Journal of Coastal Research	22	5	1025–1034	West Palm Beach, Florida	September 2006

A Postlandfall Hurricane Classification System for the United States

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ABSTRACT

SENKBEIL, J.C. and SHERIDAN, S.C., 2006. A postlandfall hurricane classification system for the United States. *Journal of Coastal Research,* 22(5), 1025–1034. West Palm Beach (Florida), ISSN 0749-0208.

The Saffir–Simpson scale is useful for evaluating maximum sustained hurricane winds and storm surge over open water in the prelandfall window, but it fails to accurately account for the observed impacts over land. A new postlandfall hurricane classification system (HCS) is proposed that redistributes the categorization of hurricanes into types according to six variables: open water storm surge, rainfall, duration of hurricane force winds, maximum sustained winds, gust score, and minimum central pressure. Hurricanes are assigned values for each variable and summed for a numerical 0–100 grade. Principal component analysis and hierarchical cluster analysis are also performed on the six variables to categorize U.S. land-falling hurricanes into storm types. A total of 41 land-falling hurricanes in the United States since 1960 have been analyzed. The summation scores show many hurricanes that are of strength similar to their Saffir–Simpson classifications, with several notable exceptions. The cluster analysis identifies five different hurricane types. These types can be arranged to identify hurricane strength and structure more effectively than the Saffir–Simpson scale. In focusing on the observed storm intensity over land and the resulting human experience, the HCS allows a way to compare hurricane impacts across different periods.

ADDITIONAL INDEX WORDS: *Hurricanes, classification systems, atmospheric hazards.*

INTRODUCTION

Hurricanes are a persistent and recurring hazard in the United States because of continued coastal population growth. Approximately five land-falling hurricanes affect the United States every 3 years (JARRELL *et al.,* 2001). An average of two major hurricanes (Saffir–Simpson category 3 and higher) make landfall in the United States every 3 years. Over the last 50 years, coastal population growth and increased property development have led to an increase in monetary damage from hurricanes, even as hurricane fatalities have significantly decreased because of improvements in warning technology, evacuation procedures, and hurricane education and mitigation (JARRELL *et al.,* 2001). While the potential loss of life is always a concern, the increasing amount of property destruction in the United States implicitly suggests a shift in catastrophic emphasis from fatality prevention to one of safeguarding coastal property interests. Furthermore, the vast majority of the human population experiencing the hurricane does so outside of the coastal zone. Therefore, a system or scale is needed to reflect the changing emphasis of hurricane damage. This article evaluates the catastrophic nature of U.S. land-falling hurricanes by evaluating the meteorological variables of 41 hurricanes from 1960 to 2004. A new scale, the Hurricane Classification System (HCS), is proposed with the dual purpose of assessing property damage potential and human injury potential based on the observed characteristics of past hurricanes.

The Saffir–Simpson (SS) Scale was created in the early 1970s in the aftermath of powerful Hurricane *Camille*[1] (SIMPSON, 1974). A need was recognized for a public awareness scale so that people could understand the relative intensity of hurricanes and thus decide whether to evacuate. The SS is widely acknowledged and easily understood by the public in warning situations. Its purpose is invaluable in the prelandfall window; however, the SS scale does not accurately account for the total damage in the postlandfall period. There is also no official reanalysis rating after a hurricane that verifies whether the storm's intensity matched its prelandfall SS classification, although in the 1990s the HURDAT project from the Hurricane Research Division of the Atlantic Oceanographic Marine Laboratory (HURDAT, 2005) began to reanalyze the intensities of past storms. Storm intensity on the SS is validated by using observations from affected anemometers and tide gauges at landfall or from the last aircraft reconnaissance measurement before landfall. Frequently, the locations of anemometers and tide gauges do not correspond to the zone of highest winds and surge. If a hurricane is thought to be of different intensity than its SS rating, a reanalysis may be performed after landfall, with *Andrew* (1992) being the prime example.

The reclassification of Hurricane *Andrew* (1992) as a cate-

DOI: 10.2112/05-0532.1 received 24 June 2005; accepted in revision 19 January 2006.

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[1] Hurricane names are italicized in this text.

Table 1. *Score thresholds for the six components of the Hurricane Classification System.*

Central Pressure (mbar)		Sustained Winds (km/h)		Gust (km/h)		Duration (h)		Surge (m)		Precipitation (cm)	
Threshold	Score	Threshold	Score	Threshold	Score	Threshold	Score	Threshold	Score	Threshold	Score
900	30	274	25	322	5	12	20	6.10	15	55.9	10
905	28	258	22	290	4	11	18	5.49	13	50.8	9
910	26	242	19	258	3	10	16	4.88	11	45.7	8
915	24	225	16	225	2	9	14	4.27	9	40.6	7
920	22	209	13	193	1	8	12	3.66	7	35.6	6
925	20	193	10	161	0	7	10	3.05	5	30.5	5
930	18	177	7			6	8	2.44	3	25.4	4
935	16	161	4			5	6	1.83	1	20.3	3
940	14	145	1			4	4	1.52	0	15.2	2
945	12	137	0			3	2			10.2	1
950	10					2	0			5.1	0
955	8										
960	6										
965	4										
970	2										
975	0										

gory 5 (National Hurricane Center Archives, 2004) has raised issues regarding the observed measurement of hurricane intensity. Other hurricanes might be reclassified were a systematic reanalysis to be performed. This knowledge is important for the public and for local governments because the SS rating is crucial for evacuation and preparation decisions. People need to understand the severity of the storm postlandfall to know if their evacuation or preparation decisions were warranted based on the observed damage at their individual locales. If a postlandfall scale rated hurricanes on the regional level and for point locations, the public could then better assess evacuation decisions in the future.

Recent evacuations (*Opal* [1995], *Georges* [1998], *Floyd* [1999]) have resulted in scenarios where the population exceeds the road capacity to evacuate it (Urbina and Wolshon, 2003). This creates significant traffic problems and results in thousands of disgruntled citizens attempting to move to safety. While contraflow traffic designs, in which both sides of a highway have traffic moving inland, have recently been implemented to speed evacuation, the congestion and hassle remains a problem that has improved little since the early 1990s because of continued coastal population growth (Gross, 1991). Evacuation congestion is further magnified if a hurricane deviates from its forecasted track, or if its forward speed increases. When possible, it is more convenient to find secure shelter or to secure a well built and elevated home instead of getting mired in evacuation traffic. If a postlandfall scale rated hurricanes on the regional level and for point locations, the public could then better assess voluntary evacuation decisions in the future.

The SS is based upon two variables, maximum sustained winds and storm surge. Rating a hurricane according to these two variables does not adequately convey the amount of total damage observed. The observed sustained winds and gusts over land are much lower than the winds associated with the SS categories, which are based on open-water situations (Sparks, 2003). Compounding this observation is that many people in the affected area do not see the most severe section of the hurricane and do not observe sustained winds above hurricane force. The present focus upon the SS 1–5 rating implicitly suggests homogenous winds throughout the hurricane. While people may understand this simple numerical rating, they may fail to understand that those conditions will only occur over a small area with most of the affected region seeing less extreme conditions. Furthermore, while relevant to property destruction, the use of the surge component of the SS is not as applicable to human life in today's hurricanes, because the coastal zone and surge-prone areas are largely evacuated for major hurricanes. From the human perspective, the amount of precipitation and the duration of hurricane force winds are more relevant. A postlandfall scale that incorporates both the human experience and the potential destruction of property and infrastructure would aid the research, planning, and disaster mitigation communities by providing a more comprehensive understanding.

It is not the attempt of this research to replace the SS, but instead to fill a void in postlandfall analysis. This paper proposes the use of a HCS, which is designed to group hurricanes into one of several types. The HCS provides a clearer picture of hurricane intensity than prelandfall warning scales. The HCS accounts for maximum sustained winds and storm surge similar to the SS scale, and adds mean precipitation, the duration of hurricane force winds, a gust score, and air pressure to categorize hurricanes into types. These hurricanes are assessed via two means. First, these six variables are weighted, and each storm is assigned a value on a linear scale for each variable. The maximum total sum across all variables is 100 points (Table 1). Next, a cluster analysis is performed on the hurricanes. Principal components analysis (PCA) is first applied to the six variables listed previously to eliminate multicollinearity as well as any implicit assumptions about which variables are most important. The result is a classification system that succinctly defines and groups Atlantic Basin hurricanes affecting the United States from 1960 to 2004 (Figure 1) into five observed hurricane types.

This article continues by next examining the differences between the SS and hurricane intensity scales in other countries. It then addresses the methodologies of studies previ-

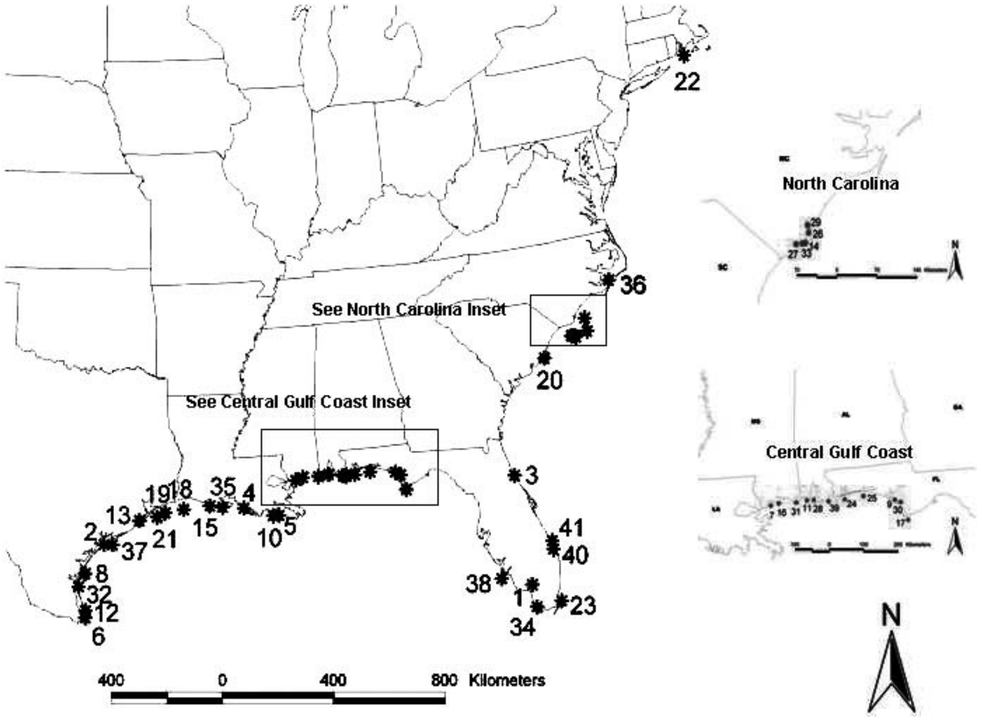

Figure 1. Landfall locations of U.S. Atlantic Basin hurricanes 1960–2004. Hurricane numbers correspond with the numbers in Table 3.

ously proposing refinements and alterations to the SS scale. The methodology is then presented, followed by a presentation and discussion of the results of the HCS categorization, inclusive of comparisons with the present-day SS classifications.

WARNING SCALES WORLDWIDE

Scales for measuring hurricane or typhoon intensity are used in the Atlantic Basin, Australia, Japan, the Pacific Basin, and the Indian Basin. All of these warning scales are prelandfall, although some use variables that are incorporated into the HCS for postlandfall analysis. The scales differ slightly in categorization methodology according to regional impacts, but all are relatively similar in structure (Table 2). Commonly these scales have a numerical or categorical rating system similar to the SS.

The primary difference between the SS and international scales is the measurement of sustained winds. Most international scales use a 10-minute mean wind speed for sustained winds whereas the SS uses a 1-minute mean. The 1-minute mean is unusual in that it is not a value that has ever been measured by an official reporting station in the

Table 2. *Regional warning scales and threshold wind values (km/h).*

Atlantic Basin	Wind	Australia	Wind	India	Wind
Depression	<61	Depression	<61	Depression	27–48
Tropical storm	62–118	Tropical cyclone gale force	62–89	Deep depression	49–61
Hurricane I	119–153	Cyclone I	G* < 126	Cyclonic storm	62–89
Hurricane II	154–177	Cyclone II	G < 171	Severe cyclonic storm	90–118
Hurricane III	178–209	Cyclone III	G < 225	Severe cyclonic storm hurricane core	>119
Hurricane IV	210–250	Cyclone IV	G < 280		
Hurricane V	>251	Cyclone V	G > 281		

Mauritius	Wind	Bangladesh and Pakistan	Wind	Hong Kong	Wind
Depression	G < 85	Depression	34–48	Depression	<61
Moderate tropical storm	G 87–118	Deep depression	49–61	Tropical storm	62–89
Severe tropical storm	G 119–158	Cyclonic storm	62–89	Severe tropical storm	90–118
Tropical cyclone	G 159–222	Severe cyclonic storm	90–118	Typhoon	>119
Intense tropical cyclone	G 223–287	Severe cyclonic storm hurricane core	>119		

G = Gust values; all others are sustained winds.
Source: Australian Bureau of Meteorology Research Centre, 2005.

United States (Sparks, 2003). It is estimated that 1-minute mean wind speeds produce values approximately 15% higher (factor 1.148) than 10-minute mean wind speeds (Simiu and Scanlon, 1978). Other differences exist on classification categories and at what intensity hurricane or typhoon level is attained.

Of all the international scales, Japan's is the most divergent from the SS in categorization (See Table 2). Japan names a typhoon when winds of 89 km/h (55 mph) are reached (International Information Institute/Japanese Meteorological Agency, 2005). The scale then escalates from this level, with the highest rating being an extreme or catastrophic typhoon at 193 km/h (120 mph). This corresponds to a category 4 SS hurricane at 222 km/h (138 mph) after using the 15% rule to convert from 10-minute to 1-minute winds. Japan's classification system is presumably structured in this way because typhoons are frequently weakening and transitioning upon approach to Japan. Additionally, Japan is unique in that it also classifies the size of typhoons into large and very large designations, based upon the radius of winds exceeding 47 km/h (29 mph).

Other scales differ from the SS as well. In Australia gusts are used for intensity classification in addition to 10-minute mean winds. This is perhaps a more accurate method of classification when compared with other systems because mean sustained winds can be very complicated to determine over a 10-minute period if there are several gusts and lulls. In Hong Kong and in the Indian Ocean a simpler system is in place. Once a tropical system reaches 119 km/h (74 mph) over a 10-minute mean, it is classified as a typhoon and no further distinction is made. The Republic of Mauritius in the Indian Ocean classifies tropical storms into two divisions, and a storm is not classified as a tropical cyclone (hurricane) until it reaches 158 km/h (98 mph) (Mauritius Meteorological Services, 2005).

The scales used in each country underlie the importance of understanding the complete nature of hurricane damage. Some countries, such as Japan and the Indian Ocean countries, appear to structure their scales with wind speed and precipitation as the major factors. Mauritius has a much higher wind threshold. The United States, the Central Pacific, and Australia share nearly common sustained wind speed classifications, but the scale used by the United States is the only one that overtly mentions storm surge. All are effective for the purpose of warnings and evacuations, but inconsistent for the purpose of assessing the comprehensive postlandfall intensity of a hurricane.

PREVIOUSLY PROPOSED SAFFIR–SIMPSON REVISIONS AND INTENSITY SCALES

The idea of revising or modifying the SS scale has recently been proposed by Balsillie (2000), Bush, Jackson, and Young (2000), and Sallenger (2000). All of these scales are more geological in emphasis with the primary focus on storm surge discrepancies between the SS scale and the actual surge heights. Because slower moving storms tend to have higher surges, the relationship between maximum sustained winds and storm surge does not always conform to the SS.

The Sallenger (2000) scale is designed to assess the impacts of storm surge on Barrier Islands. He divides surge into four impact levels with each level representing an increase in erosion potential. This scale is useful for understanding sediment transport processes and safeguarding coastal interests, but it does not account for hurricane intensity over the mainland.

Bush, Jackson, and Young (2000) proposed the hurricane impact scale (HIS). Its purpose was geared toward coastal communities and property owners both pre- and postlandfall. The HIS is performed postlandfall, and it uses the same variables as the SS while adding a spatial dimension. A 1–5 score is assigned in three categories for maximum storm surge elevation, storm surge spatial extent, and wind speed.

Balsillie (2000) also correlated storm surge with SS categories to amend the SS surge components. He created an erosion damage potential scale using the SS wind and surge components and also added storm tide rise time, as well as average and maximum erosion volume. Again, the scale has practical use for storm surge assessment and coastal planning, but it does not resolve total intensity from more than a surge and wind focus.

Though the Fujita Scale for tornadoes (Fujita, 1971) is the most famous example, there are already classification schemes that evaluate atmospheric hazards postevent. Dolan and Davis (1992) developed a Nor'easter scale for winter storms in the mid-Atlantic. They used storm duration and multiplied it by the square of maximum significant wave height and established five categories for winter storms. Kocin and Uccellini (2004) developed a similar 1–5 scale (NESIS) for snowfall in the northeast.

METHODOLOGY

The hurricane classification system that forms the basis of this research incorporates six variables, as mentioned previously: air pressure, maximum sustained winds, gust score, storm surge, duration, and precipitation. The means of assessing each of these variables is discussed first. These variables are then analyzed collectively via two means. First, a simple addition of the variables' scores was performed, and each hurricane received a score between 0 and 100. Next, a more sophisticated cluster analysis was performed to group hurricanes into categories. The HCS is the result of the interpretation of the cluster analysis. The period of the study includes all land-falling hurricanes from 1960 to 2004. The year 1960 is chosen as the beginning of the period to correspond with advances in satellite technology. To be classified, the eye of the hurricane has to completely make landfall and not just skirt the coast or a barrier island. In the event that a hurricane makes multiple landfalls (*e.g., Andrew* [1992]), the most severe landfall is used for analysis.

Variables

For both components of analysis, six variables are included. The rationale behind the inclusion, the determination of the relative weight, and scoring rubric of each of these variables is discussed in the following sections.

Atmospheric Pressure

The minimum atmospheric pressure is the best absolute measurement of hurricane intensity. For this reason it is weighted at 30% of the 100-point scale (see Table 1). The maximum score of 30 points is associated with a pressure of 900 mbar; only one hurricane that made landfall in the United States, the Labor Day Hurricane of 1935, achieved a lower reading at landfall (HURDAT, 2005). A value of 975 mbar was chosen as the bottom of the scale, because it represents the minimum threshold above which all storms in the record are labeled as hurricanes. As the winds over land are less than the open water, 975 mbar approximates the point where category 1 winds would hypothetically occur over a grassy surface (POWELL *et al.,* 2004).

Maximum Sustained Winds

The maximum sustained winds variable is evaluated similarly to the SS, utilizing 1-min means, because these values are the most readily available. Though positively correlated, the relationship between atmospheric pressure and sustained winds is does not always conform to the SS (*e.g., Charley* [2004] in which the estimated sustained winds suggested much lower pressure than the observed pressure); hence this category is included independently. If a storm affects a remote area, or if available anemometers are outside the most severe wind swath, then the SS rating of maximum sustained winds at landfall is used. The majority of storms have observed measurements confirming values near the SS winds on the immediate coast. In the absence of data, the use of gust factors was considered to reduce the maximum sustained winds over land to hypothetically observed values (POWELL *et al.,* 2004); however, it leads to increased speculation. Gust factors reduce the maximum sustained winds from surface friction according to the characteristics of the land surface. Several hurricanes such as *Celia* (1970) and *Andrew* (1992) were intensifying at landfall, and the use of gust factors to reduce the maximum sustained winds would greatly underestimate the observed winds (NHC, 2004). Observed sustained winds are 25 points with 274 km/h (170 mph) being the maximum value. This value has never been directly observed, though Hurricane *Camille* is believed to have maintained winds of this magnitude over land, with some speculated gusts of over 322 km/h (200 mph) (NHC, 2004). Hurricanes must register winds in excess of 137 km/h (85 mph) to receive the minimum points. The value of 137 km/h is chosen because hurricanes with sustained winds below this threshold are marginal and sometimes difficult to distinguish from tropical storms.

Gust Score

As discussed previously, in some cases maximum sustained winds are not completely representative of the wind characteristics of land-falling hurricanes. Some hurricanes have observed gusts that are much stronger than the maximum sustained winds. For example, Hurricane *Celia* had sustained winds of 201 km/h (125 mph), yet extraordinary gusts of 266 km/h (165 mph) impacted the west side of Corpus Christi, TX, in a narrow swath (NHC, 2004). For this reason, a possible gust score of 5 points is included to account for the damage from isolated high wind gusts. *Camille* is used as the benchmark with 322 km/h representing 5 points. A value of 185 km/h (115 mph) is the minimum gust required for at least 0.5 points because this threshold marks the boundary where major structural damage begins to occur on the SS (SIMPSON, 1974).

Storm Surge

Storm surge is a major contributor to coastal property destruction, but it is no longer a major threat to human life in the United States (JARRELL *et al.,* 2001). For this reason its importance is stressed less than it is with the SS. Procedurally, the HCS differs from the SS by ranking the mean of the two highest surge elevations over open water within 161 km (100 miles) of the landfall center. Bays and estuaries frequently have much higher surges because of the complexities of bathymetry and shoreline shape. Hurricanes affecting remote areas are given the same rating as their SS surge classification to be consistent with the maximum sustained winds methodology. *Camille* is again used as the standard, and a surge in excess of 6.1 m (20 ft) receives 15 points. A surge elevation greater than 1.52 m (5 ft) is needed to register on the scale. Anything below that elevation can be achieved in tropical storms and winter storms. Only two hurricanes of those evaluated failed to reach a surge height of 1.52 m.

Storm Duration

The storm duration variable represents the total time that hurricane force winds are experienced on shore. It is a function of the diameter of hurricane force winds divided by the average forward speed in the 18-h landfall period from the six hourly HURDAT (2005) observations. The 18-h period includes the 6 h before landfall and the 12 h during and after landfall to gauge the average forward speed of the storm surrounding the landfall time. Diameter was measured by taking the two farthest points at which hurricane force gusts were observed at landfall from surface observations. In the absence of detailed surface observations, storm diameter was estimated according to the best available text data in the NHC Archives. Hurricanes were treated as circles although it is recognized that several of the weaker SS storms are asymmetrical. The weaker storms generally have a narrow diameter of hurricane force winds, and this variable becomes insignificant unless the storm stalls at landfall. A 20-point value is provided for duration, with 12 h representing the upper threshold. In the event of a stalled storm, 12 h represents a time where all but six hurricanes in the record were downgraded to tropical storms after landfall.

Precipitation

Heavy precipitation can cause significant damage to property and threaten lives with rising floodwaters. Because heavy precipitation typically creates more significant problems inland than along the immediate coast, it represents a significant hazard to the majority of the people experiencing the hurricane. Inland flooding from *Floyd* (1999) claimed over 50 lives, and of the 30 deadliest tropical systems in the period, several caused the majority of their fatalities from inland flooding when the system was downgraded to a tropical storm or depression (JARRELL *et al.,* 2001).

Rating precipitation is difficult because, in comparison to the previously mentioned variables, it varies significantly based on the larger-scale synoptic pattern, forward speed of the storm, and orientation of the storm to the coastline. Also, locations receiving a train effect from feeder bands (where precipitation continues to develop and fall in the same area) can have substantially higher precipitation amounts in the event of a slow-moving hurricane. CERVENY and NEWMAN (2000) found that inner core precipitation accounts for 35% of the total precipitation in hurricanes of varying intensity, whereas weak hurricanes have an inner core percentage of only 25%. Consistent with the methodology utilized for the evaluation of storm surge, precipitation is evaluated via the mean of the two highest measurements within 161 km (100 miles) of the storm center at landfall. This diameter encompasses the majority of a hurricane's precipitation attributed to the hurricane itself and not to external mesoscale factors. A 24-h landfall period is used to evaluate precipitation instead of the 18-h period for duration, because precipitation is often observed before hurricane force winds arrive. The period begins 12 h prior to landfall and ends 12 h after landfall. A mean rainfall total of 56 cm (22 in) is the maximum for all 10 points. This value represents a rainfall rate of 2.34 cm/h or 0.92 in/h. Hurricane *Danny* (1997) is the only storm to exceed this value in 24 h. An amount of 10.2 cm (4 in) is the minimum for at least 1 point. All hurricanes recorded at least 10.2 cm of precipitation.

Cumulative Score

Initial analysis of the hurricane database was performed by summing up the scores of the six variables described above. The weight of each of the six variables is a subjective assessment of the relative importance to the overall hazard a hurricane represents. A hurricane achieving the maximum value in each category would receive 100 points; thus all are evaluated on a 0–100 scale.

Cluster Analysis

While the summation of the variables provides a useful indicator of the relative potency of a hurricane, the uniqueness of hurricanes is such that a linear scale is not entirely appropriate. For this reason, an additional analysis was performed to group the hurricanes into one of several types.

The grouping was performed by a hierarchical cluster analysis of the variables described above. Each hurricane is thus associated with six values, one for each of the variables. While the importance of the inclusion of each of the variables has been described, it is recognized that these variables are collinear. To mitigate this multicollinearity, we reduced the six variables by utilizing nonrotated principal components analysis. Unrotated components are appropriate when the goal is to cluster the resultant components, rather than to interpret them (YARNAL, 1993). Two components with eigenvalues over 1 were retained. The first component largely represented atmospheric pressure and wind variables; the second component reflected precipitation and storm duration. Unlike the original variables, these two components are uncorrelated. Further, the application of principal components analysis removes the assumption about which variables are most important.

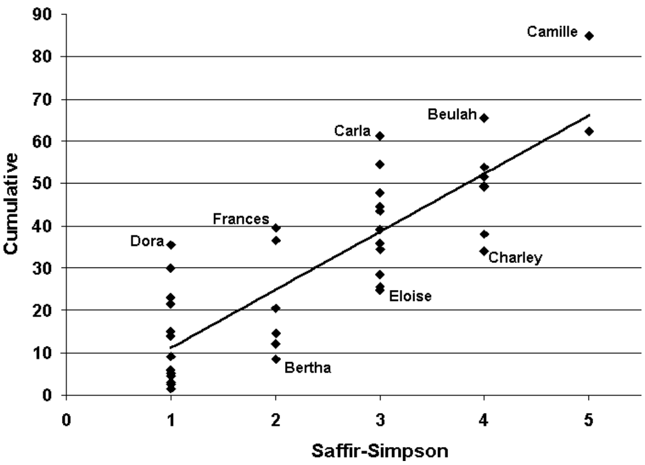

Figure 2. Scatterplot and regression line comparing the SS hurricane categories with cumulative (0–100) rating values. Several Type B HCS hurricanes have higher cumulative scores relative to SS scores, and several type A HCS hurricanes have lower cumulative scores relative to SS scores, with the exception of *Camille.*

We experimented with several different means of clustering, all of which yielded quite similar results. The results of between-groups linkage hierarchical clustering, as performed in SPSS, are presented here. In hierarchical clustering, each of the 41 hurricanes analyzed begins as its own cluster, or "group." The most similar two groups are merged; the process then iterates until there is only one group containing all 41 storms. The final decision regards where to stop clustering, *i.e.,* how many groups should be retained. This decision was based on the proximity matrix; the largest decrease in within-group similarity was observed between four and five clusters, thus suggesting five groups should be retained. Using one-way ANOVA on cluster means, we confirmed that in all cases the clusters identified were statistically significantly different from one another ($p < 0.01$).

RESULTS AND DISCUSSION

Cumulative Results

The cumulative 0–100 ratings for each hurricane are depicted, compared with the hurricane's SS scale rating (Figure 2). Storms are assigned into their SS categories based on maximum sustained winds with the exception of *Andrew,* which is given its upgraded category 5 status. A clear positive correlation is observed between the cumulative totals in this research and the SS ratings ($p < 0.01$), although there is considerable variability around the regression line (see Figure 2). Several longer duration, higher precipitation storms

Table 3. *Categorical scores and cumulative totals of individual hurricanes analyzed. Number corresponds with Figure 1.*

Number	Storm	Year	Individual Component Scores						Cumulative Total	HCS Type
			Duration	Sust. Wind	Wind Gust	Precip.	Pressure	Surge		
7	Camille	1969	10.0	25.0	5.0	4.0	26.0	15.0	85.0	3A
6	Beulah	1967	20.0	16.0	2.0	6.5	16.0	5.0	65.5	2B
23	Andrew	1992	4.0	20.5	3.8	2.0	21.0	11.0	62.3	3A
2	Carla	1961	20.0	8.5	2.8	6.0	14.0	10.0	61.3	2B
12	Allen	1980	20.0	8.5	2.0	7.0	12.0	5.0	54.5	2B
5	Betsy	1965	8.0	20.5	2.8	2.5	14.0	6.0	53.8	2A
1	Donna	1960	14.0	13.0	1.5	4.0	14.0	5.0	51.5	2B
20	Hugo	1989	8.0	16.0	2.5	2.0	16.0	5.0	49.5	2A
11	Frederic	1979	10.0	13.0	2.3	4.0	13.0	7.0	49.3	2B
39	Ivan	2004	12.0	8.5	0.8	5.5	13.0	8.0	47.8	2B
4	Hilda	1964	20.0	8.5	1.0	4.0	6.0	5.0	44.5	2B
32	Bret	1999	14.0	8.5	1.5	5.5	10.0	4.0	43.5	2B
40	Frances	2004	20.0	5.0	0.0	6.5	6.0	2.0	39.5	1B
13	Alicia	1983	18.0	8.5	0.0	3.5	5.0	4.0	39.0	2B
8	Celia	1970	4.0	13.0	3.0	2.0	12.0	4.0	38.0	2A
31	Georges	1998	14.0	5.5	0.0	9.0	4.0	4.0	36.5	1B
41	Jeanne	2004	9.0	10.0	1.5	4.5	10.0	1.0	36.0	2B
3	Dora	1964	20.0	1.0	0.0	6.5	4.0	4.0	35.5	1B
25	Opal	1995	1.5	10.0	1.5	4.5	13.0	4.0	34.5	2B
38	Charley	2004	0.0	16.0	2.0	1.0	13.0	2.0	34.0	2A
33	Floyd	1999	4.0	5.5	1.0	7.5	8.0	5.0	31.0	2B
16	Elena	1985	6.0	8.5	1.5	2.5	9.0	1.0	28.5	2B
27	Fran	1996	5.0	8.5	0.0	3.0	8.0	1.0	25.5	1A
9	Eloise	1975	0.5	10.0	1.3	1.0	8.0	4.0	24.8	2A
36	Isabel	2003	5.5	4.0	0.0	2.0	7.0	3.0	21.5	1A
29	Bonnie	1998	7.0	4.0	0.0	4.5	4.0	1.0	20.5	1A
28	Danny	1997	8.0	0.0	0.0	10.0	0.0	1.0	19.0	1B
35	Lili	2002	0.0	1.0	0.0	3.0	5.0	6.0	15.0	1A
22	Bob	1991	0.0	4.0	0.0	2.5	4.0	4.0	14.5	1A
14	Diana	1984	10.0	1.0	0.0	3.0	0.0	0.0	14.0	1A
17	Kate	1985	2.0	2.5	0.0	1.5	3.0	3.0	12.0	1A
34	Irene	1999	4.0	0.0	0.0	6.0	0.0	1.0	11.0	1A
30	Earl	1998	0.0	0.0	0.0	6.0	0.0	3.0	9.0	1A
26	Bertha	1996	1.0	5.5	0.0	2.0	0.0	0.0	8.5	1A
18	Chantal	1989	0.0	0.0	0.0	5.0	0.0	1.0	6.0	1A
24	Erin	1995	1.5	1.0	0.0	1.5	0.0	1.0	5.0	1A
37	Claudette	2003	1.5	1.0	0.0	1.5	0.0	0.5	4.5	1A
18	Bonnie	1986	0.0	0.0	0.0	2.5	0.0	0.5	3.0	1A
21	Jerry	1989	0.0	0.0	0.0	2.0	0.0	1.0	3.0	1A
19	Danny	1985	0.0	0.0	0.0	2.0	0.0	0.5	2.5	1A
10	Bob	1979	0.0	0.0	0.0	1.5	0.0	0.0	1.5	1A

have significantly higher relative HCS values compared with their SS ratings (Table 3). Hurricanes *Carla* (1961), *Dora* (1964), *Beulah* (1967), and *Frances* (2004) all slowed at landfall resulting in heavy precipitation, with hurricane force winds persisting almost 24 h in the instances of *Beulah* and *Frances.* Conversely, several short duration, low precipitation storms *Eloise* (1975), *Bertha* (1996), and *Charley* (2004) scored much lower than their SS ratings. *Charley*'s narrow wind field combined with its rapid forward speed equals a relatively low score, despite its official classification as a SS category 4. This is perhaps the greatest discrepancy between the two scales. People who experienced the 16-km (10-mi) wide swath of category 4 winds in *Charley* experienced a much different hurricane than the majority of people that barely saw winds of hurricane strength.

Table 4. *Mean variable values for each of the HCS types.*

Type	1A	1B	2A	2B	3A
Minimum central pressure (mbar)	975	969	944	948	916
Maximum sustained winds (km/h)	145	152	221	192	262
Gust (km/h)	n/a	n/a	238	210	298
Duration (h)	2.7	11.7	3.8	9.5	5.5
Precipitation (cm)	19.7	47.0	13.7	30.2	20.3
Storm surge (m)	1.9	2.4	2.7	3.0	6.4

Cluster Analysis

As just described, cluster analysis yielded five different hurricane "types" (Table 4). In evaluating the different clusters, it is clear that several distinctions were made. Some types contained noticeably stronger systems than others. In other cases, however, shorter-duration storms or higher-duration storms were clustered together. To ease interpretation, while the clusters were determined objectively, the category names were subjectively applied. Category A contains storms that are generally faster moving, of shorter duration, and hence lower precipitation. Category B contains generally slower moving, longer duration, and higher precipitation hurricanes. Intensity is designated by a 1–3 number designation. In this manner, the five categories identified are termed 1A, 1B, 2A, 2B, and 3A (Table 4).

From 1960 to 2004, 41 hurricanes have made landfall in the United States (see Figure 1). The most common type of hurricane is 1A with 17 occurrences. The number of type A hurricanes drops sharply as intensity increases. Type B hurricanes are much different. There have been only four type 1B hurricanes, but 13 Type 2B hurricanes. When a hurricane initially forms, it appears that it is more likely to be Type 1A and then later transition into type 2B if it strengthens. These two types comprise 73% of the land-falling hurricanes.

Of all five types, the 1A storm category contains the largest number of systems (17), and is most closely related to SS category 1 and 2 storms (see Table 4). The majority of 1A storms have sustained winds between 129 and161 km/h (80 and 100 mph), central pressures greater than 960 mbar, and short durations. Hurricane *Fran* (1996) is the strongest member of the group with a pressure of 954 mbar, and this is closely followed by Hurricane *Isabel* (2003) at 958 mbar. *Fran*'s winds over land never exceeded 185 km/h, but it had gusts that slightly exceeded this speed, making it unique in the 1A category (NHC, 2004). All of the recent North Carolina hurricanes fall into this type with the exception of *Floyd* (1999), which is discussed later.

The four 1B storms have the same general wind and pressure characteristics as the 1A storms; however, the 1Bs are long-duration precipitation events, with higher storm surges than their SS equivalency because of their slow and persistent movement (see Table 4). Hurricanes *Georges* (1998) and *Frances* (2004) are very similar in pressure, surge, and sustained winds. Both were associated with storm surges typical of stronger SS categories. *Danny* (1997) has the weakest winds and pressure measurements of the group, but its slow movement and massive precipitation amounts are clustered into this type (NHC, 2004). Two of the 1B hurricanes affected the east coast of Florida north of West Palm Beach, while the other two made landfall on the Central Gulf Coast.

The five 2A storms are fast-moving, short-duration SS category 3 and 4 hurricanes. Higher wind speeds are characteristic of hurricanes in this category, and most of the 2As are historically significant hurricanes on the SS. The mean maximum sustained wind speed score of the 2A hurricanes is five points higher than the 2B hurricanes, which are discussed next. The strongest members of the group are *Betsy* (1965) and *Hugo* (1989). The weakest member of the group is *Eloise* (1975). *Eloise*'s rapid forward speed 44 km/h (27 mph) and mean gusts of 201 km/h (125 mph) make it more similar to 2A storms even though its pressure (955 mbar) is relatively weak. Four out of the five 2A hurricanes made landfall in the Gulf of Mexico, and these hurricanes were generally early in the alphabet. All of the 2A storms occurred in August and September, with little or no previous tropical activity in the major strengthening region of each hurricane (NHC, 2004).

Most of the 13 2B storms are weaker than the 2A storms in wind speed, but their slower forward speed and higher precipitation amounts are associated with a different damage structure. Over half of the 2B hurricanes had sustained winds of 185–201 km/h with pressures ranging from 943 to 963 mbar. Only three storms of this type had gusts in excess of 225 km/h (140 mph) whereas all but one of the 2A hurricanes gusts greater than 225 km/h. The mean duration score of 2B storms is nine points higher than 2A storms, and the mean precipitation score is three points higher. Hurricane *Beulah* is the strongest member of type 2B. *Beulah* nearly stalled at landfall with sustained wind speeds of 225 km/h, a pressure of 935 mbar, and a duration of over 12 h. Hurricanes *Floyd* and *Opal* represent borderline 2B cases. *Floyd* did not have a lengthy duration because of its rapid forward speed, but its precipitation was high for such a fast moving system. Its pressure of 956 mbar and sustained winds of 167 km/h (104 mph) are similar to *Fran* and *Isabel,* which are both North Carolina 1A hurricanes, but *Floyd*'s surge is higher than both (NHC, 2004). On the other hand, *Opal*'s quick forward motion and short duration are typical of type 2A, but its precipitation and sustained wind measurements are more common with type 2B. Notably, 10 of the 13 2B storms have made landfall in the Gulf of Mexico from Texas to northwest Florida, including five between Galveston and Brownsville, TX (see Figure 1).

Hurricanes *Andrew* and *Camille* are the only type 3A hurricanes in the record. *Andrew* has been extensively reanalyzed, and the revised measurements were used to update its surge, gusts, and pressure measurements for this study. Andrew's official sustained winds of 233 km/h (145 mph) were upgraded to 250 km/h (155 mph). It is believed that its sustained winds were close to this speed, and it had gusts of over 274 km/h (170 mph) (NHC, 2004). Hurricane *Camille* is the strongest hurricane in the record. Hurricane *Camille's* statistics have been well documented although its measurements are debatable. Its sustained winds are conservatively estimated at 274 km/h; reported gusts of over 322 km/h are unsubstantiated but possible given the magnitude of the storm's other characteristics (NHC, 2004). Were six clusters retained, *Camille* and *Andrew* would each be placed in their own category. In this research, *Andrew* and *Camille* are likely clustered together only because they are both extreme outliers in this dataset.

Based on the subjective labeling of these objective clusters, a 3B cluster similar to types 1B and 2B may be plausible. Were a hurricane whose intensity is similar to that of *Camille* or *Andrew* to also move slowly at landfall, this cluster might be realized. No such hurricane has made landfall in the United States during the study period, although Hurricane *Mitch* which made landfall in Honduras in 1998 is representative of these characteristics and suggests that such storms are possible.

In addition to storm intensity, the dollar damage resulting from hurricanes of different HCS types is dependent on the affected population and building densities, along with inland topography. Furthermore, dollar damage values vary considerably by source. Generally the Bs have higher cumulative (0–100) scores than the As, but the 2A storms have higher mean maximum sustained wind speeds than the 2B storms. In fact, out of the costliest hurricanes (adjusted for inflation), 2A hurricanes *Hugo* and *Betsy* are the highest ranked along with both 3A hurricanes (Table 5) (JARRELL *et al.,* 2001).

Table 5. *Ten costliest huricanes from 1960–2000, and associate HCS type.*

Rank	Hurricane	Year	Damage ($bil)	HCS Type
1	Andrew	1992	35.0	3A
2	Hugo	1989	9.8	2A
3	Betsy	1965	8.5	2A
4	Camille	1969	7.0	3A
5	Frederic	1979	5.0	2B
6	Floyd	1999	4.7	2B
7	Fran	1996	3.7	1A
8	Opal	1995	3.5	2B
9	Alicia	1983	3.4	2B
10	Carla	1961	2.6	2B

Source Jarrell *et al.*, 2001.

When final values are available, it is believed that 2A *Charley* will also be listed near *Hugo* and *Betsy* (Hurricane Insurance Information Center 2005). The 2B hurricanes are all closely ranked behind *Camille,* along with 1A *Fran* (see Table 5). It is also believed that 2Bs *Ivan* and *Jeanne* and 1B *Frances* will be ranked somewhere behind *Camille* when the damage estimates are finalized. PIELKE and LANDSEA (1998) have a slightly different damage ranking prior to 1995. In their work, a similar number of 2A and 2B storms comprise the top 10 along with *Camille* and *Andrew.*

The 2B hurricanes, *Ivan* and *Frederic,* both hit major cities, Pensacola and Mobile. It is uncertain if *Ivan* and *Frederic* would have caused more or less damage had they taken the exact path of *Hugo* and *Charley,* but it is believed that they would have caused less dollar damage. There is no clear relationship between dollar damage and letter designation of the HCS although it is noted that 1B hurricanes are generally ranked higher than 1A hurricanes, with the exception of *Fran,* and the strongest 2A hurricanes are generally ranked higher than the strongest 2B hurricanes.

CONCLUSIONS

In this article, a new HCS is proposed. Unlike the prelandfall-based SS scale, the HCS categorizes hurricanes into types based on observed postlandfall measurements. It thus plays an important role in reconciling the differences between the forecasted SS intensity and the observed intensity. This facilitates public understanding by explaining a more comprehensive view of hurricane intensity. It also assists emergency management personnel with a method for assessing the dangers of hurricanes based on past experiences. There is currently no system in place that verifies the intensity of hurricanes.

Classification systems in meteorology exist to synthesize and group similar data characteristics into an easily understood format. Several previous classification systems for hurricanes have been reviewed here in the context of varying perception according to perceived threats in each geographical region. The national or regional hurricane warning scales, such as the SS in the United States, are all designed for the prelandfall period. The geological scales by BUSH, JACKSON, and YOUNG (2000) and SALLENGER (2000) are closer attempts at a classification system for hurricanes postlandfall, but their intent is too narrowly focused on the exclusive impacts of the coastal environment and storm surge. There is a need for a system that collectively analyzes the comprehensive damage and meteorological statistics from hurricanes.

The HCS incorporates the measurements of six variables that are assessed postlandfall: air pressure, maximum sustained winds, gust bonus, duration, surge, and precipitation. Each of these variables has been shown to correlate well with at least one aspect of hurricane damage. These variables have then been utilized to group hurricanes into types using cluster analysis. Five types were identified and assigned a number and letter designation: *i.e.,* 1A, 1B, 2A, 2B, and 3A. The numbers represent hurricane intensity with higher numbers being more severe. The letters represent storm characteristics. The A storms are generally shorter duration, lower precipitation hurricanes. The B storms are generally longer duration, higher precipitation hurricanes. It is important to note that the differences in the hurricane types via this system incorporate not only differences in intensity, but also character.

This initial application of the HCS has been targeted to represent the most severe conditions of each hurricane in every category. This is consistent with the SS, which also rates the most severe characteristics at the landfall location. As stated earlier, however, the HCS can be modified and applied for individual point locations, where data are available, to rate the postlandfall intensity on a smaller scale. Because the variability in damage on opposing sides of the eye can be considerable, this concept of point locational analysis has advantages when compared to a uniform approach to damage variability. The effect would be the creation of spatial zone types where the landfall location has the HCS rating presented in this paper and zones decrease radially in intensity away from the center.

UPDATE FOLLOWING THE 2005 HURRICANE SEASON

This article was originally submitted after the 2004 hurricane season. The historically active 2005 hurricane season saw 4 major landfalls in the United States: *Dennis, Katrina, Rita,* and *Wilma.* Due to the significance of the 2005 season, it is important to include the major 2005 hurricanes before this article goes to press. *Dennis, Katrina, Rita,* and *Wilma* were analyzed using the same methods previously described. The PCA factor scores were calculated based on the original loadings, and Hierarchical Cluster Analysis was then performed on the entire dataset, including the 2005 hurricanes, to produce classification results concordant with the 2004 analysis.

Although much publicized for their extraordinary low pressure over open water environments, the 2005 hurricanes share similarities with several hurricanes presented in this article. Hurricanes *Dennis* and *Wilma* are both representative of type 2A (Table 6). Although *Wilma* achieved the lowest pressure ever recorded in the Atlantic Basin, it was a category 3 SS hurricane at landfall (NHC, 2006). A postlandfall analysis from the Yucatan region could possibly indicate that Wilma was a potential type 3B at that landfall, but that analysis was not performed here.

Table 6. *Categorical scores and cumulative totals from the 2005 season.*

	Individual Component Scores							
Storm	Duration	Sust. Wind	Wind Gust	Precip.	Pressure	Surge	Cumulative Total	HCS Type
Katrina	16.0	10.0	1.5	5.5	19.0	15.0	67.0	2B
Rita	14.0	8.5	1.8	4.0	15.0	8.0	51.3	2B
Wilma	4.0	10.0	2.0	2.5	10.0	3.0	31.5	2A
Dennis	0.0	10.0	1.3	2.5	11.5	1.5	26.8	2A

Katrina and *Rita* share many characteristics of type 2B hurricanes (see Table 6). *Katrina* was the most publicized hurricane of the 2005 season due to its highly discrepant SS storm surge and the resulting fatalities. Although its storm surge is arguably the highest of any hurricane analyzed in this article, its other categorical variables are conformal with type 2B characteristics. If *Katrina* had made landfall one day prior, it is believed it would have been a potential type 3B due to its relatively long duration, high precipitation, and high sustained winds. *Katrina's* sustained winds at landfall near the Mississippi/Louisiana border were consistent with a SS category 3 hurricane (NHC, 2006).

ACKNOWLEDGMENT

We would like to thank Dr. Thomas Schmidlin for his input and suggestions in the preliminary stages of this research.

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