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A GIS MODEL TO RAPIDLY PREDICT PROBABILITY OF HURRICANE DAMAGE

By

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A GIS MODEL TO RAPIDLY PREDICT PROBABILITY OF HURRICANE DAMAGE

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Emergency managers are faced with the challenge of acting quickly after a hurricane but rarely have detailed information available about type and amount of damage. In response to this need, linear additive geospatial models based on logistic regression analyses of driving variables including wind, rain, surge, topography were developed and automation routines programmed that rapidly and accurately predict a variety of damage types. Since a preponderance of damage is associated with falling trees, over 2000 post-Katrina forested plots were used to fit and validate independent models for hardwood blowdown and pine shear. Additional models using peak wind gusts and maximum sustained winds respectively were fully automated. Most importantly, total model run time was decreased from 36 to 5 hours for the more complicated forest damage models. The models have been vetted by the Mississippi Emergency Management Agency (MEMA) and will be part of MEMA's hurricane action response plans.

DEDICATION

This Thesis is dedicated to my parents, Randy and Lisa Vaughan, who have given me so much help, support, encouragement, and love throughout my life. I would not be where I am or who I am today without them. I also dedicate this Thesis to my two brothers, Jeremy and Tyler, both of whom I could always talk to and have fun with. I have shared many great moments with both of them, and I always look back fondly on our time together. This thesis is also dedicated to Allison Kohler, my fiancée and future wife, for helping me through tough times and giving me comfort and support when I need it most. I look forward to our life together and the many happy moments that await us in the future. I also want to thank my grandparents for everything they have done for me. In moments both large and small, they always come through for me when I need them. I thank God for all of the wonderful things He has done for me, and I praise His name for the gift of grace and mercy He has bestowed upon all mankind.

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I would like to thank my major thesis advisor, Dr. William H. Cooke, for all that he has done for me throughout my college career. Dr. Cooke has always believed in me and supported me, both financially through a Research Assistantship and verbally through words of encouragement when I was discouraged and celebration when things were going well. He has challenged me to think and work hard in his classes, research projects, and all areas of life. In many ways, he is my mentor. Thank you again Dr. Cooke. Know that you are much appreciated and that you have had a big impact on my life. I would also like to thank Dr. Charles O’Hara for providing me with much-needed support in writing my code. I encountered many problems throughout the way, but with the help of Dr. O’Hara’s knowledge and expertise, I was able to learn a great deal about AML and finish with a working project. I would like to acknowledge and thank all of the professors of Mississippi State University. I have very much enjoyed my time here, and my life and knowledge is more complete thanks to your hard work. Thank you to everyone who has contributed to my life and work at Mississippi State University. Even though you may feel that you have not contributed much to me, know that I appreciate everything.

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CHAPTER I

INTRODUCTION

Hurricanes are one of the most destructive forces in all of nature. When a hurricane passes through an area, it can cause wind damage and flood damage to buildings, roads, and vegetation. As a result, it is very important to have the ability to rapidly and effectively allocate personnel and resources for hurricane response and recovery, so that the process of rebuilding and repairing can begin. Predictive models that characterize potential damage from hurricanes are a key component in effective response and recovery. In the past, however, rapid response has been hindered due to poor information availability (Lessons Learned 2006). On August 29, 2005 for instance, Hurricane Katrina caused massive damage to the Mississippi and Louisiana coasts, causing an estimated $125 billion in damages (NOAA 2007). In addition, Hurricane Katrina damaged $1.3 billion of timber (MFC 2005). The cleanup effort by FEMA and the local emergency management agencies was heavily criticized (Lessons Learned 2006). The slow response was partly due to slow availability of damage information or no damage information. Local and state emergency response agencies have explicitly indicated they need imagery of the disaster area within three days of the event; and more desirably within 24 hours of the event (Hodgson et al. 2010). After a large scale disaster, such as a hurricane, it is often difficult for emergency management officials to know what areas are most affected. Information can be obtained, but many times emergency response agencies must choose between a short response time and information availability. If the response is immediate, there is very little information available. If more data are gathered before responding, the response time is longer. Idealistically, emergency managers need to know as much as possible as soon as possible. A readily available model predicting where the hurricane debris is likely to be heaviest is needed to provide emergency management officials with the locations where their services are most needed.

To meet these needs, four hurricane damage prediction models were created. All models were designed to be available within 24 hours after a hurricane. The first model was used to predict the areas with the highest probability of hardwood blowdown and the second model was used to determine the probability of pine shear. To determine the variables that had the most effect on forest damage during a hurricane, Pearson's r correlation coefficient was used on many potential variables: cumulative wind speed, sustained wind speed, duration of hurricane force winds, peak wind gust, precipitation intensity, storm total precipitation, distance from hurricane track, elevation, distance from nearest stream, slope, distance to coast, and surface roughness (Allen 2009; Table 1). All r values greater than 0.1 or less than -0.1 were considered to explain enough actual

Table 1

Model Variables Considered

	Hardwood Blowdown			Pine Shear		
	Pearson's R	**Regression Equation**	**Weight**	**Pearson's R**	**Regression Equation**	**Weight**
Cumulative Wind Speed	0.350	y=0.0104x-4.0431	0.3712	0.238	y=0.008x-4.6676	0.0978
Sustained Wind Speed	-0.0009	NA	NA	0.058	NA	NA
Duration of Hurricane Force Winds	-0.002	NA	NA	0.026	NA	NA
Peak Wind Gust	-0.005	NA	NA	0.001	NA	NA
Precipitation Intensity	0.187	y=0.4769x-1.1338	0.1983	0.252	y=0.3766x-1.993	0.1035
Storm Total Precipitation	0.120	y=0.1525x-1.2419	0.1273	0.138	y=0.1344x-2.3633	0.0567
Distance from Hurricane Track	0.024	NA	NA	0.082	NA	NA
Elevation	-0.006	NA	NA	0.119	y=0.002x-1.9825	0.0489
Distance from Nearest Stream	-0.183	y=-0.4379x-0.3911	0.1941	0.443	y=0.7805x-2.1828	0.1820
Slope	-0.006	NA	NA	0.632	y=0.0226x-2.0491	0.2597
Distance from Coast	-0.009	NA	NA	0.220	y=-0.012x-1.445	0.0904
Surface Roughness	0.103	y=0.0167x-0.6945	0.1092	0.392	y=0.0365x-2.2321	0.1611

damage to be important in the model. Using this approach, cumulative wind, precipitation intensity, total precipitation, distance to streams, and landscape roughness were selected to predict the probability of hardwood blowdown. The variables used to determine pine shear probability were cumulative wind, precipitation intensity, total precipitation, distance to streams, landscape roughness, elevation, slope, and distance to coast. A linear weighted model was created for hardwood blowdown and pine shear using the selected variables.

The second model was designed to predict the areas of highest damage probability caused by wind and rain alone. Outside of storm surge, wind is responsible for most of the damage associated with a hurricane (Powell and Houston 1996). Rain also contributes to hurricane damage, often by interacting with wind. The rain and wind damage probability model can be used to illustrate regional damage probability across all landscape types (not just for forested areas) within 24 hours after a hurricane landfall. The third model is similar to the first two models, except maximum sustained wind speeds rather than cumulative wind were substituted for the model wind variable.

Problems Associated with Remotely Sensed Imagery

In the recent past, the extent of the hurricane damage has been assessed by remotely sensed imagery. Satellite-based sensors can cover the entire affected region, but this approach is severely limited by the difficulty in obtaining a cloud-free image. Satellites can only obtain imagery of a location at certain times, and if clouds are covering the area of interest at the time, the image has limited usefulness, and responders must wait until the next re-visit time. Waiting on space-based remote sensing imagery, therefore, is not a good approach for a speedy response.

Another remote sensing approach is obtaining imagery using airborne remote sensing data. By using this data-gathering method, clouds and re-visit times are not an issue; however, there are other problems. Airborne remote sensing is very expensive, even for small areas. In addition, the amount of area that an airborne remote sensing instrument covers is much less than a space-based satellite. In order to cover the entire area, the cost of the airborne remote sensing approach would be much too expensive to consider. Since it is impractical to collect extensive field data or to use remotely sensed imagery, a readily available source of damage information that is accurate, does not rely on cloud-free days, does not cost large amounts of money, and is easily used and understood by the user is very much needed. All of the above needs can be met by the models developed for this project.

Within 24 hours of a hurricane event, it is imperative to provide decision makers and early responders with actionable information regarding areas with highest damages. This actionable information is needed so that effective decisions regarding deploying resources and first responder may be prioritized and made in an informed basis. Since it is impossible to fly, process, and distribute aerial image data or to task, collect, process and distribute satellite observation, it is critical that predictive or model-based methods be available to provide probability-based results which are accurate, timely, cost effective, and readily understood. Even if aerial or satellite data were available, they would still need to be interpreted for damage assessment to provide decision makers with first sources of inputs to begin informing critical decision processes.

Based on statistical results from past events, the models developed for this project are capable of providing accurate predictive results that meet the needs criteria stated. This paper focuses on automating the process of predictive-results generation that provide continuous, spatially variable raster fields of damage estimates that may be used to inform the deployment of first and early responders. Their feedback and observations from the damages areas of the event provide ongoing improvements to the ‘operating picture,’ but model-based estimates and predictive maps are shown here to deliver high-quality information resources which may be the best and only information available in the immediate aftermath of a disaster event. The objectives of this project are to develop automated hurricane damage probability models that reliably predict hurricane damage within 24 hours after a hurricane landfall.

CHAPTER II

LITERATURE REVIEW

Factors Affecting Tree Damage

During a storm event, there are two main types of tree damage. The first type is blowdown of the entire tree due to strong winds. Blowdown occurs when the applied lateral forces on a tree are transmitted down the trunk to create a torque force that exceeds the resistance to turning of the root/soil plate (Stathers et al. 1994; Moore 2000). Shear is the second major type of tree damage, and it occurs when a tree is subject to lateral forces that exceed the stem strength but that are not strong enough to dislodge or break the roots and roll the root ball (Putz et al. 1983). There are two lateral forces working on the trees to cause damage: the force of the wind on the crown and stem and the force of gravity (Trousdell *et al.* 1965, Stathers *et al*. 1994, Everham and Brokaw 1996, Peltola 2006). The effect of gravity increases once the tree begins to bend and sway due to wind (Peltola 2006). Taller trees are typically more prone to damage due to increased bending of the tree stem (Curtis 1943, Everham and Brokaw 1996, Merry *et al.* 2009). Trees can resist the damaging forces using root depth, root mass, weight of the root-soil plate, and stem mass (Stathers et al. 1994, Peltola 2006). Soils are also a very important factor when determining the amount or type of tree damage. Soils with higher water tables produce trees with two to three times less bending movement than trees on dry soils (Ray and Nicoll 1998). 30% of trees on sandy soils are likely to blowdown compared to just 5% on trees on silt or clay soils (Trousdell 1965).

Topographical properties including aspect, elevation, slope, and surface roughness are important factors in determining potential damage from wind (Lugo 1983, Foster 1988, Foster and Boose 1992, Boose and Foster 1992, Everham and Brokaw 1996, Baker et al. 2002, McNab et al. 2004). The windward side of slopes typically produces more forest damage than the leeward sides (Bellingham 1991, Reilly 1991, Walker 1992). Turbulent eddies can occur on the leeward side of slopes, however, resulting in forest damage as well (O'Cinneide 1975). Slopes of greater than ten percent on the leeward side of slopes are protected from the eddies (Foster and Boose 1992). Higher elevations tend to produce greater wind speeds (Boose et al. 1994), but trees in river valleys are also prone to damage due to wind funneling (Alexander 1967, Walker 1991). More blowdown tends to occur on steep slopes but not necessarily more damage (Putz et al. 1983). Previous studies have shown that hardwoods are more likely to blow down and pines will most likely shear. (Curtis 1943, Petty and Swain 1985, Putz et al. 1983, Foster 1988a, Everham and Brokaw 1996, Hook 1991, Gardiner et al. 2000, Rodgers et al. 2006, Merry et al. 2009).

Damage Associated with Hurricane Katrina

On August 28, 2005, Hurricane Katrina made landfall in southern Louisiana as a Category 3 hurricane (NOAA 2007), but was a Category 4 storm just before landfall

(Knabb et al. 2005) according to a National Weather Service report. It was the most destructive hurricane in history in terms of economic losses, with an estimated $125 billion in damages (NOAA 2007). Hurricane Katrina's landfall was very similar to that of Hurricane Camille's landfall in 1969. Hurricane Camille made landfall as a Category 5 hurricane, but the extent of the hurricane force winds for Camille extended only 100 km to the east of the center of the storm compared to 140 km for Hurricane Katrina (Fritz et al. 2007). Since Katrina's hurricane force winds extended so far out from the center, the damage caused by Katrina affected a larger area than Camille

Hurricane Katrina caused massive timber damage in Mississippi. Hancock and Harrison Counties sustained 51 – 60% county level timber damage, Jackson County suffered 41 – 50% damage, and Pearl River, Stone, Lamar, Forrest, and Perry Counties were 31 – 40% damaged (Wayne 2006). Roughly 4.2 billion cubic feet of timber were destroyed due to Hurricane Katrina (USDA Forest Service 2005). The southernmost eight counties of Mississippi accounted for one-third of the total damaged timber for the storm (USDA Forest Service 2005). Nearly 90% of all forest damage occurred within 60 miles of the coast (USDA Forest Service 2005). Sixty percent of the damage occurred to softwoods, most of which were pines (USDA Forest Service 2005). The amount of downed and damaged wood could produce 800,000 single family homes and 25 million tons of paper and paperboard (USDA Forest Service 2005). Two hurricanes with similar landfalls to Hurricane Katrina were Hurricane Camille in 1969 and Hurricane Andrew in 1992. Roughly 11% of timber that was standing before the storm was damaged during Hurricane Camille (USDA Forest Service 2005). Similarly, 10% of previously standing timber was damaged as a result of Hurricane Andrew (USDA Forest Service 2005). Hurricane Katrina, however, proved far more damaging, with an average of 20% of timber destroyed (USDA Forest Service 2005). The rate of timber destruction near the coast was even higher, with 35 – 40% of trees damaged (USDA Forest Service 2005).

The Government's Response to Hurricane Katrina

After Hurricane Katrina, the U.S. Department of Security funded a study detailing what went wrong with the government's response to Hurricane Katrina and how to fix the problems (Lessons Learned Final Report 2008). As part of the study, the role of geospatial technologies in disaster management was evaluated. It was determined that the government needs to develop and maintain a centralized geospatial database comprised of locally accurate data, develop and improve geospatial capabilities at local/state/federal levels, and identify response culture similarities and differences that require standardized or customized geospatial products (Lessons Learned Final Report 2008). In addition, the need to develop input data criteria for analytical models and develop tools that quickly document damaged areas was addressed (Lessons Learned Final Report 2008).

GIS Risk Modeling

GIS-based risk models have a wide range of uses from epidemiology to forest fires to hurricanes and beyond. Uses in epidemiology date all the way back to 1854, when John Snow mapped distributions of cholera during an outbreak to determine where the source of the cholera occurred (Snow 1855). Since that time, GIS risk modeling has continued to develop. Clements et al. (2006) predicted the spatial distribution of intensity of *S. mansoni* infection in East Africa to identify the role of environmental factors and show how these factors can be used to develop a predictive map. Cooke et al. (2006) used landscape variables to map West Nile virus risk based on mosquito habitat suitability and climatic variables to determine seasonal risk of the virus on a zip-code level. Another study predicting West Nile virus risk produced spatial models for entomological risk of exposure, an epidemiological risk map, and a risk-classification index (Winters et al. 2008). Other diseases, such as Lyme disease (Eisen et al. 2006, Nicholson and Mather 1996, Glass et al. 1995, Beck et al. 1994) and malaria (Beck et al. 1994, Beck et al. 1997, Omumbo et al. 2005, Moffett et al. 2007) have been studied to produce risk models of infection.

Many fire risk models have also been created with the help of GIS. One study in Spain examined the role of topography, meteorological data, fuel models, and human-caused risk in a fire-prone area in central Spain to produce risk maps displaying probability of ignition, fuel hazards, and human risk (Chuvieco and Salas 1996). Cooke et al. (2007) examined fuel conditions pre- and post-Katrina to determine the impact on fire potential. A water budget management system was developed based on the interaction of precipitation and evaporation to map fire potential (Choi et al. 2009). A link between atmospheric teleconnections and fire potential was established by Dixon et al. (2008). GIS fire models can be validated using remote sensing data (Chuvieco and Congalton 1989). Preisler et al. (2004) created a fire risk model using three probabilities:

the probability of fire occurrence, the conditional probability of a large fire given ignition, and the unconditional probability of a large fire. Many other fire potential models have also been developed (Andrews and Queen 2001, Bonazountas et al. 2005, Hernandez-Leal et al. 2006).

Geospatial technologies have also been used in the past to determine the impact of disasters such as earthquakes and tsunamis, as well as some military applications. Geospatial technologies could have drastically improved the situation after the disastrous earthquake that struck Haiti on January 12, 2010. Theilen-Willige (2010) developed a GIS model that utilized a weighted overlay technique to produce susceptibility maps that showed areas where factors influencing near-surface earthquake shock occur in the same location, increasing the likelihood of soil amplification. The model was used to create landslide and flooding susceptibility maps that could have saved lives had the maps been available earlier and utilized correctly. Many recent studies have been done to use geospatial technologies to model tsunami damage (Walsh et al. 2000, Papathoma et al. 2003, Keating et al. 2004). The inundation of coastal Indian villages was mapped following the devastating Indian Ocean Tsunami on December 26, 2004 (Chandrasekar et al. 2007). The inundation information obtained from the GIS model could be used in the future to save lives. Geospatial technology even has military applications. For example, the military has used spatial decision support systems to help identify command and control structures and movements of opposing forces during the war in Iraq following the September 11 terrorist attacks (Cutter 2003).

Hurricane damage risk modeling is becoming more prevalent, especially after Hurricane Katrina. One study evaluated the long-term risks of hurricanes in the Southeastern United States by examining the statistical extreme wind climate and the expected insured losses from damage to residential structures (Huang 2001). Wesley et al. (1998) built a damage model after hurricane force winds (120-155 mph) struck the Rockies in October 1997 that attempted to determine which biotic and abiotic variables are important in predicting blowdown and where the blowdown occurred. The analysis showed that elevation, aspect, slope, distance from the Continental Divide, and landcover type were important predictor variables (Wesley et al. 1998). Baker et al. (2002) discovered that few variables contribute to blowdown, with topographical features being more important than vegetation or geologic and soil features (Baker et al. 2002). Studies show that broadleaf species might be more resistant to blowdown than pines (Curtis 1943, Foster 1988, Everham and Brokaw 1996, Ramsey et al. 1997, Peterson 2000). Kupfer et al. (2008) used H*Wind and CART (Classification and Regression Tree) models to determine significant factors that affected the forests of the Desoto National Forest in Mississippi after Hurricane Katrina.

Popular Currently-Available Risk Models

There are several hurricane risk models already available. The first is the HAZUS-MH model, developed by FEMA (Figure 2.1). The HAZUS-MH model analyzes the potential risk for losses from floods, hurricane winds, and earthquakes (FEMA 2011). It can be used before or after a hurricane strikes and includes physical damage, economic loss, and social impacts as outputs of the model. The model is best used to rapidly determine damage to buildings, but it can also determine tree debris quantities and specific structural changes needed to strengthen buildings for mitigation. The results are most accurate when aggregated on a county or regional scale. Peak wind gusts and maximum sustained winds can be estimated for specific hurricane events. The HAZUS-MH model has been criticized as being too complicated, having too coarse a spatial resolution, and being difficult to modify (Mississippi State University 2010).

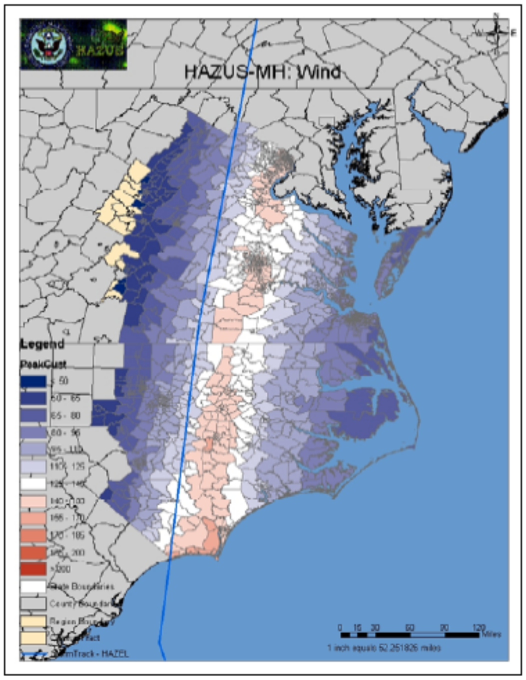


Figure 2.1

HAZUS-MH Model

Another risk assessment model is SLOSH (Sea, Lake and Overland Surges from Hurricanes) (Figure 2.2). SLOSH was developed by the National Hurricane Center

(NHC 2011) to estimate storm surge heights and winds resulting from historical, hypothetical, or predicted hurricanes by taking into account pressure, size, forward speed, track, and winds (NHC 2011). The model can be used to determine storm surge heights in feet above the National Geodetic Vertical Datum. The SLOSH model is best used to determine the potential maximum storm surge for a location. Three modeling approaches can be used by SLOSH to predict surge. The first is the deterministic approach, which solves physics equations to perform a single simulation based off of a “perfect” forecast. The second approach is known as the probabilistic approach. The probabilistic approach incorporates statistics of past forecast performances to generate multiple SLOSH runs.

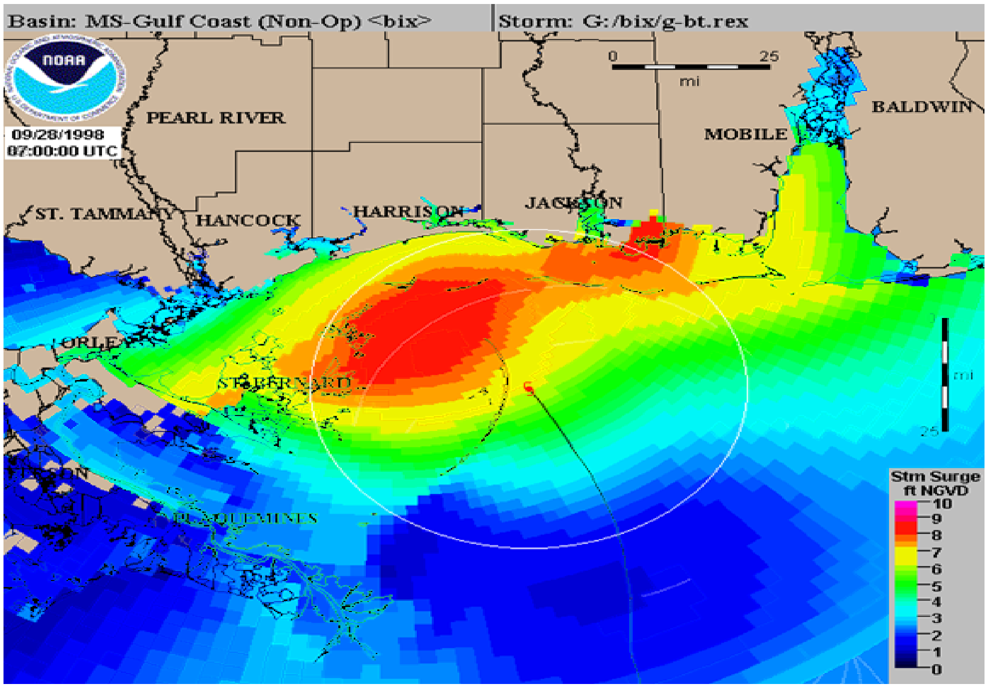


Figure 2.2

SLOSH Model

The third approach is the composite approach, which is considered by the NHC to be the best approach for determining storm surge. The SLOSH model is run several thousand times with hypothetical hurricanes under various storm conditions using the composite approach. The results of this approach are the Maximum Envelopes of Water (MEOWs) and the Maximum of MEOWs (MOMs). The MEOWs and MOMs form the basis for the development of the nation's evacuation zones. The SLOSH model provides quick computations and is able to flow through barriers, gaps, and passes. It does not account for previous flooding conditions, however, and it does not model the astronomical tides.

Sea Island Software has developed HURREVAC, a decision-support tool for emergency managers (Figure 2.3). The software combines hurricane evacuation study (HES) data with real-time weather forecast data from the National Hurricane Center (HURREVAC 2011). HURREVAC automatically downloads real-time weather data to quickly provide evacuation times, wind speed probabilities, wind fields, error cones, and rainfall forecasts. The software is often used by emergency managers due to the ease of use and ability to determine evacuation timetables.

Web-based applications that can aid emergency managers are becoming more common. For example, a joint partnership between the National Oceanic and Atmospheric Administration (NOAA) and the University of New Hampshire's Coastal Response Research Center created the Environmental Response Management Application (ERMA). ERMA is a web-based GIS tool designed to aid emergency managers who deal with incidents that adversely impact the economy (ERMA 2011). As real-time web-based applications such as ERMA become more common, emergency managers will be able to manage their time and resources more efficiently.

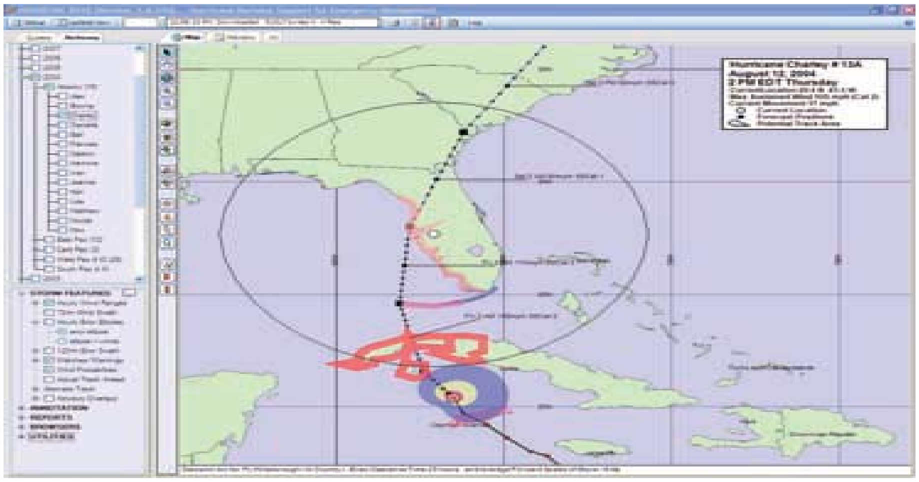


Figure 2.3

HURREVAC

CHAPTER III

METHODOLOGY

Study Area and Data Used

A southern Mississippi study area was used for all models, consisting of the counties of Hancock, Harrison, Jackson, Pearl River, Stone, George, Walthall, Marion, Lamar, Forrest, Perry, Greene, Lawrence, Jefferson Davis, Covington, Jones, and Wayne Counties, as well as portions of Simpson, Smith, Jasper, and Clarke Counties (Figure 3.1). Any size study area could be used, however, depending of data availability and the processing speed required. If increased speed is desired, the study area can be decreased. Likewise, increased area can also be obtained by sacrificing speed. Elevation was determined using a DEM (Digital Elevation Model) with ten meter spatial resolution obtained from the Mississippi Automated Resource Inventory (MARIS) web site. The DEM was analyzed to produce slope, and the rate of change of the slope was analyzed to produce an estimate of landscape ‘roughness’. The elevation, slope, and roughness grids were resampled to thirty meters, so that the models run faster. A distance function was performed on the streams polyline shapefile and the coast polyline shapefile to obtain the thirty meter distance to stream and distance to coast raster files, respectively. The wind speed data are available every three hours from NOAA (National Oceanic and Atmospheric Administration) for the spatial and temporal extent

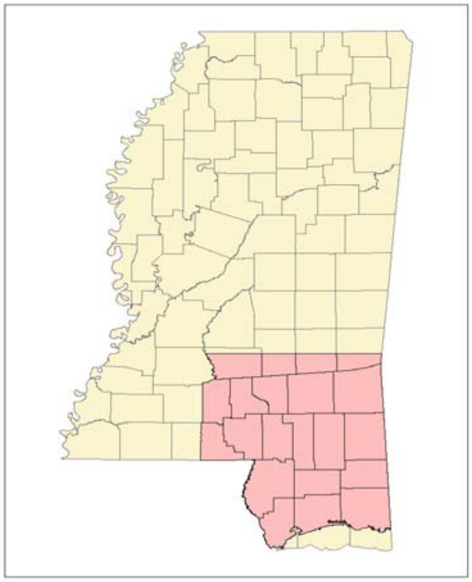


Figure 3.1

Study Area

of the hurricane using a product called H*Wind. H*Wind used wind measurements from a variety of observation platforms to develop an objective analysis of wind speeds in a hurricane (Powell and Houston 1996). The H*Wind product was also used to create maximum sustained winds after the hurricane, which is used in one of the models. The precipitation data are available every hour from NOAA as MPEs (Multi-Sensor Precipitation Estimates), which contain precipitation estimates for the United States from RADAR that are corrected with actual ground measurements (NOAA 2011). The rain intensity data were derived from the precipitation estimates by dividing precipitation by time to get an hourly rate. The cumulative wind data were derived by summing all of the relevant wind estimates in the southern Mississippi study area for the duration of the hurricane. Precipitation data are also available every twenty-four hours from NOAA. The cumulative precipitation data were derived by summing all of the twenty-four hour precipitation estimates associated with the hurricane for the study area. All files were clipped to the southern Mississippi study area.

Technical Computer Information

Once the data were obtained, work began on creating an automated process to perform all analyses on the data to create damage prediction maps using Arc Macro Language (AML), a scripting language used in ArcInfo©. Both models were run on a Microsoft Windows XP Professional 64-bit operating system. All data were stored and accessed from a Samba server network drive with four terabytes of free space. To increase the speed of the model runs, X-Win32 was used to remotely access an Oracle Solaris Unix operating system named Delta by the host, Geosystems Research Institute (GRI) at Mississippi State University. To use X-Win32 to connect to Delta, the analyst starts the program, selects "Manual" under "New Connection" and selects "ssh" as the connection method. On the subsequent screen, the analyst enters "Delta" as the connection name and "delta.hpc.msstate.edu" as the host. A user inputs a username as the login and enters and confirms a password. The user types "/usr/openwin/bin/xterm –ls" as the command. Once the connection is saved, the user selects the connection and clicks “Launch”. Once the xterm window is launched, the working directory can be changed by typing “cd”, a space, and then the location of the directory that contains the AML. For example, “cd /gri/rvaughan/hurricane/bin” can be typed to navigate to that directory. To make sure the directory is correct, “pwd” can be entered to display the present working directory. Once it is determined that the directory is correct, the user inputs “swsetup arcinfo” to be able to run ArcInfo©. Next, the user inputs the command “arc” to actually start the ArcInfo program. Once ArcInfo© has started, the AML can be run by typing “&r” followed by a space, followed by the name of the AML. For example, the analyst can type “&r forest_damage” to run the forest damage model or “&r wind_rain_damage” to run the wind and rain damage model.

Description of AML Processes

In the AML script, all processes were completed with a series of repetitive statements to automate the process. To accomplish this task, all vector layers or grids used must follow the naming convention that uses the name of the coverage or grid immediately followed by a number. The first number used must be 1 and each following file of the same name must increase the counter number by one. For example, the wind speed point coverages are named “wind_speed”. If there are fifteen wind speed coverages, the first would be named “wind_speed1” and the fifteenth coverage would be “wind_speed15”. Similar numeric naming conventions are used throughout the code, so that the looping statements can be executed, however, the only files that the user must be sure are named properly are the input coverages used for the wind and rain data. If the input coverage files are named correctly, all other files will automatically be assigned the appropriate names based on the input names. Data names with ArcInfo are case-sensitive, so inconsistencies in names with lower- and upper-case usage will cause the program to halt.

All files were converted from shapefile to the Arc coverage data model using shapearc, so that Arc would be able to read the files. The coordinate system was defined as geographic with a NAD 83 datum, since the original files were in a spherical coordinate system. The files were then re-projected to the Mississippi Transverse Mercator (MSTM) projection. The elevation, slope, roughness, distance to stream and distance to coast will be constant for every hurricane, so once these GIS layers are prepared once, they can be used for any hurricane that makes landfall on the Mississippi coast. However, extrapolation of the models to other states will require that these layers be derived and ready before hurricane season. The wind and rain, however, will be different for each time period and for each hurricane. For every time period in which data are collected, they must be interpolated so that a raster surface containing estimates for every part of the study area can be obtained. A designed spatial resolution requiring continuous raster data at a specific spatial resolution is needed for the predictive models; therefore, each time data are collected and prepared for modeling operations, data that are not spatially continuous must be interpolated to create spatially continuous raster surfaces, required as inputs for the predictive model and covering the entire study area. The Inverse Distance Weighted (IDW) interpolation method was used to obtain the raster surfaces, using k=2 ($1/d^k$), eight neighbors, a 10,000 meter search radius, and an output cell size of thirty meters.

Each interpolated grid is assigned values for all areas inside the bounds of the interpolation, but areas outside the interpolation boundaries are assigned 'no data' values. When a 'no data' cell is summed with any other value, the result is 'no data'. Since the wind data were obtained every three hours for the extent of the hurricane, the associated point grids followed the hurricanes movements, meaning that every interpolated wind grid was a different size and in a different location than every other wind grid. When the wind grids are summed to produce cumulative wind, all 'no data' values must first be converted to a value of zero, or else the resulting summed raster will only have values where input grids had actual values. The problem of summing 'no data' values also occurred with the precipitation data for different reasons. The precipitation data was available for the same nationwide spatial extent every day. All areas that had no rainfall on a given day had 'no data' values assigned after the interpolation was performed, therefore, all 'no data' values were converted to zero for the precipitation data as well. Once all 'no data' cells were given a value of zero, all interpolated grids can be summed to produce a cumulative value for each cell.

For the forest damage models, each grid used in the final analysis was designated as an independent variable in a linear regression formula (Table 1). The minimum value was subtracted from each cell in every grid, and the resulting grid was divided by the maximum value to standardize each grid to a scale of zero to one. This 'maximum score' standardization technique maintains the intervallic relationships between variable states

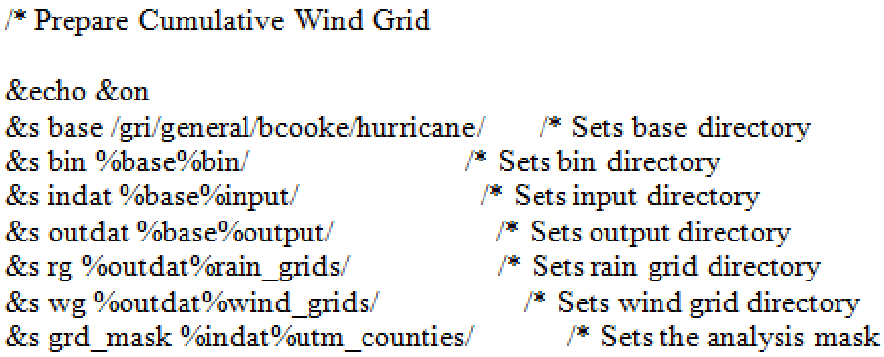
(Malczewski 2000). Two linear weighted models were created using the standardized grids. Model weights were determined by summing the r values for the variables used for each model and dividing each individual r value by the sum (Table 1). This process is similar to the one used by Cooke et al. (2006) to obtain variable weights for linear additive models used in landscape-level risk analysis for West Nile virus infections. The resulting weights were multiplied by the corresponding standardized grid and summed to produce final maps of hardwood blowdown probability and pine shear probability. For the rain and wind damage models, a subjective weighting approach was used. A weight of 0.75 was used for the final wind grid, and a weight of 0.25 was used for the final rain grid. The model will be modified in the future to allow the model user to modify these weights to examine the interactive effects of wind and rain on potential landscape damage probability estimates. Two test runs were performed for Hurricane Katrina: one with all grids at thirty meter resolution and the other test run with all interpolations performed at one hundred meter resolution and resampled to thirty meters to increase the processing speed. The model results were compared to the results of a similar model created by the USDA Forest Service and to the results of actual field work performed by the Mississippi Institute for Forest Inventory (MIFI).

CHAPTER IV

RESULTS

Description of Resulting Code

The code that was developed to produce the model results is very important to understand for any future use or modification of the models. The first section of the code is used to determine what the model is actually doing while it is running (“echo” statement), setting the directories that the model will use, and setting the study area using an analysis mask (Figure 4.1).



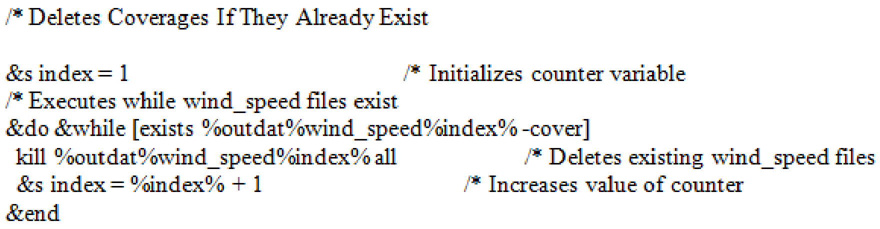
```
/* Prepare Cumulative Wind Grid

&echo &on
&s base /gri/general/bcooke/hurricane/       /* Sets base directory
&s bin %base%bin/                         /* Sets bin directory
&s indat %base%input/                      /* Sets input directory
&s outdat %base%output/                    /* Sets output directory
&s rg %outdat%rain_grids/                  /* Sets rain grid directory
&s wg %outdat%wind_grids/                  /* Sets wind grid directory
&s grd_mask %indat%utm_counties/             /* Sets the analysis mask
```

Figure 4.1

Model Code: Section 1

The second block of code is used to delete the results from the previous model runs so the same naming conventions can be used each time (Figure 4.2). Similar portions of code are distributed throughout the model code for the same purpose. The next section of code's purpose is to convert the downloaded shapefiles into coverages so that further analysis can be performed (Figure 4.3) Section 4 of the code is used to define the projection, datum, and units of the coverages (Figure 4.4).

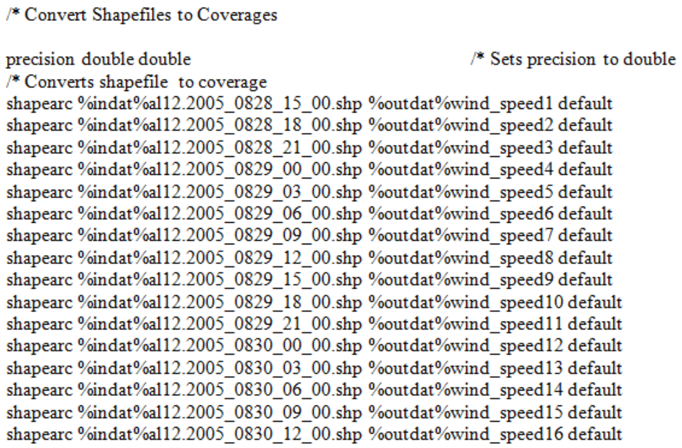


```
/* Deletes Coverages If They Already Exist

&s index = 1                                        /* Initializes counter variable
/* Executes while wind_speed files exist
&do &while [exists %outdat%wind_speed%index% -cover]
 kill %outdat%wind_speed%index% all                    /* Deletes existing wind_speed files
 &s index = %index% + 1                           /* Increases value of counter
&end
```

Figure 4.2

Model Code: Section 2

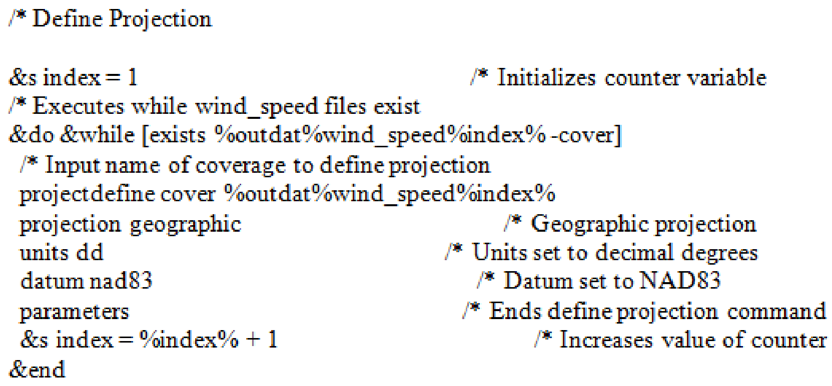


```
/* Convert Shapefiles to Coverages

precision double double                                          /* Sets precision to double
/* Converts shapefile  to coverage
shapearc %indat%al12.2005_0828_15_00.shp %outdat%wind_speed1 default
shapearc %indat%al12.2005_0828_18_00.shp %outdat%wind_speed2 default
shapearc %indat%al12.2005_0828_21_00.shp %outdat%wind_speed3 default
shapearc %indat%al12.2005_0829_00_00.shp %outdat%wind_speed4 default
shapearc %indat%al12.2005_0829_03_00.shp %outdat%wind_speed5 default
shapearc %indat%al12.2005_0829_06_00.shp %outdat%wind_speed6 default
shapearc %indat%al12.2005_0829_09_00.shp %outdat%wind_speed7 default
shapearc %indat%al12.2005_0829_12_00.shp %outdat%wind_speed8 default
shapearc %indat%al12.2005_0829_15_00.shp %outdat%wind_speed9 default
shapearc %indat%al12.2005_0829_18_00.shp %outdat%wind_speed10 default
shapearc %indat%al12.2005_0829_21_00.shp %outdat%wind_speed11 default
shapearc %indat%al12.2005_0830_00_00.shp %outdat%wind_speed12 default
shapearc %indat%al12.2005_0830_03_00.shp %outdat%wind_speed13 default
shapearc %indat%al12.2005_0830_06_00.shp %outdat%wind_speed14 default
shapearc %indat%al12.2005_0830_09_00.shp %outdat%wind_speed15 default
shapearc %indat%al12.2005_0830_12_00.shp %outdat%wind_speed16 default
```

Figure 4.3

Model Code: Section 3



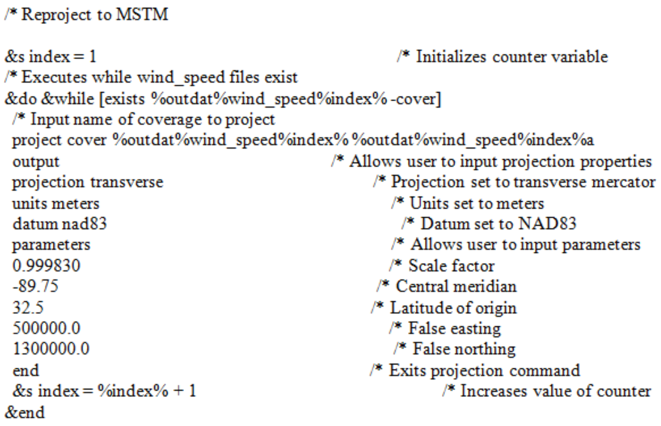
```
/* Define Projection

&s index = 1                              /* Initializes counter variable
/* Executes while wind_speed files exist
&do &while [exists %outdat%wind_speed%index% -cover]
 /* Input name of coverage to define projection
 projectdefine cover %outdat%wind_speed%index%
 projection geographic                       /* Geographic projection
 units dd                                 /* Units set to decimal degrees
 datum nad83                                /* Datum set to NAD83
 parameters                               /* Ends define projection command
 &s index = %index% + 1                          /* Increases value of counter
&end
```

Figure 4.4

Model Code: Section 4

Section five of the code changes the projection to the Mississippi Transverse Mercator (MSTM) projection. The projection, units, datum, scale factor, central meridian, latitude of origin, false easting, and false northing must be set to the MSTM parameters (Figure 4.5). After changing the projection, the discrete point data must be interpolated into a continuous grid using the Inverse Distance Weighting (IDW) method. To use IDW in the Arc Macro Language, the value field, power, number of neighbors, radius, and output cell size must be input (Figure 4.6).

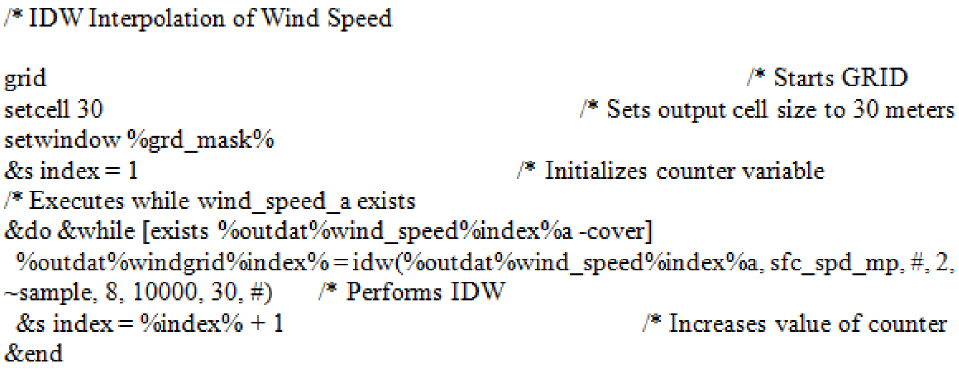


```
/* Reproject to MSTM

&s index = 1                                              /* Initializes counter variable
/* Executes while wind_speed files exist
&do &while [exists %outdat%wind_speed%index% -cover]
 /* Input name of coverage to project
 project cover %outdat%wind_speed%index% %outdat%wind_speed%index%a
 output                                          /* Allows user to input projection properties
 projection transverse                                 /* Projection set to transverse mercator
 units meters                                            /* Units set to meters
 datum nad83                                              /* Datum set to NAD83
 parameters                                              /* Allows user to input parameters
 0.999830                                                /* Scale factor
 -89.75                                                /* Central meridian
 32.5                                                 /* Latitude of origin
 500000.0                                                /* False easting
 1300000.0                                                /* False northing
 end                                                  /* Exits projection command
 &s index = %index% + 1                                         /* Increases value of counter
&end
```

Figure 4.5

Model Code: Section 5



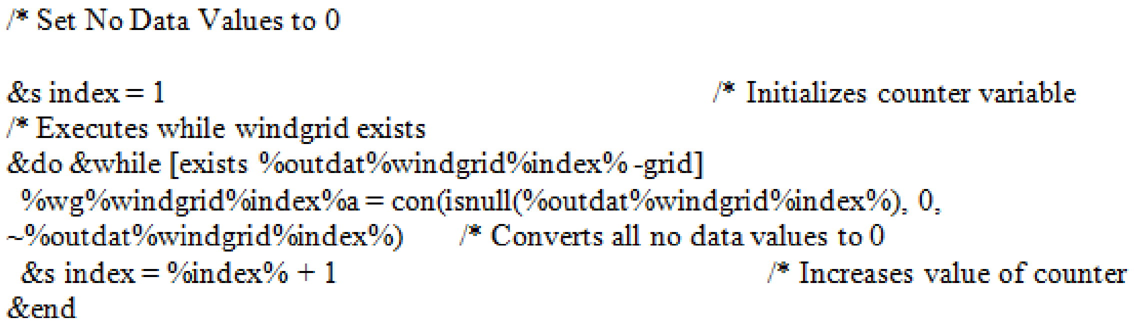
```
/* IDW Interpolation of Wind Speed

grid                                                          /* Starts GRID
setcell 30                                          /* Sets output cell size to 30 meters
setwindow %grd_mask%
&s index = 1                                    /* Initializes counter variable
/* Executes while wind_speed_a exists
&do &while [exists %outdat%wind_speed%index%a -cover]
 %outdat%windgrid%index% = idw(%outdat%wind_speed%index%a, sfc_spd_mp, #, 2,
~sample, 8, 10000, 30, #)     /* Performs IDW
 &s index = %index% + 1                                    /* Increases value of counter
&end
```

Figure 4.6

Model Code: Section 6

During the IDW, all cells outside the extent of the interpolated grid are given “No Data” values. Since the grids are going to be summed to produce a cumulative grid, all “No Data” cells must be converted to a value of zero. In order to this, a conditional statement is used that states if the value is “No Data”, then the cell should be assigned a zero value (Figure 4.7). Figure 4.8 shows the code that sums all of the individual interpolated grids to produce a final cumulative wind grid. The entire process is repeated to produce the cumulative rain grid.

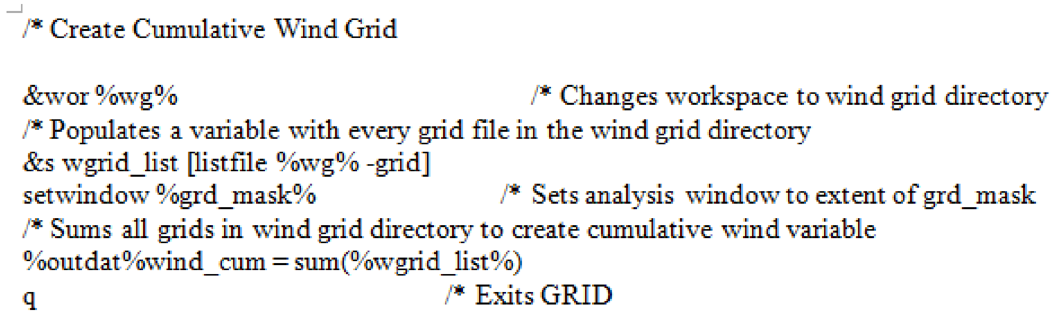


```
/* Set No Data Values to 0

&s index = 1                                          /* Initializes counter variable
/* Executes while windgrid exists
&do &while [exists %outdat%windgrid%index% -grid]
  %wg%windgrid%index%a = con(isnull(%outdat%windgrid%index%), 0,
~%outdat%windgrid%index%)     /* Converts all no data values to 0
  &s index = %index% + 1                                     /* Increases value of counter
&end
```

Figure 4.7

Model Code: Section 7



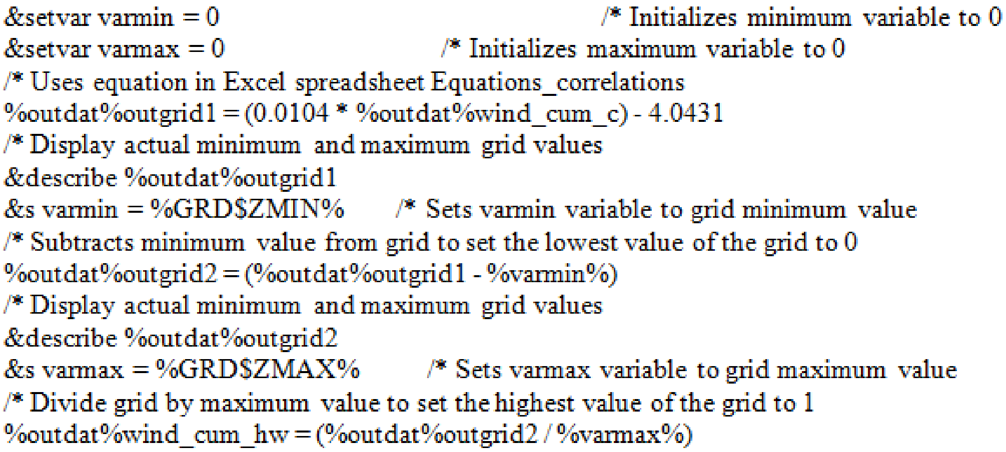
```
/* Create Cumulative Wind Grid

&wor %wg%                          /* Changes workspace to wind grid directory
/* Populates a variable with every grid file in the wind grid directory
&s wgrid_list [listfile %wg% -grid]
setwindow %grd_mask%               /* Sets analysis window to extent of grd_mask
/* Sums all grids in wind grid directory to create cumulative wind variable
%outdat%wind_cum = sum(%wgrid_list%)
q                                  /* Exits GRID
```

Figure 4.8

Model Code: Section 8

Once the cumulative wind grids are created, each grid used in the model can be put in a regression equation and standardized from zero to one (Figure 4.9). Each variable has its own regression formula (Table 1), where the value of x is replaced by each cell in the grid. Once the new values for the grid are obtained, the minimum cell value is subtracted from every cell, so that the new minimum grid value is zero. Next, all cells are divided by the maximum cell value, so that the maximum grid value is one. Now all of the cells in each grid have a value between zero and one inclusive. The standardizing process is performed so that the values in one grid are comparable to the values in another grid. The process used to obtain the regression values and standardize the grids is repeated for each grid used in the final models.

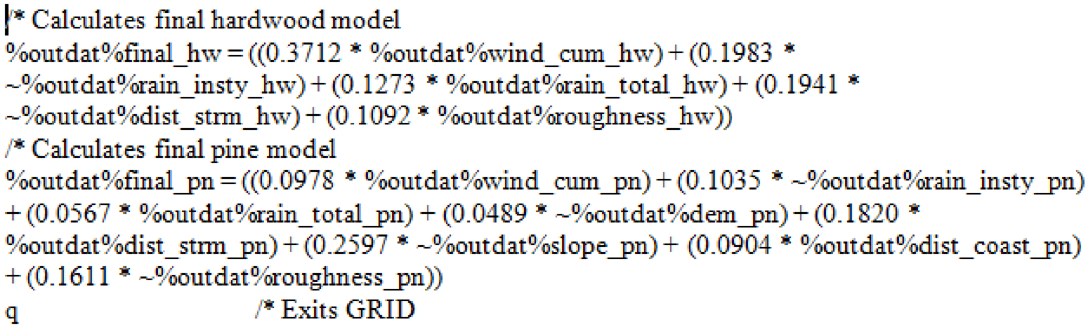


```
&setvar varmin = 0                                        /* Initializes minimum variable to 0
&setvar varmax = 0                          /* Initializes maximum variable to 0
/* Uses equation in Excel spreadsheet Equations_correlations
%outdat%outgrid1 = (0.0104 * %outdat%wind_cum_c) - 4.0431
/* Display actual minimum and maximum grid values
&describe %outdat%outgrid1
&s varmin = %GRD$ZMIN%      /* Sets varmin variable to grid minimum value
/* Subtracts minimum value from grid to set the lowest value of the grid to 0
%outdat%outgrid2 = (%outdat%outgrid1 - %varmin%)
/* Display actual minimum and maximum grid values
&describe %outdat%outgrid2
&s varmax = %GRD$ZMAX%       /* Sets varmax variable to grid maximum value
/* Divide grid by maximum value to set the highest value of the grid to 1
%outdat%wind_cum_hw = (%outdat%outgrid2 / %varmax%)
```

Figure 4.9

Model Code: Section 9

Now that all of the grids are prepared, the final models can be created. Weights for each variable in the model were derived from dividing the Pearson's r value for each variable by the sum of all Pearson's r values for variables used in the model. The resulting weights were multiplied by their respective variable, and each product was then summed to produce the final model values (Figure 4.10).



```
/* Calculates final hardwood model
%outdat%final_hw = ((0.3712 * %outdat%wind_cum_hw) + (0.1983 *
~%outdat%rain_insty_hw) + (0.1273 * %outdat%rain_total_hw) + (0.1941 *
~%outdat%dist_strm_hw) + (0.1092 * %outdat%roughness_hw))
/* Calculates final pine model
%outdat%final_pn = ((0.0978 * %outdat%wind_cum_pn) + (0.1035 * ~%outdat%rain_insty_pn)
+ (0.0567 * %outdat%rain_total_pn) + (0.0489 * ~%outdat%dem_pn) + (0.1820 *
%outdat%dist_strm_pn) + (0.2597 * ~%outdat%slope_pn) + (0.0904 * %outdat%dist_coast_pn)
+ (0.1611 * ~%outdat%roughness_pn))
q                          /* Exits GRID
```

Figure 4.10

Model Code: Section 10

Description of Resulting Maps

The resulting forest probability maps show the greatest predicted damage occurring in the southern portion of the study area, particularly the southwestern section just to the east of the hurricane track (Figure 4.11, Figure 4.12). On the model run where interpolations were performed at one hundred meter resolution and resampled to thirty meter resolution, the processing time was one hour for the forest model as well as the model using cumulative wind and rain. This method was not tested on the maximum sustained winds and rain model due to a fast processing speed even when modeled at thirty meters. The model run where all interpolations were based on 30 meter data resolutions resulted in a processing time of five hours for the forest model (Figure 4.11, Figure 4.12) and the cumulative wind and rain model (Figure 4.13). Figures 4.11, 4.12, and 4.13 depict the results of the second run, which are more accurate due to the higher spatial resolution used in the interpolations. The maximum sustained winds and rain model runs were completed in one hour and forty-five minutes (Figure 4.14). Artifacts of the cumulative wind methodology can be seen in Figure 4.14 as east/west trending boundary effects related to the methodological process in which wind speeds were assumed to be negligible in areas north of the wind grids. For future versions of the model, cumulative wind may be removed or replaced by another variable, which would correct the error. Every model shows the highest predicted damage along the eastern edge of the hurricane path. Typically, the models predict more damage along the coast than farther inland. Harrison and Stone Counties show the most predicted damage, which coincides with a post-Katrina damage survey performed by the USDA Forest Service which found that Harrison and Stone Counties had the most forest damage from Katrina (USDA Forest Service 2005). The model that used maximum sustained wind instead of cumulative wind (Figure 4.14) predicted higher damage along the hurricane path further inland than all of the models that used cumulative wind. The pine shear model (Figure 4.12) shows the effect of using the Digital Elevation Model (DEM), as evidenced by the visible stream channels.

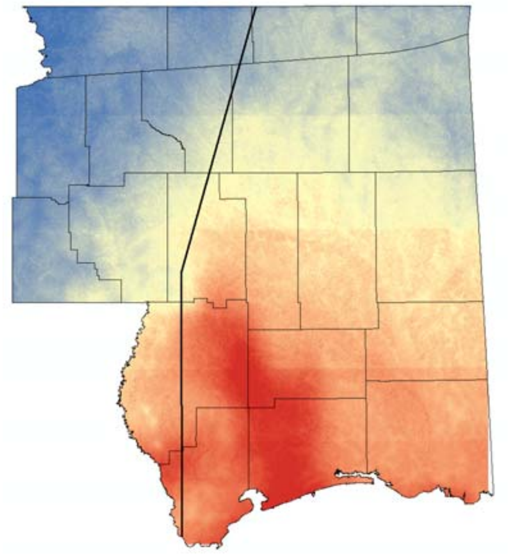


Figure 4.11

Hardwood Blowdown Prediction Model with Hurricane Track

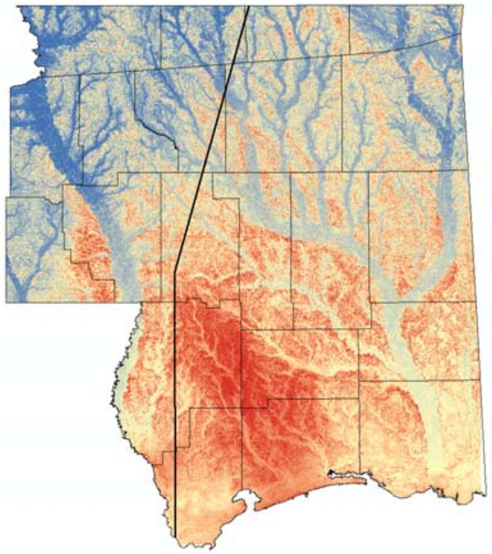


Figure 4.12

Pine Shear Prediction Model with Hurricane Track

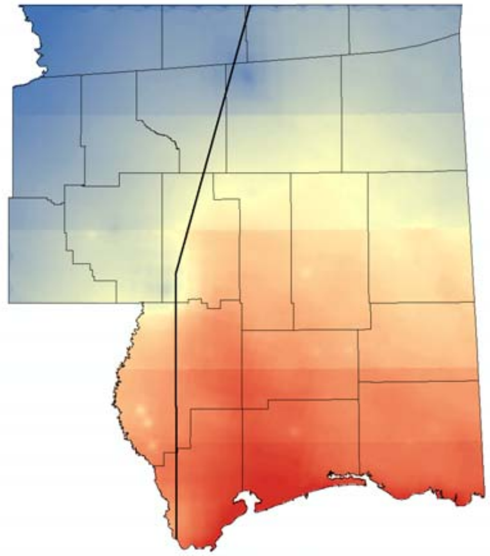


Figure 4.13

Cumulative Wind and Rain Damage Prediction Model

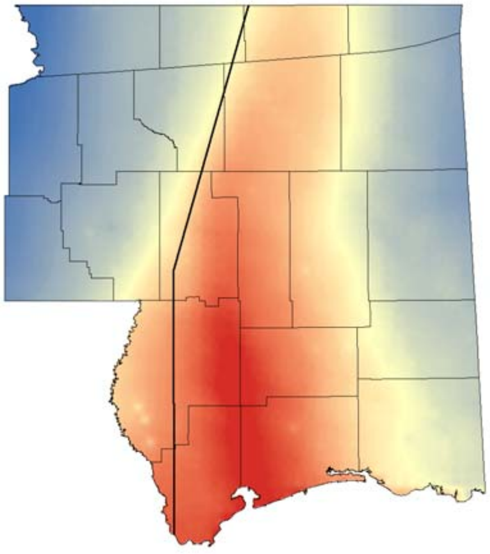


Figure 4.14

Maximum Sustained Winds and Rain Damage Prediction Model

CHAPTER V

DISCUSSION

Model Discussion

The purpose of this project is to quickly provide accurate hurricane damage predictions with the highest quality readily-available data to emergency managers. Emergency managers need quality information available to them within 24 hours after a hurricane leaves an area (Hodgson et al. 2010). All of the models created for this project can be available well within that timeframe. The models also provide accurate information when compared to other damage prediction models (USDA Forest Service 2005) and to actual field damage reports (MIFI 2007). Originally, all of the grids to be used in the model were obtained or created with a ten meter spatial resolution. The spatial resolution was changed to thirty meters after it took over 24 hours to run the models with ten meter resolution. It was determined that performing analysis on all grids at thirty meter resolution provided the best resolution while still being able to produce output within 24 hours.

Advantages of the Models

Emergency managers need imagery of the disaster area within 24 hours (Hodgson et al. 2010). Each model will be completed well within that time period. In trial runs of

Hurricane Katrina, each model was completed in around five hours. Depending on the amount of grids needed to be processed for each storm, the run-time may be slightly more or less, but it will still be easily completed in less than 24 hours. As a result, action can be taken almost immediately to determine what areas have the most damage, so decisions can be made quickly.

Another benefit to emergency managers' needs is the complete non-reliance on remotely sensed data after the storm. All of the data used in the models is either terrestrial data available before the storm (i.e. elevation, slope, distance from streams) or weather data available during the storm (i.e. wind speed, precipitation). As a result, the models can provide results very soon after a storm, with none of the problems associated with remote sensing, such as finding cloud-free days and the poor temporal resolution associated with space-based sensors and the small coverage areas and high costs of airborne imagery.

The models provide reliable predictions of likelihood of damage that have been observed to be accurate when compared to actual field observations of damage and other damage prediction models. The forest damage predicted by the models fall in line with forest damage models performed after Katrina (Figure 5.1) (USDA Forest Service 2005). The predicted damage model created by the USDA Forest Service shows the most damage associated with Katrina in the southernmost part of the state, with the damage extending farther northward closer to the hurricane path. The models created for this project show the same damage characteristics. The Mississippi Institute for Forest

Inventory (MIFI 2007) reported that the highest percentage of plots with damage occurred in Harrison and Stone counties, which the models also predict (MIFI 2007).

The maps produced are intuitive and can be understood with little or no explanation. The color scheme used associates the areas that are predicted to have the heaviest damage in red, which is a “hot” color often associated with danger. The areas that were predicted to be the least damaged are denoted on the map as blue, a “cool” color. By using this intuitive coloring system, confusion is avoided. A numbered system, such as what the USDA Forest Service used in their damage prediction map (Figure 5.1), can be confusing because a value of “1” could easily be seen as having the most damage, even when it is intended to show the least amount of damage. A well-developed coloring scheme eliminates unnecessary confusion associated with numbers, and it is visually more easily and readily understood. A layperson with no knowledge of hurricane damage could be shown the model results and easily determine where the most damage occurred. Work is being done to make the results of the models readily available on the Internet, so that the maps can be easily accessed by emergency management officials. It is also possible to drape the model results over Google Earth to aid in the ease of use. In addition, all of the models will assist in determining where to plan flight lines and what kind of remotely sensed data to use in planning forest debris cleanup. Remotely sensed imagery, especially over large areas, can be very expensive. Another problem with remotely sensed data is that clouds and revisit times of satellites can prevent data from being acquired. The results of the models can be used to determine where (or even if) imagery needs to be obtained, saving both time and money.

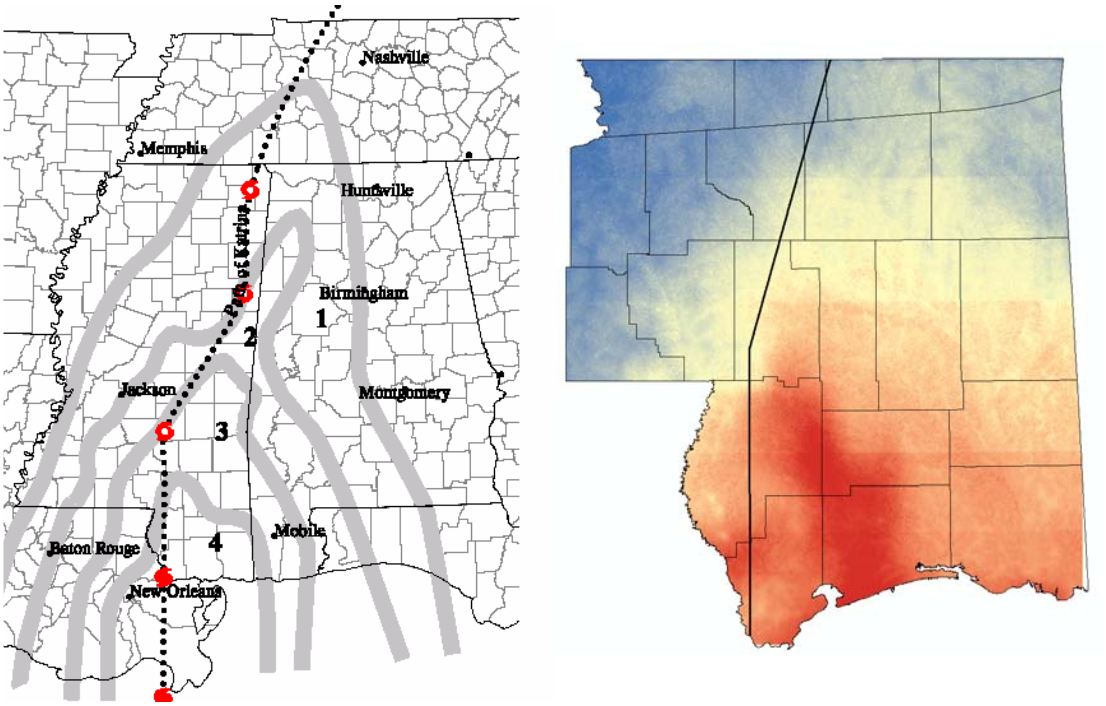


Figure 5.1

USDA Forest Service model areas of high damage (4) compared to hardwood blowdown model areas of high damage (red).

Limitations of the Models

There are several limitations to the models. One potential limitation of the model discussed previously is the problem of cumulative wind. The wind data are obtained every three hours, and each dataset contains wind speeds for the extent of the hurricane that move spatially with the hurricane. For the purpose of modeling, all locations outside the extent of the wind grid were given values of zero. In reality, however, the wind speeds in these locations are likely not zero. When all of the wind grids are summed, the error accumulates, resulting in horizontal striations in some of the models, especially noticeable in the cumulative wind and rain damage model. It may be possible to correct this error by using weather station wind data to give wind speed values to locations outside the extent of the H*wind grid. The errors associated with using zero values for non-zero wind speeds are likely not much, but the model is nevertheless slightly affected.

Logistic regression results indicated that for Katrina-associated damage to forests, precipitation intensity and cumulative precipitation are both important variables for accurate predictions of forest damage. Currently, both hardwood blowdown and pine shear models use both precipitation variables for predictions and these variables have a high degree of multicollinearity. It is not clear what degree of spatial and temporal correlation exists between these variables and further investigation is needed to assess whether the variables should be included in the model 'as is' or if a factor analysis is appropriate to derive a composite variable that is less statistically problematic.

For this study it was deemed unwise to remove either precipitation variable from the model since both variables were significant predictors of damage, and for emergency management purposes, over-prediction of damage (error of commission) is preferred for response planning purposes rather than the likely effects of under-prediction of damage that would occur should one of the wind variables be excluded from the SAW model as currently constructed.

A potential solution has been discussed that results in an ordinate approach to combining wind and rain by temporal windows for the calculation of a new variable. An index of potential damage could be created by implementing a ranking system using precipitation and wind speed. For example, a time period of high rainfall and high wind speed would receive the highest possible rank. Conversely, low rainfall and low wind speed would receive the lowest rank. The summed rankings could then be used in lieu of precipitation intensity. The threshold values for determining what constitutes high or low rainfall or wind speed and the validity of this approach have not been determined at this time. As a result of no better option at this time, the final models use both precipitation intensity, as well as total precipitation in the final models, even though there is likely some redundant information being used. Both factor analysis and indexing solutions are ‘on the table’ as potential future research topics.

A second limitation of the models is the omission of a storm surge variable. Storm surge is often considered to be one of the most, if not the most, damaging aspects of a hurricane (NHC 2010). Since it is not included in the model, there will certainly be more damage in surge-impacted areas than current model predictions that are based on wind and rain alone. There are several reasons why storm surge is not included. One reason is that the purpose of the models is to determine the affects of landscape variables and meteorological variables, such as precipitation and wind, on forest damage. A second reason is storm surge only affects the areas closest to the coast, so inclusion of storm surge in an additive spatial model for the entire hurricane-affected area is not theoretically sound.

Since a linear weighted model was used, if one of the variable’s values goes to zero, the weights or importance of the other variables are diluted. For example, suppose a linear weighted model includes three variables where the weights are equivalent and sum to one. If the value of one of the variables is zero, then the weights of the other two variables are diluted from what they could be if the variable with a value of zero was not included. If the weights for each element of the three variable model were 0.33, and the first variable went to zero, then the sum of the other two variables is only 0.66. If, however, the zero-variable is not included, the non-zero variables could both be given a weight of 0.5, therefore increasing the weight of each variable and providing more information to the model. Since damage associated with storm surge does not account for most of the study area, the variable was not included in the models to provide more weight to other variables which are associated with the whole of the study area. Work is currently ongoing on a storm surge model that could be combined with the results of the wind and rain models that could potentially solve the problems associated with not including storm surge in the current set of models.

Another limitation of the models is that conditions before the hurricane are not included in the models. Blowdown is more likely to occur when the soil is already wet from a previous rain event (Stathers et al. 1994). As a result, more forest damage may be caused by a hurricane passing over wet soil than the same hurricane passing over dry soil, even though the models treat both conditions equally. One of the biggest advantages of the models, however, is speed. To maintain the speed needed, the data must be easily and quickly accessible. No model is perfect and sacrifices must be made regardless of model goals. Any model that included prior soil conditions would take much longer to produce, and since the response speed after a hurricane is so critical, the soil conditions were excluded.

Prior studies have created hurricane damage prediction models using observations of damage to create the regression formulas. All of the available observations were used in such studies, therefore, no damage observations were withheld to test model residuals or predictive results in direct comparison to actual damages. In the future, the models created for this project can be refined by leaving out a randomly selected set of observations to be used after regression analysis and modeling to test results for calibration and best-fit estimates and to provide confidence intervals for predictive results.

CHAPTER VI

CONCLUSIONS

In the past, emergency managers have had to sacrifice either speed or accuracy when obtaining damage estimates. Furthermore, problems associated with cost or ease of use for available damage assessment methods made identifying areas of high damage even more difficult. However, the models described in this paper have been shown to address the problems emergency managers face, so that important decisions can be made quickly and with confidence. The models will be available well within 24 hours on a secure, easy to use website, providing quick access to the Mississippi Emergency Management Agency (MEMA). MEMA has adopted the models for their emergency response plan. The models do not rely on remotely sensed imagery, eliminating problems associated with space-based satellite imagery (the presence of clouds, long re-visit times) and airborne imagery (high cost, small coverage area). The models can cover as large (or small) an area as desired, with no threat of cloud interference, without having to spend a large amount of money. In addition, the models are accurate when compared to other models and actual damage reports. As a result, the outputs of the models can be trusted to help make the important decisions that need to be made in a time of emergency.

Not only do the models offer many advantages, the four different models offer a variety of results depending on the type of damage. Using the hardwood blowdown and pine shear models, emergency managers could determine where forest damage is most likely to occur and allocate resources to remove the associated debris. A build-up of forest debris is associated with an increase in wildfire potential, as well as insect infestations (Everham and Brokaw 1996, Cooke et al. 2007). The forest damage models presented will help prevent the problems associated with forest damage and assist in decision making and cleanup for emergency managers. The models using wind and rain are good for predicting the total amount of damage associated with a hurricane. The results of the wind and rain models can be combined with the results of a surge model (currently in progress) to produce accurate and realistic predictions of damage. With an array of accurate prediction models at their disposal, emergency managers can make quick, well-informed decisions for dealing with damage associated with forests or damage in general.

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APPENDIX A

AML CODE FOR FOREST DAMAGE MODEL

```
/* Prepare Cumulative Wind Grid

&echo &on
&s base /gri/general/bcooke/hurricane/      /* Sets base directory
&s bin %base%bin/                          /* Sets bin directory
&s indat %base%input/                       /* Sets input directory
&s outdat %base%output/                     /* Sets output directory
&s rg %outdat%rain_grids/                   /* Sets rain grid directory
&s wg %outdat%wind_grids/                   /* Sets wind grid directory
&s grd_mask %indat%utm_counties/            /* Sets the analysis mask

/* Deletes Coverages If They Already Exist

&s index = 1                                /* Initializes counter variable
/* Executes while wind_speed files exist
&do &while [exists %outdat%wind_speed%index% -cover]
  kill %outdat%wind_speed%index% all                /* Deletes existing wind_speed files
  &s index = %index% + 1                            /* Increases value of counter
&end

/* Convert Shapefiles to Coverages

precision double double                                 /* Sets precision to double
/* Converts shapefile  to coverage
shapearc %indat%al12.2005_0828_15_00.shp %outdat%wind_speed1 default
shapearc %indat%al12.2005_0828_18_00.shp %outdat%wind_speed2 default
shapearc %indat%al12.2005_0828_21_00.shp %outdat%wind_speed3 default
shapearc %indat%al12.2005_0829_00_00.shp %outdat%wind_speed4 default
shapearc %indat%al12.2005_0829_03_00.shp %outdat%wind_speed5 default
shapearc %indat%al12.2005_0829_06_00.shp %outdat%wind_speed6 default
shapearc %indat%al12.2005_0829_09_00.shp %outdat%wind_speed7 default
shapearc %indat%al12.2005_0829_12_00.shp %outdat%wind_speed8 default
shapearc %indat%al12.2005_0829_15_00.shp %outdat%wind_speed9 default
shapearc %indat%al12.2005_0829_18_00.shp %outdat%wind_speed10 default
shapearc %indat%al12.2005_0829_21_00.shp %outdat%wind_speed11 default
shapearc %indat%al12.2005_0830_00_00.shp %outdat%wind_speed12 default
shapearc %indat%al12.2005_0830_03_00.shp %outdat%wind_speed13 default
shapearc %indat%al12.2005_0830_06_00.shp %outdat%wind_speed14 default
shapearc %indat%al12.2005_0830_09_00.shp %outdat%wind_speed15 default
shapearc %indat%al12.2005_0830_12_00.shp %outdat%wind_speed16 default

/* Define Projection
```

```
&s index = 1                                   /* Initializes counter variable
/* Executes while wind_speed files exist
&do &while [exists %outdat%wind_speed%index% -cover]
  /* Input name of coverage to define projection
  projectdefine cover %outdat%wind_speed%index%
  projection geographic                          /* Geographic projection
  units dd                                     /* Units set to decimal degrees
  datum nad83                                      /* Datum set to NAD83
  parameters                                     /* Ends define projection command
  &s index = %index% + 1                                 /* Increases value of counter
&end

/* Deletes Coverages If They Already Exist

&s index = 1                                   /* Initializes counter variable
/* Executes while wind_speed_a files exist
&do &while [exists %outdat%wind_speed%index%a -cover]
  kill %outdat%wind_speed%index%a all              /* Deletes existing wind_speed_a files
  &s index = %index% + 1                           /* Increases value of counter
&end

/* Reproject to MSTM

&s index = 1                                               /* Initializes counter variable
/* Executes while wind_speed files exist
&do &while [exists %outdat%wind_speed%index% -cover]
  /* Input name of coverage to project
  project cover %outdat%wind_speed%index% %outdat%wind_speed%index%a
  output                                         /* Allows user to input projection properties
  projection transverse                                /* Projection set to transverse mercator
  units meters                                           /* Units set to meters
  datum nad83                                              /* Datum set to NAD83
  parameters                                             /* Allows user to input parameters
  0.999830                                               /* Scale factor
  -89.75                                               /* Central meridian
  32.5                                                /* Latitude of origin
  500000.0                                               /* False easting
  1300000.0                                               /* False northing
  end                                                 /* Exits projection command
  &s index = %index% + 1                                             /* Increases value of counter
&end

/* Deletes grids if they already exist
```

```
&s index = 1                                   /* Initializes counter variable
/* Executes while windgrid files exist
&do &while [exists %outdat%windgrid%index% -grid]
  kill %outdat%windgrid%index% all                   /* Deletes existing windgrid files
  &s index = %index% + 1                        /* Increases value of counter
&end

/* IDW Interpolation of Wind Speed

grid                                                                          /* Starts GRID
setcell 30                                              /* Sets output cell size to 30 meters
setwindow %grd_mask%
&s index = 1                                        /* Initializes counter variable
/* Executes while wind_speed_a exists
&do &while [exists %outdat%wind_speed%index%a -cover]
  %outdat%windgrid%index% = idw(%outdat%wind_speed%index%a, sfc_spd_mp, #, 2,
~sample, 8, 10000, 30, #)       /* Performs IDW
  &s index = %index% + 1                                       /* Increases value of counter
&end

/* Deletes grids if they already exist

&s index = 1                                            /* Initializes counter variable
/* Executes while windgrid_a exists
&do &while [exists %wg%windgrid%index%a -grid]
  kill %wg%windgrid%index%a all                   /* Deletes existing windgrid_a files
  &s index = %index% + 1                                     /* Increases value of counter
&end
/* Deletes wind_cum if it exists
&if [exists %outdat%wind_cum -grid] &then; kill %outdat%wind_cum all

/* Sets analysis window

setwindow %grd_mask%                    /* Sets analysis window to extent of grd_mask

/* Set No Data Values to 0

&s index = 1                                                  /* Initializes counter variable
/* Executes while windgrid exists
&do &while [exists %outdat%windgrid%index% -grid]
  %wg%windgrid%index%a = con(isnull(%outdat%windgrid%index%), 0,
~%outdat%windgrid%index%)        /* Converts all no data values to 0
```

```
  &s index = %index% + 1                                    /* Increases value of counter
&end

/* Create Cumulative Wind Grid

&wor %wg%                                    /* Changes workspace to wind grid directory
/* Populates a variable with every grid file in the wind grid directory
&s wgrid_list [listfile %wg% -grid]
setwindow %grd_mask%                        /* Sets analysis window to extent of grd_mask
/* Sums all grids in wind grid directory to create cumulative wind variable
%outdat%wind_cum = sum(%wgrid_list%)
q                                          /* Exits GRID

/* Prepare Total Precipitation Grid

/* Deletes Coverages If They Already Exist

&s index = 1                                /* Initializes counter variable
/* Executes while rain_total files exist
&do &while [exists %outdat%rain_total%index% -cover]
  kill %outdat%rain_total%index% all                /* Deletes existing rain_total files
  &s index = %index% + 1                      /* Increases value of counter
&end

/* Convert Shapefiles to Coverages
/* Must Change File Names or Will Not Convert

precision double double                                  /* Sets precision to double
/* Converts shapefile to coverage
shapearc %indat%nws_precip_20050828.shp %outdat%rain_total1 default
shapearc %indat%nws_precip_20050829.shp %outdat%rain_total2 default
shapearc %indat%nws_precip_20050830.shp %outdat%rain_total3 default
shapearc %indat%nws_precip_20050831.shp %outdat%rain_total4 default

/* Define Projection

&s index = 1                                 /* Initializes counter variable
/* Executes while rain_total files exist
&do &while [exists %outdat%rain_total%index% -cover]
  /* Input name of coverage to define projection
  projectdefine cover %outdat%rain_total%index%
  projection geographic                        /* Sets projection to geographic
  units dd                                   /* Sets units to decimal degrees
```

```
 datum nad83                          /* Sets datum to NAD83
 parameters                          /* Ends define projection command
 &s index = %index% + 1                    /* Increases value of counter
&end

/* Deletes Coverages If They Already Exist

&s index = 1                         /* Initializes counter variable
/* Executes while rain_total_a files exist
&do &while [exists %outdat%rain_total%index%a -cover]
 kill %outdat%rain_total%index%a all              /* Deletes existing rain_total_a files
 &s index = %index% + 1                    /* Increases value of counter
&end

/* Reproject to MSTM

&s index = 1                                  /* Initializes counter variable
/* Executes while rain_total files exist
&do &while [exists %outdat%rain_total%index% -cover]
 /* Input name of coverage to project
 project cover %outdat%rain_total%index% %outdat%rain_total%index%a
 output                                /* Allows user to input projection properties
 projection transverse                     /* Sets projection to transverse mercator
 units meters                               /* Sets units to meters
 datum nad83                                 /* Sets datum to NAD83
 parameters                                 /* Allows user to input parameters
 0.999830                                   /* Scale factor
 -89.75                                   /* Central meridian
 32.5                                    /* Latitude of origin
 500000.0                                   /* False easting
 1300000.0                                   /* False northing
 end                                     /* Exits projection command
 &s index = %index% + 1                              /*Increases value of counter
&end

/* Deletes Coverages If They Already Exist

&s index = 1                           /* Initializes counter variable
/* Executes while rain_total_c files exist
&do &while [exists %outdat%rain_total%index%c -cover]
 kill %outdat%rain_total%index%c all              /* Deletes existing rain_total_c files
 &s index = %index% + 1                      /* Increases value of counter
&end
```

```
/* Clip Coverages to Study Area

&s index = 1                                              /* Initializes counter variable
/* Executes while rain_total_a exists
&do &while [exists %outdat%rain_total%index%a -cover]
  clip %outdat%rain_total%index%a %indat%counties_utm
~%outdat%rain_total%index%c point     /* Clips rain_total_a to counties_utm
  &s index = %index% + 1                                        /* Increases value of counter
&end

/* Deletes grids if they already exist

&s index = 1                          /* Initializes counter variable
/* Executes while raingrid files exist
&do &while [exists %outdat%raingrid%index% -grid]
  kill %outdat%raingrid%index% all                  /* Deletes existing raingrid files
  &s index = %index% + 1                     /* Increases value of counter
&end

/* IDW Interpolation of Precipitation

grid                                                                /* Starts GRID
setcell 30                                          /* Sets output cell size to 30 meters
setwindow %grd_mask%                                  /* Sets analysis extent
&s index = 1                                                  /* Initializes counter variable
/* Executes while rain_total_c exists
&do &while [exists %outdat%rain_total%index%c -cover]
  %outdat%raingrid%index% = idw(%outdat%rain_total%index%c, Globvalue, #, 2,
~sample, 8, 10000, 30, #)     /* Performs IDW
  &s index = %index% + 1                                       /* Increases value of counter
&end

/* Deletes grids if they already exist

&s index = 1                                        /* Initializes counter variable
/* Executes while raindgrid_a files exist
&do &while [exists %rg%raingrid%index%a -grid]
  kill %rg%raingrid%index%a all                    /* Deletes existing raingrid_a files
  &s index = %index% + 1                                       /* Increases value of counter
&end
/* Deletes rain_total if it exists
&if [exists %outdat%rain_total -grid] &then; kill %outdat%rain_total all
```

```
/* Sets analysis window

setwindow %grd_mask%             /* Sets analysis window to extent of grd_mask

/* Set No Data Values to 0

&s index = 1                                                    /* Initializes counter
variable
&do &while [exists %outdat%raingrid%index% -grid]   /* Executes while raingrid exists
  %rg%raingrid%index%a = con(isnull(%outdat%raingrid%index%), 0,
~%outdat%raingrid%index%)    /* Converts all no data values to 0
  &s index = %index% + 1                                /* Increases value of counter
&end

/* Create Cumulative Rain Grid

&wor %rg%                                  /* Changes workspace to rain grid directory
/* Populates a variable with every grid file in the rain grid directory
&s rgrid_list [listfile %rg% -grid]
setwindow %grd_mask%                       /* Sets analysis window to extent of grd_mask
/* Sums all grids in rain grid directory to create total rain variable
%outdat%rain_total = sum(%rgrid_list%)

/* Deletes grids if they already exist

/* Deletes rain_total_c if it exists
&if [exists %outdat%rain_total_c -grid] &then; kill %outdat%rain_total_c all
/* Deletes wind_cum_c if it exists
&if [exists %outdat%wind_cum_c -grid] &then; kill %outdat%wind_cum_c all

/* Create Subsets

setmask %grd_mask%                         /* Sets analysis mask to extent of grd_mask
/* Creates a subset of cumulative wind grid for study area
%outdat%wind_cum_c = %outdat%wind_cum
 /* Creates a subset of total grid for study area
%outdat%rain_total_c = %outdat%rain_total
q                                   /* Exits GRID

/* Deletes grids if they already exist

&s index = 1                                          /* Initializes counter variable
```

```
/* Executes while outgrid files exist
&do &while [exists %outdat%outgrid%index% -grid]
  kill %outdat%outgrid%index% all                      /* Deletes existing outgrid files
  &s index = %index% + 1                               /* Increases value of counter
&end
&if [exists %outdat%final_hw -grid] &then; kill %outdat%final_hw all
&if [exists %outdat%final_pn -grid] &then; kill %outdat%final_pn all
&if [exists %outdat%wind_cum_hw -grid] &then; kill %outdat%wind_cum_hw all
&if [exists %outdat%rain_insty_hw -grid] &then; kill %outdat%rain_insty_hw all
&if [exists %outdat%rain_total_hw -grid] &then; kill %outdat%rain_total_hw all
&if [exists %outdat%dist_strm_hw -grid] &then; kill %outdat%dist_strm_hw all
&if [exists %outdat%roughness_hw -grid] &then; kill %outdat%roughness_hw all
&if[exists %outdat%wind_cum_pn -grid] &then; kill %outdat%wind_cum_pn all
&if [exists %outdat%rain_insty_pn -grid] &then; kill %outdat%rain_insty_pn all
&if [exists %outdat%rain_total_pn -grid] &then; kill %outdat%rain_total_pn all
&if [exists %outdat%dem_pn -grid] &then; kill %outdat%dem_pn all
&if [exists %outdat%dist_strm_pn -grid] &then; kill %outdat%dist_strm_pn all
&if [exists %outdat%slope_pn -grid] &then; kill %outdat%slope_pn all
&if [exists %outdat%dist_coast_pn -grid] &then; kill %outdat%dist_coast_pn all
&if [exists %outdat%roughness_pn -grid] &then; kill %outdat%roughness_pn all

/* Standardize each grid

&wor %outdat%                              /* Changes workspace to output directory
grid                                                           /* Starts GRID
setcell 30                                     /* Sets ouput cell size to 30 meters
setwindow %grd_mask%                 /* Sets analysis window to extent of grd_mask
&setvar varmin = 0                                      /* Initializes minimum variable to 0
&setvar varmax = 0                        /* Initializes maximum variable to 0
/* Uses equation in Excel spreadsheet Equations_correlations
%outdat%outgrid1 = (0.0104 * %outdat%wind_cum_c) - 4.0431
/* Display actual minimum and maximum grid values
&describe %outdat%outgrid1
&s varmin = %GRD$ZMIN%       /* Sets varmin variable to grid minimum value
/* Subtracts minimum value from grid to set the lowest value of the grid to 0
%outdat%outgrid2 = (%outdat%outgrid1 - %varmin%)
/* Display actual minimum and maximum grid values
&describe %outdat%outgrid2
&s varmax = %GRD$ZMAX%         /* Sets varmax variable to grid maximum value
/* Divide grid by maximum value to set the highest value of the grid to 1
%outdat%wind_cum_hw = (%outdat%outgrid2 / %varmax%)
&setvar varmin = 0
&setvar varmax = 0
```

```
%outdat%outgrid3 = (0.4769 * %indat%rain_insty) - 1.1338
&describe %outdat%outgrid3
&s varmin = %GRD$ZMIN%
%outdat%outgrid4 = (%outdat%outgrid3 - %varmin%)
&describe %outdat%outgrid4
&s varmax = %GRD$ZMAX%
%outdat%rain_insty_hw = (%outdat%outgrid4 / %varmax%)
&setvar varmin = 0
&setvar varmax = 0
%outdat%outgrid5 = (0.1525 * %outdat%rain_total_c) - 1.2419
&describe %outdat%outgrid5
&s varmin = %GRD$ZMIN%
%outdat%outgrid6 = (%outdat%outgrid5 - %varmin%)
&describe %outdat%outgrid6
&s varmax = %GRD$ZMAX%
%outdat%rain_total_hw = (%outdat%outgrid6 / %varmax%)
&setvar varmin = 0
&setvar varmax = 0
%outdat%outgrid7 = (-0.4379 * %indat%dist_strm_30) - 0.3911
&describe %outdat%outgrid7
&s varmin = %GRD$ZMIN%
%outdat%outgrid8 = (%outdat%outgrid7 - %varmin%)
&describe %outdat%outgrid8
&s varmax = %GRD$ZMAX%
%outdat%dist_strm_hw = (%outdat%outgrid8 / %varmax%)
&setvar varmin = 0
&setvar varmax = 0
%outdat%outgrid9 = (0.0167 * %indat%roughness_30) - 0.6945
&describe %outdat%outgrid9
&s varmin = %GRD$ZMIN%
%outdat%outgrid10 = (%outdat%outgrid9 - %varmin%)
&describe %outdat%outgrid10
&s varmax = %GRD$ZMAX%
%outdat%roughness_hw = (%outdat%outgrid10 / %varmax%)
&setvar varmin = 0
&setvar varmax = 0
%outdat%outgrid11 = (0.008 * %outdat%wind_cum_c) - 4.6676
&describe %outdat%outgrid11
&s varmin = %GRD$ZMIN%
%outdat%outgrid12 = (%outdat%outgrid11 - %varmin%)
&describe %outdat%outgrid12
&s varmax = %GRD$ZMAX%
%outdat%wind_cum_pn = (%outdat%outgrid12 / %varmax%)
```

```
&setvar varmin = 0
&setvar varmax = 0
%outdat%outgrid13 = (0.3766 * %indat%rain_insty) - 1.993
&describe %outdat%outgrid13
&s varmin = %GRD$ZMIN%
%outdat%outgrid14 = (%outdat%outgrid13 - %varmin%)
&describe %outdat%outgrid14
&s varmax = %GRD$ZMAX%
%outdat%rain_insty_pn = (%outdat%outgrid14 / %varmax%)
&setvar varmin = 0
&setvar varmax = 0
%outdat%outgrid15 = (0.1344 * %outdat%rain_total_c) - 2.3633
&describe %outdat%outgrid15
&s varmin = %GRD$ZMIN%
%outdat%outgrid16 = (%outdat%outgrid15 - %varmin%)
&describe %outdat%outgrid16
&s varmax = %GRD$ZMAX%
%outdat%rain_total_pn = (%outdat%outgrid16 / %varmax%)
&setvar varmin = 0
&setvar varmax = 0
%outdat%outgrid17 = (0.002 * %indat%dem_30) - 1.9825
&describe %outdat%outgrid17
&s varmin = %GRD$ZMIN%
%outdat%outgrid18 = (%outdat%outgrid17 - %varmin%)
&describe %outdat%outgrid18
&s varmax = %GRD$ZMAX%
%outdat%dem_pn = (%outdat%outgrid18 / %varmax%)
&setvar varmin = 0
&setvar varmax = 0
%outdat%outgrid19 = (0.7805 * %indat%dist_strm_30) - 2.1828
&describe %outdat%outgrid19
&s varmin = %GRD$ZMIN%
%outdat%outgrid20 = (%outdat%outgrid19 - %varmin%)
&describe %outdat%outgrid20
&s varmax = %GRD$ZMAX%
%outdat%dist_strm_pn = (%outdat%outgrid20 / %varmax%)
&setvar varmin = 0
&setvar varmax = 0
%outdat%outgrid21 = (0.0226 * %indat%slope_30) - 2.0491
&describe %outdat%outgrid21
&s varmin = %GRD$ZMIN%
%outdat%outgrid22 = (%outdat%outgrid21 - %varmin%)
&describe %outdat%outgrid22
```

```
&s varmax = %GRD$ZMAX%
%outdat%slope_pn = (%outdat%outgrid22 / %varmax%)
&setvar varmin = 0
&setvar varmax = 0
%outdat%outgrid23 = (-0.012 * %indat%dist_coast_30) - 1.445
&describe %outdat%outgrid23
&s varmin = %GRD$ZMIN%
%outdat%outgrid24 = (%outdat%outgrid23 - %varmin%)
&describe %outdat%outgrid24
&s varmax = %GRD$ZMAX%
%outdat%dist_coast_pn = (%outdat%outgrid24 / %varmax%)
&setvar varmin = 0
&setvar varmax = 0
%outdat%outgrid25 = (0.0365 * %indat%roughness_30) - 2.2321
&describe %outdat%outgrid25
&s varmin = %GRD$ZMIN%
%outdat%outgrid26 = (%outdat%outgrid25 - %varmin%)
&describe %outdat%outgrid26
&s varmax = %GRD$ZMAX%
%outdat%roughness_pn = (%outdat%outgrid26 / %varmax%)

/* Run Models

setwindow %grd_mask%                /* Sets analysis window to extent of grd_mask
/* Calculates final hardwood model
%outdat%final_hw = ((0.3712 * %outdat%wind_cum_hw) + (0.1983 *
~%outdat%rain_insty_hw) + (0.1273 * %outdat%rain_total_hw) + (0.1941 *
~%outdat%dist_strm_hw) + (0.1092 * %outdat%roughness_hw))
/* Calculates final pine model
%outdat%final_pn = ((0.0978 * %outdat%wind_cum_pn) + (0.1035 *
~%outdat%rain_insty_pn) + (0.0567 * %outdat%rain_total_pn) + (0.0489 *
~%outdat%dem_pn) + (0.1820 * %outdat%dist_strm_pn) + (0.2597 *
~%outdat%slope_pn) + (0.0904 * %outdat%dist_coast_pn) + (0.1611 *
~%outdat%roughness_pn))
q                        /* Exits GRID
```

APPENDIX B

AML CODE FOR WIND AND RAIN DAMAGE MODEL

```
/* Prepare Cumulative Wind Grid

&echo &on
&s base /gri/general/bcooke/hurricane/      /* Sets base directory
&s bin %base%bin/                           /* Sets bin directory
&s indat %base%input/                       /* Sets input directory
&s outdat %base%output/                     /* Sets output directory
&s rg %outdat%rain_grids/                   /* Sets rain grid directory
&s wg %outdat%wind_grids/                   /* Sets wind grid directory
&s grd_mask %indat%utm_counties/            /* Sets the analysis mask

/* Deletes Coverages If They Already Exist

&s index = 1                                /* Initializes counter variable
/* Executes while wind_speed files exist
&do &while [exists %outdat%wind_speed%index% -cover]
  kill %outdat%wind_speed%index% all                  /* Deletes existing wind_speed files
  &s index = %index% + 1                              /* Increases value of counter
&end

/* Convert Shapefiles to Coverages

precision double double                                   /* Sets precision to double
/* Converts shapefile  to coverage
shapearc %indat%al12.2005_0828_15_00.shp %outdat%wind_speed1 default
shapearc %indat%al12.2005_0828_18_00.shp %outdat%wind_speed2 default
shapearc %indat%al12.2005_0828_21_00.shp %outdat%wind_speed3 default
shapearc %indat%al12.2005_0829_00_00.shp %outdat%wind_speed4 default
shapearc %indat%al12.2005_0829_03_00.shp %outdat%wind_speed5 default
shapearc %indat%al12.2005_0829_06_00.shp %outdat%wind_speed6 default
shapearc %indat%al12.2005_0829_09_00.shp %outdat%wind_speed7 default
shapearc %indat%al12.2005_0829_12_00.shp %outdat%wind_speed8 default
shapearc %indat%al12.2005_0829_15_00.shp %outdat%wind_speed9 default
shapearc %indat%al12.2005_0829_18_00.shp %outdat%wind_speed10 default
shapearc %indat%al12.2005_0829_21_00.shp %outdat%wind_speed11 default
shapearc %indat%al12.2005_0830_00_00.shp %outdat%wind_speed12 default
shapearc %indat%al12.2005_0830_03_00.shp %outdat%wind_speed13 default
shapearc %indat%al12.2005_0830_06_00.shp %outdat%wind_speed14 default
shapearc %indat%al12.2005_0830_09_00.shp %outdat%wind_speed15 default
shapearc %indat%al12.2005_0830_12_00.shp %outdat%wind_speed16 default

/* Define Projection
```

```
&s index = 1                                         /* Initializes counter variable
/* Executes while wind_speed files exist
&do &while [exists %outdat%wind_speed%index% -cover]
  /* Input name of coverage to define projection
  projectdefine cover %outdat%wind_speed%index%
  projection geographic                                  /* Geographic projection
  units dd                                        /* Units set to decimal degrees
  datum nad83                                         /* Datum set to NAD83
  parameters                                        /* Ends define projection command
  &s index = %index% + 1                                     /* Increases value of counter
&end

/* Deletes Coverages If They Already Exist

&s index = 1                                         /* Initializes counter variable
/* Executes while wind_speed_a files exist
&do &while [exists %outdat%wind_speed%index%a -cover]
  kill %outdat%wind_speed%index%a all                /* Deletes existing wind_speed_a files
  &s index = %index% + 1                             /* Increases value of counter
&end

/* Reproject to MSTM

&s index = 1                                                    /* Initializes counter variable
/* Executes while wind_speed files exist
&do &while [exists %outdat%wind_speed%index% -cover]
  /* Input name of coverage to project
  project cover %outdat%wind_speed%index% %outdat%wind_speed%index%a
  output                                            /* Allows user to input projection properties
  projection transverse                                    /* Projection set to transverse mercator
  units meters                                                /* Units set to meters
  datum nad83                                                  /* Datum set to NAD83
  parameters                                                  /* Allows user to input parameters
  0.999830                                                    /* Scale factor
  -89.75                                                    /* Central meridian
  32.5                                                    /* Latitude of origin
  500000.0                                                    /* False easting
  1300000.0                                                    /* False northing
  end                                                    /* Exits projection command
  &s index = %index% + 1                                                /* Increases value of counter
&end

/* Deletes grids if they already exist
```

```
&s index = 1                                /* Initializes counter variable
/* Executes while windgrid files exist
&do &while [exists %outdat%windgrid%index% -grid]
  kill %outdat%windgrid%index% all                  /* Deletes existing windgrid files
  &s index = %index% + 1                       /* Increases value of counter
&end

/* IDW Interpolation of Wind Speed

grid                                                        /* Starts GRID
setcell 30                                         /* Sets output cell size to 30 meters
setwindow %grd_mask%
&s index = 1                                     /* Initializes counter variable
/* Executes while wind_speed_a exists
&do &while [exists %outdat%wind_speed%index%a -cover]
  %outdat%windgrid%index% = idw(%outdat%wind_speed%index%a, sfc_spd_mp, #, 2,
~sample, 8, 10000, 30, #)      /* Performs IDW
  &s index = %index% + 1                                    /* Increases value of counter
&end

/* Deletes grids if they already exist

&s index = 1                                          /* Initializes counter variable
/* Executes while windgrid_a exists
&do &while [exists %wg%windgrid%index%a -grid]
  kill %wg%windgrid%index%a all                 /* Deletes existing windgrid_a files
  &s index = %index% + 1                                  /* Increases value of counter
&end
/* Deletes wind_cum if it exists
&if [exists %outdat%wind_cum -grid] &then; kill %outdat%wind_cum all

/* Sets analysis window

setwindow %grd_mask%                  /* Sets analysis window to extent of grd_mask

/* Set No Data Values to 0

&s index = 1                                                /* Initializes counter variable
/* Executes while windgrid exists
&do &while [exists %outdat%windgrid%index% -grid]
  %wg%windgrid%index%a = con(isnull(%outdat%windgrid%index%), 0,
~%outdat%windgrid%index%)       /* Converts all no data values to 0
```

```
  &s index = %index% + 1                              /* Increases value of counter
&end

/* Create Cumulative Wind Grid

&wor %wg%                                   /* Changes workspace to wind grid directory
/* Populates a variable with every grid file in the wind grid directory
&s wgrid_list [listfile %wg% -grid]
setwindow %grd_mask%                      /* Sets analysis window to extent of grd_mask
/* Sums all grids in wind grid directory to create cumulative wind variable
%outdat%wind_cum = sum(%wgrid_list%)
q                                      /* Exits GRID

/* Prepare Total Precipitation Grid

/* Deletes Coverages If They Already Exist

&s index = 1                              /* Initializes counter variable
/* Executes while rain_total files exist
&do &while [exists %outdat%rain_total%index% -cover]
  kill %outdat%rain_total%index% all               /* Deletes existing rain_total files
  &s index = %index% + 1                     /* Increases value of counter
&end

/* Convert Shapefiles to Coverages
/* Must Change File Names or Will Not Convert

precision double double                                  /* Sets precision to double
/* Converts shapefile to coverage
shapearc %indat%nws_precip_20050828.shp %outdat%rain_total1 default
shapearc %indat%nws_precip_20050829.shp %outdat%rain_total2 default
shapearc %indat%nws_precip_20050830.shp %outdat%rain_total3 default
shapearc %indat%nws_precip_20050831.shp %outdat%rain_total4 default

/* Define Projection

&s index = 1                               /* Initializes counter variable
/* Executes while rain_total files exist
&do &while [exists %outdat%rain_total%index% -cover]
  /* Input name of coverage to define projection
  projectdefine cover %outdat%rain_total%index%
  projection geographic                      /* Sets projection to geographic
  units dd                                /* Sets units to decimal degrees
```

```
  datum nad83                         /* Sets datum to NAD83
  parameters                         /* Ends define projection command
  &s index = %index% + 1                   /* Increases value of counter
&end

/* Deletes Coverages If They Already Exist

&s index = 1                         /* Initializes counter variable
/* Executes while rain_total_a files exist
&do &while [exists %outdat%rain_total%index%a -cover]
  kill %outdat%rain_total%index%a all           /* Deletes existing rain_total_a files
  &s index = %index% + 1                  /* Increases value of counter
&end

/* Reproject to MSTM

&s index = 1                                  /* Initializes counter variable
/* Executes while rain_total files exist
&do &while [exists %outdat%rain_total%index% -cover]
  /* Input name of coverage to project
  project cover %outdat%rain_total%index% %outdat%rain_total%index%a
  output                               /* Allows user to input projection properties
  projection transverse                    /* Sets projection to transverse mercator
  units meters                              /* Sets units to meters
  datum nad83                                /* Sets datum to NAD83
  parameters                                /* Allows user to input parameters
  0.999830                                  /* Scale factor
  -89.75                                   /* Central meridian
  32.5                                    /* Latitude of origin
  500000.0                                  /* False easting
  1300000.0                                  /* False northing
  end                                     /* Exits projection command
  &s index = %index% + 1                            /*Increases value of counter
&end

/* Deletes Coverages If They Already Exist

&s index = 1                          /* Initializes counter variable
/* Executes while rain_total_c files exist
&do &while [exists %outdat%rain_total%index%c -cover]
  kill %outdat%rain_total%index%c all           /* Deletes existing rain_total_c files
  &s index = %index% + 1                    /* Increases value of counter
&end
```

```
/* Clip Coverages to Study Area

&s index = 1                                           /* Initializes counter variable
/* Executes while rain_total_a exists
&do &while [exists %outdat%rain_total%index%a -cover]
  clip %outdat%rain_total%index%a %indat%counties_utm
~%outdat%rain_total%index%c point    /* Clips rain_total_a to counties_utm
  &s index = %index% + 1                                 /* Increases value of counter
&end

/* Deletes grids if they already exist

&s index = 1                         /* Initializes counter variable
/* Executes while raingrid files exist
&do &while [exists %outdat%raingrid%index% -grid]
  kill %outdat%raingrid%index% all            /* Deletes existing raingrid files
  &s index = %index% + 1                   /* Increases value of counter
&end

/* IDW Interpolation of Precipitation

grid                                                        /* Starts GRID
setcell 30                                      /* Sets output cell size to 30 meters
setwindow %grd_mask%                             /* Sets analysis extent
&s index = 1                                             /* Initializes counter variable
/* Executes while rain_total_c exists
&do &while [exists %outdat%rain_total%index%c -cover]
  %outdat%raingrid%index% = idw(%outdat%rain_total%index%c, Globvalue, #, 2,
~sample, 8, 10000, 30, #)    /* Performs IDW
  &s index = %index% + 1                                /* Increases value of counter
&end

/* Deletes grids if they already exist

&s index = 1                                     /* Initializes counter variable
/* Executes while raindgrid_a files exist
&do &while [exists %rg%raingrid%index%a -grid]
  kill %rg%raingrid%index%a all                /* Deletes existing raingrid_a files
  &s index = %index% + 1                                /* Increases value of counter
&end
/* Deletes rain_total if it exists
&if [exists %outdat%rain_total -grid] &then; kill %outdat%rain_total all
```

```
/* Sets analysis window

setwindow %grd_mask%            /* Sets analysis window to extent of grd_mask

/* Set No Data Values to 0

&s index = 1                                                /* Initializes counter
variable
&do &while [exists %outdat%raingrid%index% -grid]   /* Executes while raingrid exists
  %rg%raingrid%index%a = con(isnull(%outdat%raingrid%index%), 0,
~%outdat%raingrid%index%)    /* Converts all no data values to 0
  &s index = %index% + 1                                 /* Increases value of counter
&end

/* Create Cumulative Rain Grid

&wor %rg%                               /* Changes workspace to rain grid directory
/* Populates a variable with every grid file in the rain grid directory
&s rgrid_list [listfile %rg% -grid]
setwindow %grd_mask%                    /* Sets analysis window to extent of grd_mask
/* Sums all grids in rain grid directory to create total rain variable
%outdat%rain_total = sum(%rgrid_list%)

/* Deletes grids if they already exist

/* Deletes rain_total_c if it exists
&if [exists %outdat%rain_total_c -grid] &then; kill %outdat%rain_total_c all
/* Deletes wind_cum_c if it exists
&if [exists %outdat%wind_cum_c -grid] &then; kill %outdat%wind_cum_c all

/* Create Subsets

setmask %grd_mask%                      /* Sets analysis mask to extent of grd_mask
/* Creates a subset of cumulative wind grid for study area
%outdat%wind_cum_c = %outdat%wind_cum
 /* Creates a subset of total grid for study area
%outdat%rain_total_c = %outdat%rain_total
q                                   /* Exits GRID

/* Deletes grids if they already exist

&s index = 1                                         /* Initializes counter variable
```

```
/* Executes while outgrid files exist
&do &while [exists %outdat%outgrid%index% -grid]
  kill %outdat%outgrid%index% all                      /* Deletes existing outgrid files
  &s index = %index% + 1                                /* Increases value of counter
&end
/* Deletes final_damage if it exists
&if [exists %outdat%final_damage -grid] &then; kill %outdat%final_damage all

/* Standardize each grid

&wor %outdat%                              /* Changes workspace to output directory
grid                                            /* Starts GRID
setcell 30                                      /* Sets ouput cell size to 30 meters
setwindow %grd_mask%                 /* Sets analysis window to extent of grd_mask
&setvar varmin = 0                             /* Initializes minimum variable to 0
&setvar varmax = 0                             /* Initializes maximum variable to 0
&describe %outdat%wind_cum_c  /* Display actual minimum and maximum grid values
&s varmin = %GRD$ZMIN%                 /* Sets varmin variable to grid minimum value
/* Subtracts minimum value from grid to set the lowest value of the grid to 0
%outdat%outgrid1 = (%outdat%wind_cum_c - %varmin%)
&describe %outdat%outgrid1         /* Display actual minimum and maximum grid values
&s varmax = %GRD$ZMAX%        /* Sets varmax variable to grid maximum value
/* Divide grid by maximum value to set the highest value of the grid to 1
%outdat%wind_cum_st = (%outdat%outgrid1 / %varmax%)
&setvar varmin = 0                             /* Initializes minimum variable to 0
&setvar varmax = 0                             /* Initializes maximum variable to 0
&describe %outdat%rain_total       /* Display actual minimum and maximum grid values
&s varmin = %GRD$ZMIN%                 /* Sets varmin variable to grid minimum value
/* Subtracts minimum value from grid to set the lowest value of the grid to 0
%outdat%outgrid2 = (%outdat%rain_total - %varmin%)
&describe %outdat%outgrid2         /* Display actual minimum and maximum grid values
&s varmax = %GRD$ZMAX%               /* Sets varmax variable to grid maximum value
/* Divide grid by maximum value to set the highest value of the grid to 1
%outdat%rain_total_st = (%outdat%outgrid2 / %varmax%)

/* Run Model
setwindow %grd_mask%                 /* Sets analysis window to extent of grd_mask
/* Calculates final damage model
%outdat%final_damage = ((0.75 * %outdat%wind_cum_st) + (0.25 *
~%outdat%rain_total_st))
q                              /* Exits GRID
```

APPENDIX C

AML CODE FOR MAXIMUM SUSTAINED WINDS AND RAIN DAMAGE MODEL

```
/* Prepare Cumulative Wind Grid

&echo &on
&s base /gri/general/bcooke/hurricane/      /* Sets base directory
&s bin %base%bin/                           /* Sets bin directory
&s indat %base%input/                       /* Sets input directory
&s outdat %base%output/                     /* Sets output directory
&s rg %outdat%rain_grids/                   /* Sets rain grid directory
&s wg %outdat%wind_grids/                   /* Sets wind grid directory
&s grd_mask %indat%utm_counties/            /* Sets the analysis mask

/* Deletes Coverages If They Already Exist

/* Deletes max_wind file if it exists
&if [exists %outdat%max_wind -cover] &then; kill %outdat%max_wind all

/* Convert Shapefiles to Coverages

precision double double                                        /* Sets precision to double
/* Converts shapefile  to coverage
shapearc %indat%katrina_lsna.shp %outdat%max_wind default

/* Define Projection

projectdefine cover %outdat%max_wind    /* Input name of coverage to define projection
projection geographic                        /* Geographic projection
units dd                                   /* Units set to decimal degrees
datum nad83                                    /* Datum set to NAD83
parameters                                   /* Ends define projection command

/* Deletes Coverages If They Already Exist

/* Deletes max_wind_a file if it exists
&if [exists %outdat%max_wind_a -cover] &then; kill %outdat%max_wind_a all

/* Reproject to MSTM

/* Input name of coverage to project
project cover %outdat%max_wind %outdat%max_wind_a
output                                      /* Allows user to input projection properties
projection transverse                               /* Projection set to transverse mercator
units meters                                            /* Units set to meters
datum nad83                                               /* Datum set to NAD83
```

```
parameters                                          /* Allows user to input parameters
0.999830                                            /* Scale factor
-89.75                                             /* Central meridian
32.5                                               /* Latitude of origin
500000.0                                            /* False easting
1300000.0                                           /* False northing
end

/* Deletes grids if they already exist

/* Deletes maxwindgrid file if it exists
&if [exists %outdat%maxwindgrid -grid] &then; kill %outdat%maxwindgrid all

/* IDW Interpolation of Wind Speed

grid                                                                /* Starts GRID
setcell 30                                             /* Sets output cell size to 30 meters
setwindow %grd_mask%
/* Performs IDW
%outdat%maxwindgrid = idw(%outdat%max_wind_a, maxsfc_mph, #, 2, sample, 12,
~10000, 30, #)
q                                    /* Exits GRID

/* Prepare Total Precipitation Grid

/* Deletes Coverages If They Already Exist

&s index = 1                                  /* Initializes counter variable
/* Executes while rain_total files exist
&do &while [exists %outdat%rain_total%index% -cover]
  kill %outdat%rain_total%index% all                 /* Deletes existing rain_total files
  &s index = %index% + 1                         /* Increases value of counter
&end

/* Convert Shapefiles to Coverages
/* Must Change File Names or Will Not Convert

precision double double                                 /* Sets precision to double
/* Converts shapefile to coverage
shapearc %indat%nws_precip_20050828.shp %outdat%rain_total1 default
shapearc %indat%nws_precip_20050829.shp %outdat%rain_total2 default
shapearc %indat%nws_precip_20050830.shp %outdat%rain_total3 default
shapearc %indat%nws_precip_20050831.shp %outdat%rain_total4 default
```

```
/* Define Projection

&s index = 1                                   /* Initializes counter variable
/* Executes while rain_total files exist
&do &while [exists %outdat%rain_total%index% -cover]
  /* Input name of coverage to define projection
  projectdefine cover %outdat%rain_total%index%
  projection geographic                           /* Sets projection to geographic
  units dd                                     /* Sets units to decimal degrees
  datum nad83                                    /* Sets datum to NAD83
  parameters                                   /* Ends define projection command
  &s index = %index% + 1                            /* Increases value of counter
&end

/* Deletes Coverages If They Already Exist

&s index = 1                                  /* Initializes counter variable
/* Executes while rain_total_a files exist
&do &while [exists %outdat%rain_total%index%a -cover]
  kill %outdat%rain_total%index%a all                /* Deletes existing rain_total_a files
  &s index = %index% + 1                           /* Increases value of counter
&end

/* Reproject to MSTM

&s index = 1                                              /* Initializes counter variable
/* Executes while rain_total files exist
&do &while [exists %outdat%rain_total%index% -cover]
  /* Input name of coverage to project
  project cover %outdat%rain_total%index% %outdat%rain_total%index%a
  output                                        /* Allows user to input projection properties
  projection transverse                              /* Sets projection to transverse mercator
  units meters                                        /* Sets units to meters
  datum nad83                                           /* Sets datum to NAD83
  parameters                                          /* Allows user to input parameters
  0.999830                                            /* Scale factor
  -89.75                                            /* Central meridian
  32.5                                             /* Latitude of origin
  500000.0                                            /* False easting
  1300000.0                                            /* False northing
  end                                              /* Exits projection command
  &s index = %index% + 1                                        /*Increases value of counter
```

```
&end

/* Deletes Coverages If They Already Exist

&s index = 1                                    /* Initializes counter variable
/* Executes while rain_total_c files exist
&do &while [exists %outdat%rain_total%index%c -cover]
  kill %outdat%rain_total%index%c all                 /* Deletes existing rain_total_c files
  &s index = %index% + 1                            /* Increases value of counter
&end

/* Clip Coverages to Study Area

&s index = 1                                                  /* Initializes counter variable
/* Executes while rain_total_a exists
&do &while [exists %outdat%rain_total%index%a -cover]
  clip %outdat%rain_total%index%a %indat%counties_utm
~%outdat%rain_total%index%c point     /* Clips rain_total_a to counties_utm
  &s index = %index% + 1                                        /* Increases value of counter
&end

/* Deletes grids if they already exist

&s index = 1                                 /* Initializes counter variable
/* Executes while raingrid files exist
&do &while [exists %outdat%raingrid%index% -grid]
  kill %outdat%raingrid%index% all                 /* Deletes existing raingrid files
  &s index = %index% + 1                         /* Increases value of counter
&end

/* IDW Interpolation of Precipitation

grid                                                                /* Starts GRID
setcell 30                                           /* Sets output cell size to 30 meters
setwindow %grd_mask%                                  /* Sets analysis extent
&s index = 1                                                   /* Initializes counter variable
/* Executes while rain_total_c exists
&do &while [exists %outdat%rain_total%index%c -cover]
  %outdat%raingrid%index% = idw(%outdat%rain_total%index%c, Globvalue, #, 2,
~sample, 8, 10000, 30, #)     /* Performs IDW
  &s index = %index% + 1                                       /* Increases value of counter
&end
```

```
/* Deletes grids if they already exist

&s index = 1                                            /* Initializes counter variable
/* Executes while raindgrid_a files exist
&do &while [exists %rg%raingrid%index%a -grid]
  kill %rg%raingrid%index%a all                     /* Deletes existing raingrid_a files
  &s index = %index% + 1                                         /* Increases value of counter
&end
/* Deletes rain_total if it exists
&if [exists %outdat%rain_total -grid] &then; kill %outdat%rain_total all

/* Sets analysis window

setwindow %grd_mask%              /* Sets analysis window to extent of grd_mask

/* Set No Data Values to 0

&s index = 1                                                         /* Initializes counter
variable
&do &while [exists %outdat%raingrid%index% -grid]   /* Executes while raingrid exists
  %rg%raingrid%index%a = con(isnull(%outdat%raingrid%index%), 0,
~%outdat%raingrid%index%)    /* Converts all no data values to 0
  &s index = %index% + 1                                      /* Increases value of counter
&end

/* Create Cumulative Rain Grid

&wor %rg%                                 /* Changes workspace to rain grid directory
/* Populates a variable with every grid file in the rain grid directory
&s rgrid_list [listfile %rg% -grid]
setwindow %grd_mask%                         /* Sets analysis window to extent of grd_mask
/* Sums all grids in rain grid directory to create total rain variable
%outdat%rain_total = sum(%rgrid_list%)

/* Deletes grids if they already exist

/* Deletes rain_total_c if it exists
&if [exists %outdat%rain_total_c -grid] &then; kill %outdat%rain_total_c all
/* Deletes max_wind_c if it exists
&if [exists %outdat%wind_cum_c -grid] &then; kill %outdat%max_wind_c all

/* Create Subsets
```

```
setmask %grd_mask%                      /* Sets analysis mask to extent of grd_mask
/* Creates a subset of cumulative wind grid for study area
%outdat%max_wind_c = %outdat%maxwindgrid
/* Creates a subset of total grid for study area
%outdat%rain_total_c = %outdat%rain_total
q                                 /* Exits GRID

/* Deletes grids if they already exist

&s index = 1                                            /* Initializes counter variable
/* Executes while outgrid files exist
&do &while [exists %outdat%outgrid%index% -grid]
  kill %outdat%outgrid%index% all                        /* Deletes existing outgrid files
  &s index = %index% + 1                                  /* Increases value of counter
&end
/* Deletes final_maxwind if it exists
&if [exists %outdat%final_maxwind -grid] &then; kill %outdat%final_maxwind all

/* Standardize each grid

/* Standardize each grid

&wor %outdat%                                /* Changes workspace to output directory
grid                                                      /* Starts GRID
setcell 30                                   /* Sets ouput cell size to 30 meters
setwindow %grd_mask%                    /* Sets analysis window to extent of grd_mask
&setvar varmin = 0                                /* Initializes minimum variable to 0
&setvar varmax = 0                               /* Initializes maximum variable to 0
/* Display actual minimum and maximum grid values
&describe %outdat%max_wind_c
&s varmin = %GRD$ZMIN%                  /* Sets varmin variable to grid minimum value
/* Subtracts minimum value from grid to set the lowest value of the grid to 0
%outdat%outgrid1 = (%outdat%max_wind_c - %varmin%)
/* Display actual minimum and maximum grid values
&describe %outdat%outgrid1
&s varmax = %GRD$ZMAX%                 /* Sets varmax variable to grid maximum value
/* Divide grid by maximum value to set the highest value of the grid to 1
%outdat%max_wind_st = (%outdat%outgrid1 / %varmax%)
&setvar varmin = 0                                /* Initializes minimum variable to 0
&setvar varmax = 0                               /* Initializes maximum variable to 0
&describe %outdat%rain_total       /* Display actual minimum and maximum grid values
&s varmin = %GRD$ZMIN%                  /* Sets varmin variable to grid minimum value
/* Subtracts minimum value from grid to set the lowest value of the grid to 0
```

```
%outdat%outgrid2 = (%outdat%rain_total - %varmin%)
&describe %outdat%outgrid2        /* Display actual minimum and maximum grid values
&s varmax = %GRD$ZMAX%            /* Sets varmax variable to grid maximum value
/* Divide grid by maximum value to set the highest value of the grid to 1
%outdat%rain_total_st = (%outdat%outgrid2 / %varmax%)

/* Run Model

setwindow %grd_mask%              /* Sets analysis window to extent of grd_mask
/* Calculates final maxwind model
%outdat%final_maxwind = ((0.75 * %outdat%max_wind_st) + (0.25 *
~%outdat%rain_total_st))
q                                 /* Exits GRID
```