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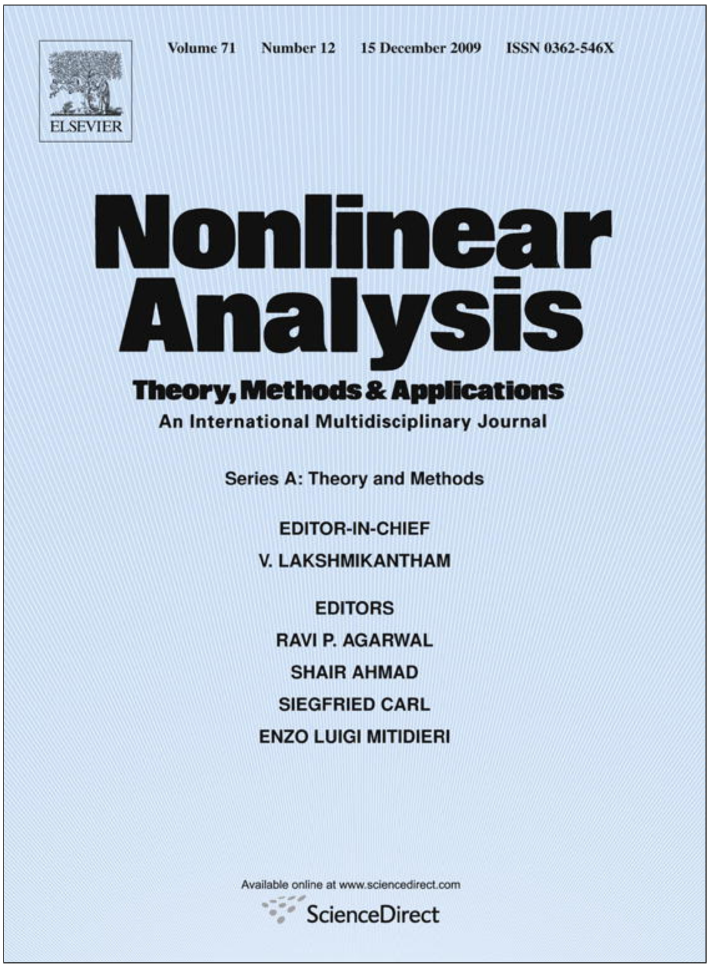

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A proposed new scale to identify the category of a Hurricane's status

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ABSTRACT

The present study is concerned with the relationship between wind speeds in a hurricane and the pressure or depression. We propose a new index for categorizing hurricane force winds. Our method is developed utilizing statistical procedures and modeling with molecular physics. Our results are compared with the commonly used Saffir–Simpson scale.

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1. Introduction

Hurricanes are significant phenomena that we must make every effort to understand and monitor. Although the present study concentrates on the hurricanes in the western hemisphere, similar methodology, modeling and procedures can be applied to other regions where tropical cyclones are a factor [1].

Hurricane force **winds** are primarily categorized by the **pressure** as defined by the **Saffir–Simpson Scale**. Such a scale (index) is used to give an estimate of the wind velocity which is used to identify the potential property damage and flooding expected along the coast from a hurricane landfall. Wind speeds are one of the determining factors in the storm surge and play a very important role. In the present study, we will introduce a new index process using statistical inference and the most recent hurricane information gathered every six hours by the National Oceanic and Atmospheric Association (NOAA).

2. Description of five category five hurricanes in the 21st century

Previous studies have shown that contrary to common belief, a drop in pressure is not the cause of an increase in wind speed, but that an increase in wind speeds causes a drop in pressure; either approach there is a relationship between wind speed and atmospheric pressure. Five storms, namely **Isabel** (2003), **Ivan** (2004), **Katrina** (2005), **Rita** (2005) and **Wilma** (2005), were used to determine the wind speeds at which there is a significant change in pressure. Consider the box plot for pressure by recorded wind speeds are illustrated in Fig. 1. For most wind speeds the pressure is rather stable; however, there are a few wind speeds where the pressure is more variant indicative of a transition within the storm. For example, in the proposed scale category 2 hurricanes are formed when wind speeds hit 78 knots. In this transitional stage the pressures have high variability as illustrated by Fig. 1.

To further analyze this disparity, we compared the mean pressures versus wind speeds for the original five storms, Fig. 2, to the mean pressure versus wind speeds for all storms recorded in the 1990s, Fig. 3 and the 1980s, Fig. 4. The scatter plots in Fig. 1 through 3, illustrate that there is a well-defined relationship between atmospheric pressure and wind speed. In addition, this relation has curvature. Hence, we begin to analyze the relationship between wind speeds and atmospheric pressure alone. Consider the box plots for mean pressure of wind speed as shown by Fig. 1. There are several wind speeds where the pressures are more variable; that is, pressures where the storm is potentially in transition to greater wind velocities are more likely to follow as instabilities in the atmosphere churn as temperature and pressure differential seek equilibrium.

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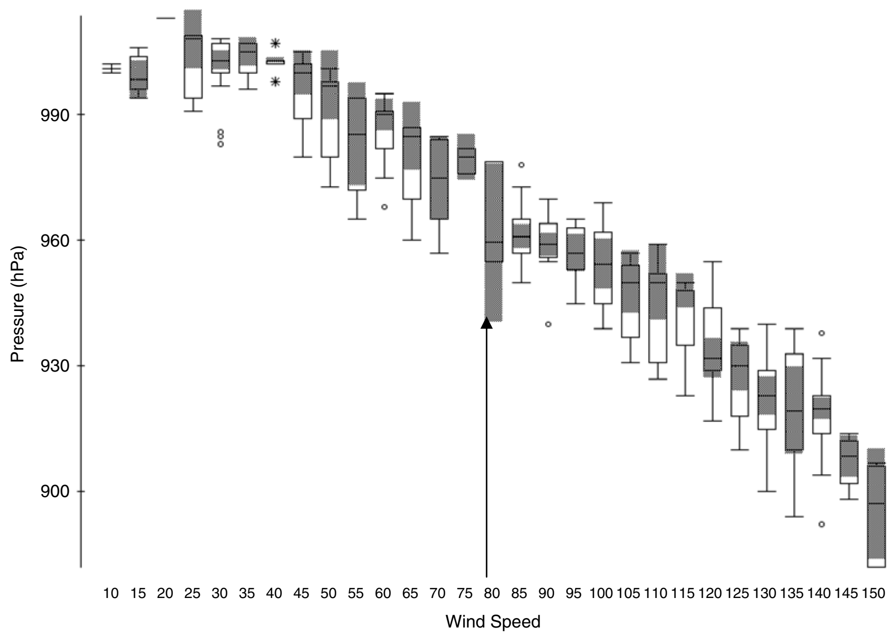

Fig. 1. Box plot for pressure with respect to recorded wind speeds for the listed five storms.

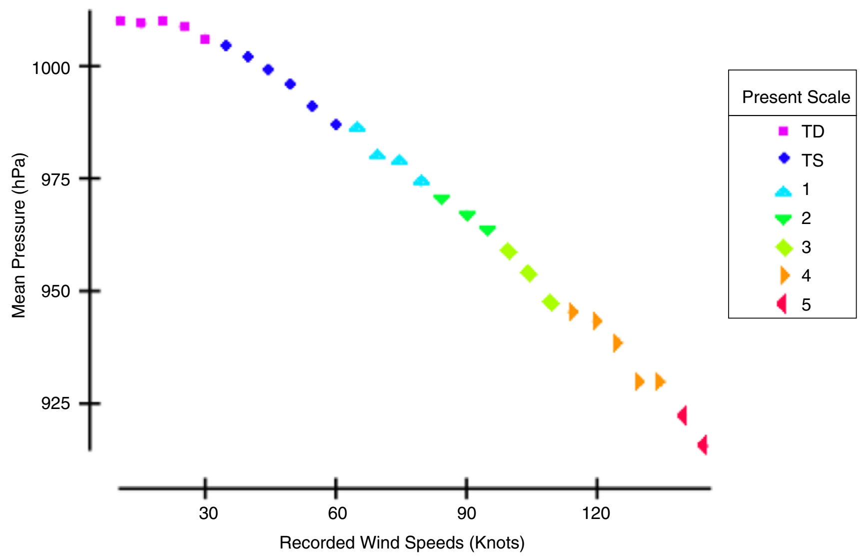

Fig. 2. Mean pressure versus wind speeds for the listed five storms.

3. Parametric analysis of hurricane force winds over pressure

Consider that probable wind speeds as categorized by pressures under the assumption of normality; that is, assuming that for any given wind speed, the probability distribution of the associated pressures follows the normal distribution. These winds are recorded in multiples of five using the Dvorak Method [2] and therefore, using hypothesis testing to determine if the mean pressure is significantly different (depression) as the wind speed increases; that is, using the mean recorded pressure, $\bar{p}_w$, for the given wind speed, w, we can test the hypothesis the mean pressure for a given wind speed, w, is equal to the mean pressure for the next highest wind speed, $w+5$. The probabilities that such differences may occur by chance are given in Table 1; significantly different mean pressures are shown in bold. Hence, statistically we can conclude that there is a common relationship between wind speeds and pressure (specifically as the winds increase, the pressure decreases); this relationship also has curvature, that is the relationship is not linear, the rate at which the pressure changes decreases when higher wind speeds are present. Using standard parametric analysis and the student t-distribution we determined among which wind speeds the most significant difference in pressure occurs.

Hence, at a level of significance of 0.10, there are six distinct groupings (that is, intervals of wind speeds between which there is a significant drop in pressure); between 10 and 40 knots, between 45 and 70 knots, between 75 and 80 knots, between 100 and 105 knots, between 120 and 125 knots and finally, between 140 and 145 knots. There is a significant difference between 145 and 150; however, this difference is not as significant as between 140 and 145. There is a significant

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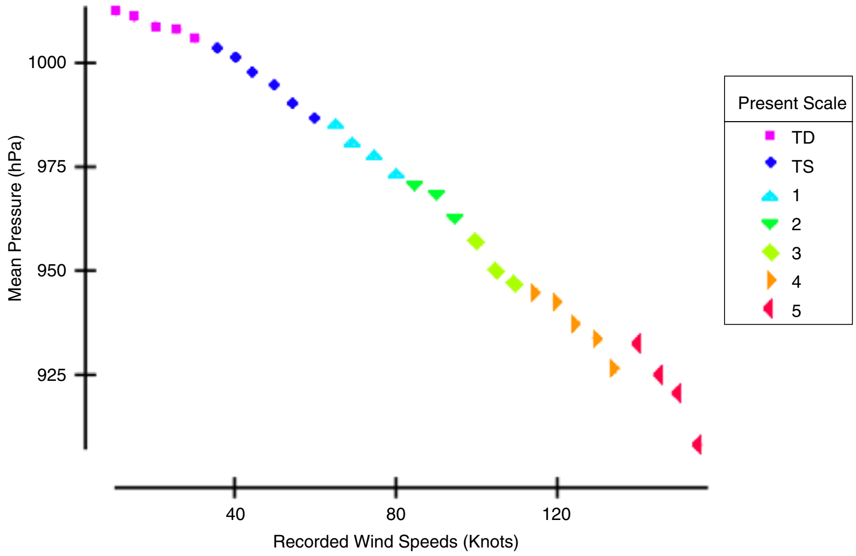

Fig. 3. Mean pressure versus recorded wind speeds for all storms recorded in the 1990s.

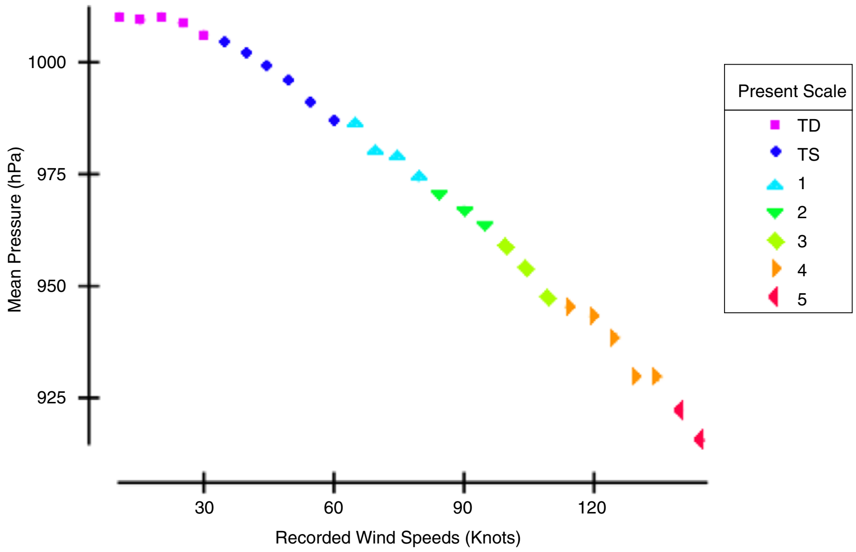

Fig. 4. Mean pressure versus recorded wind speeds for all storms recorded in the 1980s.

difference between 50 and 55 knots; however this interval is superseded by the difference between 40 and 45 knots. There is a significant difference between 115 and 120 knots as well as between 125 and 130, but both are not as significant as the differences between 120 and 125 knots.

Now we need to address the first three unevenly distributed categories: 10–40, 45–120 and 125–140. If we define wind speeds between 10 and 40 knots as category 0 (both tropical depressions and tropical storms), and define wind speeds between 125 and 140 as category 4, then we need to partition wind speeds between 45 and 120 knots into the three remaining categories; namely, category 1, category 2 and category 3. As shown in Table 1, there are several different breaking points at the significance level of 0.10, two of which fall reasonably with our interval, thus we will define wind speeds between 45 and 70 as category 1, between 75 and 100 to be category 2 and finally wind speeds between 105 and 120 as category 3.

Note that the above statistical findings are based on the data follows the Gaussian probability distribution. What happens if that assumption is not met? In the section below we address this issue using non-parametric or distribution free methods.

4. Non-parametric analysis of hurricane force winds over pressure

The assumption of normality may not hold [3–5], especially in levels of wind speeds with less than five observations, hence we shall use the non-parametric Mann–Whitney (Wilcoxon Rank Test), to repeat the above statistical analysis.

For each pair of wind speeds $(w, w+5)$ the data consist of the two random variables P_{wi}; $i = 1, \dots, n_w$ and $P_{(w+5)j}$; $j = 1, \dots, n_{w+5}$. These collective pressures are then ranked from 1 to $N = n_w + n_{w+5}$, using average ranks for any ties.

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Table 1
Test for mean pressure.

$H_0 : \bar{p}_w = \bar{p}_{w+5}$		*p*-value
w	$w+5$	
10	15	0.388
15	20	–
20	25	–
25	30	0.291
30	35	0.118
35	40	0.431
40	**45**	**0.00672**
45	50	0.312
50	*55*	*0.0595*
55	60	0.338
60	65	0.134
65	70	0.302
70	75	0.211
75	***80***	***0.0651***
80	85	0.831
85	90	0.336
90	95	0.258
95	100	0.12
100	***105***	***0.0676***
105	110	0.684
110	115	0.408
115	120	0.0221
120	**125**	**0.00626**
125	*130*	*0.0493*
130	135	0.641
135	140	0.711
140	**145**	<**0.001**
145	**150**	**0.00831**

First, we defined T to be the sum of ranks assigned to the sample from the first population given by $T = \sum_{i=1}^{n_W} R(P_{wi})$. Using apportionment, the expected value under the hypothesis that these are from the same distribution is $\mu_T = \frac{n_w(N+1)}{2}$. Moreover, since there are many ties, the standard error is $SE = \sqrt{\frac{n_w n_{w+5}}{N(N-1)} \sum_{k=1}^{N} R_k^2 - \frac{n_w n_{w+5}(N+1)^2}{4(N-1)}}$ and therefore, including correction for continuity associated with the test statistic, is given by $t_w = \frac{T-\mu_T}{SE}$. Since we are looking for the levels with the most significant difference in pressure, we will consider the largest absolute value of the test statistics, $|t_w|$ to determine where there should be a categorical break in the wind speeds.

The most significant difference is between 140 and 145 knots (the proposed break between category 4 and 5), the second is between 40 and 45 knots (the proposed break between category 0 and category 1) and the third is between 145 and 150 knots (however this interval is superseded by the first interval.) The pressure difference ranked forth is between 115 and 120 knots, however if we consider the absolute value of the test statistics peaks before this fourth ranked peak, this occurs between 75 and 80 knots and again between 100 and 105 knots. Ranked 9th and 13th respectively, these significant test statistics are given in Table 2. Table 2 is color coded with the proposed scale and includes the parametric analysis alongside the non-parametric analysis; these analyses both support the proposed scale. A comparison of the proposed scale and the scale presently used is given in Table 3. This new scale would increase what is presently referred to as a tropical storm as the first stage (category 1) of a hurricane.

To refine the proposed scale and define the intervals more clearly, we shall consider the molecular physics behind wind speeds.

5. The thermodynamics behind molecular velocity

Consider the analytical thermodynamic structure for kinetic temperature [6] given by

$$\left[\frac{1}{2}mv^2\right]_{average} = \frac{3}{2}kT,$$

where m is the mass of the particles in motion, v is the linear velocity of the particle, k is Boltzmann constant ($k \approx 1.3806503 \times 10^{-23}$ m^{2}kg s^{-2}K^{-1}) and T is the temperature in Celsius. If we further consider the ideal gas law $PV = nRT$, where n is the number of moles, R is the universal gas constant, $R = 8.3145$ J/mol K; assuming the volume V and the mass m are constant, we have the following relationship between the relative wind speed and the depression (change in pressure): $(w - w_{\min})^2 = \alpha\,(P - P_{\max})$. Using this as the base for analyzing a quadratic relationship between wind speed and pressure,

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Table 2
Comparison of parametric and non-parametric analysis of pressures categorized by wind speed.

Proposed scale			*p*-value (Parametric)	Test statistic rank (Non-parametric)	Peaks
TD	10	15	0.388	0.92	
TD	15	20	–	−1.56	
TD	20	25	–	1.65 (12)	
TD	25	30	0.291	2.06 (8)	P
TS	30	35	0.118	−0.7	
TS	35	40	0.431	1.64	
TS	**40**	**45**	**0.00672**	3.06 (2)	P
1	45	50	0.312	0.63	
1	*50*	*55*	*0.0595*	2.27 (6)	P
1	55	60	0.338	−1.3	
1	60	65	0.134	2.28 (5)	P
1	65	70	0.302	1.57	
1	70	75	0.211	−0.46	
1	***75***	***80***	***0.0651***	1.77 (9)	P
2	80	85	0.831	−0.16	
2	85	90	0.336	0.84	
2	90	95	0.258	0.98	
2	95	100	0.12	1.17	
2	***100***	***105***	***0.0676***	1.72 (13)	P
3	105	110	0.684	0.56	
3	110	115	0.408	1.82 (10)	
3	115	120	0.0221	2.50 (4)	P
3	**120**	**125**	**0.00626**	2.11 (7)	
4	*125*	*130*	*0.0493*	1.78 (11)	
4	130	135	0.641	0.61	
4	135	140	0.711	0.34	
4	**140**	**145**	$<$**0.001**	3.21 (1)	P
5	**145**	**150**	**0.00831**	2.90 (3)	

98.6% of the variation in the pressure can be explained by the least square regression of pressure onto wind speed using the developed statistical model given by

$$\hat{P} = -0.00285818w^2 - 0.312669w + 1012.96. \quad (1)$$

This statistical model is consistent with the fact that normal atmospheric pressure (mean sea level pressure) when little wind is present ($w \to 0$) is 1013.25 which is practically the same as the estimated atmospheric pressure, $\hat{P} = 1012.96$ when $w = 0$ in the model (1).

Inverting this regression we have the following model to estimate wind speed based on model (1) above and using historically data we have

$$\hat{w} = \sqrt{\frac{(1021.511 - P)}{0.00285818}} - 54.69722, \quad (2)$$

where $\hat{w}$ is the estimated wind speed given the atmospheric pressure P.

Note that this statistical model supports the proposed scale, that is, the statistical relationships between wind speed and pressure shown by Table 4. The clarified results using the Saffir–Simpson scale are given in Table 5. The scale presently (Saffir–Simpson) used does not have a pressure interval for tropical depressions and tropical storms, nor do the pressure and wind speeds match up exactly with the statistical model developed. For example, the present scale matches a minimum pressure of 980 (hPa) with a maximum wind speed of 82 knots; however, according to the developed statistical model, the maximum associated wind speed is approximately 65 knots. The transition between hurricane category 1 and category 2 matches a minimum pressure of 965 (hPa) with a maximum wind speed of 95 knots; the developed statistical model estimates this wind speed as 86 knots.

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Table 3
Comparison of present scale and proposed scale of pressures categorized by wind speed.

Present scale	*w*	Proposed scale	*w*	*p*-value	*t*	Peaks
TD	10	TD	10	0.388	0.92	
TD	15	TD	15	–	−1.56	
TD	20	TD	20	–	1.65	
TD	25	TD	25	0.291	2.06	P
TD	30	TS	30	0.118	−0.70	
TS	35	TS	35	0.431	1.64	
TS	40	TS	40	**0.00672**	3.06	P
TS	45	1	45	0.312	0.63	
TS	50	1	50	*0.0595*	2.27	P
TS	55	1	55	0.338	−1.30	
TS	60	1	60	0.134	2.28	P
1	65	1	65	0.302	1.57	
1	70	1	70	0.211	−0.46	
1	75	1	75	***0.0651***	1.77	P
1	80	2	80	0.831	−0.16	
2	85	2	85	0.336	0.84	
2	90	2	90	0.258	0.98	
2	95	2	95	0.12	1.17	
3	100	2	100	***0.0676***	1.72	P
3	105	3	105	0.684	0.56	
3	110	3	110	0.408	1.82	
4	115	3	115	0.0221	2.50	P
4	120	3	120	**0.00626**	2.11	
4	125	4	125	*0.0493*	1.78	
4	130	4	130	0.641	0.61	
5	135	4	135	0.711	0.34	
5	140	4	140	<**0.001**	3.21	P
5	145	5	145	**0.00831**	2.90	

Table 4
Index of wind speeds by pressure according to the proposed scale developed using historical data for the five hurricanes outlined in the study.

Type: Proposed scale	Category	Pressure (hPa)	Wind (knots)
Tropical depression/Tropical storm	0	995–1010	10–42
Hurricane	1	972–994	43–77
Hurricane	2	951–971	78–102
Hurricane	3	932–950	103–122
Hurricane	4	911–931	123–142
Hurricane	5	<911	>143

6. Comparison of the proposed scale with the Saffir–Simpson scale

We shall use the mean pressures by category for the five storms to compare the proposed scale Fig. 5, and the Saffir–Simpson Scale, Fig. 6. The proposed scale exhibits less variance across the scale whereas the Saffir–Simpson scale is less stable.

Furthermore, we shall define the mean pressure by categories according to the proposed scale, $\bar{P}_{Wi}$; $i = 0, 1, \ldots, 5$ as well as the associated standard errors given by $SE = \frac{\sigma_{P_{Wi}}}{\sqrt{n}}$ which take into account the fact that the sample sizes vary between categories. We convert each pressure by category to a standard z-score defined by $z_j = \frac{P_j - \bar{P}_{Wi}}{SE}$ where P_j is the jth observation in the ith category. These transformations for the proposed scale are illustrated in Fig. 5 below by category. All centers are approximately zero (see Table 6) and while some categories show large variability, all are rather symmetric with no outliers.

Similarly, convert each pressure by category to a standard z-score defined by $z_j = \frac{P_j - \bar{P}_{Si}}{SE}$ where P_j is the jth observation in ith category as outlined by the Saffir–Simpson scale and the mean pressure by category according to the currently used

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Table 5
Index of wind speeds by pressure according to the presently used scale.

Type: Present scale	Category	Pressure (hPa)	Wind (knots)
Tropical depression/Tropical storm	0	–	<64
Hurricane	1	>980	64–82
Hurricane	2	965–980	83–95
Hurricane	3	945–965	96–113
Hurricane	4	920–945	114–135
Hurricane	5	<920	>135

Table 6
Descriptive statistics for pressure by category: Newly proposed scale.

Proposed scale	Count	Mean	Median	Variance	Std dev	Range	Min	Max	SE
0	77	1002.77	1003	16.287	4.036	18	995	1013	**0.4599**
1	56	984.91	985.5	37.865	6.153	22	972	994	**0.8222**
2	84	959.69	959	26.602	5.158	20	951	971	**0.5628**
3	73	941.33	940	38.418	6.198	18	932	950	**0.7254**
4	79	922.39	923	33.959	5.827	19	912	931	**0.6556**
5	28	900.36	901	68.164	8.256	28	882	910	**1.5602**

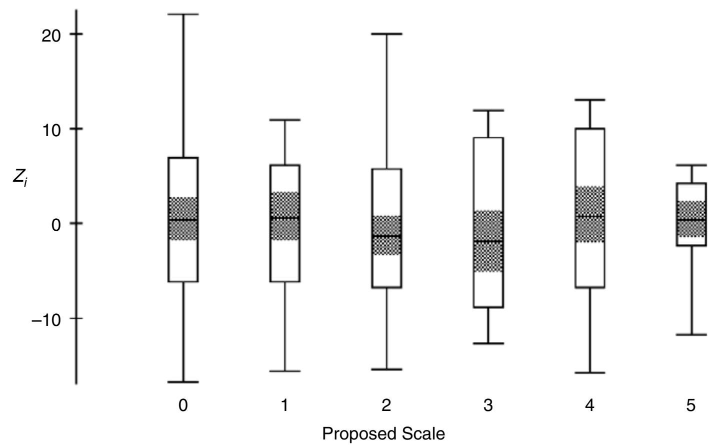

Fig. 5. Bar chart of standardized measurements of pressure by category.

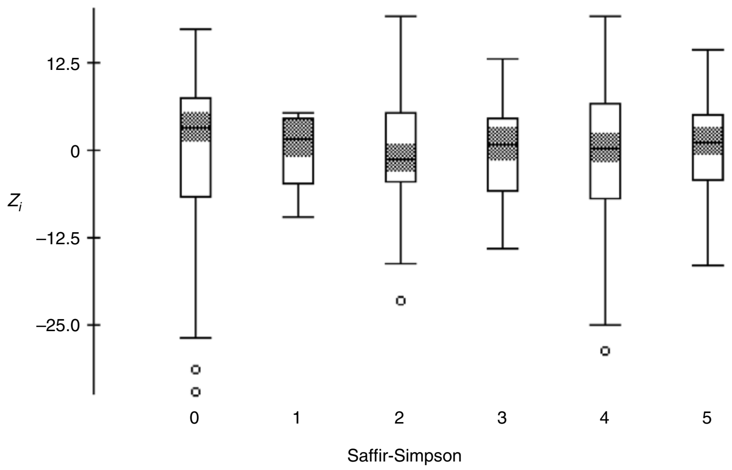

Fig. 6. Box chart of standardized measurements of pressure by category.

scale $\bar{P}_{Si}$; $i = 0, 1, \ldots, 5$ and the associated standard errors given by $SE = \frac{\sigma_{P_{Si}}}{\sqrt{n}}$. These transformations for commonly used scale are illustrated in Fig. 6 below by category. There are outliers present and are illustrated by the circles in Fig. 6, in the 0th, 2nd and 4th categories.

The range of the associated z-scores for the proposed scale is between 17.9 and 39.1 whereas the scale presently used is between 14.9 and 52.1 over the five different categories; the proposed scale has a smaller range in all categories except hurricane category 1, however lower range (14.9) this is coupled with an inflated range (52.1) in category 0.

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Table 7
Descriptive statistics for pressure by category: Saffir–Simpson scale.

Saffir–Simpson	Count	Mean pressure	Median	Variance	Std dev	Range	Min	Max	SE
0	116	996.91	1000	98.288	9.914	48	965	1013	0.9205
1	27	975.15	979	123.746	11.124	32	955	987	2.1408
2	52	960.00	959	45.686	6.759	38	940	978	0.9373
3	47	948.70	950	111.475	10.558	42	927	969	1.5400
4	106	930.46	931	170.441	13.055	61	894	955	1.2680
5	49	911.61	914	162.742	12.757	56	882	938	1.8224

Table 8
Descriptive statistics for wind speed as assigned by the proposed scale and the Saffir–Simpson Scale.

Proposed	Count	Mean	Median	Variance	Std dev	SE
C0	65	28.385	30	59.459	7.711	**0.95643**
C1	79	56.899	55	82.887	9.104	**1.02428**
C2	76	91.645	90	39.592	6.292	0.72174
C3	77	114.026	115	28.973	5.383	**0.61345**
C4	87	133.046	130	36.254	6.021	**0.64552**
C5	18	147.222	145	6.536	2.557	0.60269
Saffir–Simpson	Count	Mean	Median	Variance	Std dev	SE
C0	121	39.421	40	190.913	13.817	1.25609
C1	27	70	70	28.846	5.371	1.03365
C2	52	89.327	90	14.734	3.839	**0.53237**
C3	47	104.362	105	18.062	4.25	0.61993
C4	106	123.679	125	44.906	6.701	0.65086
C5	49	142.653	140	14.69	3.833	**0.54757**

Table 9
Descriptive statistics for mean sea level pressure as assigned by the Saffir–Simpson scale and the proposed scale.

Proposed scale	Count	Mean	Median	Variance	Std dev	SE
C0	65	1002.077	1003	40.416	6.357	**0.4599**
C1	74	986.257	987	133.015	11.533	**0.8222**
C2	76	958.329	958.5	68.624	8.284	**0.5628**
C3	77	941.143	943	106.361	10.313	**0.7254**
C4	87	921.057	921	123.125	11.096	**0.6556**
C5	18	901.500	904	106.618	10.326	**1.5602**
Saffir–Simpson	Count	Mean	Median	Variance	Std dev	SE
C0	116	996.914	1000	98.288	9.914	0.9205
C1	27	975.148	979	123.746	11.124	2.1408
C2	52	960.000	959	45.686	6.759	0.9373
C3	47	948.702	950	111.475	10.558	1.5400
C4	106	930.462	931	170.441	13.055	1.2680
C5	49	911.612	914	162.742	12.757	1.8224

As shown in Tables 6 and 7, the proposed scale has smaller standard errors in all five categories. Additionally, the distribution of count (an indication of the progression between the different status of a hurricane categories) under the proposed scale is more uniformly distributed with 77, 56, 84, 73, 79, and 28 as opposed to 116, 27, 52, 47, 106, and 49 under the scale presently used.

Comparisons of categorical wind speeds between the proposed scale and the scale presently used show that the proposed scale has a much more balanced distribution in most measures: count, total variance, and individual ranges, see Table 8. In the Saffir–Simpson scale, the variance among the various categories range between 14.60 and 190.913 whereas in the proposed scale, the variance ranges between 6.536 and 82.887. The standard deviations and standard errors are also an indication that the proposed scale is more stable.

Comparisons of categorical pressures between the proposed scale and the Saffir–Simpson Scale show that the proposed scale has a much more balanced (uniform) distribution in most measures: count, total variance, and individual ranges, see Table 9. In the Saffir–Simpson scale, the variance among the various categories range between 45.686 and 170.441 whereas in the proposed scale, the variance ranges between 40.416 and 123.125. The standard deviations and the standard errors are also an indication that the proposed scale is more stable.

7. Usefulness of proposed scale

Hurricanes affect us in several ways; according to NOAA "in an average 3-year period, roughly five hurricanes strike the US coastline, killing approximately 50 to 100 people anywhere from Texas to Maine; of these, two are typically "major"

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or "intense" hurricanes (a category 3 or higher storm on the Saffir–Simpson Scale)". Lack of hurricane awareness and preparation are shared traits among all major hurricane disasters; this was made devastatingly clear after Hurricane Katrina. Had the residence been aware of the destructive powers of the storm, more residents could have escaped New Orleans; there were 346 deaths directly related to the storm, but moreover there were an additional 980 deaths caused in the aftermath. New Orleans was not prepared for a category five hurricane, much less the levees being compromised by the surging waters. In general, this more stable scale can be used to develop strategies for the safety of our citizens [7], through simulation [8–12], and forecasting [13] as well as social planning. The developed scale can be used effectively to address these issues.

8. Conclusion

In the present study, we utilized existing information such as hurricane force wind speed and atmospheric pressure of five recent storms which reached category five status to develop a more accurate and consistent characterization of a given storm. We accomplished this by using parametric statistical analysis assuming a Gaussian distribution in conjunction with distribution free methods to concur the accuracy of the developed scale. Furthermore, we used molecular physics to develop a statistical model that accurately estimates the wind velocities of a storm as a function of atmospheric pressure. Finally, a statistical comparison of the proposed scale to that of the commonly used Saffir–Simpson scale used to identify the status of a storm; the statistical results clearly support the proposed scale to more precise in identifying the intensity of a given storm to be categorized.

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