A WIND-WAVE INTERACTION EXPLANATION FOR JELESNIANSKI'S OPEN-OCEAN STORM SURGE ESTIMATION USING HURRICANE GEORGES' (1998) MEASUREMENTS

S. A. Hsu

Coastal Studies Institute
Louisiana State University
Baton Rouge, Louisiana

Abstract

On 28 September 1998, Hurricane Georges made its final landfall near Biloxi, Mississippi with maximum one-minute sustained surface winds of 46 m s^{-1} (90 kt) and a minimum central pressure of 960 hPa. The measured peak storm surge was approximately 3 m (10 ft) at Pascagoula, Mississippi. Using Jelesnianski's nomograph for open-ocean surge along with adjustments for shoaling factor and storm motion, the peak surge on the coast is estimated to be 10 ft, in excellent agreement with the measurement. It is shown that Jelesnianski's open-ocean peak-surge nomograph can be further substantiated by the recent advance in wind-wave-surge interaction studies using the data from a buoy located near Hurricane Georges' track. For rapid estimation of the surge before shoaling, an analytical formula incorporating both the wind-stress tide and the barometric tide is also provided for operational use.

1. Introduction

According to Dean and Dalrymple (2002), the NOAA/National Weather Service uses the SLOSH (Sea, Lake, and Overland Surges from Hurricanes) model (Jelesnianski et al. 1992) operationally to predict storm surges. The numerical SLOSH model runs on a grid system. Convective accelerations are neglected, but some nonlinearities are included (particularly in shallow water). Comparisons with historical storms show that the model is accurate to within ± 20% of observed values.

On the other hand, according to the USACE (1977), Jelesnianski (1972) combined empirical data with his theoretical calculations to produce a set of nomographs that permit the rapid estimation of peak surge for any geographical location when a few storm parameters are known.

In September 1998, Hurricane Georges made eight landfalls in its 17-day journey, from islands in the northeastern and northern Caribbean Sea to the Florida Keys and finally to Biloxi, Mississippi (Pasch et al. 2001). Figure 1a shows a portion of the storm track plotted on a visible satellite image from the NOAA-14 polar-orbiting environmental satellite. A low-level wind circulation analysis of Hurricane Georges near the satellite overpass time is provided in Fig. 1b. Storm Surges related to

Hurricane Georges were measured at locations along the Gulf Coast from Louisiana to Florida (Fig. 2). A NOAA/NWS/National Data Buoy Center buoy (42040; see Fig. 1a) was located near Georges' track and recorded wave characteristics necessary for the wind-wave interaction study related to this storm.

The purpose of this investigation is to estimate the peak open-ocean surge using Jelesnianski's nomograph and to further substantiate this nomograph by recent wind-wave interaction formulations.

2. Application of Jelesnianski's Nomograph

According to Jelesnianski (1972), the corrected peak surge on the coast, S_P, can be estimated by

$$S_P = S_I F_S F_M \tag{1}$$

where S_I is the peak open ocean surge (i.e., before shoaling), F_S is a shoaling factor, and F_M is a correction factor for storm motion. Nomographs for S_I, F_S, and F_M are available (e.g., USACE 1977; see Figs. A1 - A4 in Appendix).

Around 1130 UTC 28 September 1998, Georges made its final landfall near Biloxi, Mississippi, with maximum sustained surface winds of 46 m s^{-1} (90 kt), and a minimum central pressure (P_0) of 960 hPa measured by an Air Force Reserve Command (AFRC) "Hurricane Hunter" reconnaissance aircraft at 0503 UTC (Pasch et al. 2001). The radius of maximum wind (R) was approximately 50 km (30 miles; Hsu et al. 2000). Since P_0 = 960 hPa, ΔP = (1010 hPa - P_0) = 50 hPa. Using ΔP = 50 hPa and R = 30 miles, one finds S_I = 11.2 ft from Jelesnianski's nomograph (see Fig. A1). Furthermore, F_S is approximately 1.1 (see Fig. A2). The speed of the storm was about 3.6 m s^{-1} (7 kt or 8 mph). If one approximates its track to be nearly perpendicular to the shore, F_M = 0.8 (from Fig. A4). Therefore, from Eq. (1) S_P = 9.9 ft. From Fig. 2, the surge is about 2.9 m (9.6 ft) at Pascagoula, Mississippi. Hence, we can say that Eq. (1) is a useful analytical formula.

3. Application of Wind-Wave Interaction Formulas

In order to further substantiate Eq. (1) physically, formulas related to wind-wave interaction are employed.
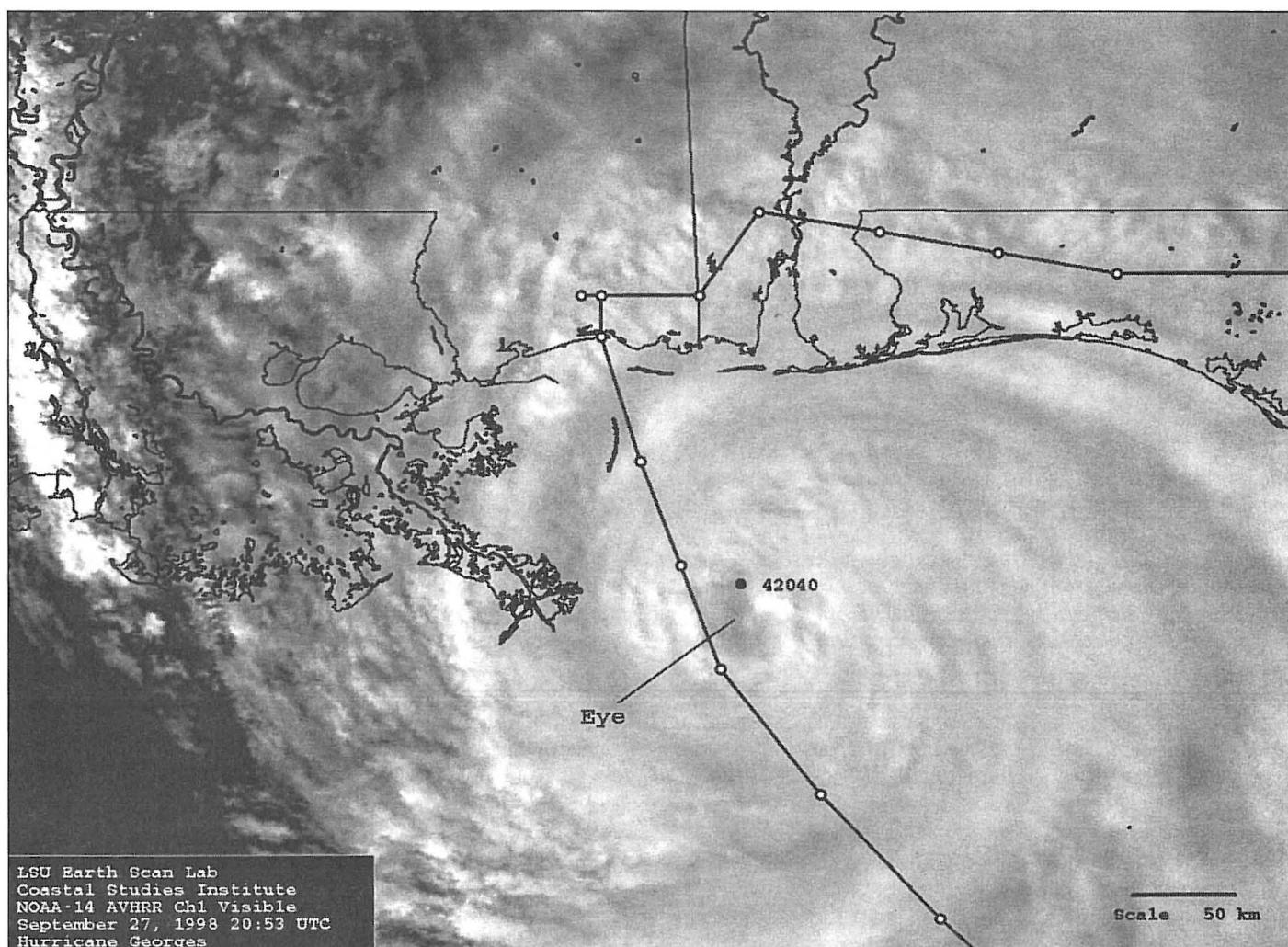
Fig. 1a. Visible image from NOAA-14 satellite and the storm track of Hurricane Georges in the northeast Gulf of Mexico. Because of its proximity to the track, data sets from NDBC buoy 42040 are employed in this study. Eye center on satellite image is estimated since cloud filled. Image courtesy of A. Babin, Earth Scan Lab, Louisiana State University.

According to the *Shore Protection Manual* (USACE 1977), the total water level rise at the coast during a hurricane is

$$S_T = S_x + S_y + S_{\Delta P} + S_e + S_A + S_W + S_L \qquad (2)$$

where S_T = total setup,

S_x = x-component setup (i.e., the direct transport by the wind stress) or the wind stress tide;

S_y = y-component setup (i.e., the Ekman transport by the wind stress) or the Coriolis tide;

$S_{\Delta P}$ = atmospheric pressure setup or the barometric tide;

S_e = initial water level;

S_A = astronomical tide;

S_W = wave setup; and

S_L = local conditions, such as freshwater runoff from land into bays or rivers.

An example of the relative magnitude for the above terms is provided for Hurricane Camille of 1969 as follows:

$S_T = 7.6$ m (25 ft);

$S_x = 6.1$ m (20 ft), or 80% of S_T;

$S_y = 0.6$ m (2 ft), or 8% of S_T;

$S_{\Delta P} = 0.3$ m (1 ft), or 4% of S_T;

$S_e = 0.4$ m (1.2 ft), or 4.8% of S_T; and

$S_A = 0.2$ m (0.8 ft), or 3.2% of S_T.

It is clear that 80% of the total surge was contributed by the x-component setup during this hurricane.

The x-component setup along the hurricane track before shoaling has been parameterized by Hsu (1999):

$$S_x = \left(\frac{\rho_a}{\rho_w K^2} \right) \left(\frac{u_*}{U_{10}} \right)^2 \left(\frac{D_s}{H_s} \right)^{-1} H_s \qquad (3)$$

where ρ_a and ρ_w are the air and water densities, respectively. K (= 0.0016) is the wind-wave interaction coefficient, u_* is the friction velocity, U_{10} is the wind speed at a height of 10 m, H_s is the significant wave height, and D_s is the shoaling depth. Note that the parameters (u_*/U_{10}) and (D_s/H_s) are normalized friction velocity and shoaling depth, respectively. It follows from Eq. (3) that from the viewpoint of dimensional analysis, S_x has the same units as H_s (meters or feet).

In order to estimate S_x from H_s, we must further parameterize (u_*/U_{10}) and (D_s/H_s). This parameterization is accomplished as follows. In the atmospheric surface boundary layer under hurricane conditions, the stability is near neutral (see Simpson and Riehl 1981, p. 201) so that

$$U_Z = \frac{u_*}{\kappa} \ln \frac{Z}{Z_0} \qquad (4)$$

where U_Z is the wind speed at height Z, κ (0.4) is the von Kármán constant, and Z_0 is the roughness length.

According to Taylor and Yelland (2001),

$$\frac{Z_0}{H_s} = 1200 \left(\frac{H_s}{L_p} \right)^{4.5} \qquad (5)$$

$$L_p = \frac{g\, T_p^2}{2\,\pi} \qquad (6)$$

where L_p is the deepwater dominant wave length, g is the gravitational acceleration, and T_p is the dominant wave period at the spectral peak. From Eq. (4) and setting $Z = 10$ m,

$$\frac{u_*}{U_{10}} = \frac{0.4}{\ln \dfrac{10}{Z_0}} \qquad (7)$$

Hurricane Georges 2230 UTC 27 September 1998
Max. 1-min sustained surface winds (kt) for marine exposure
Analysis based on 850 mb AF C-130 Recon minobs adj. to sfc. from 1753 - 2156 z;
Three GPS Dropwindsondes; C-MAN, buoys, and ships from 1800 - 2100 z;
CIMSS GOES Low-Level cloud drift winds adj. to sfc from 1900 z
2230 z position extrapolated from 2111 z fix using 320 deg @ 7 kt

Valid only for MARINE exposure at 10-m

Max Sustained Wind
77 kt 27 nm NE of center
based on 1256 z GPS Dropwindsonde

Experimental research product of :
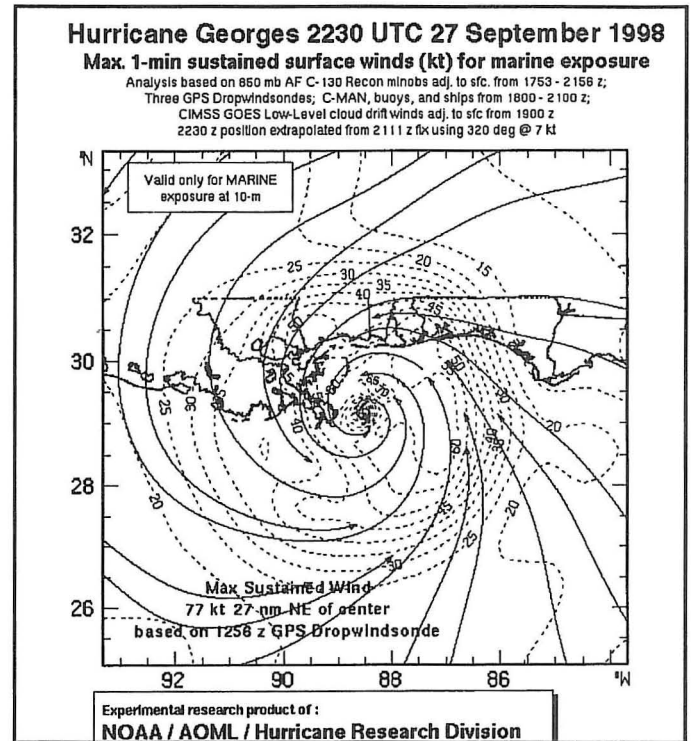**NOAA / AOML / Hurricane Research Division**

Fig. 1b. The wind circulation of Hurricane Georges at 2230 UTC 27 September 1998, based on the composite datasets provided by the NOAA Atlantic Oceanographic and Meteorological Laboratory, Hurricane Research Division.
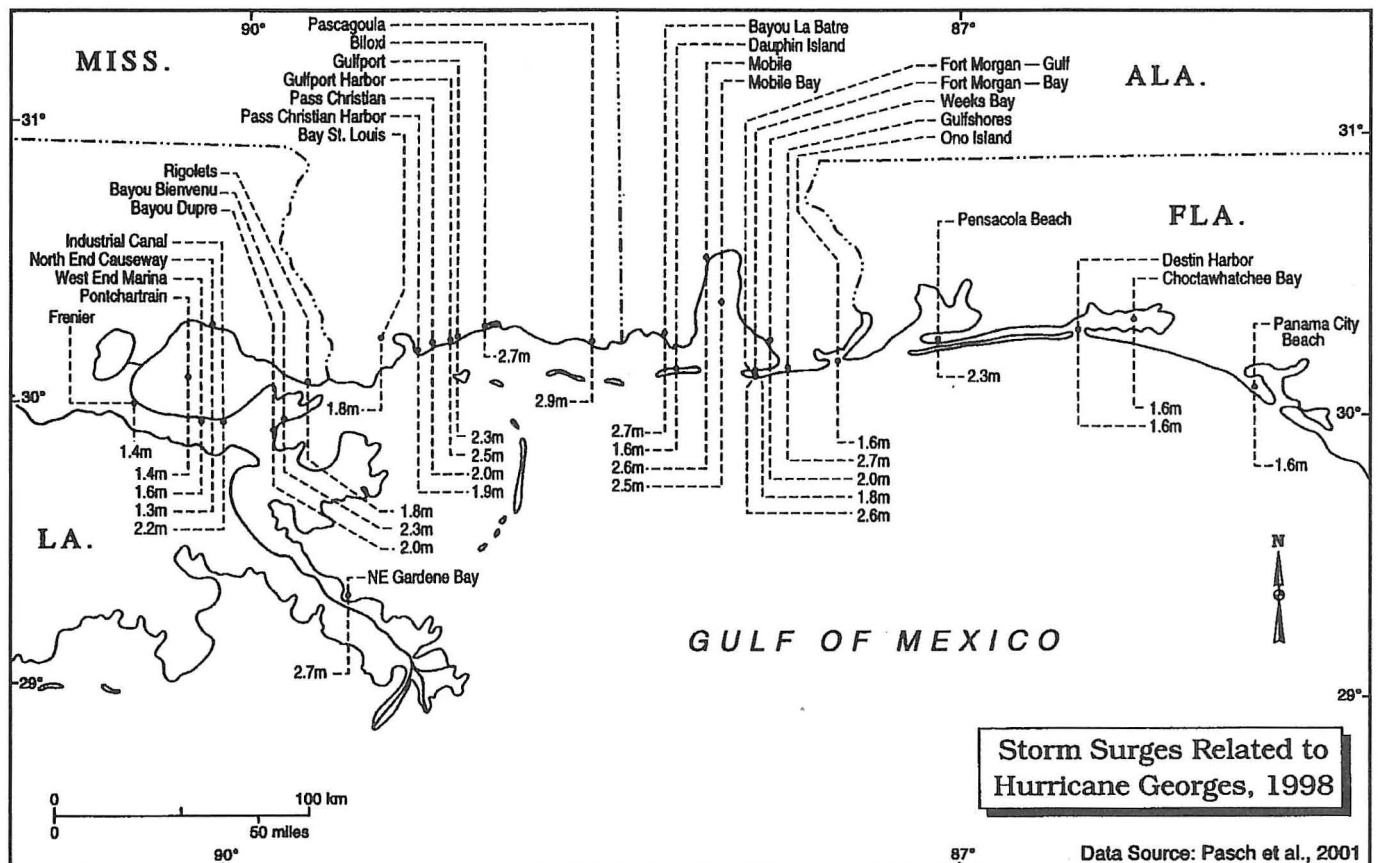

Fig. 2. Measured storm surges at locations along the northeast Gulf coast induced by Hurricane Georges. The hurricane made landfall near Biloxi, Mississippi on 28 September 1998. For clarity, the storm track is omitted.

Table 1. Measured wave parameters from NDBC buoy 42040 in the Gulf of Mexico during Hurricane Georges, 27-28 September 1998. (Data source: http://seaboard.ndbc.noaa.gov)

Date	Time (UTC)	H_S (m)	T_P (sec)	$\dfrac{H_S}{gT_p^2}$	$\dfrac{u_*}{U_{10}}$
27	11	8.21	12.5	0.0054	0.048
	12	9.36	14.29	0.0047	0.045
	13	9.97	12.5	0.0065	0.055
	14	8.56	12.5	0.0056	0.049
	15	8.84	12.5	0.0058	0.050
	16	9.48	12.5	0.0062	0.053
	17	8.98	12.5	0.0059	0.051
	18	9.87	11.11	0.0082	0.064
	19	10.88	12.5	0.0071	0.059
	20	9.83	12.5	0.0064	0.054
	21	8.99	11.11	0.0074	0.059
	22	7.86	11.11	0.0065	0.053
	23	7.13	10.0	0.0073	0.056
28	0	7.43	9.09	0.0092	0.066
	1	7.02	9.09	0.0087	0.063
	2	6.09	9.09	0.0075	0.056
	3	7.16	10.0	0.0073	0.056
	4	6.51	9.09	0.0080	0.059
	5	6.40	9.09	0.0079	0.058
	6	5.88	9.09	0.0073	0.055
	7	6.13	9.09	0.0076	0.056
	8	5.78	9.09	0.0071	0.054
	9	5.76	9.09	0.0071	0.054
	10	5.37	11.11	0.0044	0.042
	11	5.19	9.09	0.0064	0.050
	12	5.21	9.09	0.0064	0.050
	13	5.40	9.09	0.0067	0.051
	14	5.02	10.0	0.0051	0.044
	15	5.17	9.09	0.0064	0.050
	16	5.06	7.69	0.0087	0.060
	Mean			0.0068	0.054
	Standard Deviation			0.0012	0.0057
	Coefficient of Variation			17.6%	10.6%

and from Eqs. (5) and (6)

$$Z_0 = 1200\, H_s \left(\frac{2\,\pi\,H_s}{g\,T_p^2} \right)^{4.5} \tag{8}$$

Simultaneous measurements of H_s and T_p during Hurricane Georges in 1998 are provided in Table 1. The mean and standard deviation during this 30-h period for u_*/U_{10} are 0.054 ± 0.0057. Therefore, the coefficient of variation (ratio of s.d. / mean) is 10.6%. Note that this mean value is not significantly different from that of 0.0504 for $U_{10} > 20$ m s^{-1} as suggested by Amorocho and DeVries (1980), since the difference between the two means is less than 7%.

According to Taylor and Yelland (2001), a large increase in the sea surface roughness is predicted for shoaling waves if the depth is less than about 0.2 L_p (where L_p is the peak wavelength for the combined sea and swell spectrum). If one approximates that

$$D_s = 0.2\, L_p = 0.2 \frac{g\, T_p^2}{2\,\pi} \tag{9}$$

then

$$\frac{D_s}{H_s} = \frac{0.2\, g\, T_p^2}{2\,\pi\, H_s} = \frac{0.2}{2\,\pi} \left(\frac{H_s}{g\, T_p^2} \right)^{-1} \tag{10}$$

According to USACE (1984, p. 3-85, Eq. 3-64),

$$T_p = 12.1 \sqrt{\frac{H_s}{g}} \tag{11}$$

$$\therefore \frac{H_s}{g\, T_p^2} = 0.0068 \tag{12}$$

Eq. (12) is verified in Table 1 since the mean H_s/gT_p^2 is 0.0068.

Substituting Eq. (12) into Eq. (10) yields

$$D_s = 4.68\, H_s \tag{13}$$

Now, substituting the following values into Eq. (3)
 $\rho_a = 1.2$ kg m^{-3}
 $\rho_w = 1025$ kg m^{-3}
 $K = 1.6 * 10^{-3}$
 $u_*/U_{10} = 0.054$
and Eq. (13), we have

$$S_x = 0.285\, H_s \tag{14a}$$

From Table 1, the maximum H_s was 10.88 m, therefore Eq. (14a) becomes

$$S_{x\,\text{max}} = 0.285 * 10.88\ m = 3.1\ m \tag{14b}$$

According to Dean and Dalrymple (2002; p. 84), the total storm surge is the sum of four components: the barometric tide, the wind-stress tide, the Coriolis tide, and the wave setup. Since both Coriolis tide and wave setup have greatest effect in the nearshore region, we postulate from Eq. (2) that, before shoaling,

$$S_I = S_x + S_{\Delta P} \tag{15}$$

Also, from Dean and Dalrymple (2002; p. 81)

$$S_{\Delta P} = 0.0104 \, \Delta P \qquad (16)$$

Since $\Delta P = 50$ mb, $S_{\Delta P} = 0.5$ m. $S_x = 3.1$, hence the maximum S_I is 3.6 m (11.8 ft) from Eq. (15). The difference between this value and that of 3.4 m (11.2 ft; see Section 2) is about 5%, therefore we can say that Jelesnianski's nomograph is further substantiated by the physics of wind-wave interaction.

4. Further Simplification of Equation 14a

Because measurements of H_s are often not as available as those of ΔP, we need to use the pressure difference in Eq. (14a). This is done as follows:
According to Hsu (1991, 1994) and Hsu et al. (2000),

$$H_s = 0.2 \, \Delta P \qquad (17a)$$

$$\Delta P = \left(1013 \; hPa - P_0 \right) \qquad (17b)$$

Equation (17b) is used traditionally in wind-wave interaction (see, e.g., USACE 1977). However, under hurricane conditions, $\Delta P = (1010 \text{ hPa} - P_0)$ is normally applied (J. Chen, personal communication). To be consistent for the tropical environment, Eq. (17b) is adjusted so that

$$H_s = 0.2 \left(1013 \; hPa - P_0 \right) = A \left(1010 \; hPa - P_0 \right) \quad (17c)$$

where

$$A = \frac{0.2 \left(1013 \; hPa - P_0 \right)}{\left(1010 \; hPa - P_0 \right)} \qquad (17d)$$

Since $P_0 = 960$ hPa for Georges,

$$\begin{aligned} A &= 0.21 \\ \therefore H_s &= 0.21 \left(1010 \; hPa - P_0 \right) \end{aligned} \qquad (17e)$$

Now substituting Eq. (17e) into Eq. (14a), we have

$$S_x = 0.060 \left(1010 \; hPa - P_0 \right) \qquad (18)$$

From equations (15), (16), and (18), we get

$$S_I = 0.070 \left(1010 \; hPa - P_0 \right) \qquad (19)$$

Using $\Delta P = 50$ hPa as before, Eq. (19) estimates that $S_I = 3.5$ m (11.5 ft). This value is in excellent agreement with that of 3.4 m (11.2 ft) as estimated from Jelesnianski's

nomograph as discussed in Section 2. Therefore, the following equation is useful, that from Eq. (1) and Eq. (19)

$$S_P = \left(0.070 \, \Delta P \right) F_S F_M \qquad (20a)$$

where

$$\Delta P = \left(1010 \; hPa - P_0 \right) \qquad (20b)$$

5. Some Comments on the S_I Nomograph

According to Jelesnianski (1972), the nomograph for S_I was constructed for a hurricane moving perpendicular to the coastline at a speed of ~ 6.7 m s^{-1} (15 mph). Under these conditions the highest surge elevations occur with large values of ΔP for $R = \sim 48$ km (30 statute miles). This curve may be digitized so that S_I varies approximately linearly with ΔP as

$$S_I = 0.069 \, \Delta P \qquad (21)$$

where S_I is in meters and ΔP in hPa.

It is interesting to note that this R value (48 km) is also the composite mean (with a standard deviation of only 3 km) between categories 2 and 4 based on 59 hurricanes affecting the U.S. coastline from 1893 through 1979 (Hsu and Yan 1998). The composite mean R is 47 km for all hurricanes as compiled with central presssures between 909 and 993 hPa. Since Eq. (21) and Eq. (19) are nearly the same, and since 90% of the hurricanes studied were within categories 2 and 4, Eq. (20a) is an excellent approximation for operational use.

Furthermore, some information about the general movement or speed of a typical hurricane may be useful. According to Simpson and Riehl (1981, Table 36), there were 48 hurricanes between 1893 and 1979 with major open-coast storm surges affecting the U.S. for which definitive speeds were obtained. The mean speed is 5.5 m s^{-1}, with a standard deviation of 1.7 m s^{-1}. The coefficient of variation is approximately 0.3; consequently about 70% of the hurricanes moved at a speed of 5.5 m s^{-1} (12 mph). Since this mean speed is not very much different from that of 15 mph as used in construction of the S_I nomograph, this further reinforces our recommendation that Eq. (20a) and Eq. (20b) are useful operationally. This rapid estimation method may be applied as a supplement to the numerical simulation such as SLOSH model as mentioned in Section 1.

6. Conclusions

Several conclusions can be drawn from this study:
a. The measured peak storm surge along the northeast Gulf coast induced by Hurricane Georges in 1998 was approximately 3 m (10 ft), and was located within the radius of maximum wind as expected;

b. Estimation of the peak onshore surge is also about 3 m (10 ft) based on Jelesnianski's nomographs;

c. Jelesnianski's open ocean surge nomograph is further substantiated physically by recent advances in wind-wave-surge interaction studies;

d. For operational use, an analytical formula Eq. (20a) is provided. It is recommended that this equation be subjected to further verification and improvement using more pertinent tropical cyclone datasets.

Acknowledgments

Author

Dr. S. A. Hsu has been a Professor of Meteorology at LSU since 1969, after he earned his Ph.D. in Meteorology from the University of Texas at Austin. He is the author of *Coastal Meteorology* (Academic Press, 1988) and numerous papers on coastal and marine meteorology and air-sea interaction. Dr. Hsu is also an AMS Certified Consulting Meteorologist. Dr. Hsu can be contacted at the LSU Coastal Studies Institute, 308 Howe-Russell Geoscience Building, Baton Rouge, Louisiana 70803-7527; e-mail: sahsu@antares.esl.lsu.edu.

References

Amorocho, J., and J. J. DeVries, 1980: A new evaluation of the wind stress coefficient over water surfaces. *J. Geophys. Res.*, 85(C1), 433-442.

Dean, R. G., and R. A. Dalrymple, 2002: *Coastal Processes With Engineering Applications*. Cambridge University Press, 475 pp.

Hsu, S. A., 1991: Forecasting hurricane waves. *Mariners Weather Log*, 35(2), 57-58.

_____, 1994: Estimating hurricane waves. *Mariners Weather Log*, 38(1), 68.

_____, 1999: Effects of wave dynamics on the wind setup in deep water. *The Wind-Driven Air-Sea Interface*, M. L. Banner, Ed. School of Mathematics, The University of New South Wales, Sydney, Australia, 57-64. [Available from CEMAP, School of Mathematics, University of New South Wales, Sydney, NSW, 2052, Australia.]

_____, M. F. Martin, Jr., and B. W. Blanchard, 2000: An evaluation of the USACE's deepwater wave prediction techniques under hurricane conditions during Georges in 1998. *J. Coastal Res.*, 16, 823-829.

_____, and Z. Yan, 1998: A note on the radius of maximum wind for hurricanes. *J. Coastal Res.*, 14, 667-668.

Jelesnianski, C. P., 1972: SPLASH (Special Program to List Amplitudes of Surges for Hurricanes): 1. Landfall storms. NOAA Tech. Memo. NWS TDL-46, 52 pp. [NTIS COM-72-10807.]

_____, J. Chen, and W. A. Shaffer, 1992: SLOSH: Sea, lake, and overland surges from hurricanes. NOAA Tech. Rep. NWS 48, 71 pp. [Available from NOAA/AOML Library, 4301 Rickenbacker Causeway, Miami, FL 33149.]

Pasch, R. J., L. A. Avila, and J. L. Guiney, 2001: Atlantic hurricane season of 1998. *Mon. Wea. Rev.*, 129, 3085-3123.

Simpson, R. H., and H. Riehl, 1981: *The Hurricane and Its Impact*. Louisiana State University Press, Baton Rouge, LA, 398 pp.

Taylor, P. K., and M. J. Yelland, 2001: The dependence of sea surface roughness on the height and steepness of the waves. *J. Phys. Oceanogr.*, 31, 572-590.

U. S. Army Corps of Engineers (USACE), 1977: *Shore Protection Manual*. 3rd ed. US Government Printing Office, 3-101 - 3-145.

_____, 1984: *Shore Protection Manual*. 4th ed. US Government Printing Office, 1088 pp.

Appendix
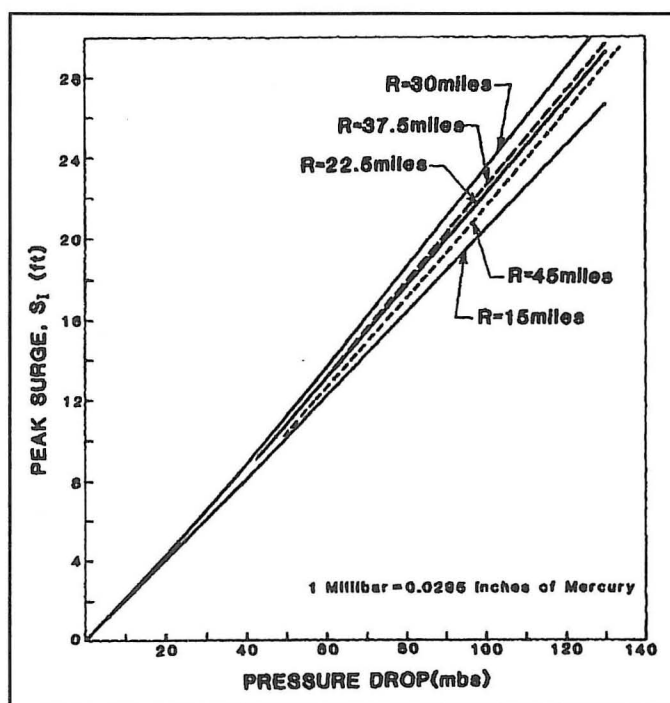
Figures from Jelesnianski (1972)

Fig. A1. Preliminary estimate of peak surge.

Fig. A2. Shoaling factors for Gulf Coast.

Fig. A4. Correction factor for storm motion.

Fig. A3. Shoaling factors for East Coast.