Relation between Saffir–Simpson Hurricane Scale Wind Speeds and Peak 3-s Gust Speeds over Open Terrain

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Abstract: The Saffir–Simpson scale for categorizing hurricane intensity and damage potential is increasingly being used by hurricane forecasters and emergency managers. The hurricane intensity categories are associated in the scale with 1-min wind speeds. For structural engineering purposes the ASCE 7 Standard defines these 1-min speeds as speeds at 10 m over open water. This technical note provides estimates of the ratio of peak 3-s wind speeds at 10 m over open-terrain exposure—the speeds used in the ASCE 7 wind map—to 1-min speeds at 10 m above open water. Based on the ASCE 7 power-law model, the estimated ratio is 1.03. Based on the logarithmic law model, depending upon assumptions pertaining to the surface roughness for flow over open water, and upon the estimation method, the ratio varies from 1.03 to 1.12.

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Introduction

As defined by the National Hurricane Center, National Weather Service, National Oceanic and Atmospheric Administration (NOAA): "The Saffir–Simpson Hurricane Scale is a 1–5 rating based on the hurricane's present intensity. This is used to give an estimate of the potential property damage and flooding expected along the coast from a hurricane landfall. Wind speed is the determining factor in the scale, as storm surge values are highly dependent on the wind speed and the slope of the continental shelf in the landfall region. Note that all wind speeds are using the U.S. 1-min average" (NOAA 2005).

The estimate of potential property damage by the Saffir–Simpson (SS) scale is approximate—it is qualitative, rather than quantitative. For insurance purposes more elaborate, quantitative damage estimation methods have been developed (see, e.g., FEMA 2003; Pinelli et al. 2004). For these methods, the wind speeds are defined in a precise manner as, e.g., peak 3-s gusts over terrain with open exposure or, if the property of interest is located in a built-up environment, peak 3-s gusts over terrain with exposure estimated for that terrain. The SS hurricane scale is, nevertheless, widely viewed as useful for the purposes for which it was developed, and is increasingly being adapted for use by hurricane forecasters and emergency managers.

It is desirable to relate the wind speeds associated with the five hurricane categories specified in the SS scale with wind speeds specified for design purposes in the current version of the *ASCE 7 Standard* (ASCE 2005), that is, peak 3-s wind speeds at 10 m above terrain with open exposure. To do so a more complete definition of the SS scale wind speeds is needed than the definition provided in (NOAA 2005), where it is indicated only that those speeds are 1-min averages. This more complete definition requires specifying the height above the surface at which the 1-min average speed is considered, as well as the surface exposure for that speed.

The Commentary to the *ASCE 7-05 Standard* has adopted a definition in which the SS scale wind speeds are 1-min average wind speeds at 10 m above open water (ASCE 2005, p. 314). For example, a Category 4 hurricane is defined as one for which those speeds are between 131 and 155 mph.

Note that before its adoption of the peak 3-s gust at 10 m over terrain with open exposure as the basic wind speed, the *ASCE 7 Standard*, e.g., in its 1993 version (ASCE 1993) defined the basic wind speed the fastest-mile wind speed at 10 m above terrain with open exposure. The computations used to estimate the change in the wind speed as the wind moves from water to land, discussed in the following sections, assume that the wind speed transition models used here and developed using nonhurricane models of the boundary layer are applicable in the case of hurricanes.

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Wind Speeds at 33 ft (10 m) over Open-Water Exposure and Open-Terrain Exposure

Use of Power-Law Description of Sustained Wind Speeds

The logarithmic law is used for the description of extreme wind speeds by the meteorological community and (CEN 2004) and (Australian/New Zealand Standard 2002) in the United States, Canada, and Japan the power-law model is used in design (Zhou et al. 2002).

For the purposes of this note, and for the sake of consistency with the ASCE Standard, it is therefore appropriate to also consider the power-law model in effecting the conversion of speeds above open-water exposure to speeds over open exposure. The power-law model as used in the current version of the *ASCE 7 Standard*, which is based on peak 3-s gusts, is consistent with the power-law model used in ASCE (2005) in conjunction with fastest-mile wind speeds. For open-terrain exposure (Exposure C) and open-water exposure (Exposure D), ASCE (1993) specifies a ratio of the respective fastest-mile wind speeds at 33 ft (10 m) above ground equal to the ratio of the square roots of the respective quantities K_z (ASCE 1993, Table 6 of the Standard), that is, after interpolation between 30 and 40 ft, $(1.01/1.40)^{1/2}=0.85$. Therefore, according to the ASCE 7-93 power-law model for sustained wind speeds, sustained wind speeds at 10 m above open-terrain exposure are 15% lower than their counterparts over the ocean, i.e., their values are 85% of the values specified for sustained wind speeds at 10 m above open-ocean waters. One can arrive at the same results utilizing the mean hourly profile exponents for the two respective terrains given in Table 6.2 of ASCE (2005).

Strictly speaking, the calculations just performed are applicable to fastest-mile speeds, rather than to 1-min speeds. However, as is implicit in the ASCE (1993) Table 6, and is indicated explicitly in Table C6 of its Commentary (ASCE 1993) it specifies, appropriately, the same power-law exponents and gradient heights for all fastest-mile wind speeds, meaning that for sustained wind speeds, such as the fastest-mile speed or the 1-min speed, the exponents and the gradient heights vary relatively little as a function of wind speed or averaging time. This is in our opinion entirely appropriate for calculations pertaining to the SS classification, based as it is on qualitative measures of the wind speed, that is, on engineering judgment rather than on measurements or rigorously established property damage criteria.

The ratio between peak 3-s gust speeds and 1-min wind speeds at 10 m above open-terrain exposure is about 1.52/1.25 (ASCE 2005). Therefore, approximately, the ratio between peak 3-s gusts at 10 m above terrain with open exposure and its 1-min speed over open-water counterpart is $1.52\times0.85/1.25=1.03$, where the factor 0.85 is based on the calculations of the second paragraph of this section.

We now proceed to verifying the results based on the power law as applied to sustained wind speeds by using the more elaborate procedure described by Simiu and Scanlan (1996).

Use of Logarithmic Law Description of Wind Speeds

The following expression is used:

$$U_t(z)=U_{3600}(z)+c(t)[\mathrm{rms}(u')]=U_{3600}(z)\left[1+\frac{\beta^{1/2}c(t)}{2.5\ln\dfrac{z}{z_0}}\right] \quad (1)$$

where $U_t(z)$=speed averaged over $t(s)$; $U_{3600}(z)$=speed averaged over 3,600 s; and u'=longitudinal flow velocity fluctuation. Table C6.8 of the Commentary to ASCE (2005) suggests values of the roughness length z_0 for open terrain between 0.01 and 0.15 m. It, therefore, appears reasonable to assume for the purposes of this technical note a typical value of z_0 in Exposure C is about 0.05 m. The hurricane simulation model used to define the wind speeds along the hurricane-prone coastline in the current version of the ASCE 7 Standard is based on the assumption that over open-terrain exposure z_0=0.03 m. This assumption is conservative.

To estimate the roughness length over open water we consider the results of Powell et al. (2003), who present estimates of the open-sea roughness in winds greater than about 40 m/s. According to Simiu and Scanlan (1996), that roughness does not continue to increase at mean wind speeds beyond about 40 m/s, but rather reaches a limiting value of the roughness length $z_0\approx0.003$ m. The hurricane wind model developed in the late 1990's used to define the over water wind speeds as specified in ASCE 7-05 employs the use of the previously commonly held assumption that the surface roughness continues to increase with increasing wind speed. The results of Powell et al. (2003) are consistent with results of full-scale measurements reported by Kareem (1983) and subsequent results obtained numerically (Donelan et al. 2004) and in a wind-wave tank (Moon 2004). However, to account for possible measurement errors we also examine the case of z_0=0.005 m. Note, however, that deviations from mean results are accounted for by safety margins, which reflect deviations of independent variates, of which the roughness length is only one among many. Therefore, designs or standard specifications need not be based on largest values of any single variate.

For the elevation z=10 m, $\beta\approx6.5$, and $z_0\approx0.003$ m over open water; and $\beta\approx6.0$ and $z_0\approx0.05$ m over open terrain; and $c(t)\approx1.29$, [see Simiu and Scanlan (1996) Eqs. (2.3.36) and (2.3.37) and Tables 2.3.1 and 2.3.3]. It follows that for flow over water the 1-min speed at 10 m elevation is

$$U_{60}^{w}(10\text{ m})=1.16U_{3600}^{w}(10\text{ m})$$

that is

$$U_{3600}^{w}(10\text{ m})=0.86\ U_{60}^{w}(10\text{ m})$$

The friction velocity for the flow over water is [Simiu and Scanlan 1996, Eq. (2.2.18)]

$$u_*^w=\frac{0.86U_{60}^{w}(10\text{ m})}{2.5\ln\dfrac{10}{0.003}}=0.0424U_{60}^{w}(10\text{ m})$$

The corresponding friction velocity for the flow over open terrain is [Simiu and Scanlan 1996, Eq. (2.2.32)]

$$u^{*\mathrm{open}}=(0.05/0.003)^{0.0706}u^{*w}=1.22u^{*w}$$

$$=1.22\times0.0424U_{60}^{w}(10\text{ m})$$

$$=0.0517U_{60}^{w}(10\text{m})$$

(A similar expression is also used in the Eurocode.) The hourly mean speed at 10 m above open terrain is, therefore [Simiu and Scanlan 1996, Eq. (2.2.18)]

Table 1. $U_3^{\text{open}}(10\text{ m})/U_{60}^{\text{water}}(10\text{ m})$ for Various Open-Water and Open-Land (Exposure C) Roughness Length Values, Based on Eq. (1)

Open-water surface roughness (m)	Exposure C surface roughness (m)	
	0.03	0.05
0.003	1.07 (1.09)	1.03 (1.05)
0.005	1.09 (1.12)	1.06 (1.08)

Note: Numbers in parentheses are based on Engineering Sciences Data Unit (1992).

$$U_{3600}^{\text{open}}(10\text{ m}) = 2.5 \times 0.0517 U_{60}^{w}(10\text{ m}) \ln(10/0.05)$$
$$= 0.685 U_{60}^{w}(10\text{ m})$$

Using again Simiu and Scanlan [1996, Eqs. (2.3.36) and (2.3.37) and Tables 2.3.1 and 2.3.3)], the following result is obtained:

$$U_{60}^{\text{open}}(10\text{ m}) = 0.685 U_{60}^{w}(10\text{ m})\left(1 + \frac{6^{1/2} \times 1.29}{2.5 \ln \dfrac{10}{0.05}}\right)$$
$$= 0.85 U_{60}^{w}(10\text{ m})$$

The approximate ratio of the 3-s peak gust speed at 10 m over open exposure to the 1-min wind speed at 10 m above open water is, therefore, $(1.52/1.25) \times 0.85 = 1.03$, that is, the same as the ratio obtained by using the power-law description.

To estimate the effect of roughness lengths different from those assumed in the calculations just presented, we show in Table 1 ratios of $U_{60}^{\text{water}}(10\text{ m})$ to $U_3^{\text{open}}(10\text{ m})$ for open-water roughness lengths 0.003 and 0.005 m, open-terrain roughness lengths 0.03 and 0.05 m, and the same values of β used earlier. Also included are results obtained by utilizing the Engineering Sciences Data Unit (1992). It follows from the results of Table 1 that it is reasonable for practical purposes to assume that the ratio $U_3^{\text{open}}(10\text{ m})/U_{60}^{\text{water}}(10\text{ m})$ is about 1.03–1.12. For operational purposes a value of, say, 1.07 is likely to be reasonable. Should consistency with the use of the power law in the ASCE 7 Standard dictate consideration of the estimate based on the power law, that ratio would be about 1.05.

It is emphasized that we considered at all times speeds over open water, as indicated in the Commentary to the ASCE 7-05 Standard, not over water near the coast, where, as suggested by Powell et al. (2003), shoaling effects may be important and the roughness may be larger than that experienced over the open ocean. The roughness of the sea in hurricanes near the coast is an area of ongoing research.

Summary and Conclusions

The Saffir–Simpson scale for categorizing hurricane intensity and damage potential is increasingly being used by hurricane forecasters and emergency managers. The hurricane intensity categories are associated with 1-min wind speeds in the scale. For structural engineering purposes the ASCE 7-Standard defines these 1-min speeds as speeds at 10 m over open water. This technical note provides estimates of the ratio of peak 3-s wind speeds at 10 m over open-terrain exposure—the speeds used in the ASCE 7 wind map—to 1-min speeds at 10 m above open water. Based on the ASCE 7 power-law model, the estimated ratio is 1.03. Based on the logarithmic-law model, depending upon assumptions pertaining to the surface roughness for flow over open water, and upon estimation method, the ratio varies from 1.03 to 1.12.

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