Forest impact estimated with NOAA AVHRR and Landsat TM data related to an empirical hurricane wind-field distribution

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Abstract

An empirical model was used to relate forest type and hurricane-impact distribution with wind speed and duration to explain the variation of hurricane damage among forest types along the Atchafalaya River basin of coastal Louisiana. Forest-type distribution was derived from Landsat Thematic Mapper image data, hurricane-impact distribution from a suite of transformed advanced very high resolution radiometer images, and wind speed and duration from a wind-field model. The empirical model explained 73%, 84%, and 87% of the impact variances for open, hardwood, and cypress–tupelo forests, respectively. These results showed that the estimated impact for each forest type was highly related to the duration and speed of extreme winds associated with Hurricane Andrew in 1992. The wind-field model projected that the highest wind speeds were in the southern basin, dominated by cypress–tupelo and open forests, while lower wind speeds were in the northern basin, dominated by hardwood forests. This evidence could explain why, on average, the impact to cypress–tupelos was more severe than to hardwoods, even though cypress–tupelos are less susceptible to wind damage. Further, examination of the relative importance of wind speed in explaining the impact severity to each forest type showed that the impact to hardwood forests was mainly related to tropical-depression to tropical-storm force wind speeds. Impacts to cypress–tupelo and open forests (a mixture of willows and cypress–tupelo) were broadly related to tropical-storm force wind speeds and by wind speeds near and somewhat in excess of hurricane force. Decoupling the importance of duration from speed in explaining the impact severity to the forests could not be fully realized. Most evidence, however, hinted that impact severity was positively related to higher durations at critical wind speeds. Wind-speed intervals, which were important in explaining the impact severity on hardwoods, showed that higher durations, but not the highest wind speeds, were concentrated in the northern basin, dominated by hardwoods. The extreme impacts associated with the cypress–tupelo forests in the southeast corner of the basin intersected the highest durations as well as the highest wind speeds. © 2001 Published by Elsevier Science Inc.

Keywords: Forested wetlands; Hurricane impacts; Satellite remote sensing; Wind-field model

1. Introduction

As a catastrophic modifying force, tropical cyclones play an important role in molding forest stand composition and pattern, maintaining floristic diversity, and controlling productivity (Boose, Foster, & Fluet, 1994; Foster & Boose, 1992; Miller, 1967; Shaw, 1983). However, the complex relationship between forest damage and wind speed and duration is not fully understood (Boose et al., 1994). Variation in wind speed, mostly associated with wind gusts, is linked to damage, while sustained wind speeds are linked to structural fatigue (Boose et al., 1994, Fujita, 1971; Powell, 1982) and possibly increased sensitivity to wind gusts. Meteorological factors alone, however, cannot explain the spatial pattern of damage resulting from tropical cyclone impact on the forest landscape (Foster & Boose, 1992; Shaw, 1983). Local wind speed and direction, biotic conditions (e.g., canopy gaps, health, vigor), topographic characteristics, and antecedent natural and human disturbances intermix to determine the site susceptibility to a storm (Boose et al., 1994; Foster & Boose, 1992).

Damage at about the 1-km stand scale often reveals deviations from general patterns. Those deviations may be caused by (1) localized wind gusts and convection, (2) variations in site exposure, (3) variations in species suscept-
ability, and (4) factors related to morphology, age, size, form, health, and rooting conditions (Boose et al., 1994). In a study of tropical cyclone impacts on a northeastern forest in the United States, Foster and Boose (1992) found the affected areas to be predominately less than 0.2 ha. In fact, a continuum of effects created a heterogeneous mosaic of smaller areas that included tree throw, branch break, and defoliation to individual or scattered trees and uprooting of entire stands (Foster & Boose, 1992). Along with wind exposure, the spatial diversity of responses to the tropical cyclone were mostly explained by using fairly easily obtainable measures of biotic and edaphic factors, especially site composition (damage was greater in conifers than hardwoods) and structure (mainly height) (Foster & Boose, 1992). Damage intensity was therefore not only a function of the current wind field but also influenced by antecedent forces (e.g., past storm damage) and activities (e.g., preferential logging) that altered the structure and composition of the forest (Foster & Boose, 1992).

The mosaic of mixed ages and species within a forest landscape may be, in part, the legacy of repeated exposure to tropical cyclones and the differential intensity of disturbance across the landscape (Foster & Boose, 1992; Shaw, 1983). Susceptibility, however, may not always be a direct result of wind-field and biotic variation, but an indirect and delayed reaction to variation in environmental conditions, surviving vegetation, and availability in propagulates (Foster & Boose, 1992). Further, trees experiencing even minor damage (e.g., defoliation) may be rendered more susceptible to other disturbances (e.g., drought, insects), resulting in enhanced mortality (Shaw, 1983).

1.1. Hurricane Andrew in Louisiana

Hurricane Andrew made landfall in Louisiana on August 26, 1992. Its impact covered over 300 square miles of cypress–tupelo swamp and bottomland hardwood forests of the Atchafalaya River basin (Doyle, Keeland, Gorham, & Johnson, 1995; Fig. 1). Early assessments suggested 10% of the live-tree volume was downed, and 63% of the trees showed some degree of foliage damage (Kelly, 1993). A previous study determined that National Oceanic and Atmospheric Administration’s (NOAA) advanced very high resolution radiometer (AVHRR) data could be used to map forest impact (Ramsey, Chappell, & Baldwin, 1997). On inspection of the impact variance and comparison to post-hurricane videography (provided by the U. S. Forest Service), it seemed that not only damage extent but also information on damage severity and type might be extracted from the suite of AVHRR images.
To test the ability to extract more information, forest type determined from prehurricane Landsat thematic mapper (TM) image data was integrated with the impact magnitude estimated from AVHRR image data (Ramsey, Chappell, Jacobs, Sapkota, & Baldwin, 1998). Visual comparison of the merged data sets seemed to corroborate earlier studies of hurricane damage that indicated the impact was greater to hardwoods than to cypress–tupelo (Doyle et al., 1995; Kelly, 1993). Outside the early reconnaissance areas, however, the integrated data sets revealed dominant cypress–tupelo areas had suffered some of the highest impacts. Conversely, mostly hardwood areas in the northwest of the basin sustained some of the lowest impacts even though they were located at or to the left of the storm track as it turned eastward. Statistical analyses were used to find that cypress–tupelo forests were more likely to be associated with higher impact magnitudes than were hardwood forests. These results, however, did not necessarily dispute earlier suggestions that hardwoods are more susceptible to wind damage than are cypress–tupelo. It is the wind field superimposed on the forest site and stand characteristics, including preferential resistance, that determines impact severity.

The goals of this study were to determine first whether the hurricane wind-field distribution could explain the spatial distribution of impact severity. Secondly, to investigate the hypothesis that the wind-field distribution was responsible for the apparent paradox of higher wind resistance but seemingly higher relative impacts associated with cypress–tupelo compared to hardwoods. In order to attain these goals, first we compiled products generated in earlier studies that described the spatial variation of hurricane impacts at 1-km resolution and the relative proportions of cypress–tupelo, hardwood, and open canopy mixed (willows and more open canopy cypress–tupelo) forests within each 1-km² cell (Ramsey et al., 1997, 1998). Second, we developed a cyclone wind-field distribution model that estimated the variation of wind speed over time, and thus the wind-speed duration in each cell. Third, we linked the impact, forest composition, and wind-field estimates within a common database and subsequently analyzed the correspondence between forest type, impact severity, and wind speed and duration. Finally, we offered an explanation for the paradox of increased cypress–tupelo damage despite lower susceptibility to wind damage.

2. Methods

Pre- and posthurricane AVHRR images (NOAA 11), one, a composite of June 23 and July 6 images, and the other from August 29 (3 days after Hurricane Andrew’s passage), were georeferenced to a conic projection at a 1-km resolution, transformed to reflectance estimates, and finally converted to Normalized Difference Vegetation Index (NDVI) values (Ramsey et al., 1997). For comparison to the TM image and the model output, the AVHRR NDVI images were then reprojected to a UTM projection and were subset to an area coincident with the Atchafalaya River basin extent. Adjusted for an expected late summer decrease, the residual NDVI decrease between the pre- and posthurricane image data was the estimate of hurricane impact to the forest. The hurricane impact was defined by differencing the NDVI values obtained before and three days after the hurricane passage (Fig. 2).

A progressive clustering technique was adapted to identify the vegetation classes from the georeferenced TM image (Ramsey et al., 1998; Ramsey & Laine, 1997). Forest classes consisted of mainly hardwoods, cypress–tupelos, and mixed open canopies. A class-stratified random sampling technique referenced to color infrared photography indicated an 85.9% classification accuracy. In a second accuracy assessment, forest type at 175 forest inventory and analysis (FIA) sites within the Atchafalaya basin resulted in an 82.8% classification accuracy (Ramsey et al., 1998). The forest-type distribution was generated with a single date TM image.

![Fig. 3. The composition of (a) hardwoods, (b) cypress–tupelo, and (c) open forest per AVHRR pixel (about 1 km). The forest-type distribution was generated with a single date TM image.](image-url)
al., 1998). At each FIA site, forest types were derived by interpreting aerial photographs and site visits (U. S. Forest Service, 1992).

The proportion of forest type per 1-km² cell was calculated by spatially linking the 25-m classified TM forest map to the 1-km resolution AVHRR NDVI difference image (Ramsey et al., 1998; Fig. 3a–c). Pixels containing more than 15% of developed land, floating vegetation, or water classes were identified and excluded from subsequent analysis. As stated earlier, hurricane impact was defined by differencing the NDVI values obtained before and three days after the hurricane passage whereas the weighted impact for each of the three forest classes was defined by multiplying the impact by the proportion of the target forest class in each pixel (a pixel consisted of about a 1-km² area).

2.1. Wind-field model

The wind-field distribution model estimates the wind speed, direction, and duration for the geographic region affected by the storm. The model uses a spatially distributed, time-integrating method to simulate historic storm winds for a specific hurricane track. By tracking the motion of the storm and modeling its wind distribution at any point in time, wind direction and magnitude maps were created. Cataloging wind characteristics at each point through time (e.g., for each 5-min period) produced a simulation of the tropical cyclone’s history.

There are several simulation studies of hurricane wind fields available in the literature. The more sophisticated ones may require extensive aerial and surface data for analyzing storm development (e.g., Powell, 1982, 1987; Powell, Houston, & Reinhold, 1996; Thompson & Cardone, 1996) and modeling and forecasting the hurricane track (examples in Anthes, 1982; Overland, 1977). Others concentrate on predicting the probability of occurrence and distribution (e.g., Batts, Cordes, Russell, Shaver, & Simiu, 1980). In our application, however, we were interested in assessing the ecological impacts of tropical cyclones without forecasting their movement. In particular, we were interested in a model that could be used for mapping wind fields from historic hurricanes with limited data. To carry out the assessment, we relied upon the fact that despite obvious differences between tropical cyclones (URL: www.aoml.noaa.gov), past research has shown that the basic structure and dynamics of all tropical cyclones are similar including the broad-scale structure of the surface wind field (e.g., Frank, 1977; Kraft, 1961; Miller, 1967; Overland, 1977; Simpson & Riehl, 1981). Following these meteorological studies and work by Boose et al. (1994), we implemented a model of hurricane surface winds that generalizes physical processes and limits the model to landscape-scale analysis. Calibrated with meteorological data, the model provides broad-scale estimates of the tropical-storm wind field (Boose et al., 1994). In essence, we used simple measurements based on Boose et al. (1994) that described the result of the complex set of forces to model the instantaneous tropical cyclone wind-field distribution. We have extended the instantaneous model to a dynamic model to map the duration of winds. The model does not account for local topography, convective scale effects, tornadoes, and geostrophic wind or environmental pressure gradients (Boose et al., 1994). The model estimates the sustained wind speed (1-min average at a 10-m height) within the eye ($V_s$) and outside the eye ($V_{sp}$), using the hurricane position, forward speed and direction, eye diameter, maximum wind speed, wind-profile constant, and surface landcover type (Eqs. (1) and (2), after Boose et al., 1994).

$$V_s = F[V_m - V_f (1 - \sin \theta)] \frac{R}{R_{mv}}$$

(position inside eye)

$$V_{sp} = F[V_m - V_f (1 - \sin \theta)] \left( \frac{R_{mv}}{R} \right)^x$$

(position outside eye)

where: $F=$ reduction of velocity (e.g., 0.8 for land and 1.0 for water; Powell, 1982); $V_m =$ maximum sustained wind velocity on water; $V_f =$ forward velocity of hurricane; $\theta =$ clockwise angle of point $p$ from hurricane forward direction; $R =$ radial distance of $p$ from hurricane center; $R_{mv} =$ radius of hurricane eye (location of maximum winds); $X =$ wind profile constant parameterized for each hurricane ($0.4 \leq X \leq 0.8$; Simpson & Riehl, 1981).

The peak gust velocity ($V_g$) is estimated from the sustained wind velocity (Powell, 1982) as (Eq. (3)):

$$V_g = GV_s$$

where $G =$ gust factor (e.g., 1.12 over water, 1.40 over land).

Sustained wind direction ($D_s$) and peak gust wind direction ($D_g$) are estimated from Eq. (4):

$$D_s = D_g = B - 90 - I$$

where: $B =$ bearing from the hurricane center to a point $P$. $I =$ cross-isobar inflow angle (e.g., 20° for water, 40° for land; Powell et al., 1996).

Though broadly similar in structure, mechanisms and life cycle (Frank, 1977) of each cyclone are unique with different meteorological conditions and therefore with different effective impacts on the landscape (Boose et al., 1994; Simpson & Riehl, 1981). Unique characterization of hurricanes includes information gathered from aerial overflights, satellites, and surface observations. Hurricane Andrew’s location, central pressure, maximum wind speeds, and forward velocity were obtained from the Tropical Prediction Center (TPC) “Best Tracks” information (NOAA, 1993). The wind speeds in the TPC Best Tracks represent the maximum wind in the storm averaged over a 1-min period at 10 m above the surface (Hurricane Specialist J. Franklin of
NOAA-TPC, personal communication). Geographic positions in the TPC Best Tracks data are interpolations on fixed 6-h intervals (e.g., 0000, 0600, ... UTC). The radius of maximum winds (R_{mw}) were obtained from aerial reconnaissance conducted previous to hurricane landfall (acquired by Hurricane Hunters-Keesler Airforce Base). Powell (1987) points out that surface features of the tropical cyclone may differ or be absent at flight level. For instance, eyewall tilt may cause estimates of the R_{mw} derived from flight-level data to be from one to several kilometers inside of the R_{mw} on the surface (Powell et al., 1996). Differences can be corrected with an adequate set of surface and over-flight observations, but these data were not available for Hurricane Andrew’s passage through Louisiana. In consequence, our implementation assumes no eyewall tilt, and therefore, no explicit correction for the surface R_{mw} estimated from flight-level data.

Frictional and wind-profile constants included in the model were approximated by fitting the model predictions to in situ wind speed and direction observations during Hurricane Andrew (Dingler, Hsu, & Foote, 1995). Observations were obtained at a marsh site about 40 km (25 miles) south of the Atchafalaya basin and about 24 km (15 miles) inland from the coast. Wind speeds were recorded with anemometers at 2- and 6-m heights until about 6 h after landfall when the instruments failed (Fig. 4). The 10-min averaged wind speeds at 2- and 6-m heights were first converted to a standard height of 10 m above the surface assuming neutral conditions (Dingler et al., 1995) and then to 1-min averages by multiplying by a constant factor of 1.11 (Powell et al., 1996).

Using the surface observations, an average value for the R_{mw} of 19 nm (35 km approximately), and Eqs. (1) and (2), the model was then parameterized for this anemometer site (Fig. 4). Model parameters were adjusted to produce similar profiles and magnitudes while retaining comparable peak winds speeds at the point of closest approach. A reduction of velocity factor (F) for land of 0.80 and a wind profile constant (X) of 0.80 produced the best modeled reproduction of the anemometer readings of wind speeds (Fig. 4).

Our instantaneous modeled 10-m wind velocity distribution was compared to the wind velocity distribution based on observations analyzed by the NOAA’s Hurricane Research Division (HRD). Along with the best-fit velocity-reduction factor F and wind profile constant X, our wind-field model used the TPC Best Track information for 0600 UTC 26 August 1992. For comparison, we used a constant R_{mw} of 20 nm (37 km approximately) obtained at 0526 UTC and 0724 UTC 26 August 1992 and discarded the observation of 12 nm (22 km approximately) at 0624 UTC because it was inconsistent with the majority of R_{mw} measurements obtained from the aircraft reconnaissance. The wind-field analysis conducted by Dr. M. Powell of HRD-NOAA/AOML used the data obtained from ships, buoys, and C-MAN, Coastal Metar, and aircraft reconnaissance from 0624 UTC 26 August 1992 although the maximum wind speed was taken from a 0522 UTC 26 August 1992 aircraft observation (Hurricane Hunters-Keesler Airforce Base). Both models simulated a 1-min average wind speed at the 10-m level over the ocean excluding land influences. The slight difference in the hurricane eye position is due to differences in times (0600 UTC vs. 0624 UTC) and location data (TPC’s Best Track vs. Hurricane Hunters’ position) used in the two model simulations (Fig. 5).

Our model simulation based on generalized physical processes provided a fairly generalized wind-field distribution with the highest winds speeds (115 kts = 213 km/h) located to the right of the projected northwest storm track and the lowest wind speeds to the southwest. The less generalized and more sophisticated HRD wind-field analysis places the region of highest winds speeds (101 kts = 187 km/h approximately) slightly southeast of our model projected highest winds speeds (Fig. 5). Outside the immediate vicinity of the eye, the wind-speed and direction-distribution simulations of the two models, however, generally agreed and even though site-specific differences may have occurred, we believe that, on average, our model provided an adequate estimate of the actual wind-field integrated over the approximate 1-km spatial scale used in this analysis. Consequently, the model provided an adequate simulation of the wind field for landscape scale analysis and was used to simulate the wind-field distributions having an impact on the Atchafalaya River basin.

Inputs to the model included TPC Best Track data (central track location, storm forward velocity and direction, maximum wind speed) every 6 h, the land and water spatial distribution, spatial scale for the output maps, the prediction...
The last recorded R_{mw} of 211 nm (39 km approximately) obtained from the final aircraft reconnaissance at 1102 UTC 26 August 1992 (near landfall) was used in all simulations. Simulations were carried out at 5-min increments by linear interpolation of TPC Best Track data.

The continuous wind speeds generated by using the hurricane model were classified into 13 wind-speed intervals (WSIs) with equal class intervals of 5-mph increments. These intervals included tropical depression (<39 mph), tropical storm (39–73 mph), and Category I (74–95 mph) hurricane wind speed. Aggregating the wind speed into intervals simplified the analysis and helped account for differences between the actual and predicted wind speeds. Less than 5% of the study area in each forest class (e.g., 1.6% in hardwoods, 1.7% in cypress–tupelo, and 1.9% in open canopy forest) was exposed to wind speeds exceeding 91 mph that lasted longer than 5 min. Therefore, in order to stabilize the regression model, data with wind speeds exceeding 91 mph were excluded leaving 12 WSIs (from 31 to 35 mph to 86 to 90 mph) to be included in the analysis.

In our wind-field distribution model, empirically estimated peak gust speeds are proportional to the sustained wind speed and therefore offered no additional information. Duration and wind steadiness (Powell, Houston, & Ares, 1995) are both important to assessing damage. Wind steadiness, as a measure of the extent of wind direction shifts during the passage of the hurricane, however, was not examined in this study. WSI durations (WSIDs) were determined by tracking and summing the time (in 5-min increments) that each WSI affected each landcover cell (1-km2 area) over the total time of the impact of Hurricane Andrew on the Atchafalaya River basin (from 0000 UTC 25 August to 0000 UTC 27 August 1992).

2.2. Linking WSID, impact, and forest type

WSID, impact, and forest composition were entered into a single, georeferenced, spatial database (PCI Geomatics, 1998). Visual display of the WSIs and the associated WSIDs indicated higher wind speeds in the southern basin (Fig. 1). Because hardwood forests dominate the northern basin and cypress–tupelo and open forests dominate the central and southern basin, the progressive movement of the higher wind speeds to the south suggests that the cypress–tupelo, and to some extent the open forests, were more likely to be affected by higher wind speeds than the hardwoods forests.

2.2.1. Regression model development

Our next step used multiple regression analysis to determine if forest type and impact magnitude were linked to wind speed and duration. In the full model, 12 WSIDs were used as regressor variables. As a first step in selecting the most predictive variables to explain the weighted impact variance and to diminish the possible influences of multicollinearity, a stepwise linear regression analysis (Draper & Smith, 1981; Neter, Wasserman, & Kutner, 1990; SAS, 1989) was conducted for each of the three vegetation classes. Even if selected by the stepwise regression analysis, WSIDs with estimated negative parameters were excluded from the analysis.
The stepwise regression analysis resulted in an optimum model containing the most significant predictive regressors (WSIDs) for each of the forest types. Though the linear model and its explanatory variables were statistically significant ($P$ value < .01), the total variations of each of the vegetation types explained by the WSIDs were not substantially high. The $R^2$ values were .63 for cypress–tupelo, .67 for hardwoods, and .34 for open-canopy forests.

Plots of vegetation impact against WSID indicated a nonlinear relationship. The model with a square root transformation on vegetation impact was a better predictor of the impact than was a linear one. Therefore, a square root transformation (weighted impact variable) was used in the stepwise regression analysis to isolate the WSIDs that best explained the total variability of each forest-type impact. Even though the square of the individual wind velocity is directly proportional to the wind force, regression analyses using the squared wind velocities did not produce higher $R^2$ values. The square root transformation of the vegetation impact, however, implicitly indicated that the weighted impact was related to the square of the aggregated wind velocity, and thereby, to the force of the wind exerted on the trees. The model was of the form (Eq. (5)),

$$[(\text{Percentage of forest type per pixel}) \times (\text{impact within the pixel})]^{1/2} = C_1D_1 + C_2D_2 + \cdots + C_{12}D_{12} + \text{Error term} \quad (5)$$

where $D_1$ to $D_{12}$ are the WSIDs and $C_1$ to $C_{12}$ are their respective coefficients (weighted impact per duration). The forest-type weighting of the response variable was calculated by overlaying the impact 1-km map on the 25-m classification map. A 30% impact pixel containing 40% hardwoods would be assigned a response of 12% impacted (affected) hardwood in the regression model. An assumption was made that if WSID equaled zero, there would be no impact on the vegetation. Thus, regression models with zero intercepts were used in the analysis (Freund & Littell, 1991).

### 2.2.2. Model parameter independence

The large number of similar independent variables (WSIDs) suggested the possibility of multicollinearity in the regression model. As a first check on the existence of multicollinearity, correlation coefficients and their significance were examined within a correlation matrix. If high collinearity existed between any or all of the independent variables, the regression may have produced coefficients (model parameters) that could not be used to judge the importance of any one independent variable (WSID) in explaining the variance of the dependent variable (weighted impact). In such a case, the usefulness of the model would be to predict the distribution of the dependent variable and not to explain the contribution of any single WSID in the regression. Statistical tests were carried out to determine the presence or absence of multicollinearity. In case of an inconclusive result, the strength of collinearity was examined by its magnitude as well as its autocorrelation effect in the error term.

To determine the existence of significant correlations among the independent variables, a test of multicollinearity was also used by invoking a variance inflation factor (VIF; $I/(1 - R^2)$) in the (regression) model statement (Neter et al., 1990; SAS, 1989). A VIF value of the overall regression model greater than 10 or any individual VIF of the independent variables greater than the overall VIF value of the model was considered as an indicator of a model with multicollinearity (Freund & Littell, 1991; Neter et al., 1990).

The Durbin–Watson test for autocorrelation was used to determine the first-order serial correlation in the error term. The presence or absence of autocorrelation was decided on the basis of whether or not the sample Durbin–Watson $D$ statistic was outside the prescribed lower and upper bounds ($d_L$ and $d_U$) by using the Durbin–Watson table for the test of autocorrelation (Montgomery & Peck, 1992). Unfortunately, neither the exact table values nor the algorithms to determine $P$ values for large samples ($n > 100$) with independent variables more than five were available. An approximate test was carried out at .01 level of significance using the table value for sample size of 100 and five independent variables.

In case of inconclusive test results, residual plots against the sequential period indicator (sample size) were examined for any systematic trends or cyclic patterns indicating an autocorrelation effect (SAS, 1989). Finally, the estimated value of the first-order autocorrelation itself was judged. A value of this estimate around .5 was considered to indicate a moderate autocorrelation in the model (Freund & Littell, 1991).

### 3. Results

The full model used to estimate the weighted impact on each of the forest types consisted of 12 WSIDs, ranging from a high tropical depression of 31–35 mph wind to a Category I hurricane with wind speed up to 90 mph. Using this model, $R^2$ values of .85, .87, and .74 were obtained for the forest types hardwood, cypress–tupelo, and open canopy, respectively. The full model showed that some of the independent variables were insignificant ($P > .05$), suggesting that keeping these variables in the model would not contribute to higher explanation of the total variance of the affected forest types. Therefore, a stepwise regression analysis was applied to best describe each vegetation impact with the least number of WSIDs as regression variables.

The stepwise model for hardwood impact had the least number of regressors (Table 1). The analysis chose WSIDs of 31–35, 36–40, and 46–50 mph to be the most significant positively correlated variables and explained 84% of the total variance of the affected hardwood forest. For
The correlation between 41–45 and 46–50 mph WSIDs was extremely high ($r = .99$). To be consistent with the full model (Fig. 6), the WSID related to the 41–45 mph was substituted for the 46–50 mph WSID in the restricted model. Even with the substitution, the explanation of the hardwood impact variance remained at 84%. The WSIDs of 31–35, 36–40, 41–45, 51–55, 66–70, 71–75, and 76–80 mph had the most significant positive relationship with the affected cypress–tupelo forest. These WSIDs explained 87% of the total variance. In the case of open-canopy forest, the WSIDs of 31–35, 36–40, 41–45, 51–55, 71–75, 76–80, and 86–90 mph had the most significant positive relationship, explaining 73% of the total variance (Table 1).

### 3.1. Model parameter independence

In all forest types, simple correlations between the durations of the adjacent WSIs ranged from a low of around .05 (31–35 and 36–40 mph) to a high of about .99 (between 41–45 and 46–50 mph), but most often were around .50, indicating low to moderate correlations between the durations of adjacent WSIs. Because of the high correlation between the durations of WSIs at 41–45 and 46–50 mph, stepwise regression analysis selected only one WSID between these two in the restricted model. However, except for hardwoods, the selection of 41–45 mph WSID by the stepwise analysis was consistent (significant positive coefficient) with the full model. In each of the forest-type regressions (Table 1), the overall VIF ($< 10$) was larger than the individual VIF of the WSIDs, also suggesting no multicollinearity among the selected independent variables (Freund & Littell, 1991; Neter et al., 1990). The observed $D$ values of .74, .72, and .84 for hardwood, cypress–tupelo, and open-canopy forests, respectively, generated by the Durbin–Watson test for autocorrelation for the full model and similar values from the model prescribed by the stepwise analysis (see Table 1) were lower than the approximate table value for the lower bound of $D$ statistic at .01 level of significance (1.44 for a large sample, $n = 100$). The observed lower $D$ values suggested the existence of positive first-order autocorrelation (Montgomery & Peck, 1992). The values of the first-order autocorrelation for the full model, however, were low to moderate (.63 for hardwood, .64 for cypress–tupelo, and .58 for open canopy) (Freund & Littell, 1991) indicating moderate autocorrelation. Furthermore, the residual plots against the sequential period indicator showed no obvious trend or cyclic pattern. There was no substantial change in observed $D$ values, values of the first-order autocorrelation (Table 1), and the residual plots for the full as well as models prescribed by the stepwise regression.

For each forest type, in the final (restricted) model the multicollinearity and autocorrelation tests suggested no multicollinearity and only moderate autocorrelation existed between the predictor variables and their residuals. Consequently, model wind speeds and associated durations were considered to be fairly independent estimators of the weighted impact, and thus, the importance of each model WSID in the regression could be estimated by the associated parameter magnitude.

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**Table 1**

Regression analysis of impacted vegetation on different duration of wind speeds

<table>
<thead>
<tr>
<th>Vegetation</th>
<th>Wind speed selected by stepwise regression&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Estimated coefficient (weighted impact/hour)</th>
<th>Model $R^2$</th>
<th>P value</th>
<th>VIF&lt;sup&gt;b&lt;/sup&gt;</th>
<th>First-order autocorrelation</th>
<th>$D$ statistic&lt;sup&gt;c&lt;/sup&gt;</th>
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<sup>a</sup> Variables yielding negative and or insignificant ($P > .05$) coefficient are excluded.

<sup>b</sup> Variance inflation factor.

<sup>c</sup> Durbin–Watson $D$ statistics.
3.2. Wind speed and duration

Using the regression model parameter magnitudes as guides, a comparison was performed between the importance of the WSI and WSID and the weighted impact variable in each forest-type regression (Table 1). Differentiations between parameter magnitudes were shown within each regression and between regressions (Fig. 6). Durations of tropical-depression to tropical-storm winds (peaks between 31 and 45 mph) were the highest explanatory variables for hardwoods impact. A slight increase in importance was also associated with WSID of 86–90 mph of the Category I hurricane wind speed. The model parameter, however, associated with this WSID (i.e., the 86–90 mph) was not significant at the .05 level. WSIDs associated with cypress–tupelo impact were important at tropical storm, and at near and above hurricane force wind speeds. Impacts on open forest had a distribution pattern similar to cypress–tupelo forests.

4. Discussion

In associating impact and WSID, both the full model and the restricted model (selected by stepwise regression) yielded similar results in all forest-type regression analyses. Therefore, subsequent discussion addressing the restricted model results is also directly pertinent to results obtained with the full model.

Significant and high associations were found between the weighted impact and modeled hurricane WSIs and WSIDs. Both the full model, containing all 12 WSIDs, and the restricted model, containing a subset of the 12 WSIDs, were significant. Even with the restricted model, explanation percentages associated with hardwood and cypress–tupelo forests were 84% and 87%, respectively, and 73% for the open-mixed forests (Table 1).

Comparison of parameters associated with each forest-type regression model showed hardwood forests were differentially affected at lower wind speeds and cypress–tupelo and open forests mainly at higher wind speeds. This comparison explicitly answered the paradox: cypress–tupelo could have been less susceptible to wind damage than hardwoods but still have had an overall higher impact from the hurricane passage. Two main impact peaks in the cypress–tupelo and open forests related to tropical-storm and near and above hurricane-force winds seemed to imply two types of forest response to hurricane impact.

The best and clearest evidence was related to the differences in inland extent associated with the different WSIs. As illustrated by the wind-field model (Fig. 1), there was a progressive movement of higher wind speeds to the southern...
basin in response to the lessened inland extent as the wind speed increased. The higher wind speeds did not extend as far inland. Added to the prevalent distribution of cypress–tupelo and open forests in the central and southern basin, those forests were more likely to experience higher wind speeds than the more northern hardwood forests. This association, in itself, seems to answer the paradox of cypress–tupelo sustaining more severe impacts even though less susceptible to wind damage than hardwoods.

Questions remain, however. First, why were cypress–tupelo and open forests related to two main peaks? Second, how could the extreme impacts to the dominantly cypress–tupelo forest in the extreme southeast of the basin be explained. Third, could the importance of duration be decoupled from wind speed?

In an effort to answer these questions, we examined the covariance of wind speed and weighted mean impact for different WSIDs (Fig. 7a–c). Weighted mean impact for each WSID (e.g., >0 to <1, 1 to <2 h, 2 to <3 h) were obtained by summing the weighted impact (as discussed earlier) within these WSIDs and dividing by the sum of weights (forest-type proportions). Plots illustrate those WSIDs that were most prominent in areas of higher impacts. Durations of less than 1 h at wind speeds higher than about 56–60 mph covered all forest areas showing little relation to regression peaks (Fig. 6). WSIDs of 2 to 3 h were linked to moderate and nearly uniform weighted mean impacts associated with all forest types from WSIs of about 41–45 mph to about 71–75 mph. At 86–90 mph, prominent peaks in this WSID were associated with cypress–tupelo and open forest and were linked to a small (13 km²) area near the southeast corner of the basin. The cypress–tupelo regression coefficient was not significant at this WSI; however, the coefficient of open forest was high and significant. Weighted mean impact magnitudes within the 1 to 2 h WSID associated with all forest types were moderate and near constant up to 51–55 mph. As in the 2- to 3-h WSID, this region of moderate and near constant weighted mean impacts may be associated with the average impact typifying each forest type. In cypress–tupelos the average impact seemed to be associated with widespread defoliation and some limb loss, while in hardwoods the average impact additionally included downed trees. Above 51–55 mph, the weighted mean impacts dip in magnitude until about 66–70 mph where they again increase to a high prominent peak at 76–80 mph associated with hardwood and cypress–tupelo forests, and 71–75 mph associated with open forest. These highly prominent peaks in the 1 to 2 h WSIDs were linked to an intensely impacted area in the southeast corner of the basin dominated by cypress–tupelo forests but also including some scattered hardwood and open forest stands. No wind speeds exceeding 71–75 mph lasted more than 3 h in any part of the study area. The plots of WSID and mean impact of each forest type also corroborate the results of the multiple regression model illustrated in Fig. 6.

Fig. 7. WSID, forest impacts, and wind-speed magnitudes. The >1 to 3 h WSIDs are associated with broadly distributed impacts to the (a) hardwood forests, (b) cypress–tupelo, and (c) open forests at the tropical-depression to tropical-storm wind speeds, and to the intense impacts associated with cypress–tupelo and open forests at wind speeds slightly below and in excess of Category I hurricane-force wind speeds. More detailed (every half hour) WSIDs with respect to their spatial distribution are shown in Fig. 8.
The juxtaposition of WSI and WSID help explain the dependency of forest type and impact on duration at key WSIIs. To illustrate the spatial association between WSI and forest type, the 36–40, 41–45, 51–55, and 71–75 mph durations were mapped (Fig. 8a–c). The distribution of 76–80 mph duration was similar to the 71–75 mph duration distribution but restricted in areal coverage. The longest durations of 36–40 mph wind speeds were associated with the higher impacted hardwood areas in the northern basin and the hardwood forest corridor along the southeast of the basin (Figs. 2, 3, and 8). The highest durations of 41–45 mph wind speeds were associated with the impacted north-central cypress–tupelo and open forests while somewhat lower durations within this WSI were also associated with the impacted hardwood forest in the northeast of the basin (Figs. 2, 3, and 8). The highest 51–55 WSIIs were linked spatially to cypress–tupelo and open forests somewhat lower in the basin than the 41–45 mph. The highest 71–75 WSIIs were primarily associated with the most severe cypress–tupelo impact areas, especially the area in the southeast corner where durations over 2 h occurred.

The spatial associations suggested that hardwoods were for the most part extensively damaged by the long duration high-tropical-depression to tropical-storm winds. The existence of two significant and prominent WSI peaks related to cypress–tupelo impacts may also be partly related to the duration. Relatively long-duration hurricane winds were centered on the severely affected cypress–tupelo forest in the extreme southeast corner of the basin. The tropical-storm WSI important in explaining cypress–tupelo impacts incorporated WSIIs above 3 h. These WSIIs seemed linked primarily to less severe impacts. One explanation for the two significant WSI peaks is that tropical-storm winds associated with moderate-to-high WSIIs were strong enough to cause broad low-to-moderate impact in the cypress–tupelo forests (i.e., defoliation and some limb loss). In effect, this impact may have lowered their resistance to the higher speed winds, and in consequence, lowered their susceptibility to more severe impacts. The longer duration and higher WSI hurricane winds may have overcome this threshold, resulting in the severe impacts associated with downed cypress–tupelo trees in the southeast of the basin.

Alteration or differences in architecture may also help explain why the cypress–tupelo and hardwood impacts were related to different wind speeds. Each forest architecture responds differently to wind. Different responses to wind damage have been shown to be at least partly due to species-specific features (e.g., leaf and leaf clusters) that differentially reduce wind drag as wind speed increases (Vogel, 1993). Cypress–tupelo’s architecture or the transformed architecture in response to the wind may lessen the overall resistance of the tree to impact, while hardwoods may lose their leaves less easily. In consequence, the hardwoods may retain higher resistance to the wind and may be more prone to severe impact at lower wind speeds than are the cypress–tupelo trees. Cypress–tupelo trees finally would have succumbed to the increased wind speeds by totally or partly defoliating and further lowering their resistance. Increasingly, these higher and longer duration winds were only affecting predominately cypress–tupelo forests in the southern basin.

There was a tendency for the WSI to increase as the model parameter increased for hardwood and cypress–tupelo forests. In fact, it seems likely that the higher duration of near and above hurricane wind speeds was responsible, at least partly, for the concentrated impacts in the southeast corner of the basin. The association between wind duration and speed and forest impact is certainly more complicated than just a simple increase in duration and speed accounting for an increase in impact. The selective importance of the model parameters, and thus the WSIIs, indicate more complicated interactions. As mentioned earlier, wind steadiness can be another important factor in explaining the distribution of hurricane impacts (Powell et al., 1995) to the forest. Interestingly, the higher impacts along the river corridors and mostly within the northern basin occurred near the projected radius of the maximum wind at about 21 nm (39 km). This area would be expected to experience large wind shifts (Boose et al., 1994) resulting in lowered wind steadiness (Powell et al., 1995) and therefore the possibility of more severe impacts. Wind steadiness will be incorporated in future work performed with a refined wind-field distribution model. The results of this study, however, strongly suggest that the simulated wind field explains the higher impact associated with cypress–tupelo versus hardwoods, implies a normally positive relationship between increasing duration and impact, and may even support a differential response of the hardwoods and cypress–tupelos to the wind.

5. Conclusions

The goal of this study was to determine whether the hurricane wind-field distribution could explain the spatial distribution of forest damage. To accomplish this comparison, forest-type distribution derived from TM image data, hurricane-impact distribution estimated from a suite of transformed AVHRR images, and wind speeds at set intervals from 31 to 90 mph with associated durations generated with a derived wind-field model were considered. A further goal was to uncover why — as was shown in previous analyses of Hurricane Andrew’s impact — the cypress–tupelo forests generally were more severely affected than the hardwood forests, even though cypress–tupelos were less susceptible to wind damage.

The wind-field distribution model satisfactorily explained the WSI and WSID distributions throughout the forested area surrounding the Atchafalaya River basin during the passage of Hurricane Andrew. This contention was supported by the fact that the impact estimate weighted by forest-type proportion was highly related to the WSID.
categorized by WSI. Explanations of the weighted impacts were 84%, 87%, and 73%, respectively, for hardwood, cypress–tupelo, and open forests.

Fig. 8. Overlays of wind-speed durations at the WSIs of (a) 36–40 mph, (b) 41–45 mph, (c) 51–55 mph, and (d) 71–75 mph. The higher durations for the 36–40 mph WSI are concentrated in the north and along the river corridor towards the south. Note the general similarities especially in the WSIDs associated with the 36–40 and 41–45 mph WSIs and the impact pattern (Fig. 2), including the west-central to northeast high durations and impacts and the low WSIDs in the northwest hardwood forests and the south central cypress–tupelo forests. The higher WSIDs associated with the 51–55 mph WSI extend further to the south while the lower WSIDs cover the south-central basin. The highest WSIDs associated with the 71–75 and 76–80 mph (not shown) WSI are located in the southeast area of the basin.

One critical piece of evidence provided by the wind-field model simulation was that higher WSIs associated with higher WSIDs tended to be located more in the southern
than the northern basin. Combined with the spatial distribution of cypress–tupelos in the central and southern basin and hardwoods in the northern basin, this spatially modulated wind field suggested differential impact of the cypress–tupelo forests by higher wind speeds than those affecting the hardwood forests.

The relative independence of the regression model parameters allowed confirmation of higher wind speeds affecting the open and cypress–tupelo forests more than hardwood forests and also suggested definition of the response of the different forest types to increasing wind speeds. Illustrated with the model parameter magnitudes, hardwood impacts were mainly a result of tropical-depression to tropical-storm wind speeds while cypress–tupelo impacts were more related to tropical-storm winds and wind speeds near and above Category I hurricane force. Open forests (a mixture of willows and cypress–tupelo) were affected somewhat similarly to cypress–tupelo.

Wind speed and duration were combined in the model. This combination simulated by the wind-field model led to a robust prediction of the impact severity generated with the suite of transformed AVHRR data and classified TM data. Decoupling of the duration and speed, however, was not fully realized, even though evidence hinted that impact severity was positively related to higher durations at critical wind speeds. Graphic overlays of durations at wind speeds that were important in the empirical model also illustrated the positive relationship between duration and impact. In the WSIs important in explaining the severity of hardwood impact, higher WSIDs were concentrated in the northern basin dominated by hardwoods. The extreme impacts associated with the cypress–tupelo forests in the southeast corner of the basin also intersected the highest durations of the critical wind speeds.

In total, the wind-field model not only is a valid simulator of wind speed and duration at the landscape level, but also combined with independent measures of impact severity and forest-type distributions, it provided information useful in answering the paradox uncovered in earlier studies. Overall, the more damage-resistant cypress–tupelo were subjected to higher wind speeds than were the hardwoods, which resulted in the higher impacts to cypress–tupelo in comparison to hardwoods. Not only was the information determined from integrating the TM, AVHRR, and wind-speed model output data sources useful in uncovering the general linkages between impact severity, forest type, and wind speed and duration, but the combined model also showed a probable disparity in responses of the hardwoods and cypress–tupelo to wind.

Finally, this study corroborated and extended earlier studies that indicated preferential resistance of cypress–tupelo to hurricane damage. Only by spatially superimposing impact severity, forest type, and wind speed and duration, were we able to examine this preferential resistance in the context of the Hurricane Andrew’s impacts in the Atchafalaya River basin.

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