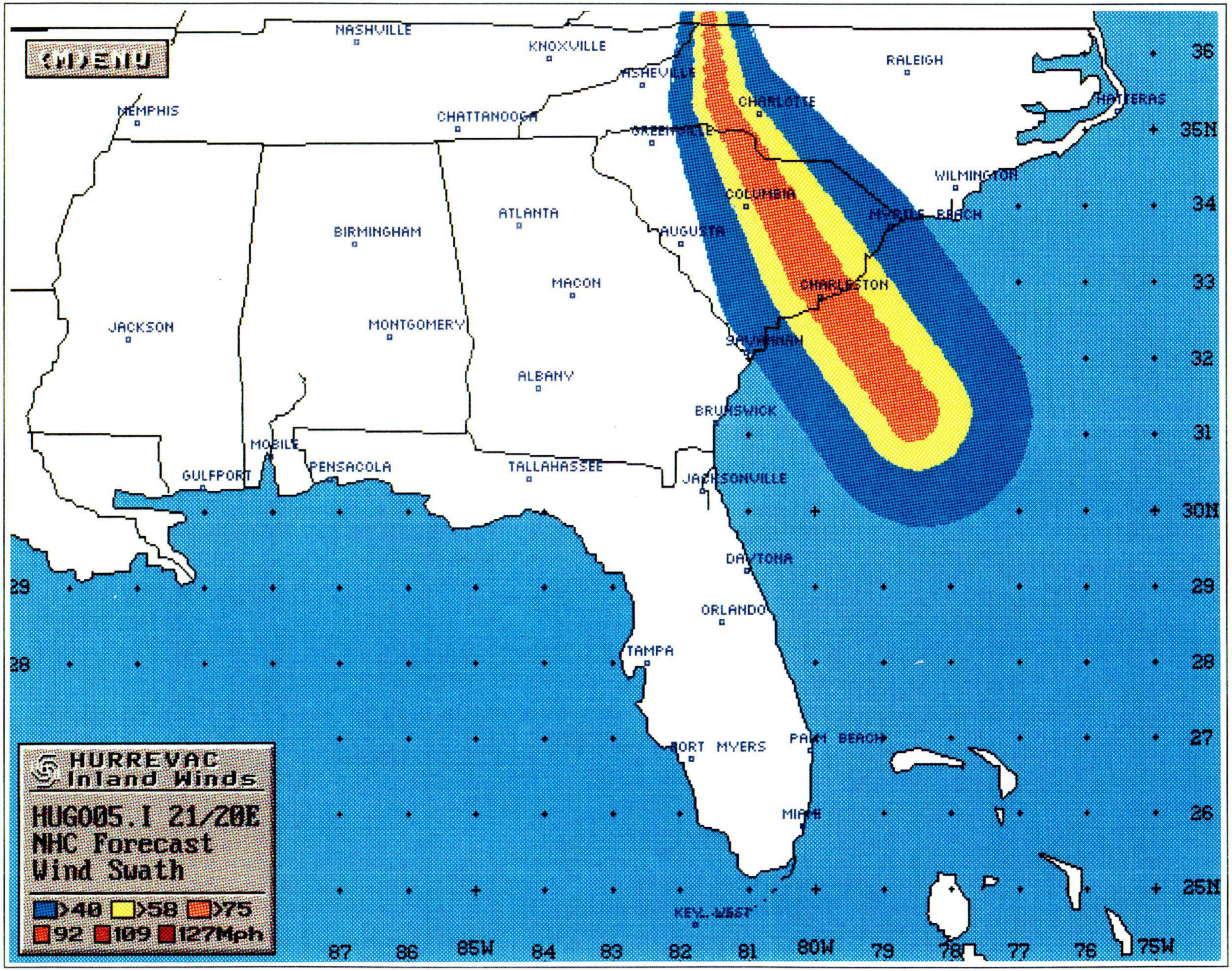

Figure 5-4. Inland Wind Forecast (Hurricane Hugo).

Rather than decaying the gradient wind speed, the Inland Wind Model, using the NHC estimates of over-water surface speeds, drops the speeds by only 10 percent to convert them to over-land speeds. It then allows the storm to decay. In Hurricane Opal, NHC estimated the maximum sustained speed to be 85 percent of the gradient speed. Hence, the model started with an over-land speed of 77 percent of the gradient speed, approximately equal to the maximum gust speed expected. In fact, the only locations where the observed gust speed exceeded the sustained speed, predicted by the model, were those where convective activity was suspected such as Hurlburt Field, Florida, and Maxwell AFB, Alabama.

Even if the decay rate were correct, the failure to apply proper boundary layer corrections would result in overpredictions of at least 25 percent. These errors, quite apparent in the Hurricane Opal wind field, did not become apparent during the testing of the program, because it was calibrated against tracks with estimated intensities, which ignored the reality of inland wind measurements.

To correct these deficiencies, it is recommended that the Model make direct use of reconnaissance aircraft measurements to create a gradient wind field. That field should then be allowed to decay, and surface speeds should then be estimated by the application of an appropriate boundary layer correction. At the moment, for areas more than a few miles from the coast, it is suggested that maximum 2-minute wind speeds be forecast as 60 percent of the gradient speed. Maximum, 5-second wind speeds should also be included in the forecast and set equal to 75 percent of the gradient speed, and a warning should be provided that in thunderstorms local gusts could reach 100 percent of the gradient speed.

NHC Comment

6 COMPARISONS OF HURRICANE OPAL EFFECTS: ACTUAL VS. PREDICTED

6.1 Wind Speeds

The recorded wind speeds were obtained from 29 weather station sites in the four-state area affected by Hurricane Opal. Table 4.1, in Section 4, shows the recorded and adjusted speeds and includes the anemometer heights and primary wind direction recorded at the time of the peak gust.

Table 6.1 shows a comparison of the area and distance covered by the Opal inland winds for the three wind speeds of 39-54 mph, 55-74 mph, and >75 mph for the PC version of the Inland Wind Model predictions and the actual recorded maximum sustained winds.

Table 6.1 Comparison of Wind Field Data -- PC Version vs. Actual Sustained

		Model	Actual
Wind Speed 39 - 54 mph	Maximum Distance Inland (miles)	~382	400
	Area of Wind Field (square miles)	5,390	2,356
Wind Speed 55-74 mph	Maximum Distance Inland (miles)	~300	140
	Area of Wind Field (square miles)	2,550	825
Wind Speed >75 mph	Maximum Distance Inland (miles)	210	~45
	Area of Wind Field (square miles)	720	250

Note: ~ indicates approximate value

It should be noted that the inland distances and areas of the actual sustained wind fields are approximately 30 percent to 50 percent of those predicted by the PC version of the model. The NHC model shown graphically in Figure 5.3 is approximately 10 percent more accurate than the PC version with smaller wind fields. The model prediction was for hurricane-force winds 100 miles inland.

Figures 6-1 and 6-2 graphically represent the wind speeds displayed in Table 6.1. The wind fields of the recorded sustained winds shown in Figure 6-2 are very close to the recorded wind information developed by the NHC. Recorded peak gust wind fields are shown in Figure 6-3. The information developed by the NHC is included in Appendix G. The wind speed information in Appendix G is given in knots (1 knot = 1.15 mph).

6.2 Structural Damage

Structural damage information was obtained for residential buildings, commercial buildings, public buildings such as schools and hospitals, and manufactured homes. Appendix H provides a summary by state and county of the percentages of structures that suffered major damage. These data were assembled from information provided by the American Red Cross and FEMA.

The primary wind-related damage to residential structures, including manufactured homes, was caused by trees falling on the structure. There was very little damage reported to manufactured homes that could be attributed to wind.

Some damage to commercial structures was caused by wind, particularly to the roofs. Several metal roofs were peeled back by the wind. One metal building used as a warehouse was cut in half by the wind. Several small tornadoes were reported to have touched down; they may have caused some of the damage to commercial buildings.

Some schools, which in many cases were used for shelters, sustained wind damage. This damage occurred primarily in areas of Florida where the highest wind speeds were recorded.

Using the data in Appendix H, Table 6.2 summarizes the major damage that was observed. For the three wind fields shown in Figures 6-2 and 6-3, Table 6.2 shows the percentage of single-family homes, manufactured homes, and apartment units that sustained major wind damage. Structures were considered to have sustained major damage if they were either totally destroyed or damaged to the extent that owners were displaced until repairs could be made.

The following information about structural damage should be noted:

- The numbers of damaged buildings in the Florida counties include water-damaged buildings; therefore, the damage percentages in those areas, particularly for apartment units and single-family homes, are higher than they would be if only wind-damaged structures were accounted for. Note that the apartment damage is based on numbers of units damaged, not buildings.

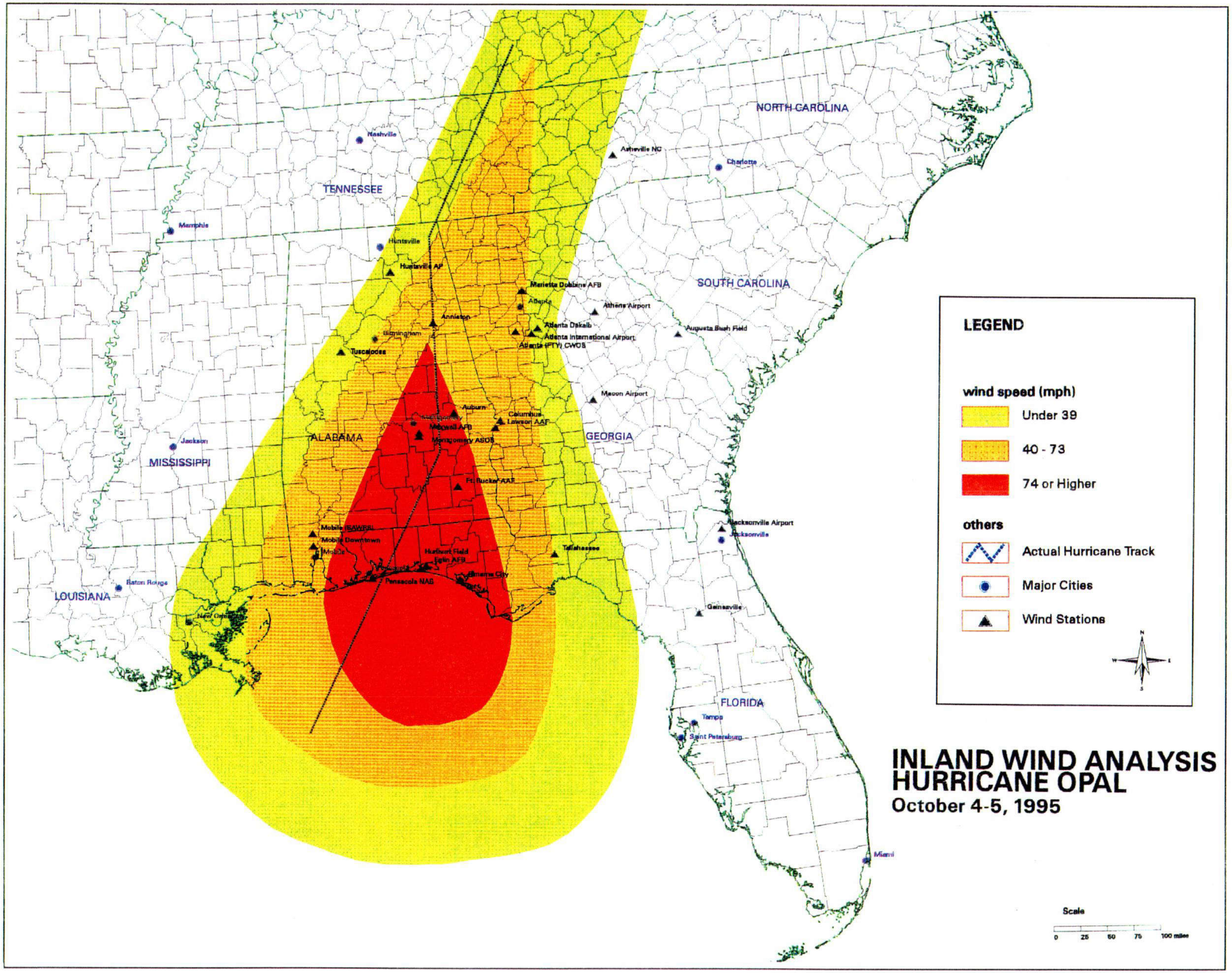

Figure 6-1. Model Wind Map

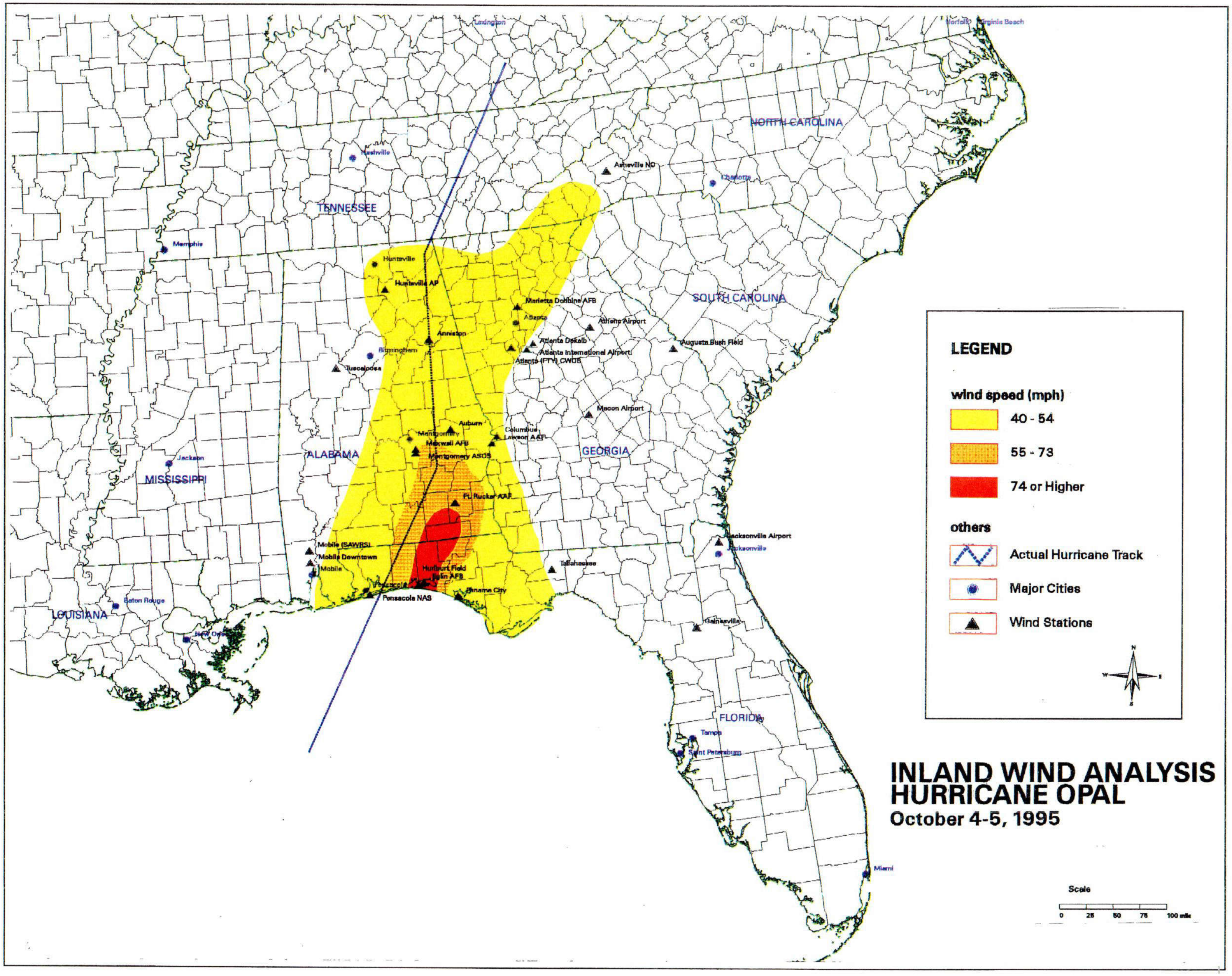

Figure 6-2 Map of Actual Sustained Winds

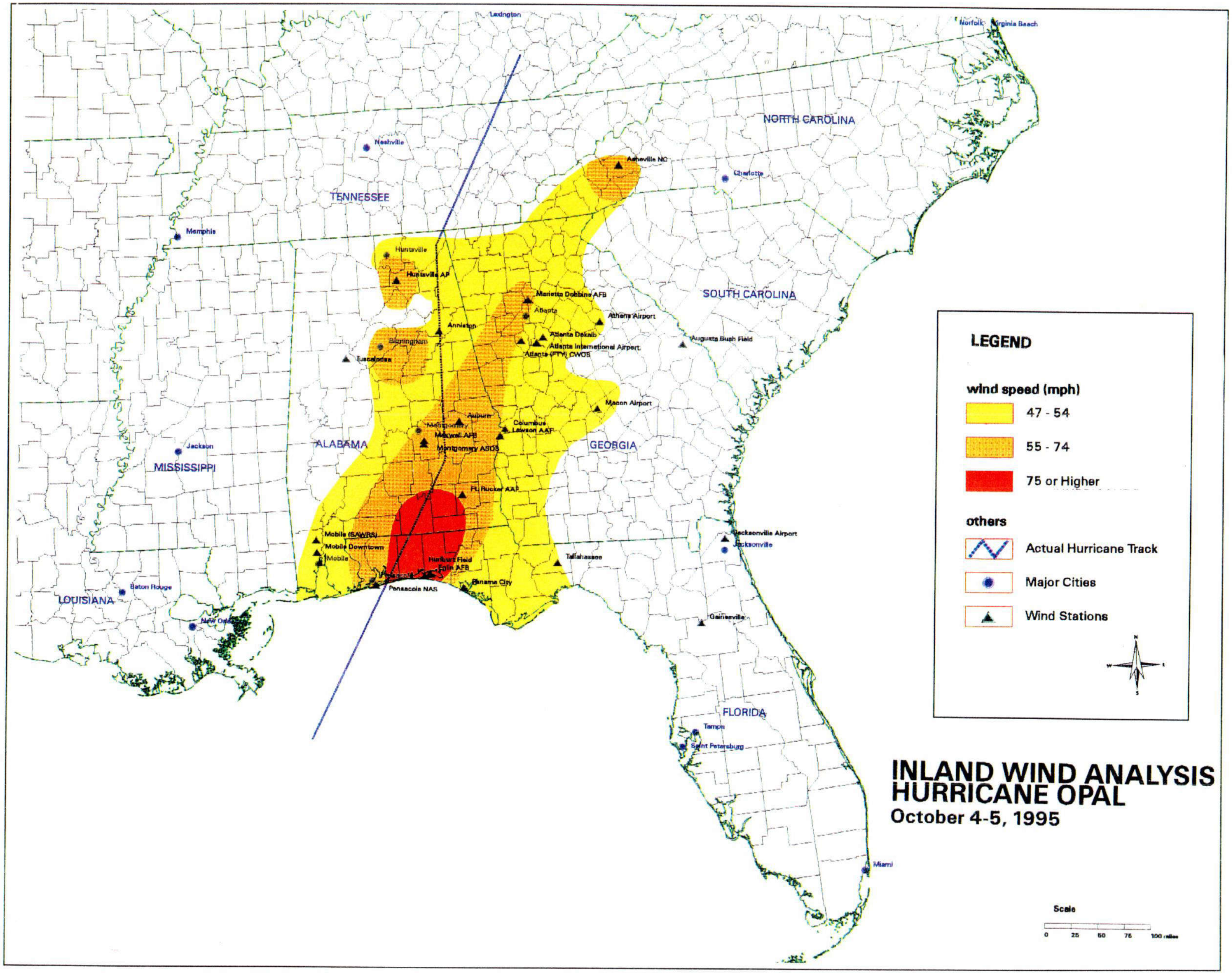

Figure 6-3 Map of Actual Peak Gusts

Table 6.2 Percent of Major Structural Damage

Sustained Winds	Peak Gusts (mph)	Single-Family Homes	Manu-factured Homes	Apartment Units
Gale-Force Wind (39-54 mph)	50-70	< 0.1%	0.1 - 0.5%	>2%
Storm-Force Wind (55-74 mph)	71-95	0.1 - 0.5%	0.5 - 1%	0
Hurricane-Force Wind (>75 mph)	>95	0.5 - 2%	0.5 - 1%	>2%

- The percentages for all major damage types are very low and therefore provide further evidence that the reported wind speeds in Table 4.1 are close to the actual speeds. The actual damage levels closely match the levels that would be expected at the reported speeds. See Table 7.1 for the expected damages.

- The structural damage from Hurricane Opal could be described as light.

- There was no reported damage in any county above 0.1 percent that is outside the envelope of the peak gust wind fields shown in Figure 6-3.

The types and distribution of structural damage are show graphically in Figure 6-4.

6.3 Utility Damage

Utility damage information was obtained from the major utility companies, newspaper stories, and FEMA Damage Survey Reports. Much of the utility service in the rural areas of the affected states is provided by electric cooperatives who had only sketchy information about the numbers or percentages of customers who had lost power at the height of the storm. Where necessary, the percentage of customers without power was determined from newspaper accounts of "customers" without power and estimated 1995 census information provided by the U.S. Census Bureau. For this determination, a residential "customer" (meter connection) was assumed to consist of a household comprising 2.7 persons. The resulting number of households was then increased by 15 percent to arrive at the estimated number of residential and commercial customers.

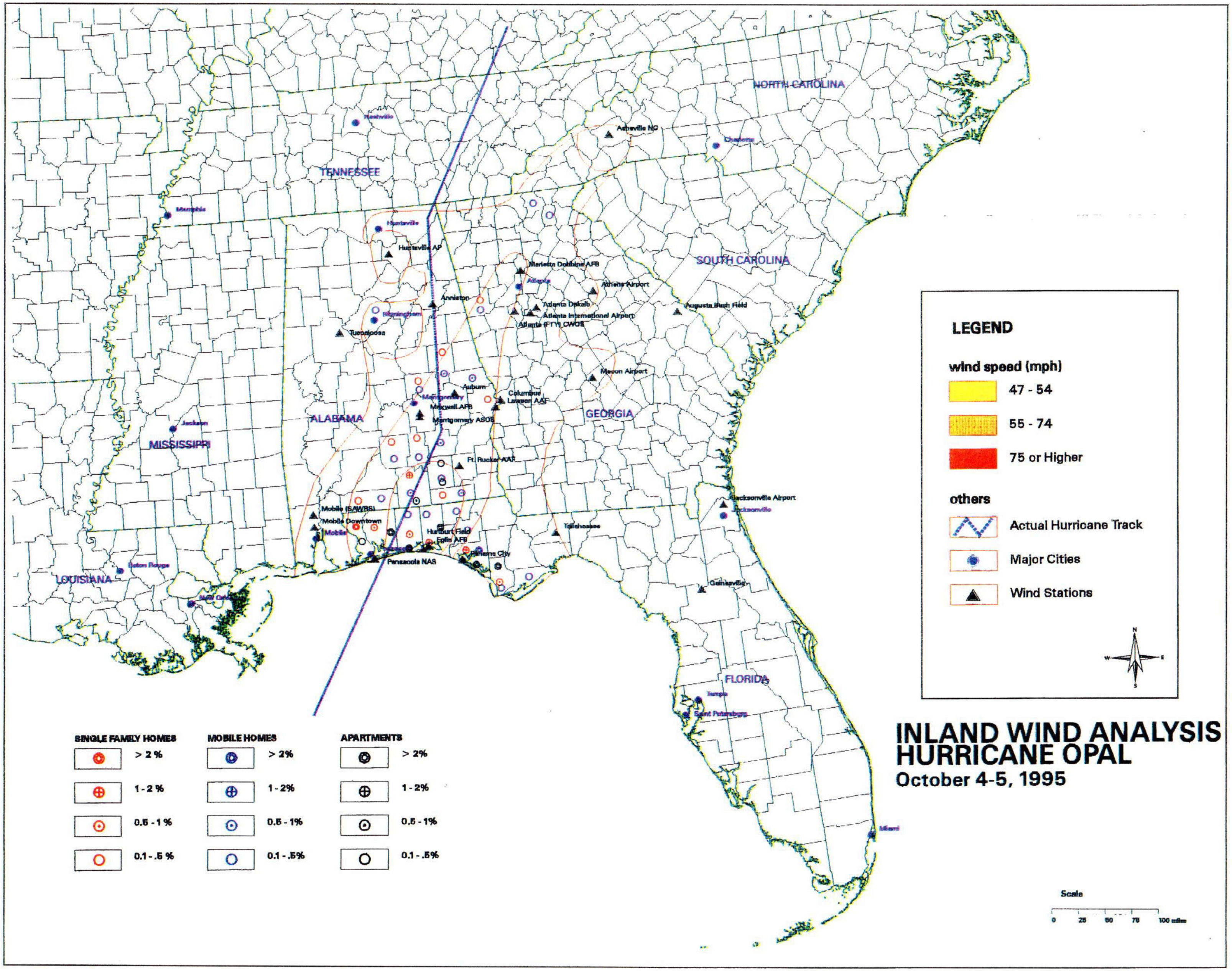

Figure 6-4 Map of Structure Damage

Table 6.3 lists and Figure 6-5 shows the maximum percentages of customers without power in the area affected by the storm. It should be noted that because of the distribution of power in service areas, the number of customers affected by power outages probably included some who were not in the swath of the storm. In addition, in some extensively forested areas, such as in North Carolina, power outages were due largely to trees falling on power lines and interrupting distribution networks.

Table 6.3 Power Distribution System Damage

Sustained Winds	Peak Gusts (mph)	Power Distribution Damage Percentage of Customers Without Power
Gale-Force Wind (39-54 mph)	50-70	15-39 %
Storm-Force Wind (55-74 mph)	71-95	40-69 %
Hurricane-Force Wind (>75 mph)	>95	> 70 %

6.4 Tree and Vegetation Damage

The winds of Hurricane Opal caused extensive damage to trees in the many forested areas of the four states, particularly northern Florida, southern and central Alabama, and the western mountains of North Carolina. The damage was done primarily to shallow-rooted trees such as pecans and hardwoods and to tall pine trees. The shallow-rooted trees were uprooted; the tall pines were bent or broken. Forest service and soil conservationists attribute much of the uprooting to very wet soil conditions, which resulted in softening of the soils that allowed the wind to tear trees out of the ground. Soils in the areas of damage varied from sand to clay; soil conservationists did not attribute the extensive damage to a predominant soil type.

The tree damage information has been difficult to "normalize" or "standardize" because of the many variations in reporting and the lack of completeness and accuracy of the damage assessments conducted immediately after the storm by the agencies involved. For this assessment, the damage is being classified as light, moderate, or severe based on observations made by forest service experts

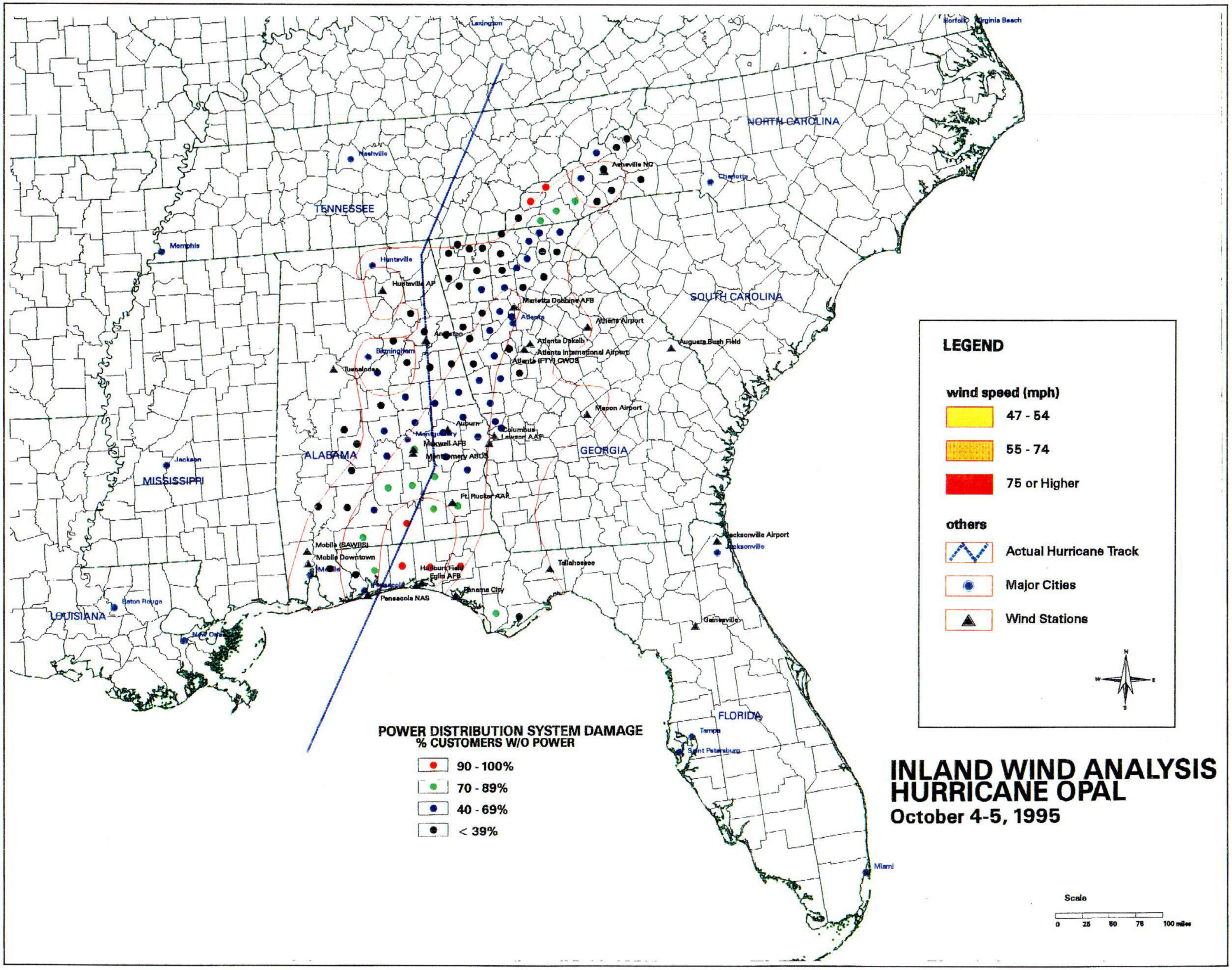

Figure 6-5 Map of Power System Damage

and reported either to FEMA after the storm or to the investigators collecting information for this study.

Generally, severe damage was confined to forests in the Florida panhandle and southern Alabama. Damage reported near Auburn, Alabama, is considered moderate. Damage in Georgia was considered light by the Georgia Forestry Commission. Damage in North Carolina was considered moderate to severe. The acceleration of wind by terrain may account for the increased tree damage in North Carolina. This moderate damage occurred almost 500 miles inland.

6.5 Other Effects

A large number of billboards and other signs were damaged by Hurricane Opal's winds. Evidence of this damage was noted during the field visits conducted for this study, 5 months after the storm.

The loss of power and the downing of trees caused a number of problems. The loss of power necessitated the use of emergency generators by hospitals in the affected area. There were many reports of hospitals that continued to operate on emergency power. The loss of power also caused municipal water and wastewater disposal systems to shut down. In some areas, these outages lasted days. Throughout the area affected by the storm, roads and bridges were blocked by fallen trees. Transportation systems were also seriously affected by the intense rainfall that occurred during the storm. These heavy rains washed out roads, undermined bridges, and altered drainage patterns.

7 CONCLUSIONS

7.1 Accuracy of the Inland Wind Model

A comparison of wind data recorded in two storm events -- Hurricanes Opal and Hugo -- with data generated by the Inland Wind Model, both the NHC model and the PC version, provides a basis for assessing the accuracy of the model. The comparison reveals that the Model's predictions of both the distance inland that winds of hurricane force will penetrate and the size of the affected area are two to three times the actual distances and areas recorded during the two storms. During Hurricane Opal, storm-force and gale-force winds traveled inland approximately ¾ to ½ the distance predicted by the model, but the area covered by these winds was nearly ½ to ⅓ that predicted by the model. In summary, the wind speed starting point appears to be too high from the conversion of over-water to over-land speed.

?

model was not used to Depict Areas Forecasters Did this by SWAG

The sustained winds predicted by the model are closer to the actual peak gusts that occurred during the storm than they are to the actual sustained winds. This finding correlates well with the originally devised Saffir-Simpson Scale (see the discussion in Section 3.2). Refer to Table 7.1 for a comparison of the maximum sustained speeds predicted with the PC version of the Inland Wind Model and the actual peak gusts.

Chang focus of this

7.2 Damage Predictions

The damage levels that can be predicted from various wind fields were discussed in Section 3. The starting point for the proposed damage potential scale (Table 7.2) is the Beaufort Scale used by NWS to estimate "sustained" wind speeds. Although the Beaufort Scale is intended to be used with 10-minute mean speeds, the assumption has been made that because it is an approximate scale, it can be applied to the 2-minute wind recorded by an ASOS station.

The expected damages described in Table 7.2 are based on the original Beaufort Scale, the Saffir-Simpson Scale corrected to the form originally intended by Saffir, and observations of the effects of Hurricanes Frederic, Hugo, and Opal. These damages are approximately the same as those observed and reported for the same wind speeds. Therefore, we conclude that the adjusted wind speeds actually experienced during Hurricane Opal, as shown in Table 4.1, are approximately correct. This damage evidence also verifies that at similar wind speeds, inland winds will create the same type and degree of damage as winds near the coast. For similar wind speeds, the increased exposure right at the coastline does increase the damage in that area.

?

Table 7.1 Comparison of Wind Speeds -- PC Version vs. Peak Gusts

		Model	Actual
Wind Speed 39 - 54 mph	Maximum Distance Inland (miles)	~382	~420
	Area of Wind Field (square miles)	NOT VALID 5,390	3,861
Wind Speed 55 -74 mph	Maximum Distance Inland (miles)	~300	420
	Area of Wind Field (square miles)	2,550	1,728
Wind Speed >75 mph	Maximum Distance Inland (miles)	210	100
	Area of Wind Field (square miles)	720	288

Note: ~ indicates approximate value

Estimated by forecasters

As examples, the following damages related to Hurricane Opal illustrate the use of the Damage Potential Scale.

- In the extensive area covered by storm-force winds (55-63 mph), trees were uprooted, but very little of any other type of damage occurred.
- Few incidences of significant manufactured home damage were reported, and no evidence of such damage was observed in the field, which suggests that winds were generally less than 75 mph.
- Few building envelopes (e.g., windows, doors) were reported broken by wind-blown debris, which suggests that winds were frequently less than 55-63 mph.
- Damage to roofs by the wind was minor, which suggests that the wind speeds were in the range of 64-74 mph.
- Minor damage occurred to signs, canopies, and porch roofs, which suggests that, depending on age and condition of the structure, the winds were not greater than approximately 75 mph.

Table 7.2 Damage Potential Scale

Description	Maximum 2-Minute Sustained Wind (mph)	Maximum 5-Second Gust (mph)	Effects
Gale	39 - 46	50 - 60	• Twigs broken off trees • Progress impeded
Strong Gale	47 - 54	61 - 70	• Slight structural damage occurs • 15-40 percent of power will be out
Storm	55 - 63	71 - 80	• Trees uprooted • Considerable damage occurs • Insurance claim ratio less than 20 percent • Avgerage insurance loss less than 0.2 percent of insured value
Violent Storm	64 - 74	81 - 95	• Damage to unanchored mobile homes • Damage to signs, canopies, porches, etc. • Roof damage evident • Small stones become airborne • 40-69 percent of power out • Some mobile homes overturned • Insurance claim ratio 20 percent - 70 percent • Average insurance loss 0.2 - 2.0 percent
Hurricane	75 - 95	96 - 125	• Foliage blown off trees • Poorly constructed signs blown down • Roofing material damage occurs • Window and door damage occurs • Structural damage to small buildings • Mobile homes destroyed • 70+ percent of power out • Insurance claim ratio 70 - 100 percent • Average insurance loss 2 - 10 percent
Strong Hurricane	96 - 110	126 - 145	• Trees, shrubs, signs all down • Extensive roofing damage • Failure of many roof structures • Some curtainwall failures • Large stones become airborne • Insurance claim ratio ~ 100 percent • Average insurance loss 10 - 60 percent
Extreme Hurricane	>111	>146	• Extensive structural failures • Extensive glass failures • Small buildings overturned, blown away • Average insurance loss > 60 percent

7.3 Use of the Inland Wind Model as a Prediction Tool

It does appear that the Inland Wind Model can be successfully used as a tool to help predict the effects of inland winds on communities. It was successfully used during Hurricane Opal in several locations to help communities prepare for the storm. The more accurately the model predicts the effects, the more accurate inland forecasts will become, which will increase the confidence emergency managers will have in using this tool to help them manage preparation efforts for a landfalling hurricane.

The use of an NHC model to aid forecasting and a different (PC) version for emergency managers is confusing and provides an unnecessary opportunity for mistakes in predicting effects. It would seem only one version that uses only one decay rate is all that is necessary once the accuracy of the model has been tested with a sufficient number of storms.

Discuss with Bill—

FEMA model must have readily available input data

Note— The FEMA IWM utilizes specific information from the NHC's ~~TF/A~~ package. The NWS model was not used operationally during the 1995 Hurricane Season. It was used as a reference tool for the Hurricane forecaster when developing the wind fields on the TF/A.

It is anticipated that the model will be afforded greater use during the 1996 season.

8 RECOMMENDATIONS

8.1 Wind Speeds

Based on the comparison of results of the wind model and experience, and based on the fact that most wind damage is caused by gusts, it is recommended that the predictions of the wind effects be based on peak gusts, not sustained winds.

The beginning wind speeds for the model should be evaluated in light of the Hurricane Opal experience to determine whether they are too high to accurately predict the expected inland storm effects. The current decay rate seems to be approximately accurate. See earlier note - Opal windspeeds

An additional wind field for the PC version of the model should be added above >75 mph because significant damage doesn't normally occur until speeds reach 95+ mph. This would be equivalent to a Strong Hurricane. maybe

The MEOWs in the PC version should be used to predict inland wind fields because the exact predicted location of the storm track appears to be very uncertain. Using the MEOWs will increase the number of communities for which high-wind warnings are issued. NO

Additional forward speed of the storm above 25 mph should be added to the MEOW program. Hugo is an example of a storm that had a forward speed of approximately 30 mph. [illegible] [illegible]

There should be only one decay rate used for any version of the inland wind program in use for PC or the NHC. ?

8.2 Descriptive Reference Guide

The effects caused by various wind speeds could be described as shown in Table 8.1.

8.3 Mitigation Measures

Mitigation measures are presented by categories of the most likely failure modes:

- Structural failure from excessive wind force

Table 8.1 Descriptive Reference Guide

Sustained Wind (mph)	Peak Gust (mph)	Effects
39 - 47 (Gale)	50 - 60	• Twigs broken off trees • Progress impeded
47 - 54 (Strong Gale)	61 - 70	• Slight structural damage occurs • Minor wind blown debris • Falling limbs cause minor power outages • Difficult to walk in the wind
55 - 63 (Storm)	71 - 80	• Shallow-rooted trees blown over • Falling trees cause structural damage • Downed trees block roads • Power outages on order of 20 - 40 percent occur • Power outages affect hospitals and shelters • Power outages affect water and wastewater treatment facilities • Small stones (¾-inch diameter) can be moved by the wind • Some sign damage occurs
64 - 74 (Violent Storm)	81-95	• Small stones (¾-inch diameter) can become airborne • Roof damage begins to occur • Power outages on order of 40 - 60 percent occur • Power outages affect additional critical care facilities • Power outages completely shut down most water and waste treatment facilities • Tree damage is significant • Difficult to stand up in the wind • Some mobile homes overturned
75 - 95 (Hurricane)	96 -125	• Damage begins to occur to building envelopes, particularly windows and doors; most damage caused by windblown debris • Damage occurs to signs, canopies, porch roofs, and overhangs • Damage occurs to unanchored mobile homes • Large stones (1½-inch diameter) can be moved by the wind • Gravel on ballasted roofs scours; some flat roof damage occurs • Power outage is 100 percent, shutting down all water, wastewater, and critical care facilities

Table 8.1 Descriptive Reference Guide (continued)

Sustained Wind (mph)	Peak Gust (mph)	Effects
96 - 110 (Strong Hurricane)	126 -145	• Major structural damage occurs to mobile homes • Extensive damage to signs, overhangs, canopies, etc. • Large stones (1½-inch diameter) can become airborne • Major damage begins to occur to building envelopes, particularly windows and doors • Major sections of flat roofs are damaged or lost • No major damage expected to structures built to current codes and adequately maintained • Infrastructure is crippled by downed trees and power lines • Wind can move heavy objects such as signs, trash cans, sections of buildings or building materials
>111 (Extreme Hurricane)	>146	• Foliage is blown off trees • Significant damage occurs to roofing materials and building envelopes, structural failures are prevalent • Some structural damage occurs to small buildings • Mobile homes are destroyed

- Building envelope failure from wind and windborne debris
- Missile penetration of the building envelope
- Support services (power, water, waste disposal) severed and infrastructure affected

8.3.1 Structural Failure -- Excessive Wind Force

The mitigation measure that will help prevent failure of the structural system of any building is conformance to the current building codes and practices. The pertinent codes in place in the area of the country impacted by Hurricane Opal are the Standard Building Code; the SBCCI Standard SSTD 10-93, *Hurricane Resistant Residential Construction*; and the ASCE Design document *Minimum Design Loads for Buildings and Other Structures* also known as ASCE 7-95.

It should be noted that the speeds shown for the 3-second peak gust on the wind map in ASCE 7-95 were not exceeded anywhere during Hurricane Opal. See Figure 8-1 for the portion of the ASCE wind map that pertains to the area affected by Hurricane Opal.

One important mitigation measure is to treat carports, canopies, porches, overhangs, and similar appurtenances as structures. If they were always treated as structures, they would be designed to resist the significant uplift they experience when high winds get under them. If this effect is not considered, the wind can rip them away from the main structure. Therefore, these appurtenances must be adequately secured to the structure and anchored to prevent uplift. An alternative mitigation measure is to enclose them to prevent the wind from entering and causing uplift.

An important mitigation measure for manufactured homes is to the install them on permanent foundations that are anchored securely to prevent the homes from overturning or sliding off their foundations when acted on by wind pressure. Once a manufactured home loses attachment to its foundation, it becomes a windborne missile and may cause damage to other structures. An unsecured manufactured home can be overturned by a wind gust speed of approximately 80-95 mph.

Too high ??

8.3.2 Building Envelope Failure

The building envelope is defined as the part of a structure that keeps out the elements and therefore includes the roof, windows, doors, and exterior siding. In most residential structures, the primary concern is keeping the roof on and the windows and doors intact. The primary mitigation measures are therefore to

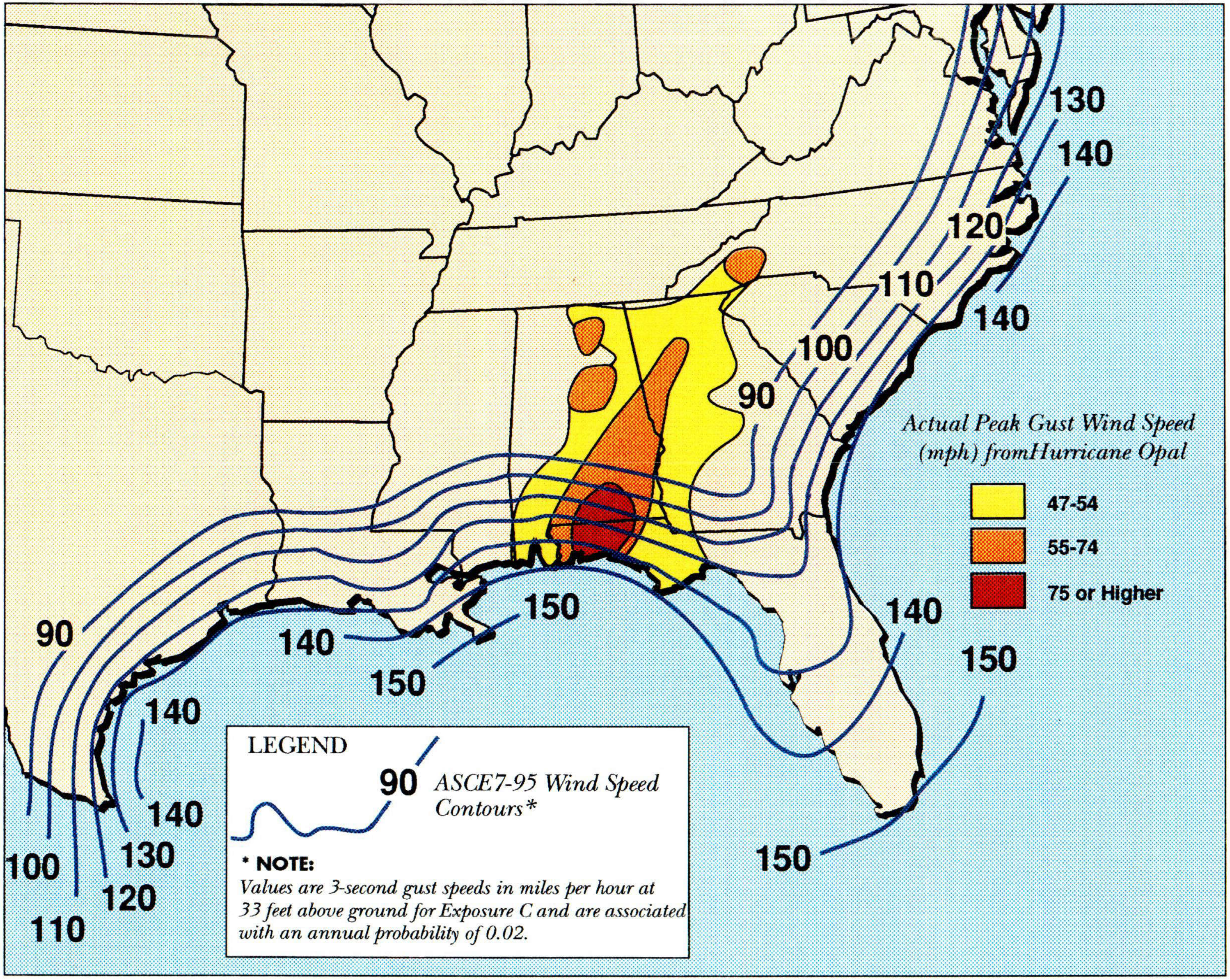

Figure 8-1. Inland Extent of Actual Peak Gusts Superimposed on Portion of ASCE7-95 Wind Map

protect (cover) the windows and doors and to install or Retrofit the roof so that it does not fail under the design wind conditions.

Windborne debris begins to be created at wind gusts of approximately 80 mph (storm-force winds). A mitigation measure known to be successful is to protect the windows and doors from breaking and thereby prevent the wind from entering the structure and creating more damage. It is suggested that the recommendation be made that building owners cover the openings in their buildings when wind gusts are expected to exceed 80 mph.

Roof covering failures begin to occur at sustained wind speeds of approximately 70 mph, although shingles and other coverings can come loose in 60-mph winds. These failures can be prevented if new roofs are designed and installed according to the appropriate building code documents and engineering standards, including ASCE 7-95. If roofs were designed and installed to these standards, the expected wind events would not do serious damage to them. Even winds moving at 60 mph significantly increase in speed at the edges of the roof surface. Additional care in the installation of roof materials in these critical areas would reduce damage.

8.3.3. Missiles

The concept of eliminating missiles is very important whenever wind gusts are expected to exceed 65 mph. At this speed the wind will begin to blow small, loose objects about, potentially creating missiles that will break the glass in a window or door and allow wind and rain to penetrate the building envelope.

When wind gusts reach approximately 75 mph, small stones can become airborne and add to the missile hazard because of their greater weight and greater potential for causing damage. Before a significant wind event occurs, owners should be encouraged to tie down or put away items on their property that could blow around and cause damage. Such items would include trash cans, lawn chairs, small toys, landscaping decorations, loose branches, flags, and debris.

At higher wind speeds, larger objects such as stones and tree limbs become more dangerous missiles. Stone is frequently used as ballast for flat roof systems such as built-up asphalt and single-ply membranes. High winds can scour the roof, picking up stone. Roof stone missiles can be eliminated if the ballast is replaced with pavers, particularly around the roof edges, which are most vulnerable to scour and uplift. Alternatively, larger stone in greater quantities could be used to increase the weight on the roof and make scour by wind less likely.

Trees growing near buildings are a frequent source of damage. Mitigation measures include pruning trees back so that no branches overhang any portion of the roof; removing diseased trees, damaged trees, and trees that have split trunks; and planting trees no closer to a building than the expected height of the full-grown tree.

8.3.4 Support Services

The primary failures in support services occur because of damage to the power distribution system. Power failures affect other community services, such as water distribution, waste water treatment, shelters, and critical care facilities.

Assuming that power failures are inevitable, plans must be developed for providing continued service to the community. Critical care facilities and shelters must therefore have independent emergency power systems that are fully operational when needed, and they must have plans for periodic testing of those systems. Critical care facilities must also have plans in place for dealing with the loss of municipal water and wastewater treatment.

Community-wide service providers such as water and wastewater treatment facilities must decide with the help of the community how and at what level service will be maintained when the power goes out. Major power interruptions can be expected when wind gusts reach approximately 70 mph.

Mitigation measures available to reduce power distribution loss are limited to placing the power system underground and expanding the clear area around transmission lines, poles, and transformers. This clear area can be increased by trimming back trees so that the distance from the tree line to the power system is at least equal to the expected height of the trees. Where this distance cannot be achieved, a tree trimming schedule should be initiated to maintain as much space between the trees and power system as rights-of-way allow. If new trees are to be planted, deep-rooted types should be considered because they will survive high winds better than shallow-rooted trees. Shallow-rooted trees begin to be uprooted and cause major damage when sustained wind speeds reach approximately 60 mph.

Table 8.2 summarizes the mitigation measures discussed above. For four wind speed ranges it lists the types of damage most likely to occur and the mitigation measure(s) that will reduce the damage. The measures are intended to be applied cumulatively as the expected wind speed increases.

8.4 Future Storms

The quality of the information derived from this model will be significantly improved with the evaluation of more storm data. Such data can be gathered for future landfalling hurricanes and other high-wind events in practically "real time" with the use of the Internet, computers, and a pre-storm workplan. It is recommended that continuing storm evaluation services be provided for the foreseeable future. The required work would include collecting and analyzing storm, wind, and damage information for every hurricane that makes landfall, no matter what category. The goal would be to enhance the quality and quantity of information provided to emergency managers and the timeliness of the delivery of that information.

Table 8.2 Mitigation Measures

Expected Sustained Wind (mph)	Expected Peak Gust (mph)	Mitigation Measures
55 - 63 Storm Force	71 - 80	• Secure loose objects. • Cut trees back away from buildings and power lines. • Plant new trees at distance from building equal to height of full-grown tree. • Provide and test generator back-up power. • Install roofing materials according to design specifications, particularly at edges.
64 - 74 Storm Force	81 - 95	• Cover windows and doors. • Add pavers or ballast to flat roofs. • Mechanically fasten single-ply roof membranes and eliminate ballast. • Protect critical care facilities and shelters and make them self sufficient.
75 - 94 Hurricane Force	96 - 125	• Install roof coverings according to design specifications for high-wind areas. • Design structural roof framing for high-wind areas. • Design structural building attachments, e.g., porches, canopies, overhangs, signs, for high-wind areas. • Anchor manufactured homes to prevent overturning.
> 95 Hurricane force	>126	• Design all structural connections, building attachments, and building envelope protection for hurricane-force winds.

The Inland Wind Model would probably not be appropriate for predicting winds and wind damages for storms striking islands, because the land mass of an island is usually so small. However, the model should be used for any hurricane striking the United States, regardless of location.

The quality of the information used in the evaluation of storms depends entirely on the quality of the wind measurements. This quality is seriously jeopardized when wind recording instruments are not provided with backup power. Sufficient evidence is available to predict that power is likely to be lost at wind speeds of 60 to 70 mph. Therefore, any recording station will probably be rendered useless during hurricane-force winds. It is recommended that NOAA and the NWS work diligently toward providing backup power to all weather recording stations.

In addition, this study identified 19 ASOS weather stations that were noncommissioned and thus had no data stored for the time of the storm. It seems there are many more recording locations that could be providing useful information if they were commissioned, and it is recommended that these additional stations be made fully operational as soon as practicable.

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Note: Addresses for Internet data sources are provided in Appendix I

APPENDIX A

Information Sources Contacted During the Investigation

CONTACTS IN ALABAMA

Alabama Emergency Management Agency
Pete McGough

Alabama Power Company
Jean Ellis

Alabama Rural Electric Association
Glen Reeves

Alabama Power
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Andalusia Star News
Tabitha Senn

ASOS Weather Station
Wade Hilton

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Dick Martin, Department of Forestry

Bullock County Emergency Manager
Randi Priori

City of Fairfield
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Coffee Co., Extension Service
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Charles Webb

Conecuh National Forest
Rick Lint

Covington County
Wayne Sowell, County Emergency Manager

Crenshaw County
Anita West

Dale County
Gerald McDaniel

Dixon Center
Rhet Johnson

Elba Clipper
Marvin Mciaowin

Enterprise Ledger
Michelle McCloud

Extension Service at Auburn University
Roger Getz

Fairfield, AL
Greg Mays

Fairfield City Hall
Danny Fields

Forestry Group, University of Auburn
Dick Martin

Fort Rucker
Cecil High

Grand National Golf Course
Buddy Williams

Jefferson County EMA
Elwood Odom

Lee County
Bill Thornton, County Emergency Manager

Macon County
William Gunn

Marcus Cable Company
Cynthia Walfork

Maxwell AFB
Captain Moore

Montgomery Advertiser
Earl Thaxton

Montgomery County, AL
Anita Patterson

Muscle Shoals Regional Airport
Rich Steinkemp

Opelika Auburn News
Cecline Buskin

Opp News
Tracy

Southeast Sun
Pattie Weiland

State of AL Infrastructure
Dave Poundstone

State of AL, Public Information Officer
Scott Adcock

State of AL Operations Manager
Jim Jones

State of Alabama Family Grant Programs
Judy Johnson

Talladega County
Griffin Holcomb, Jr.

Talladega National Forest
Kent Davenport, District Ranger

Talladega Super Speedway

Talladega National Forest
Kent Davenport

The Dothan Eagle
Jeanne

Tory Messenger
Huck Treadwell

Troy AL Airfield
Tom Catrett, Vivilian Weather Observer

Troy, Pike County
Ralph Fowee, Pike County Emergency Manager

Tuskegee National Forest
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Tuskegee Forest
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Tommy Anderson

WAAY TV Weather
Rick Mecklenberg

WABM TV
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CONTACTS IN FLORIDA

Blackwater State Forest
Vernon Compton

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Escambia County, FL Emergency Manager
Janice Kilgore, Jeff Milandor

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Santa Rosa Co., FL Emergency Manager
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CONTACTS IN GEORGIA

Atlanta Constitution
Pam Prouty, John

Channel 11
Martha Lawrence

Cobb County Emergency Manager
John Riley

Columbus Department of Emergency Management
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Dekalb Co Emergency Manager
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Ms. Bartlett

Fulton County Emergency Manager
Al Wright

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GEMA-Floyd County
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Georgia Emergency Management Agency
Chuck Gregg

Georgia Power

Kenesaw Mountain National Battlefield Park
Gene Waits, Maintenance Foreman

Muscogee Co Emergency Manager
Rali Land

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Amy Knowles

State of Georgia Public Assistance Officer
Tina Palmiere

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USFS, Atlanta
John Taylor

USFS, Atlanta
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USFS, Cohutta District
William Black

USFS, Tallulah District
Joe Dinkins

USFS, Toccoa District
R.E. Vann

USFS-Brasstown District
Larry Luckett

USFS-Chattahoochee Forest
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USFS-Coweeta Hydrologic Laboratory
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USFS-Toccoa District
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USFS, Highlands Ranger District
Jim Kidd

USFS-Ashville
Robin Castler

Waynesville Mountaineer
Cathy

APPENDIX B

Summary of Site Visits

INLAND WIND ANALYSIS - HURRICANE OPAL
FIELD VISIT REPORT
William L. Coulbourne
Montgomery, Alabama to Pensecola, Florida
March 26, 1996 through March 28, 1996

DATE: **March 26, 1996**
LOCATION: Montgomery, Ala. airport (Dannelly Field)
CONTACT: Wade Hilton - ASOS Weather Station Chief
SUMMARY COMMENTS:
- No structural damage to airport
- Power went out during the storm however, the emergency generator was started prior to losing power
- Peak wind gust was 63 mph
- Winds were stronger East of the airport
- Anemometer is standard 33' high and is in open (see photo no. 1)

LOCATION: Maxwell AFB, Montgomery, Ala.
CONTACT: Captain Moore, Weather Office, Base Operations
SUMMARY COMMENTS:
- Anemometer is Model FMQ13 and is 13' high and located in open (see photo no. 2)
- Peak gust of 78 knots was recorded but at the same time as 26 knot sustained winds. This data is suspect.

LOCATION: South of Montgomery, Ala. toward Crenshaw County
SUMMARY COMMENTS:
- Damage to many single family homes from fallen trees south of Montgomery (see photo no. 3)
- Damage to trees along Route 331 South. Trees were blown down from Northeasterly to Easterly direction

LOCATION: Luverne, Crenshaw County, Ala.
CONTACT: Anita West, Crenshaw County Emergency Manager
SUMMARY COMMENTS:
- Minor damage to one school, no damage to churches or other potential shelters
- Chicken and dairy operations without power however did not lose operational capability
- Power lost to 75% of population of 14,000 people
- Little to no mobile home damage
- Most houses are on crawl spaces or slabs on grade
- No restored power lines were placed under ground. All power restored on poles
- Terrain is flat to gently rolling
- Minimal flooding due to heavy rains
- Minimal structural damage to business in Luverne - awning and glass storefront damage

LOCATION: Troy, Pike County, Ala.
CONTACT: Ralph Fowee, Pike County Emergency Manager
SUMMARY COMMENTS:

- Supplied video taken in Troy, Ala. day after the storm
- Lost partial roofs on one school and two churches
- Minimal damage to mobile homes, approximately 2500 to 3000 mobile homes in county with 26,000 population
- Estimated 40% of all buildings had roofs replaced or repaired
- Minimal flooding
- No water, communications, cellular towers were damaged
- Troy State Univ. had band festival weekend after hurricane that almost caused a problem of inadequate motel space with the large number of disaster workers needing housing
- Some structural and tree damage visible (see photo nos. 5, 6, 7)

LOCATION: Troy, Ala. airfield
CONTACT: Tom Catrett, Civilian Weather Observer
SUMMARY COMMENTS:

- Has two anemometers, one vane type and one "hot wire"
- Neither anemometer has battery back up power
- Peak gust of 37 knots was recorded at 00:04 am on 10/5/95 (UTC) and then power was lost

DATE: **March 27, 1996**
LOCATION: Fort Rucker (Ozark), Ala.
CONTACT: Cecil High, Emergency Operations
SUMMARY COMMENTS:

- Inland wind model saved them because it gave them faith that their emergency planning decisions were correct
- Lost power at anemometer site at 00:49 UTC on 10/5/95
- Weather observers left when the wind reached 40 knots
- Simms hand held anemometer was used to record gust of 85 knots
- Anemometer at the airfield is FMQ13 "hot wire" type
- Mark Zettlemoyer of the USAF supplied the weather data
- Minor damage at airfield including erosion (see photo nos. 32, 33)

LOCATION: Covington County, Ala.
CONTACT: Wayne Sowell, Covington County Emergency Manager
SUMMARY COMMENTS:

- Little damage left to see, very little damage done to mobile homes
- Covington Electric Cooperative is major supplier of electric service to county

- One county owned recreation building that had access blocked by high water. Some flat roof loss to shelter buildings
- Some windows in courthouse broken by wind borne debris
- Radio station lost tower, all other towers were OK
- Roof damaged at South Highlands Elem. School. Roof is very shallow pitched
- Some structural and roof covering damage visible (see photo nos. 9, 10, 11, 13)
- Most houses built on crawl space or concrete slab on grade
- Most tree damage to shallow roots systems like pecans and oaks

DATE: **March 28, 1996**
LOCATION: Okaloosa County, Fla.
CONTACT: George Collins, Okaloosa County Emergency Manager
SUMMARY COMMENTS:

- No significant flooding in homes away from the beach. Some storm water runoff problems
- Some damage to schools which act as shelters. Crestview High school had 1300 people in school when tornado destroyed field house (see photo no. 27)
- Church in Fort Walton lost roof
- Power is supplied by Choctawhatchee Power in Northwestern part of county
- Gulf Power supplies Crestview and southern part of county
- Hurricane Erin thinned out trees and poorly maintained power poles
- Most total tree damage done to pecan and oak trees, pine trees bent (see photo no. 16)
- Auburn Water supply (small private distributor) was down about 1 week with contaminated water supply
- House owned by Bob Sikes family was moved off foundation (see photo 23)
- Hospitals continued operation with no loss of service
- Hurlbert Field (AFB) has two anemometers of the "hot wire" type. North recorder was being monitored continuously during storm with consistently increasing winds. South recorder indicated 125 knot gust but sustained winds only 61 knots.
- Some structural damage visible (see photo nos. 18, 20, 21, 28, 29, 30)
- Roof damage visible along coast immediately after storm (see photo no. 31)

WAWTAC Task 10 - Trip Summary
Eileen Miller

3-26-96 Tuskegee National Forest, Tuskegee, AL
David L. Carter, District Ranger

- visited four sites with typical damages
- mostly sandy soil with pine trees
- topography - rolling hills, surrounding areas are plains
- blowdowns appear to have occurred in areas adjacent to low-lying areas where wind was allowed to increase in strength due to topography
- some diseased trees (typical in the South) although this did not appear to be cause of blowdown to those trees
- see detailed topo map for areas hit and for areas visited

3-27-96 Auburn University, Auburn, AL
Dick Martin, Department of Forestry

- photographed anemometer at university
- viewed some downed trees at campus, including 200-year old hardwood trees
- viewed damages along drive to Camp Hill
- visited Camp Hill, site located about ___ miles northwest of Auburn
- viewed blowdown areas at Camp Hill

3-27-96 Talladega National Forest, Talladega, AL
Kent Davenport, District Ranger

- see topo map for sites visited
- photographed anemometer -- used primarily to determine fire hazard, therefore wind data may not be compatible with other anemometers. Kent will send recorded data, as available.
- drove through forest, observed single trees down
- observed single trees down as well as blowdowns
- mixed hardwoods and pines
- rocky soils, mountainous topography, shallow soil depths, shallow tree roots
- some selected cutting areas
- trees were not diseased
- observed blowdowns in areas along Rt 219
- Kent **estimated** 1 to 2% of total stand downed from Opal

3-28-96 City of Fairfield, AL
Greg Maze, Assistant Superintendent, Public Works

- reviewed photographs of trees downed by Opal and photos of minimal structural damage, copied selected photos
- contacted TV stations regarding anemometer

INLAND WIND ANALYSIS HURRICANE OPAL
SUMMARY OF FIELD VISIT (EJL)

Date: 3/26/96
Point of Contact: Atlanta Constitution, October 6, 1995 photo
Materials Received: None
Site Location(s): Springdale Road, SW Atlanta, GA
Observations of Damage: Damage had been repaired, there was little evidence of stumps. The neighborhood is situated on a small hillside exposed to the south. Homes were masonry and wood frame.

Date: 3/26/96
Point of Contact: Al Wright, Fulton County Emergency Manager
Materials Received: None
Site Location(s): Alden Avenue (near 25th and 25th), midtown Atlanta, GA
Observations of Damage: Damage had been repaired to neighborhood. The homes are on the windward side (south) of a small hill. The construction used was masonry and wood frame.

Date: 3/26/96
Point of Contact: Art Comeau, Base Meteorologist
Materials Received: Wind data, base map with anemometer locations, anemometer specifications
Site Location(s): Dobbins, AFB, Marietta, GA
Observations of Damage: Photographed roof torn off of generator building near the control tower and door blown into the weather office. Observed some tree damage on the eastern (Navy) part of the base and observed damage on the northeast perimeter. Tree damage was restricted to isolated areas that were exposed to the southeastern wind. Observed both anemometers located 13' above the runway centerline. The east gage usually has more wind speed than the west gage (active during the storm).

Date: 3/26/96
Point of Contact: John Riley, Cobb County Emergency Manager
Materials Received: None
Site Location(s): Church Street, Marietta, GA
Observations of Damage: Observed home with damaged roof and possible home with chimney damage located in residential area of Marietta, GA. No other damage observed. (See photos EJL 1:14-16)

Date: 3/27/96
Point of Contact: Gene Waits, Maintenance Foreman
Materials Received: Tourist Map of Park
Site Location(s): Kenesaw Mountain National Battlefield Park, north of Marietta, GA
Observations of Damage: Observed tree damage throughout the park on mostly red clay soils. Surprisingly, there was little damage on Kennesaw Mountain (the highest elevation in the park). The rocky soils may have stabilized the trees and protected them from the winds. Much of the tree damage was to older trees that were diseased (observed hollow fallen trees and pine bole beetle damage). Some damage to various species was observed on the crests of hills and somewhat down the leeward side. The area around the park has experienced rapid growth of residential single family homes. Many of the more expensive homes that were damaged in the area completed little landscaping near the homes (the homes were 'built in' the forest).

Date: 3/27/96
Point of Contact: David Ashburn, Walker County Emergency Manager/Police Chief/Fire Chief
Materials Received: County Map with flood and wind damage highlighted
Site Location(s): Chickamauga, GA, Halls Mill Road Culvert, various other places in the county
Observations of Damage: The county is situated such that runoff from the mountains on the eastern and western sides of the county quickly flows to the central valley where many homes are located. Walker County has had major problems with flash flooding in the past. Observed area in downtown Chickamauga where substantial flood damage occurred to residential and mobile homes due to Hurricane

Opal (see photos 2:3-9). This area was in the floodplain and many of the residents have received money from FEMA to modify their homes in the past. Some mobile homes were flooded which were located on a small tributary where water flowed over the road (see photos 3:8-9). Damage from Opal also observed was a small culvert washout (see photos 3:10-11), a damaged bridge and roadway (see photos 3:12-13), tree damage on the leeward side of a high plain, and a wind damaged hardware store warehouse (see photos 3:18-20). Soils in the area vary from a Chirt-type in the mountains to alluvial clay and silt in the valley.

Date: 3/27/96
Point of Contact: Gerald Collins, USFS-Toccoa District
Materials Received: Topographic maps of areas visited
Site Location(s): Blue Ridge Lake, Brawley Mountain, GA
Observations of Damage: Observed various tree damage including a large blowdown (possible tornado) at the dam at Blue Ridge Lake (See photos EJL 3:15-20). High elevation (around 3,000 ft.) poplar and oak blowdowns (50-70% lost) were observed on the windward and crest of southeastern facing ridges on Brawley and Tipton Mountains. These areas had been selectively cut (removal of approx. 30% of trees) 3 years previous to the Hurricane Opal. Some white pines that were blowndown were observed near Gaddistown, Ga around 2,200 feet on a southeastern facing slope. The soils type observed was red clay at most elevations. Most of the trees that were blowndown were healthy.

Date: 3/28/96
Point of Contact: Larry Luckett, USFS-Brasstown District
Materials Received: Map of Chattahoochee National Forest and pictures of damage to the forest and USFS building in Brasstown, GA
Site Location(s): Ivylog and Gumlog Mountain, Brawley Mountain, GA
Observations of Damage: Observed various tree damage around 3,000 feet on the crests and leeward side of mostly southeastern facing ridges. USFS personnel estimate that Hurricane Opal damaged approximately 5% (10 million board feet of 110,000 acres) of the trees in their district. The Brasstown USFS district was the hardest hit in Georgia.

Date: 3/28/96
Point of Contact: Larry Luckett, USFS-Brasstown District
Materials Received: Map of Chattahoochee National Forest and pictures of damage to the forest and USFS building in Brasstown, GA
Site Location(s): Ivylog and Gumlog Mountain, Brawley Mountain, GA
Observations of Damage: Observed various tree damage around 3,000 feet on the crests and leeward side of mostly southeastern facing ridges. USFS personnel estimate that Hurricane Opal damaged approximately 5% (10 million board feet of 110,000 acres) of the trees in their district. The Brasstown USFS district was the hardest hit in Georgia. There are many soil types in the district.

Date: 3/28/96
Point of Contact: Wayne Swank-Mark Crawford, USFS-Coweeta Hydrologic Laboratory
Materials Received: Map of Coweeta Forest and Anemometer data (4 sites throughout forest)
Site Location(s): Various watersheds in the Coweeta
Observations of Damage: Observed various tree damage around 3,300 -3,00 feet on the crests and windward side of mostly southeastern facing ridges. Damage was caused to hardwoods (mostly poplar and oaks). Most of the Coweeta forest is composed of hardwoods. Trees sometimes fell down the steep slopes towards the southeast (not observed in other areas). Also observed land slippages in upper elevations near Reynolds gap. Two other areas observed were locations where wind was deflected off of steep-south facing rock walls and tunneled through a gap area (near Blue Rock Gap). Destruction of various species was observed in the gap.

APPENDIX C

Saffir-Simpson Hurricane Scale

APPENDIX C

SAFFIR-SIMPSON HURRICANE SCALE[1]

Category One Hurricane -- Weak

Winds[2]: 75 - 95 mph (65 - 82 kt) at standard anemometer elevations. F-scale is 1.0 - 1.4. Damage is primarily to shrubbery, trees, foliage, and unanchored mobile homes. No real damage occurs to building structures. Some damage is done to poorly constructed signs.[3]

Storm Surge: Nominally is 4 - 5 ft (1.2 - 1.5 m) above normal. Low-lying coastal roads are inundated, minor pier damage occurs, some small craft in exposed anchorages break moorings.

Category Two Hurricane -- Moderate

Winds: 96 - 110 mph (83 - 95 kt) at standard anemometer elevations. F-scale is 1.5 - 1.9. Considerable damage is done to shrubbery and tree foliage, some trees are blown down. Major structural damage occurs to exposed mobile homes. Extensive damage occurs to poorly constructed signs. Some damage is done to roofing material, windows, and doors; no major damage occurs to building structures.

Storm Surge: Nominally is 6 - 8 ft (1.8 - 2.4 m) above normal. Coastal roads and low-lying escape routes inland are cut by rising water 2 - 4 hr before arrival of storm center. Considerable pier damage occurs, marinas are flooded. Small craft in unprotected anchorages break moorings. Evacuation of some shoreline residences and low-lying island areas is required.

Category Three Hurricane -- Strong

Winds: 111 - 130 mph (96 - 113 kt) at standard anemometer elevations. F-scale is 2.0 - 2.4. Damage occurs to shrubbery and trees: foliage is blown off trees, large trees are blown down. Practically all poorly constructed signs are blown down, some roofing material damage occurs, some window and door damage occurs, and some structural damage occurs to small residences and utility buildings. Mobile homes are destroyed . There is a minor amount of curtainwall failure.

Storm Surge: Nominally is 9 - 12 ft (2.7 - 3.7 m) above normal. Serious flooding occurs at the coast with many smaller structures near the coast destroyed. Larger structures are damaged by battering of floating debris. Low-lying escape routes inland are cut by rising water 3 - 5 hr before the storm center arrives. Terrain continuously lower than 5 ft (1.5 m) above sea level may be flooded inland 8 mi (12.9 km) or more. Evacuation of low-lying residences within several blocks of the shoreline may be required.

Category Four Hurricane -- Very Strong

Winds: 131 - 155 mph (114 - 135 kt) at standard anemometer elevations. F-scale is 2.5 - 2.9. Shrubs and trees blown down, all signs are down. Extensive roofing material damage occurs, extensive window and door damage occurs, complete failure of roof structures occurs on many small residences, and complete destruction of mobile homes occurs. Some curtainwalls experience failure.

Storm Surge: Nominally is 13 - 18 ft (3.9 -5.5 m) above normal. Terrain continuously lower than 10 ft (3 m) above sea level may be flooded inland as far as 6 mi (9.7 km). Major damage occurs to lower floors of structures near the shore due to flooding and battering action. Low-lying escape routes inland may be cut by rising water 3 - 5 hr before the storm center arrives. Major erosion of beach areas occurs. Massive evacuation of all residences within 500 yd (457 m) of the shoreline may be required and of single-story residences on low ground within 2 mi (3.2 km) of the shoreline.

Category Five Hurricane -- Devastating

Winds: Greater than 155 mph (135 kt) at standard anemometer elevations. F-scale is 3.0 or greater. Shrubs and trees are down, roofing damage is considerable, all signs are down. Very severe and extensive window and door damage occurs. Complete failure of roof structures occurs on many residences and industrial buildings. Extensive glass failures occur, some complete buildings fail, small buildings are overturned and blown over or away, and complete destruction of mobile homes occurs.

Storm Surge: Height is nominally greater than 18 ft (5.5 m) above normal. Major damage occurs to lower floors of all structures located less than 15 ft (4.6 m) above sea level and within 500 yd (457 m) of the shoreline. Low-lying escape routes inland are cut by rising water 3 - 5 hr before the storm center arrives. Massive evacuations of residential areas situated on low ground within 5 - 10 mi (8 - 16 km) of the shoreline may be required.

---

[1] The Saffir-Simpson Hurricane (SSH) Scale does not apply to the Pacific Islands.

[2] Definition of a sustained wind (from Fujita and Simpson, 1972). A sustained wind is one that persists for the minimum time period to establish optimal dynamic forces on a nominal building structure.

[3] T. Fujita, 1971: “Proposed Characteristics of Tornadoes and Hurricanes by Area and Intensity,” University of Chicago (SMRP) Research Paper No. 91.

APPENDIX D

Anemometer Station Data

WAWTAC Task 10 -- Hurricane Opal Inland Winds

Anemometer Station Data

Station	Date/Time Peak Gust UST	Adjusted Max. Sust. Wind (mph)	Adjusted Peak Wind Gust (mph)	Location		Elev. (feet)	Source of Data
				Latitude	Longitude		
Hurlburt Field, FL	10/4: 2142	87	115	30°26' N	86°41' W	38	NCDC
Pensacola NAS, FL Nautrametoc FAC	10/4: 1936 - 2225	44	71	30°21' N	87°19' W	30	NCDC
Tallahassee, FL	10/5: 0352	33	53	30-23' N	84-22' W	55	NCDC - trace
Eglin AFB, FL	10/4: 2304	87 (E)	112 (E)	30°29' N	86°32' W	85	NCDC
Panama City, FL		14		30-12' N	85-41' W	15	NCDC
Apalachicola, FL		32	59	29-44' N	85-02' W	19	NCDC
Gainesville, FL Flight Ser Sta (not a NWS)	10/4	14	_	29°41' N	82°16' W	138	SERCC
Jacksonville, FL International Airport	10/4	22	35	30°29' N	81°42' W	26	SERCC
Anniston/Calhoun Co., AL	10/5: 335	31	42	33-35' N	85-51' W	599	NCDC
Auburn, AL	10/5: 533	45	58	32-37' N	85-26' W	774	Internet
Birmingham Mun., AL	10/5: 530	33	60	33-34' N	86-45' W	620	NCDC - trace
Caims AAF/Ozark (Ft. Rucker)	10/5: 0024	67	81	31-17' N	85-43' W	298	NCDC
Huntsville, AL Huntsville-Madison County AP	10/5: 0600	43	55	34°39' N	86°46' W	624	SERCC
Montgomery, AL ASOS Dannelly Field	10/5: 110	55	65	32°18' N	86°23' W	192	NCDC

Montgomery, AL Maxwell AFB	10/5: 340	51	67	32°23' N	86°22' W	168	NCDC
Tuscaloosa, AL	10/5: 600	27	38	33-14' N	87-37' W	170	NCDC
Mobile, AL Bates Field	10/4: 2222	38	59	30-41' N	88-15' W	211	NCDC - trace
Mobile, AL (SAWRS) Brookley Airport	10/4: 1950	27	38	30-38' N	88-04' W	26	NCDC
Atlanta, GA ASOS International Airport	10/5: 0728	33	49	33°38'25" N	84°25'37" W		NCDC
Atlanta, GA (LAWRS) DeKalb/Peachtree	10/5: 0547	38	54	33-53' N	84-18' W	1002	NCDC
Atlanta, GA (FTY) CWOS	10/5: 0857	28	50	33-47' N	84-31' W	840	NCDC
Columbus, GA	10/5: 0419	38	52	32°30'58" N	84°56'20" W	445	NCDC
Marietta, GA Dobbins AFB	10/5: 0835	47	72	33°55' N	84°31'W	1068	NCDC
Augusta, GA/Bush Field		35	46	33°22' N	81°58' W	136	SERCC
Macon, GA Lewis B. Wilson Airport		36	47	32°42' N	83°39' W	354	SERCC
Athens, GA Municipal Airport	10/5: 900	31	49	33°57' N	83°19' W	802	SERCC
Asheville, NC	10/5: 1149	36	60	35-26' N	82-33' W	2140	NCDC
Chattanooga, TN	10/5: 0931	31	37	35°02'07" N	85°12'14" W	665	NCDC
Lawson AAF, GA	10/5: 0410	44	64	32°20' N	85°00' W	232	NCDC

J:\J3651\TASK10\WIND.TBL

APPENDIX E

Program Output Options

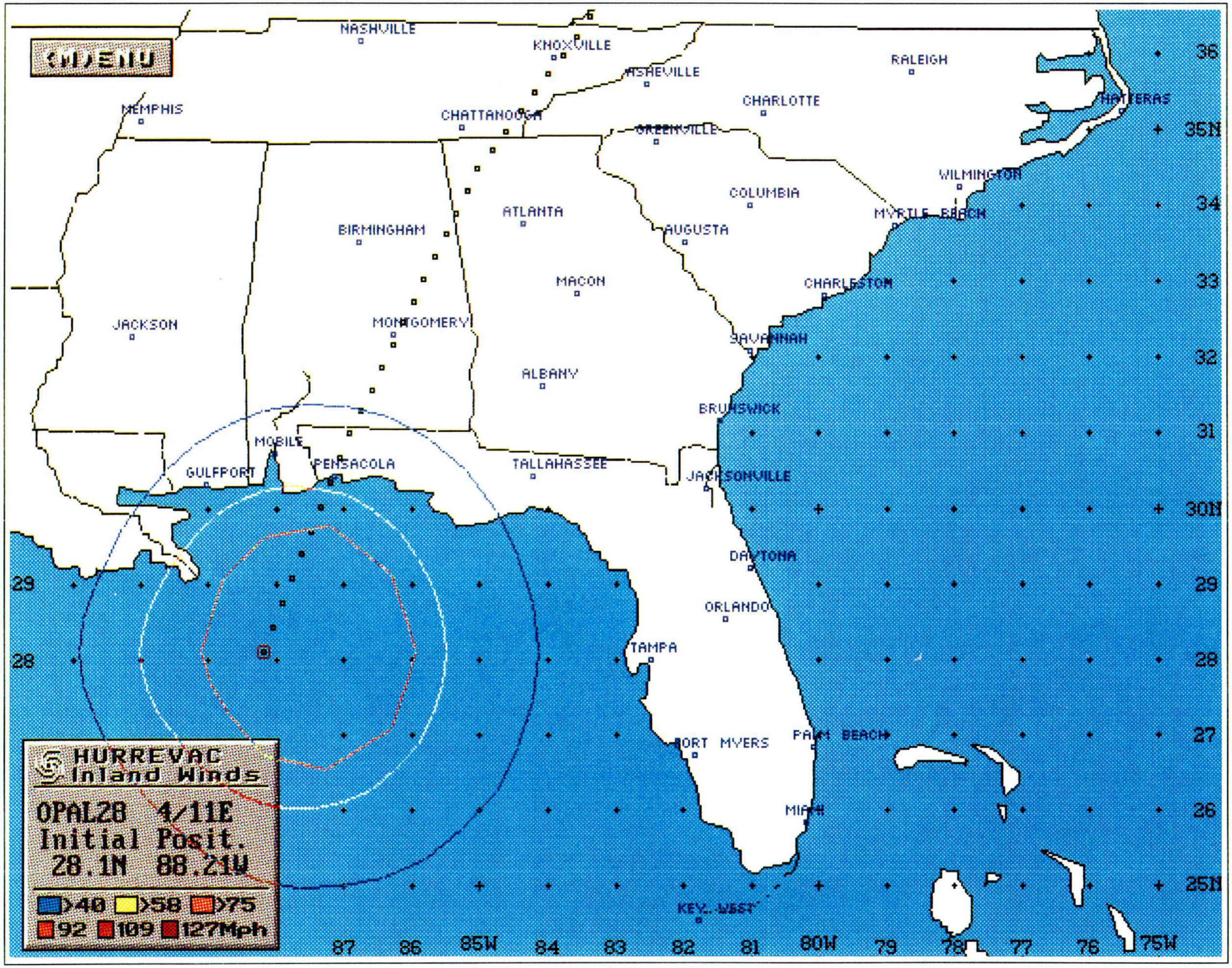


Figure E-1. Example of Model Output Option: Hurricane Track Estimate at Hurricane Advisory Number 28.

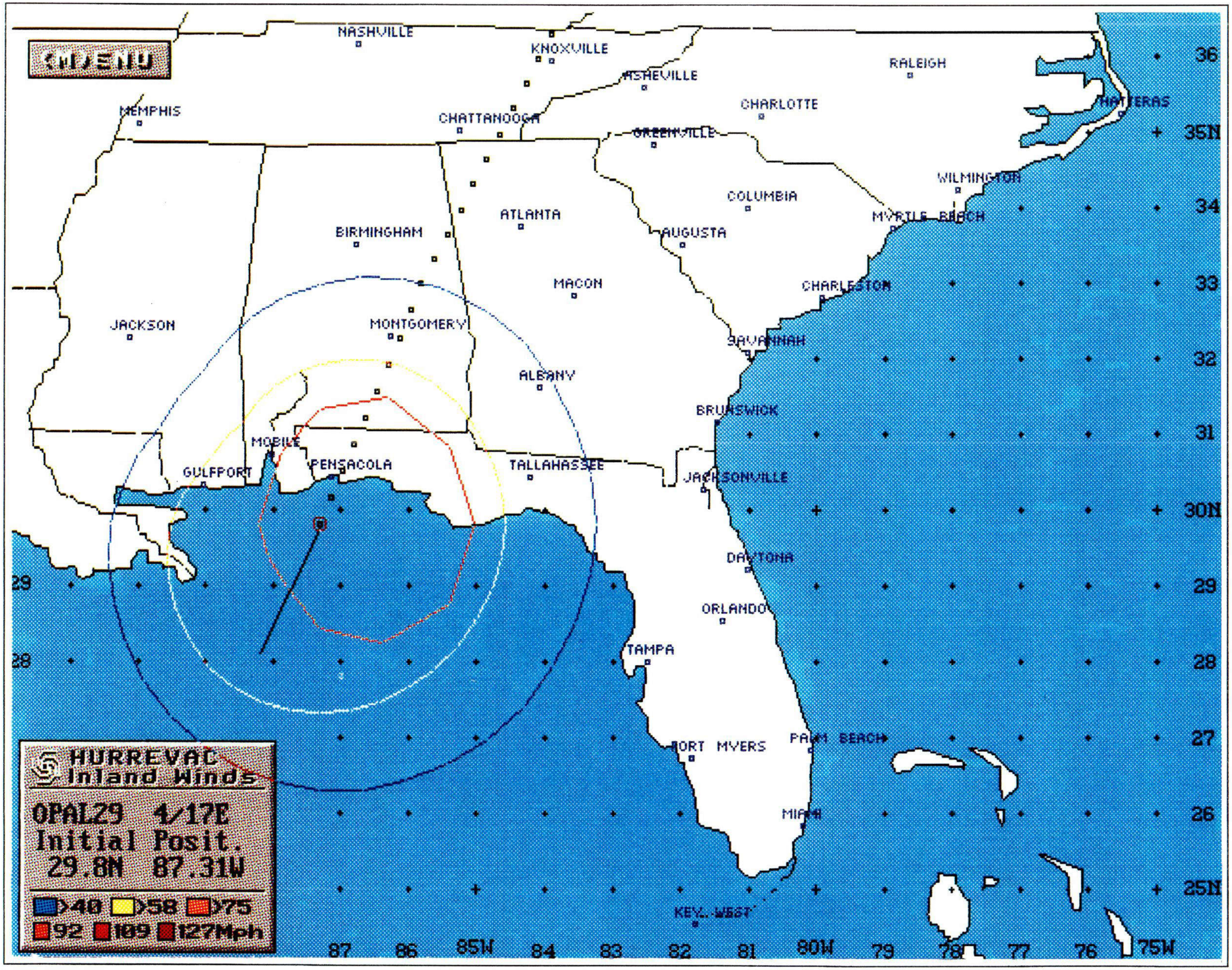


Figure E-2. Example of Model Output Option: Hurricane Track Estimate at Hurricane Advisory Number 29.

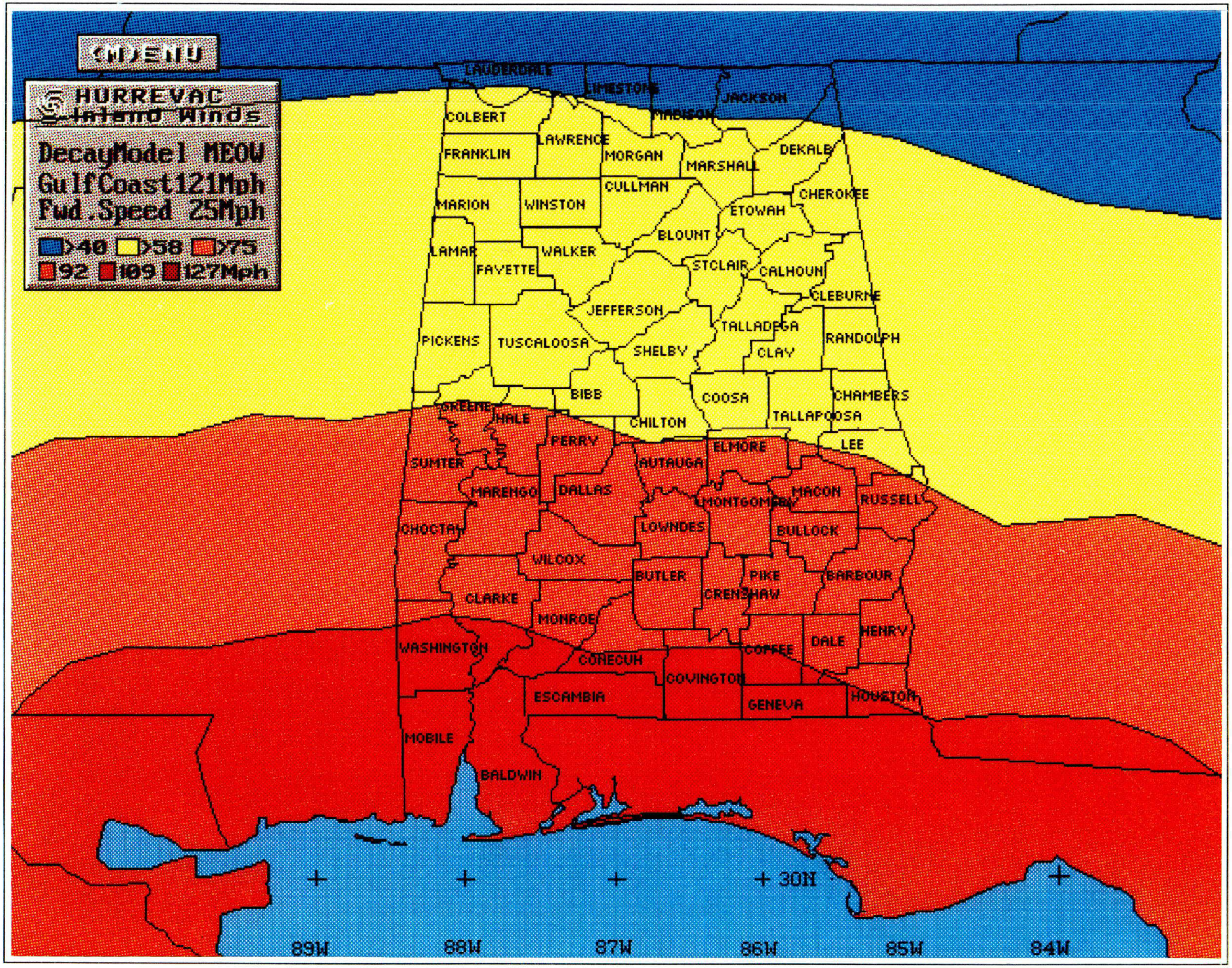


Figure E-3. Example of Model Output Option: Maximum Envelope of Winds (MEOW) at Hurricane Advisory Number 29.

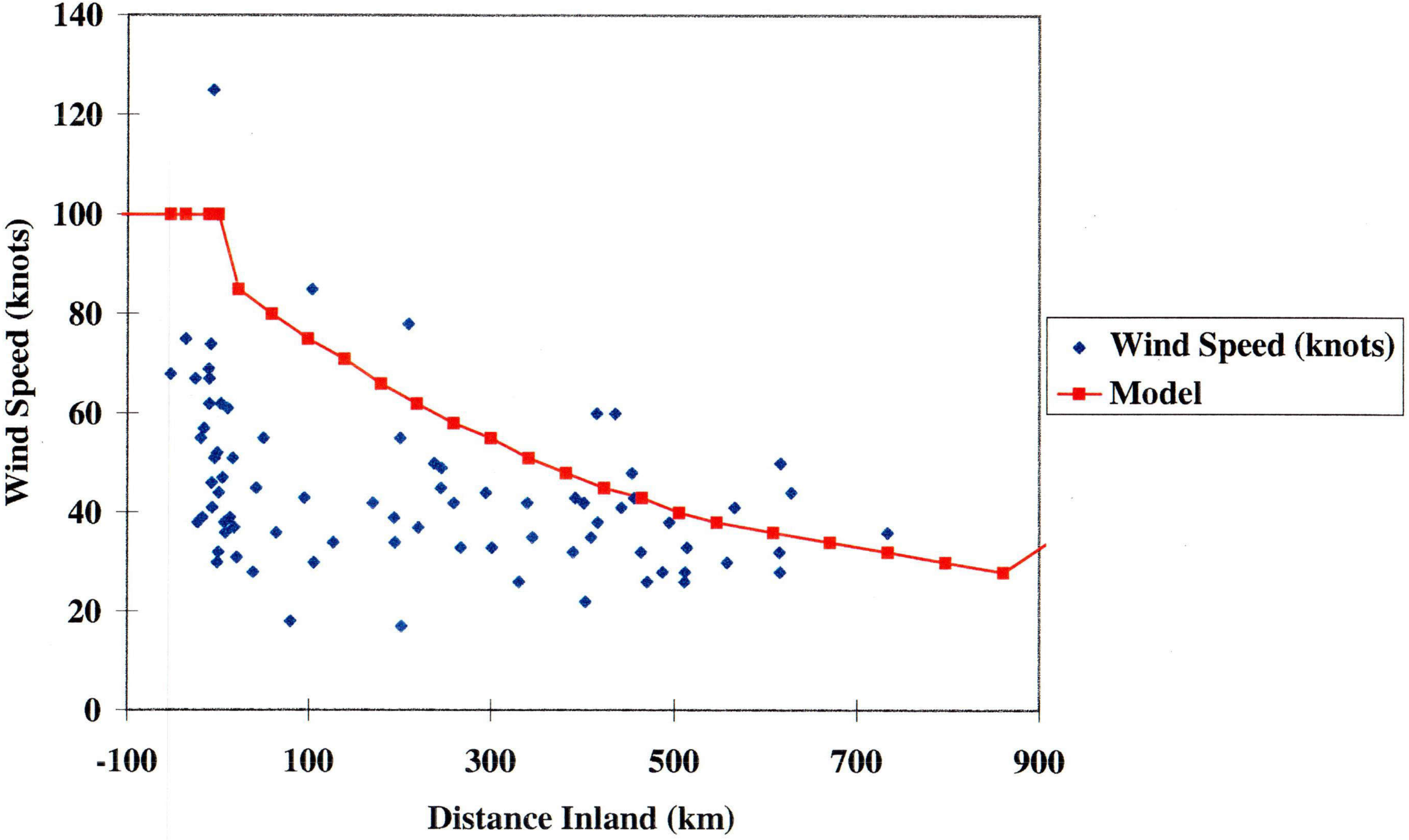
```
HURREVAC - INLAND WINDS - NHC Forecast Implied Effects/Timing
AL Counties Affected Using NHC Advisory : OPAL29.INL
Sort Type : Alphabetical (default)
-----------------------------------------------------------------------
 AL-52 Counties 40mph  58mph  75mph  75end(hrs) 58end(hrs)  40end(hrs)
-----------------------------------------------------------------------
AUTAUGA          4/17   4/19                         (71)       (73)
BALDWIN          4/17   4/17   4/17   4/20( 3)   5/00( 7)   5/01( 8)
BARBOUR          4/17   4/18   4/20   5/00( 4)       (72)       (73)
BIBB             4/17   4/22                         (68)       (73)
BLOUNT           4/23                                           (67)
BULLOCK          4/17   4/18   4/22   5/01( 3)       (72)       (73)
BUTLER           4/17   4/17   4/18   5/00( 6)   5/02( 9)       (73)
CALHOUN          4/21   5/00                         (66)       (69)
CHAMBERS         4/17   4/21                         (69)       (73)
CHEROKEE         4/23   5/02                         (64)       (67)
CHILTON          4/17   4/21                         (69)       (73)
CHOCTAW          4/17                                       5/01( 8)
CLARKE           4/17   4/17                     5/00( 7)   5/02( 9)
CLAY             4/18   4/23                         (67)       (72)
CLEBURNE         4/20   5/00                         (66)       (70)
COFFEE           4/17   4/17   4/17   5/00( 7)   5/02( 9)       (73)
CONECUH          4/17   4/17   4/17   4/23( 6)   5/02( 9)   5/02( 9)
COOSA            4/17   4/21                         (69)       (73)
COVINGTON        4/17   4/17   4/17   4/23( 6)   5/02( 9)   5/02( 9)
CRENSHAW         4/17   4/17   4/18   5/00( 6)       (73)       (73)
DALE             4/17   4/17   4/18   5/00( 6)   5/02( 9)       (73)
DALLAS           4/17   4/18                         (72)       (73)
DEKALB           5/01                                           (65)
ELMORE           4/17   4/20   5/00       (66)       (70)       (73)
ESCAMBIA         4/17   4/17   4/17   4/22( 5)   5/01( 8)   5/02( 9)
ETOWAH           4/23   5/02                         (64)       (67)
GENEVA           4/17   4/17   4/17   4/23( 6)   5/01( 8)   5/02( 9)
GREENE           4/17                                       5/01( 8)
HALE             4/17                                       5/02( 9)
HENRY            4/17   4/17                     5/02( 9)       (73)
HOUSTON          4/17   4/17   4/18   4/23( 5)   5/01( 8)   5/02( 9)
JEFFERSON        4/19                                           (71)
LEE              4/17   4/21                         (69)       (73)
LOWNDES          4/17   4/18   4/21   5/00( 3)       (72)       (73)
MACON            4/17   4/19   4/23   5/01( 2)       (71)       (73)
MARENGO          4/17   4/19                     5/00( 5)   5/02( 9)
MARSHALL         5/01                                           (65)
MOBILE           4/17   4/17                     4/23( 6)   5/00( 7)
MONROE           4/17   4/17   4/18   4/19( 1)   5/02( 9)       (73)
MONTGOMERY       4/17   4/18   4/21   5/01( 4)       (72)       (73)
PERRY            4/17   4/21                     5/02( 5)       (73)
PIKE             4/17   4/17   4/19   5/01( 6)       (73)       (73)
RANDOLPH         4/19   4/23                         (67)       (71)
RUSSELL          4/17   4/20                         (70)       (73)
SHELBY           4/18   4/23                         (67)       (72)
ST.CLAIR         4/20   5/00                         (66)       (70)
SUMTER           4/17                                       5/01( 8)
TALLADEGA        4/18   4/23                         (67)       (72)
TALLAPOOSA       4/17   4/20   5/00       (66)       (70)       (73)
TUSCALOOSA       4/18                                           (72)
WASHINGTON       4/17   4/17                     4/23( 6)   5/00( 7)
WILCOX           4/17   4/17                     5/02( 9)       (73)
-----------------------------------------------------------------------
```

```
HURREVAC - INLAND WINDS
AL Counties Affected Using Decay Model Max Envelope of Winds (MEOW)
MEOW -  GULF COAST 121Mph(105Kt) - 25Mph(22Kt) Forward Speed
======================================================================
----------------------------------------------------------------------
Counties with MAX wind 109Mph(95Kt) or GREATER.....
----------------------------------------------------------------------
----------------------------------------------------------------------
Counties with MAX wind in range 92 to 108 Mph (80 to 95Kt)
----------------------------------------------------------------------
 BALDWIN        CLARKE         COFFEE         CONECUH        COVINGTON
 DALE           ESCAMBIA       GENEVA         HOUSTON        MOBILE
 MONROE         WASHINGTON
----------------------------------------------------------------------
Counties with MAX wind in range 75 to 91 Mph (65 to 80Kt)
----------------------------------------------------------------------
 AUTAUGA        BARBOUR        BULLOCK        BUTLER         CHOCTAW
 CRENSHAW       DALLAS         ELMORE         GREENE         HALE
 HENRY          LEE            LOWNDES        MACON          MARENGO
 MONTGOMERY     PERRY          PIKE           RUSSELL        SUMTER
 TALLAPOOSA     WILCOX
----------------------------------------------------------------------
Counties with MAX wind in range 58 to 74 Mph (50 to 65Kt)
----------------------------------------------------------------------
 BIBB           BLOUNT         CALHOUN        CHAMBERS       CHEROKEE
 CHILTON        CLAY           CLEBURNE       COLBERT        COOSA
 CULLMAN        DEKALB         ETOWAH         FAYETTE        FRANKLIN
 JACKSON        JEFFERSON      LAMAR          LAUDERDALE     LAWRENCE
 LIMESTONE      MADISON        MARION         MARSHALL       MORGAN
 PICKENS        RANDOLPH       SHELBY         ST.CLAIR       TALLADEGA
 TUSCALOOSA     WALKER         WINSTON
----------------------------------------------------------------------
Counties with MAX wind in range 40 to 57 Mph (35 to 50Kt)..
----------------------------------------------------------------------
======================================================================
```

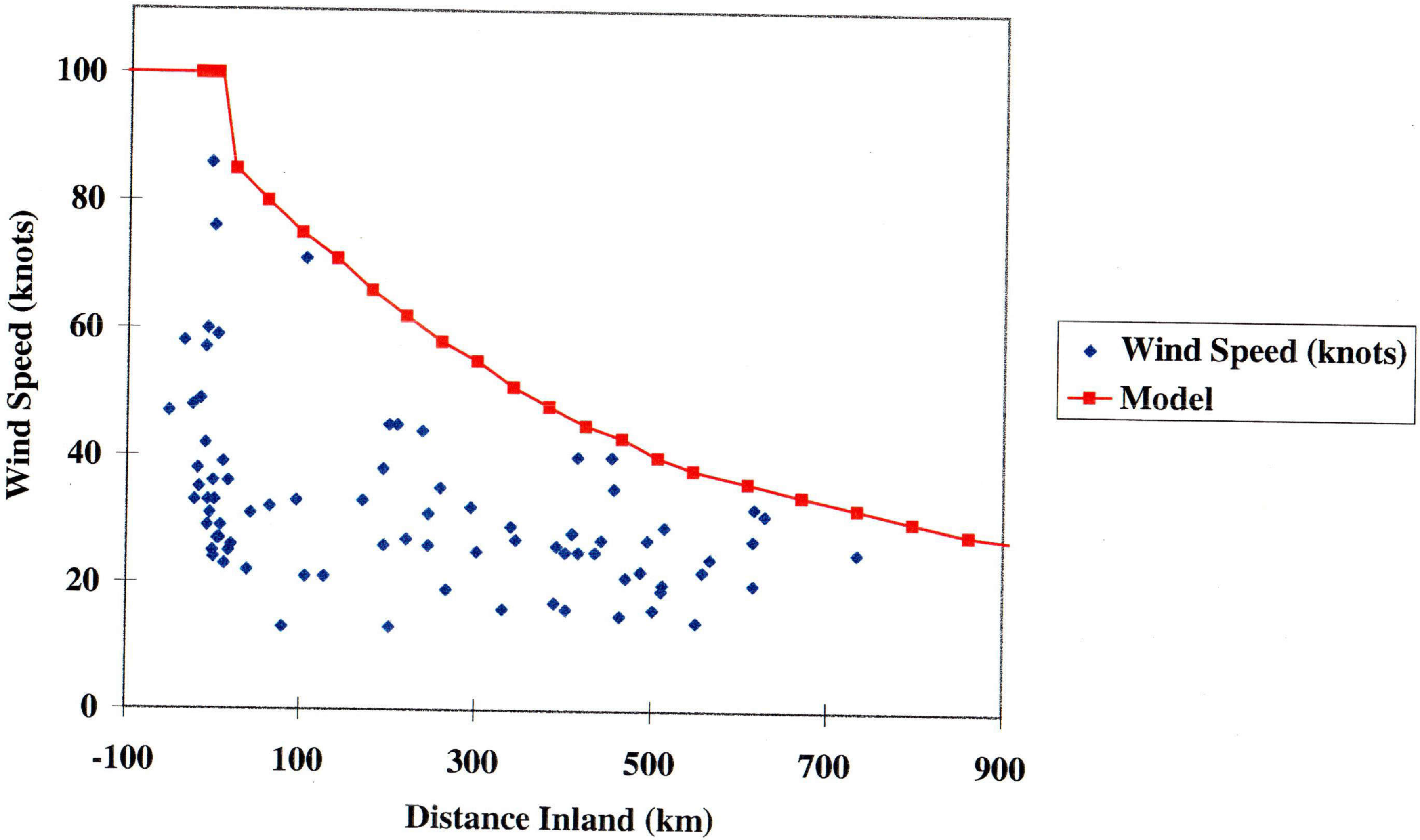
APPENDIX F

Graphs of Predicted vs. Actual Wind Speeds

IWDM and Wind Gusts vs. Distance Inland

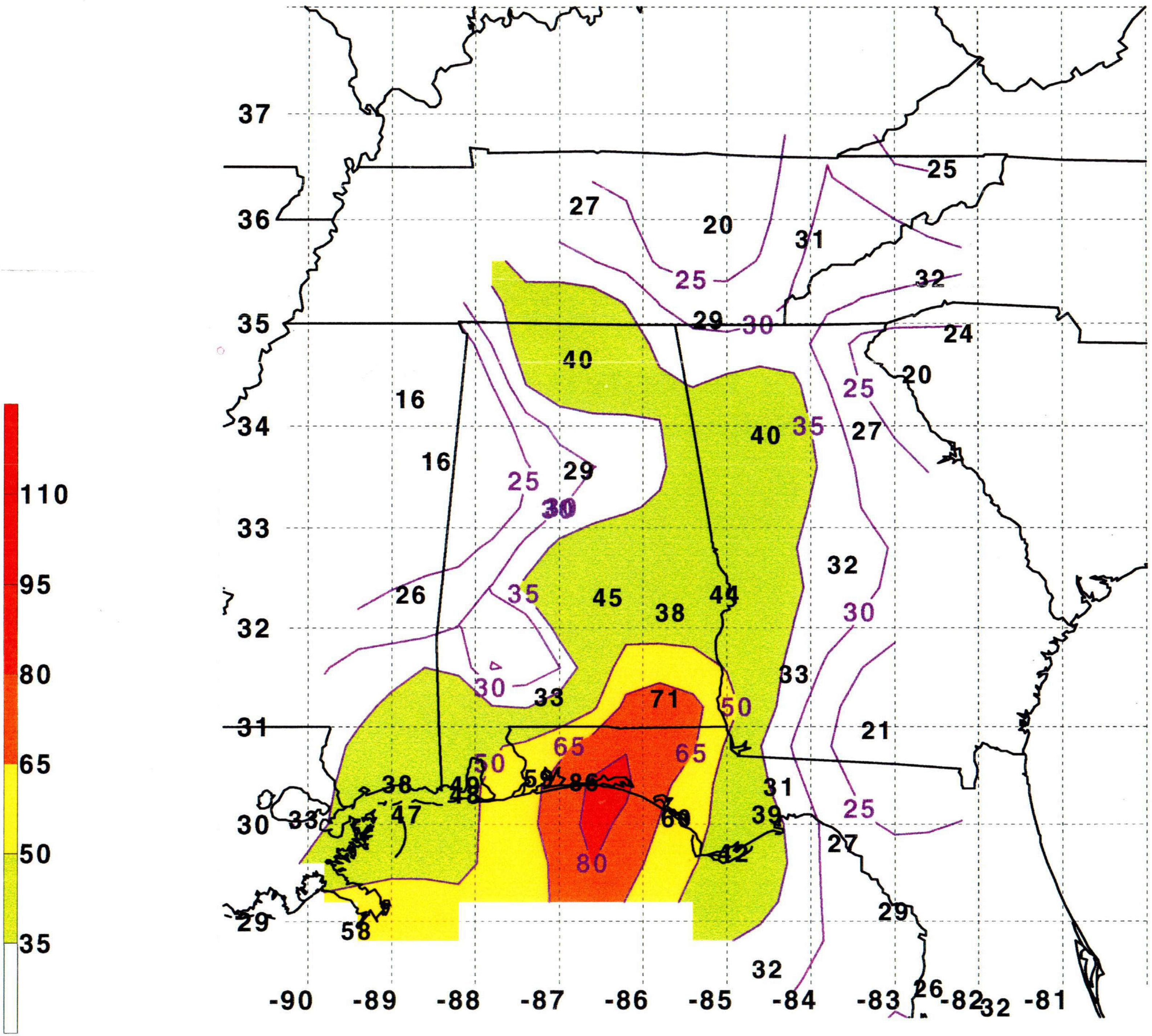


IWDM and Sustained Winds vs. Distance Inland



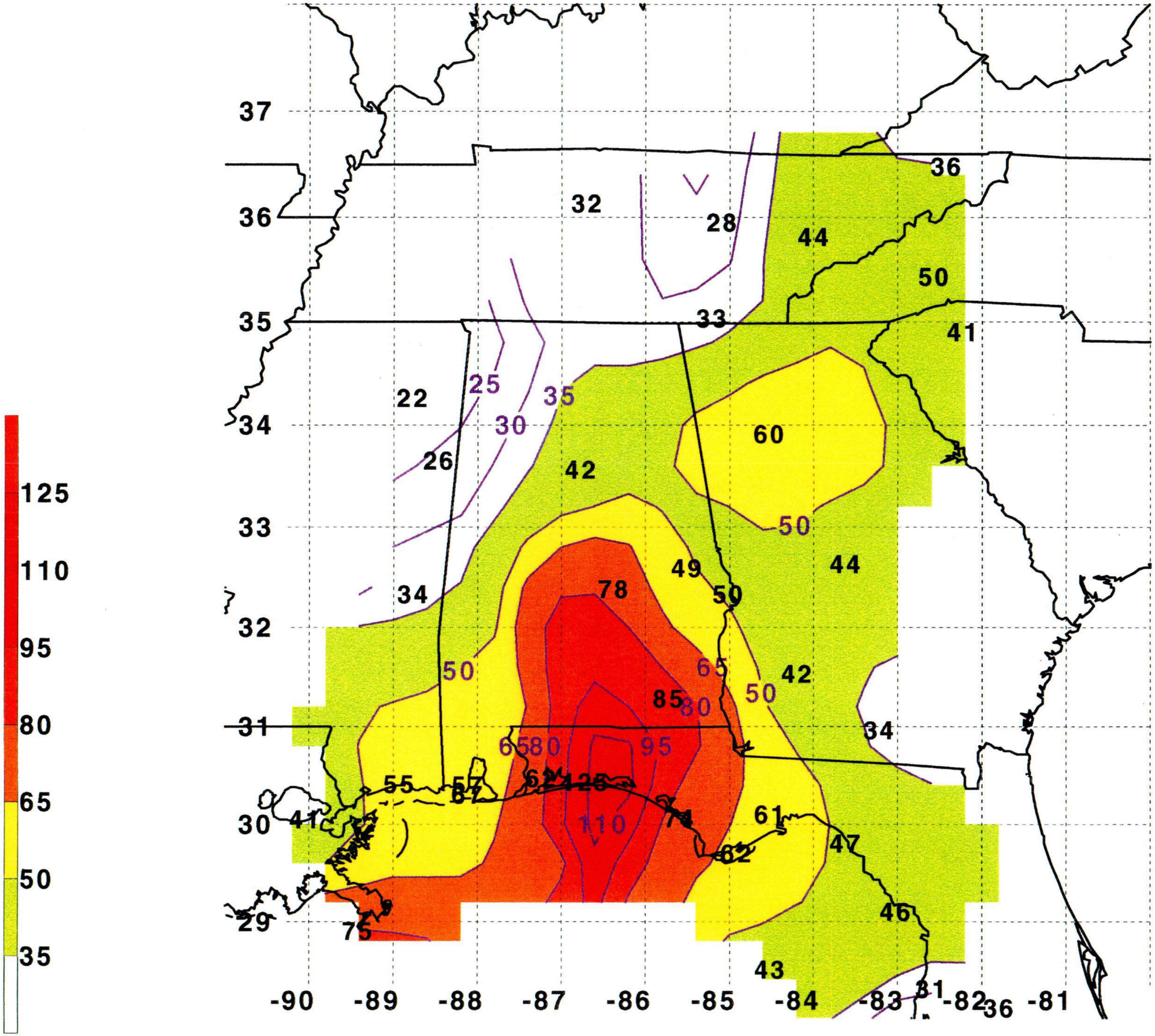
APPENDIX G

Wind Speed Maps

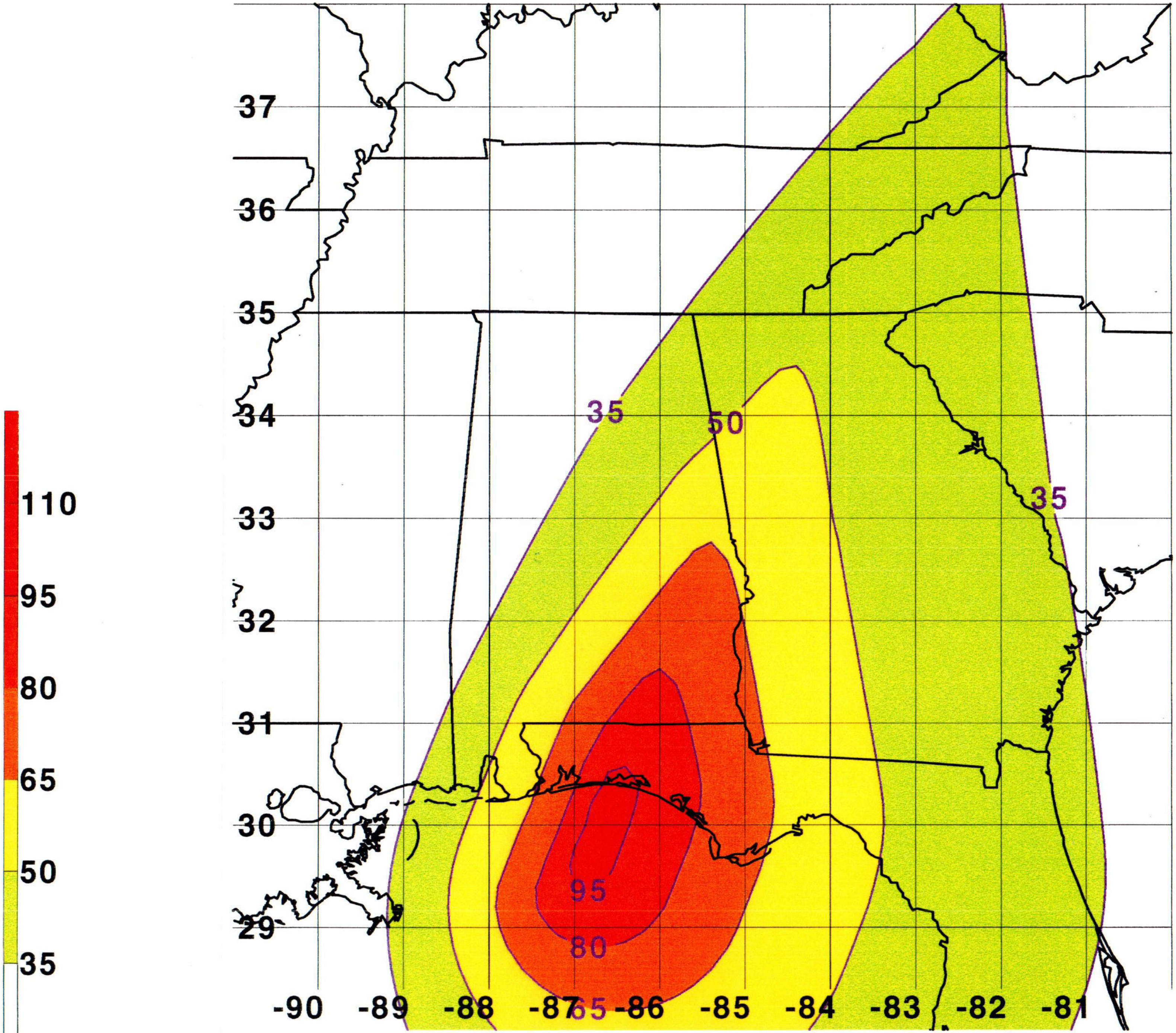


951004-951005 OPAL MAX. SUSTAINED WINDS (KTS)

②



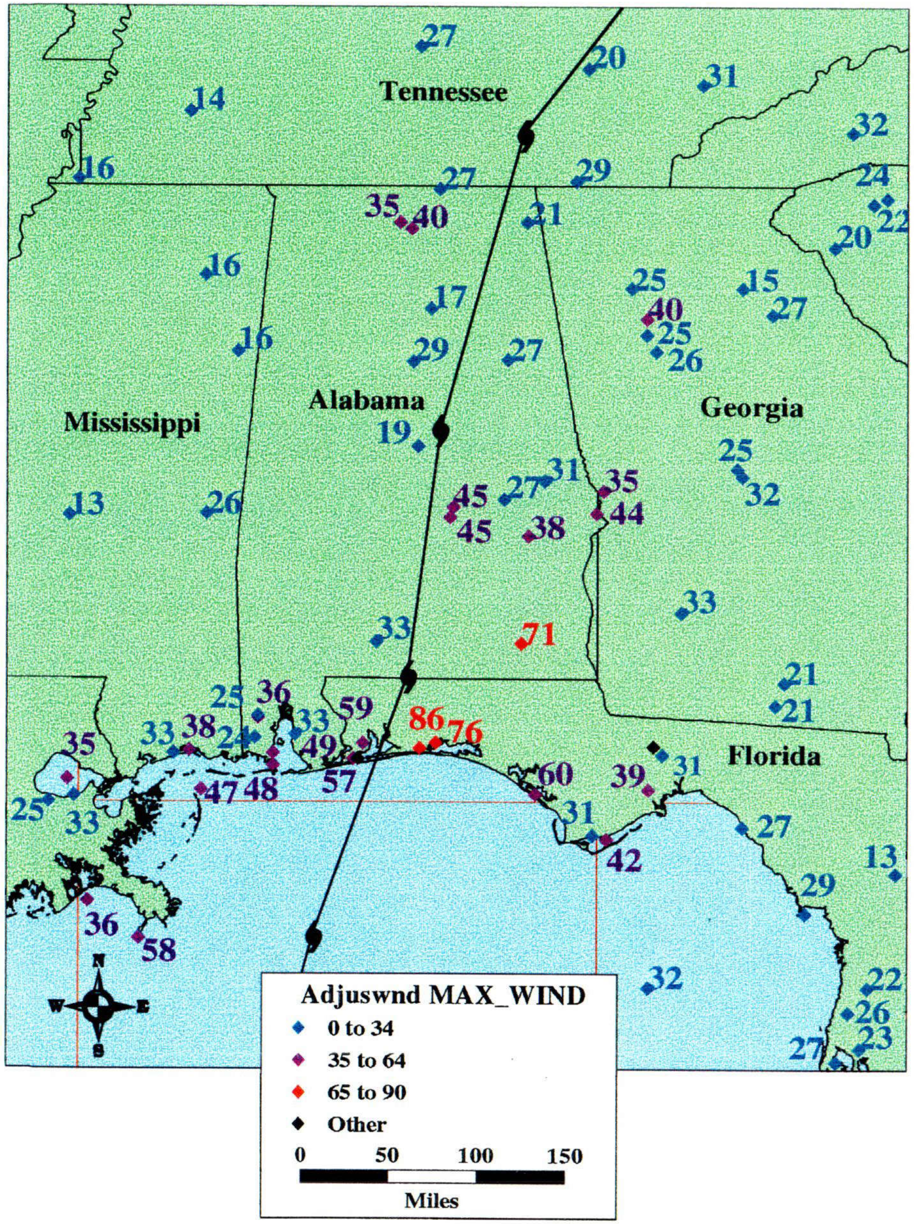
951004-951005 OPAL PEAK GUSTS (KTS)



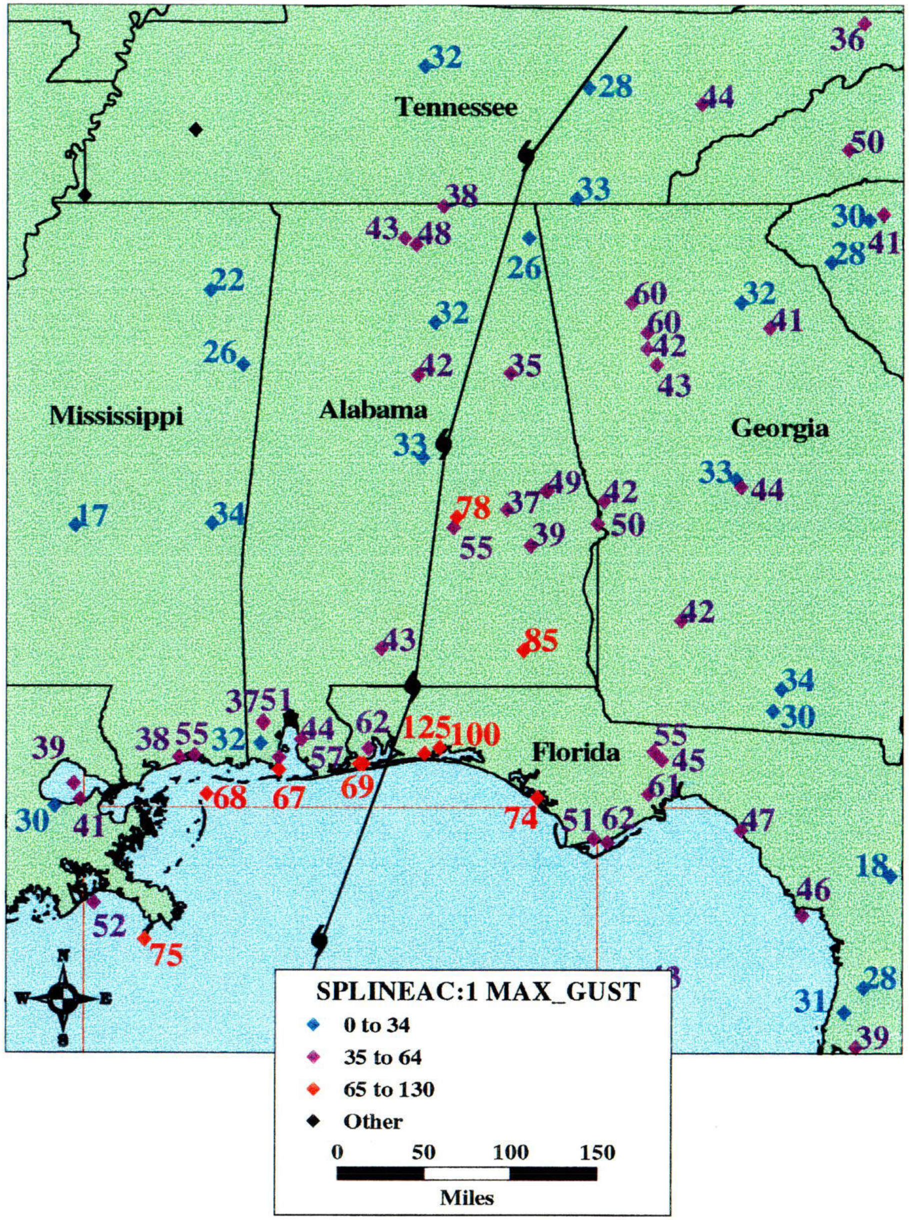
Model inland winds for OPAL from 951004/21-951006/06
Initial Conditions from 951004/2100Z Forecast

Hurricane Opal

Observed Maximum Sustained Winds



Observed Peak Gusts



APPENDIX H

Structural Damage Analysis

STRUCTURAL DAMAGE ANALYSIS

FLORIDA

COUNTY	% SINGLE FAMILY	% MOBILE HOMES	% APARTMENT	# PUBLIC BLDGS.
Bay	1.3	2	3.5	10
Dixie	0	.08	0	0
Escambia	.18	,02	.27	11
Franklin	.07	.2	.4	0
Gulf	.53	.16	4.8	1
Holmes	.04	.16	0	0
Jackson	0	0	0	0
Okaloosa	.6	.4	6.3	6
Santa Rose	.48	.07	3.5	4
Walton	.92	.36	9.5	1
Wakulla	0	0	0	0
Washington	.03	.18	0	0

ALABAMA

COUNTY	% SINGLE FAMILY	% MOBILE HOMES	% APARTMENT	# PUBLIC BLDGS.
Barbour	.08	.09	0	0
Butler	.1	.1	0	0
Calhoun	.03	.04	0	0
Chambers	.13	.26	0	0
Coffee	.33	.51	.18	2
Covington	1.7	.78	.46	2
Crenshaw	.22	.29	0	0
Elmore	.14	.15	0	0
Escambia	.13	.16	0	0
Geneva	.18	.47	0	0
Jefferson	.01	.14	0	0
Lee	.09	.63	0	1
Montgomery	.03	.03	.02	0
Pike	.06	.42	.03	0
Russell	.1	.08	0	1
Tallapoosa	.19	.17	0	0

GEORGIA

COUNTY	% SINGLE FAMILY	% MOBILE HOMES	% APARTMENT	# PUBLIC BLDGS.
Bartow	.02	.03	0	0
Carroll	.25	.11	0	0
Chatooga	.02	0	0	0
Coweta	.03	0	0	0
Floyd	.02	.01	0	0
Forsyth	0	.03	0	0
Fulton	.04	0	0	0
Gordon	0	0	0	0
Murray	.04	.08	0	0
Union	.07	.16	0	0
Walker	0	.04	0	0
White	0	.13	0	0

Notes:

1) Source of residential damage information is the American Red Cross. The % damaged includes both units destroyed and those with serious damage.

2) The % damaged is calculated by dividing the number of damaged units by the number of dwelling units in the 1990 census.

3) The % of apartments damaged include all those buildings which house two or more families listed in the 1990 census.

4) The number of public buildings was obtained from FEMA DSR's. The building types include schools, county facilities, hospitals, etc. There is no infrastrucutre included or flood damaged buildings if there was an indication of specific damage. A limit of $10,000 was selected arbitrarily as the lower threshold at which major strucutral damage would occur.

5) There is no information for North Carolina because there were no cases opened up by the Red Cross in this state.

6) There is one significantly damaged residential structure included in the North Carolina DSR summary. This structure is located in Jackson County in the Nantahala National Forest. The county is located along the southern N.C. border.

APPENDIX I

Addresses for Internet Data Sources

APPENDIX I

ADDRESSES FOR INTERNET DATA SOURCES

http://bose02.delphi.com:80/young-america/weather/beau.html

http://bose02.delphi.com:80/young-america/weather/tool.html#anemo

http://cirrus.sprl.umich.edu/wxnet/tropical.html

http://sercc.dnr.state.sc.us/

http://thunder.atms.purdue.edu/gopher-data/hurricane/1995/OPAL/track.dat

http://thunder.atms.purdue.edu/gopher-data/hurricane/1995/OPAL/track.gif

http://thunder.met.fsu.edu/explores/tropical/td17/atlon.html

http://www.alpeng.com/alpine/hurrica1.htm#windflow

http://www.anbg.gov.au/jrc/kayak/beaufort.html

http://www.atom.com/tv35/opal

http://www.awis.auburn.edu/0/forms/dastaAL.html

http://www.crossnet.org/arc/whats_new/disaster/opal3.htm

http://www.eqe.com/opal.htm

http://www.eqe.com/opalsum.htm

http://www.eqe.com/opalsum.html

http://www.eqecat.com/rswind1.htm

http://www.fema.gov/fema/opfinal.html

http://www.hiwaay.net/cwbol/scale.html

http://www.met.fsu.edu/~nws/search.html

http://www.ncdc.noaa.gov/onlineprod/tfsod/climvis/readme.html

http://www.noaa.gov/nws/nws/html

http://www.noaa.gov/nws/nws_cac.html

http://www.noaa.gov/nws/nws_nhc.html

http://www.noaa.gov/nws/nws_nmc.html

http://www.noaa.gov/nws/nws_om.html

http://www.usatoday.com/weather/whfore96.htm

http:www.nodc.noaa.gov/BUOY/buoy.html