2012

# The Reduction of Storm Surge by Vegetation Canopies: Three-Dimensional Simulations

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## Original Publication Citation

Sheng, Y. P., Lapetina, A., & Ma, G. (2012). The reduction of storm surge by vegetation canopies: Three-dimensional simulations. *Geophysical Research Letters*, *39*(20), L20601. doi:10.1029/2012GL053577

# The reduction of storm surge by vegetation canopies: Three-dimensional simulations

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Received 15 August 2012; revised 7 September 2012; accepted 11 September 2012; published 16 October 2012.

[1] Significant buffering of storm surges by vegetation canopies has been suggested by limited observations and simple numerical studies, particularly following recent Hurricanes Katrina, Rita, and Wilma. Here we simulate storm surge and inundation over idealized topographies using a three-dimensional vegetation-resolving storm surge model coupled to a shallow water wave model and show that a sufficiently wide and tall vegetation canopy reduces inundation on land by 5 to 40 percent, depending upon various storm and canopy parameters. Effectiveness of the vegetation in dissipating storm surge and inundation depends on the intensity and forward speed of the hurricane, as well as the density, height, and width of the vegetation canopy. Reducing the threat to coastal vegetation from development, sea level rise, and other anthropogenic factors would help to protect many coastal regions against storm surges. **Citation:** Sheng, Y. P., A. Lapetina, and G. Ma (2012), The reduction of storm surge by vegetation canopies: Three-dimensional simulations, *Geophys. Res. Lett.*, *39*, L20601, doi:10.1029/2012GL053577.

## 1. Introduction

[2] We analyze the effectiveness of coastal vegetation as natural barriers against storm surges and waves. Sparse observations have found a decrease in storm surge of nearly 1 m over a 20 km transect [*Krauss et al.*, 2009]. But the few existing observations are not sufficient to quantitatively determine the importance of different vegetation parameters, such as density, width, and height, in blocking storm surge and reducing inundation, because of their inability to isolate the effects of vegetation-induced drag and Reynolds Stresses from changes in bathymetry, bottom friction, and individual storm characteristics.

## 2. Recent Past Studies

[3] Recent numerical simulations of storm surge over vegetation canopies [*Loder et al.*, 2009; *Wamsley et al.*, 2010] used a two-dimensional storm surge model and parameterized the vegetation-induced friction with a Manning coefficient (0.1–0.3) an order of magnitude larger than that for sand (0.02). This 2D approximation, however, fails to adequately account for the complex flow over and within vegetation in storm and non-storm conditions. This study uses a 3D model and explicitly accounts for the drag forces (skin friction drag and profile drag) introduced by the vegetation canopy throughout the water column, as well the creation of turbulent kinetic energy (TKE) by the wakes behind vegetation [*Nepf and Vivoni*, 2000], and Reynolds stresses associated with shear.

## 3. This Study

[4] We use a three-dimensional vegetation-resolving storm surge model with idealized topography to estimate the effect of vegetation canopies on storm surge and inundation. The inundation is defined as the total inundation volume generated by a storm. The effect of vegetation on total inundation volume is measured by a quantity defined as the Vegetation Dissipation Potential (VDP), which is the percent reduction of total inundation volume (TIV) due to the presence of vegetation canopy. VDP, determined for a given simulation is:

$$VDP = 1 - \frac{(TIV)_v}{(TIV)_0} = 1 - \frac{\iint_{Landward\ area} H_v\, dxdy}{\iint_{Landward\ area} H_0\, dxdy} \qquad (1)$$

where $H(x, y)$ is the maximum water level over the course of an entire simulation, and where the subscript $v$ indicates the presence of a vegetation canopy and the subscript 0 indicates the absence of a canopy. The VDP represents the maximum possible vegetation-induced reduction of inundation by taking into account all effects of the canopy in all directions and using a change in maximum occurring water level over a large area, allowing comparison between different hurricanes. This approach enables accurate calculation of the total dissipative effects of the vegetation canopy for an entire storm over an entire domain. For example, if 10 km$^3$ is the total inundation volume from a given hurricane with no vegetation present, but a vegetation canopy reduced this volume to 6 km$^3$, the vegetation dissipates 40% of the storm surge, and the VDP is 40%. The benefit of this spatially integrated metric over the single-point metric ($H_v/H_o$ at a given $x$, $y$ location) is demonstrated by the significant spatial variability of $H_v/H_o$ [*Loder et al.*, 2009] which underscores the need for a spatially integrated vegetation dissipation potential (VDP) to quantify the impacts of vegetation on a regional scale.

## 4. A Vegetation-Resolving Storm Surge Modeling System

[5] The coupled CH3D-SWAN model, an integrated storm surge-wave model, was selected in part for its demonstrated skill in reproducing the observed storm surges and waves

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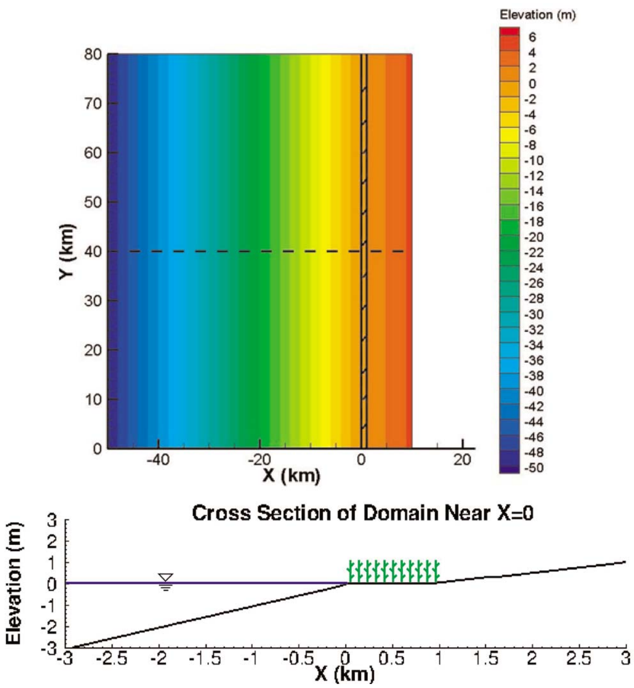


**Figure 1.** Theoretical domain for evaluating the influence of vegetation canopies on dissipating storm surge. Hashed region in plan view denotes where the elevation is 0 and vegetation may be present in Experiments 1 and 2. Dashed line is hurricane path.

during hurricanes [*Sheng et al.*, 2010a, 2010b; *Davis et al.*, 2010; *Sheng and Liu*, 2011]. The model includes a TKE model to represent the vegetation-induced skin friction drag and profile drag as well as the turbulence generation by the wakes behind the vegetation, by simplifying a vegetation-resolving Reynolds Stress turbulence model [*Lewellen and Sheng*, 1980; *Sheng*, 1982]. In the mean flow equations, the skin friction drag and the profile drag are proportional to the wetted vegetation area and frontal vegetation area, respectively, both using a quadratic stress law. In the TKE equation, the generation of TKE by the turbulent wakes behind the vegetation is included. The drag coefficients are set to 0.125 and 0.2 for skin friction drag and profile drag, respectively, both consistent with the available literature [*Novak et al.*, 2000]. Detailed CH3D model equations and boundary conditions can be found in *Sheng et al.* [2010a, 2010b] and *Sheng and Liu* [2011], while detailed SWAN equations are found in *Booij et al.* [1999] and *Suzuki et al.* [2012]. Detailed vegetation-resolving TKE model equations are shown in the Appendix. The TKE model is found to accurately simulate unsteady flow and turbulence over vegetation canopy in laboratory flume experiments [*Neumeier*, 2007] as well as steady flows [*Nepf and Vivoni*, 2000].

## 5. Vegetation Effects on Mean Flow and Turbulence

[6] The major improvement to understanding the physics of storm surge provided here is the inclusion of drag, shear and Reynolds stress from the vegetation to allow accurate quantitative calculation of vegetation dissipation. Prior efforts to study the influence of vegetation on storm surge were limited to simulating it entirely as bottom friction, but this study uses more realistic and complete physical modeling of flow through emergent and submerged canopies. During a storm surge event, coastal vegetation starts as fully emergent, and as water moves onshore, transitions to having a water depth equal to canopy height. Eventually, the vegetation is fully submerged. Flow and turbulence structures are highly dependent upon water depth to vegetation height ratios in a non-linear fashion [*Nepf and Vivoni*, 2000], and the inclusion of Reynolds Stresses, shear and drag in these simulations is necessary and unprecedented.

## 6. Important Storm and Vegetation Parameters

[7] Important parameters of storms to consider include storm intensity and forward speed. Storm intensity is dictated by wind speed via the Saffir Simpson scale (http://nhc.noaa.gov/aboutsshws.php), with higher maximum wind speeds correlating to higher category storms. Forward speed, the translational speed of the eye of the storm, determines the duration over which the storm is driving water onshore. Intuition and limited observations suggest that faster moving storms will have higher dissipation, because there is less time for the storm wind to overcome friction from the vegetation canopy. Important parameters of the vegetation canopy to consider are vegetation height, vegetation density, and width of the vegetation zone. Laboratory experiments have demonstrated that increases in vegetation height and density cause flow reduction and turbulence production, which would increase VDP [*Neumeier*, 2007; *Nepf and Vivoni*, 2000]. It is expected that wider canopies would result in greater dissipation, but the rate of increase is unknown.

## 7. Three-Dimensional Numerical Simulations

[8] For these simulations, an idealized bottom slope of 1:1000 over 50 km of the continental shelf is used which represents the typical bottom slope in the northern Gulf of Mexico (Figure 1). Along the shoreline, at an elevation of zero, and extending along the entire domain, is a strip of land where vegetation is introduced. Winds are parameterized from the Holland wind model [*Holland*, 1980], and waves are included through two-way coupling between CH3D and SWAN, which includes a vegetation model for wave energy [*Suzuki et al.*, 2012]. However, while waves are included in the model simulation, their contribution to inundation is negligible on gently sloping shelves where coastal vegetation canopies exist [*Resio and Westerink*, 2008], and observations show that waves are depth limited and dissipated within a few wavelengths from the canopy edge [*Smith et al.*, 2010]. These findings are consistent with our model results.

## 8. Simulation Results

[9] Results from two experiments are presented here. In experiment 1, a Category 2 storm (maximum sustained winds of 49 m/s) moves at 6.71 m/s (15 mph) onshore over vegetation canopies varying in height (50–125 cm), density (100–300 stems/$m^2$), and width (0.5–1.5 km), and the variability in dissipation is found. In experiment two, a typical canopy (75 cm tall, 200 stems/$m^2$, 1 km wide) is forced with storms of varying intensity (Category 1–5) (maximum sustained winds between 33.8 m/s and 70.2 m/s) and forward speed (4.47–8.94 m/s) (10–20 mph). Vegetation was a Spartina-like

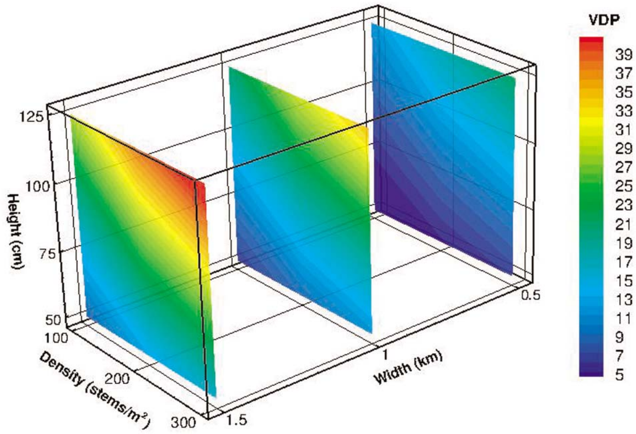


**Figure 2.** Dissipation of storm surge by vegetation canopies for a Category 2 (maximum sustained winds of 49 m/s) storm moving onshore at 6.71 m/s (15 mph).

canopy, with a stem diameter of 1.3 cm and a leaf area 8 times that of the frontal area, like other studies using leafy vegetation [*Lewellen and Sheng*, 1980]. We consider landfalling hurricanes which approach the coastline perpendicularly and produce the highest possible storm surge compared to hurricane approaching from other directions. Results for each experiment are shown in Figures 2 and 3, respectively. The model results follow similar trajectory and pattern as *Loder et al.* [2009]. However, *Loder et al.* [2009] estimated the vegetation dissipation by considering only a few selected stations which, in combination with the use of a simplistic 2D model and Manning's n approach to parameterize vegetation dissipation, produced excessively high vegetation dissipation (~90%).

## 9. Discussion

[10] The first experiment clearly shows that dissipation is greater in canopies of increased density, height and width. As shown in Figure 2, VDP varies between 5–40%, it increases approximately 3-fold when canopy density increases from 100 to 300 stems/m$^2$, when canopy height increases from 50 to 125 cm, or when canopy width increases from 0.5 to 1.5 km. It is clear that the three factors are equally important in increasing vegetation dissipation although canopy width seems slightly more important. Increases associated with density are results of greater drag within the canopy and greater turbulence production. Increases associated with height are results of the shift of shear layers upwards, which reduces depth integrated flows within the canopy. Increases from increased canopy width are a result of the canopy's influence on a greater spatial dimension of the surge.

## 10. Effect of Vegetation Parameters

[11] As shown in Figure 1, each simulation begins with water levels at an elevation of 0, and water levels increase as inundation occurs, with flood water eventually receding. The result within the vegetation canopies is that at various times some cells have emergent flow while others have fully submerged flow, and some canopies have highly submerged flow. Figure 4 illustrates this by showing a transect parallel to the y-axis on the landward side of the hashed region of Figure 1. Compared in each panel are maximum water levels from a vegetation free simulation and the maximum water levels with 1.5 km wide canopies. Note that for some locations in 1–1.25 m canopies, flow is always emergent, whereas shorter canopies have highly submerged flows. Figure 4 also illustrates the inability of the variation in water level at a single location to properly account for the total influence of the canopy on the storm surge event, and thus the value of the VDP.

## 11. Effect of Storm Parameters

[12] The second experiment shows that fast and strong storms exhibit greater VDP as compared to slow and weak storms. Fast storms have higher dissipation because onshore winds are present for a shorter duration, indicating an increased relative resistance of vegetation as compared to slow storms with onshore winds lasting longer. VDP doubles as the forward speed doubles from 4.47 to 8.94 m/s. Strong storms blow faster winds, and because profile drag and skin friction follow quadratic relationships, greater resistance to inundation is observed, particularly at higher forward speed. Also, strong storms blow stronger winds over a larger length of canopy, utilizing the dissipative potential of a greater area of canopy than weak storms. This agrees with limited observations from slow moving and fast moving storms [*Resio and Westerink*, 2008]. During a slow moving hurricane, vegetation dissipation is rather low (VDP < 15%) even in a Category 5 hurricane.

## 12. Conclusion

[13] Coastal vegetation can clearly play a role in reducing storm surge and coastal inundation in gently sloping shelves. Vegetation height, density, and width are greatly influenced by numerous anthropogenic and natural factors. A better understanding of the relationship between these factors (e.g., the destructive forces of storm surge, winds, waves, and erosion; and sea level and salinity) and vegetation is needed

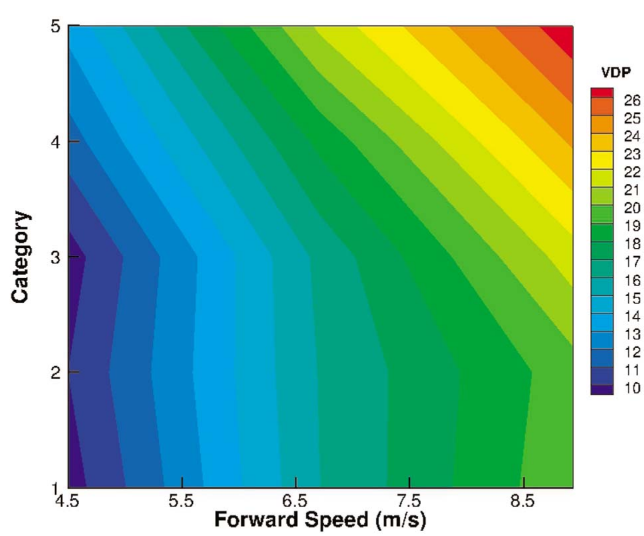


**Figure 3.** Dissipation of storm surge by a 75 cm tall vegetation canopy of 200 stems/m$^2$ for storms of varying magnitude and forward speed.

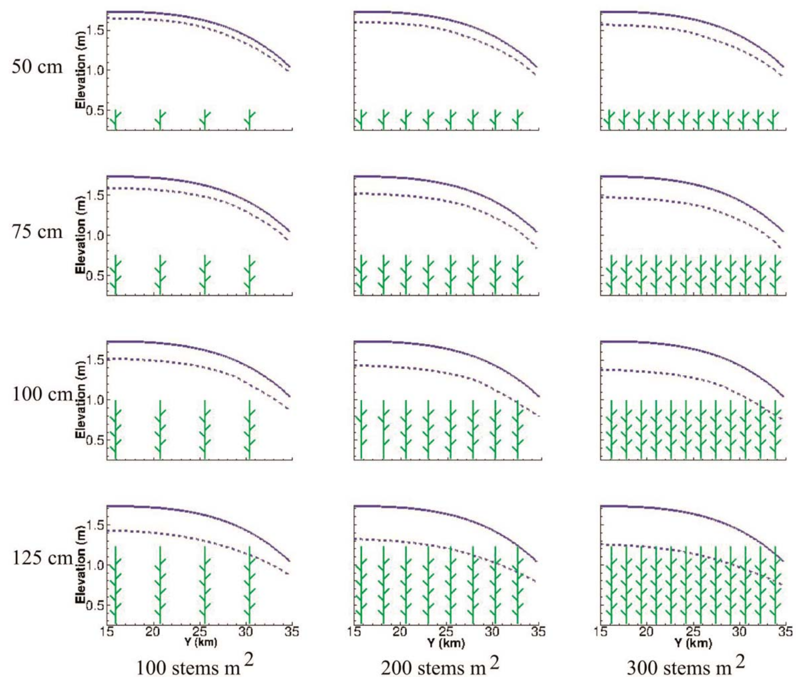


**Figure 4.** Maximum water levels on landward side of hashed region in Figure 1 for Category 2 storm in Experiment 1. Solid blue line shows maximum water levels over the course of the storm for vegetation-free simulation, dashed lines show maximum water levels when vegetation canopy present. All results shown for a 1.5 km wide canopy.

to more accurately quantify the dissipation of storm surge by vegetation canopies.

## Appendix A: Equations for the 1D TKEM (Turbulent Kinetic Energy Model)

[14] The equations for the TKEM for 1D flow in the presence of a vegetation canopy are shown [*Lewellen and Sheng*, 1980; *Sheng*, 1982]. Both turbulent and viscous stresses are considered. In the limit of no vegetation, this TKEM and the Reynolds Stress Model (RSM) from which this TKEM is derived are equivalent a well validated vegetation-free TKEM and RSM [*Sheng and Villaret*, 1989].

[15] Mean Momentum Equation:

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = \left[ C_f A_w + C_p A_f \left( 1 + \frac{u_j^2}{q^2} \right)^{1/2} \right] q u_i - \frac{1}{\rho} \frac{\partial P}{\partial x_i} - \frac{\partial}{\partial x} \left[ A_v \frac{\partial u_i}{\partial x_j} \right] + \frac{\partial}{\partial x_j} \left( \nu \frac{\partial u_i}{\partial x_j} \right) \quad \text{(A1)}$$

TKE Equation:

$$\frac{\partial q^2}{\partial t} + u_k \frac{\partial q^2}{\partial z} = 2C_p \left( e^2 + q^2 \right)^{1/2} A_f e^2 - 2 C_f A_w q^3 + 2A_v \left[ \left( \frac{\partial u}{\partial z} \right)^2 + \left( \frac{\partial v}{\partial z} \right)^2 \right] + 0.3 \frac{\partial}{\partial z} \left( q \Lambda \frac{\partial q^2}{\partial z} \right) - \frac{q^3}{4\Lambda} \quad \text{(A2)}$$

where ($i$, $j$, $k$) = (1, 2, 3), $x_i$ are coordinate axes, $t$ is time, ($u_i$, $u_j$, $u_k$) are the mean velocity components, $q = \left( \overline{u_l' u_l'} \right)^{1/2}$ is the total rms fluctuating velocity, $\kappa$ is molecular diffusivity, $\Lambda$ is the turbulence macroscale which is a measure of the average turbulent eddy size, $C_p$ is the profile drag coefficient, $C_f$ is the skin friction coefficient, $A_w$ is the wetted area per unit volume, $A_f$ is the frontal area per unit volume, $q$ is the square root of twice the TKE, and $\nu$ is molecular viscosity. The drag term shown in equations (A1) and (A2) is different from those typically used by civil engineers or ocean engineers, but is believed to be more accurate and suitable for turbulent flow in vegetation canopies, since the root mean square turbulent velocity is included in the quadratic stress relationship. $C_f$ is determined from:

$$C_f = c_1 \left( \frac{\nu}{q\Lambda} \right)^{1/4} \quad \text{(A3)}$$

where $\nu$ is molecular viscosity and $c_1$ is a constant.

[16] The profile drag can also break up the eddies to increase the dissipation which is accounted for by reducing the dissipation length scale $\Lambda$, giving [*Wilson and Shaw*, 1977]:

$$\left| \frac{d\Lambda}{dz} \right| \le 0.65 \quad and \quad \Lambda \le \frac{\alpha}{C_p A_f} \qquad \Lambda = 0 \; at \; z = 0 \quad \text{(A4)}$$

where $\alpha$ is a model constant dependent upon canopy geometry. $A_v$ and $K_v$ are turbulent eddy viscosity and diffusivity, which can be derived from the RSM as:

$$K_v = \frac{2C_p (e^2 + q^2)^{1/2} A_f w^2 + \frac{q^3}{4\Lambda}}{A_1 A_2} \qquad A_v = \frac{A_2^2}{(A_1 A_2)} K_v \quad \text{(A5)}$$

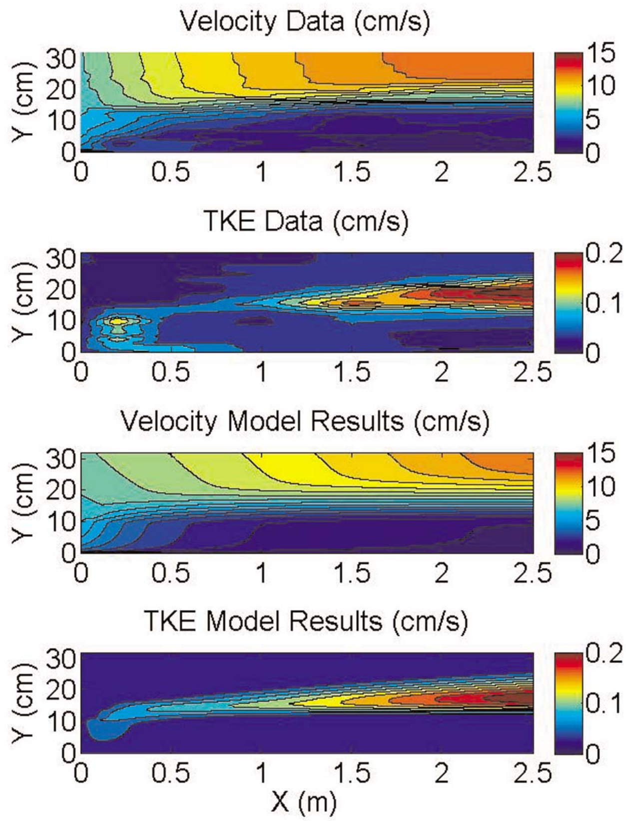


**Figure A1.** Continuous velocity and turbulence profiles from experiments by *Neumeier* [2007]. Top panels show data from Case BB, and bottom panels show model results.

where

$$A_1 = 2C_f A_w q + \frac{q}{\Lambda} \quad (A6)$$

$$A_2 = C_f A_w q\left(1 + \sigma_t^{0.7}\right) + 0.75\frac{q}{\Lambda} \quad (A7)$$

$$A_3 = 2C_f \sigma_t^{0.7} A_w q + 0.45\frac{q}{\Lambda} \quad (A8)$$

$$\sigma_t = \frac{\kappa}{\nu} \quad (A9)$$

where $\sigma_t$ is the Schmidt number, and $e^2 = u^2 + v^2 + w^2$.

[17] The model's ability to simulate flow and turbulence in an unsteady flow flume experiment is shown in Figure A1 [*Neumeier*, 2007]. This laboratory experiment used real *Spartina anglica* grasses, and shows both good correlation between data and modeling, as well as the ability of the model to simulate shear production, drag, and dissipation within the canopy.

[18] **Acknowledgments.** The work is supported by the University of Florida and Florida Sea Grant.

[19] The Editor thanks Tad Murty and Urs Neumeier for assisting in the evaluation of this paper.

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