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Impacts of hurricanes on surface water flow within a wetland

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1 Impacts of Hurricanes on Surface Water Flow within a Wetland

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38 **Abstract:** Between 2001 and 2005, seven category 3 or higher major hurricanes made
39 landfall within the U.S. The hydrologic impacts of these distinct climatic phenomena
40 frequently occurring in wetland watersheds, however, are not well understood. The focus
41 of this study was to evaluate the impacts of hurricane wind and rainfall conditions on
42 water velocity and water elevations within the study wetland, the Florida Everglades.
43 Specifically water velocity data was measured near two tree islands (Gumbo Limbo (GL)
44 and Satin Leaf (SL)) and wind speed, water elevation, and rainfall were obtained from
45 nearby wind observation stations. During the direct impacts of the hurricanes (Hurricanes
46 Katrina and Wilma), water speed, flow direction, and hydraulic gradients were altered,
47 and the extent of variation was positively related to wind characteristics, with significant
48 alterations in flow direction at depth during Hurricane Wilma due to higher wind speeds.
49 After the direct impacts, the longer lasting effect of hurricanes (time scale of a few days)
50 resulted in altered flow speeds that changed by 50% or less. These longer lasting
51 changes in flow speeds may be due to the redistribution of emergent vegetation.

52

53 **Keywords:** hurricane; wetland; water velocity; wind velocity

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59 **1. Introduction**

60 Water flow is a major determinant in all wetlands significantly impacting ecosystem
61 quality and function (Reimold, 1994). Anecdotal evidence indicates that hurricanes are
62 able to cause major changes in wetland hydrology thereby affecting processes that
63 influence wetland sustainability (Twilley, 2007). However, due to the recent
64 advancements and proliferation of monitoring systems quantitative studies evaluating the
65 impacts of hurricanes on wetlands are generally very recent and have been limited to
66 evaluation of phosphorous releases from wetlands (Novak et al. 2007), changes in
67 wetland microbial communities (Williams et al., 2008), impacts on salinity (Batllori and
68 Febles 2007), changes in plant communities (Goode et al. 2008; Hoepfner et al. 2008;
69 Ugarte et al. 2006; Kovacs et al. 2001), changes in sedimentation rates (Turner et al. 2007;
70 Turner et al. 2006; Parsons 1998; Kang and Trefrey 2003) and overall changes in wetland
71 size (Costanza et al. 2008; Ramsey et al. 1998). But limited information is available on
72 wetland water flows under hurricane conditions. The only publication available on this
73 topic is from Harvey et al. (2009) who found that during Hurricane Wilma in 2005 water
74 speed and water levels increased above pre-hurricane levels. Considering the key role of
75 surface water flow patterns in shaping substrates, biogeochemical cycling, restoration,
76 and ecosystem characteristics in wetlands, the impacts of extremely strong winds, such as
77 hurricanes, on wetland water flow are of great interest. For example, surface water speed
78 is recognized as a critical factor in particulate settling and re-suspension in wetlands, two
79 processes in maintaining the ridge and slough ecosystems (Bazante et al. 2006; Larsen et

80 al. 2007). In the Everglades, a subtropical wetland in Florida, USA, the estimated critical
81 surface water velocity to re-suspend particles in water ranges within 2.5 - 7.0 cm/s
82 (Bazante et al. 2006; Larsen et al. 2007). However, water speed measured in the wetland
83 rarely exceeds the rate, suggesting that re-suspension of particulars is almost non-existent
84 (He et al., 2010). Nevertheless, the amount of suspended solids likely increases
85 dramatically during storm conditions, as a result of increases in water speed. Hurricanes
86 are ranked based on their maximum sustained wind speeds using the Saffir-Simpson
87 Hurricane Scale. A category 1 hurricane has the lowest maximum wind speed of
88 33-42.5 m/s (119-153 km/h), whereas the maximum wind speed of a category 5 hurricane
89 is greater than 69 m/s (249 km/h). In a typical 3-year span, the U. S. coastline is struck on
90 average five times by hurricanes, two of which are designated as major hurricanes (\geq
91 category 3). Between 2001 and 2005, seven major hurricanes made landfall in the United
92 States, making it difficult to design monitoring systems specifically tailored to assess the
93 impacts of hurricanes.

94 To our knowledge, this study is one of two (Harvey et al. 2009) which provide
95 quantitative measures of water speed and direction within a wetland under hurricane
96 conditions. These data (as were those collected by Harvey et al. 2009) were collected as
97 part of a long-term monitoring network used to evaluate water velocity within the
98 Everglades. By chance two hurricanes, Hurricanes Katrina and Wilma, traveled through
99 the Everglades either directly over or very near our monitoring sites during the
100 monitoring period, which thus provided a unique opportunity to document and assess

101 water velocity impacts during hurricane wind conditions for two events during the same
102 hurricane season. Harvey et al. (2009), because of the location of their monitoring
103 stations located 20 km to the north of our sites, monitored the effects of one of the two
104 hurricanes and the wind speeds for that hurricane (Hurricane Wilma) were about ½ of
105 those observed at the sites described as part of the current manuscript.

106 The objectives of this paper are to: 1) document the characteristics of water flow
107 (speed and direction) within the wetland during hurricanes; 2) to compare variations of
108 water flow before and after these hurricanes; and 3) to evaluate effects of local rainfall,
109 hydraulic gradient, water elevation, upstream gate operation, and wind speed on water
110 speed during hurricanes. Given that data were collected during two different hurricanes,
111 the results were compared to establish whether the flow responses were different during
112 each hurricane event.

113 **2. Site Description**

114 The Everglades is a large (10,000 km²) sub-tropical wetland located in the southern
115 portion of the U.S. within the State of Florida and is characterized by densely vegetated
116 ridges, relatively open sloughs, and tear-shaped tree islands. Shallow, slow-moving
117 surface water in the Everglades flows southwardly or southwestwardly from Lake
118 Okeechobee to Florida Bay and to the Gulf Coast of Florida. Everglades National Park
119 (ENP), which includes the southern portion of the Everglades, is located in southeastern
120 part of the State of Florida (Figure 1). Shark River Slough is the major water flow
121 pathway through the central Everglades, with an approximately 32 km wide northern

122 border, and a 10 km wide discharge at the mangrove ecotone. The hydraulic gradient
123 along its longitudinal northeast–southwest axis is generally 3 to 4.7 cm/km (Olmsted and
124 Armentano, 1997). The climatic characteristics in this area are: an average annual air
125 temperature of about 24°C; an average annual precipitation of 1320 mm; and periods of
126 intense evapotranspiration (ET) resulting in estimated ET of 70–90% of the total amount
127 of rainfall (Mcperson and Halley, 1997). The region is characterized by two seasons, a
128 wet season (typically from June to November), and a dry season (typically from
129 December to May) (Noe et al., 2001). A series of water control structures (S-12A, S-12B,
130 S-12C, S-12D, and S 333) located on Tamiami Trail Road, which are operated by South
131 Florida Water Management District (SFWMD), defines the northern boundary of ENP
132 (Figure 1). Water control structures impacting flow to our sites are S-12C, S-12D, and S
133 333, as a roadway exists immediately to the west of the study site thereby minimizing
134 impacts from gates S-12A and S-12B (Figure 1).

135 Water flow data in the Shark River Slough have been investigated temporally and
136 spatially. Bazante et al. (2006) showed that mean velocities observed near three tree
137 islands varied from 0.9 to 1.4 cm/s, with slightly higher mean velocities of 1.2–1.6 cm/s
138 during the wet season versus 0.8–1.3 cm/s during the dry season. He et al. (2010) found
139 consistent results with low flow speeds at five sites (< 3 cm/s) and showed that 70% of
140 the variance of the measured speed could be explained by the local hydraulic gradient,
141 water depth, and vegetative resistance. Riscassi and Schaffranek (2002, 2004) reported
142 that horizontal velocities in several locations with different hydrological conditions

143 varied between 0.0 and 4.5 cm/s, and horizontal flow direction generally ranged from 180
144 to 275 degrees, clockwise with respect to magnetic north (MN), during the wet seasons of
145 1999-2001 and 2002-2003.

146 Water velocity measurements for this study were collected at sites in the vicinity of
147 two tree islands within the Shark River Slough of ENP, known as Gumbo Limbo
148 Hammock (GL) (25.6305°N, 80.7430°W), and Satin Leaf Hammock (SL) (25.6591°N,
149 80.7571°W) (Figure 1). The latter island has also been referred to as Indian Camp
150 Hammock and Tiger Hammock in other documents. The measurements recorded during
151 the hurricanes were collected as part of a continuous monitoring program focusing on the
152 hydrology of these islands. These data collection stations were installed in *Cladium*
153 *jamaicense* (sawgrass) marsh on the west side of each tree island just south of the
154 hardwood hammocks in areas not covered by the tree canopies (Bazante et al.2006;
155 Leonard et al. 2006). Soils in the vicinity of GL and SL are peats with a high organic
156 matter content of >80%, except for small areas at the elevated heads of the tree islands
157 where outcropping limestone and carbonate rich mineral soils are found (Ross et al.,
158 2004).

159

160 **3. Hurricanes Katrina and Wilma through South Florida**

161 At approximately 17:30 (Eastern Standard Time, EST) on 25 August, 2005,
162 Hurricane Katrina made its first landfall in the United States to the east of the Everglades
163 (Figure 1) as a category 1 hurricane with maximum sustained winds of 36 m/s (130

164 km/hr). A well-defined eye was evident and remained intact as it crossed South Florida
165 with the strongest winds and heaviest rains occurring to the southeast of the hurricane
166 track. The center of Katrina emerged into the southeastern Gulf of Mexico 6 hours later
167 on 26 August, weakened to a tropical storm with maximum sustained winds of 31 m/s
168 (111 km/hr). Rain totals were greater than 25 cm to the south of the hurricane track and 5
169 to 10 cm to the north (Knabb et al., 2005).

170 In contrast to Hurricane Katrina, Hurricane Wilma approached southwestern Florida
171 from the Gulf of Mexico and made land fall at 5:30 (EST) on 24 October, 2005, with
172 maximum sustained winds of 54 m/s (195 km/h) (category 3). Four and a half hours later,
173 the eye reached the Atlantic coast and moved out over open water. By this time,
174 maximum wind speeds had decreased to 49 m/s (176 km/h) (category 2). Rain totals in
175 Florida ranged from 7 to 17 cm (Pasch et al., 2006).

176 **4. Methods**

177 Hourly rainfall and water elevation data were obtained from three monitoring
178 stations NP 201 (25.718° N, 80.726°W), NP 202 (25.661° N, 80.712°W) and NP 203
179 (25.624° N, 80.739°W) operated by Everglades National Park. As shown in Figure 1, NP
180 201, 202, and 203 are approximately aligned in the direction of flow within 3 km of GL
181 and SL. The distances between NP 201 and 202 and between NP 202 and 203 are 6.52
182 and 5.15 km, respectively. The hydraulic gradients of NP 201-202, NP 202-203, and NP
183 201-203 were calculated according to their water elevation differences and distances,
184 respectively.

185 Water velocities at the two monitoring stations (GL and SL) were measured in three
186 dimensions (x, y, and z directions) in 15 min intervals using fixed Acoustical Doppler
187 Velocity meters (ADV) (SonTek Argonaut-ADV, San Diego, CA, firmware version 11.6).
188 These units were designed with a “sidelooking” orientation where the acoustical signal
189 was transmitted to the side of the instrument rather than below, thereby allowing for
190 measurements of water velocity in x, y, and z directions in water as shallow as 15 cm.
191 Horizontal velocities were computed through the vector sum of the x and y coordinates.
192 The fixed ADVs were programmed to store averages of 3000 measurements over a period
193 of 5 minutes for each 15-min interval. An approximately 6/10 depth of measurement was
194 maintained through vertical adjustment of the probes.

195 Surface mean wind velocity data were available from several weather observation
196 stations, the two closest of which were within Everglades National Park at a height of 2
197 m from ground surface, at stations known as Tenraw (TE), and Chekika (CH) (MesoWest
198 Data website, <http://www.met.utah.edu/jhorel/html/mesonet/> of the Department of
199 Meteorology at the University of Utah). TE (25.6097 °N 80.8503 °W) and CH (25.6250
200 °N 80.5797 °W) were located 11.9 km west and 18.2 km east from GL, respectively. Wind
201 data were collected at TE and CH at 1 hour time intervals. Wind data at TE and CH were
202 first interpolated in terms of time to estimate values during time periods consistent with
203 the sampling periods for the velocity measurements. These interpolated wind data for TE
204 and CH were then interpolated in terms of longitude to estimate the wind characteristics
205 at GL and SL during the hurricanes. To readily compare the directions of water flow

206 and wind, the wind in this study is described as where it blows to, clockwise with respect
207 to magnetic north (MN). All times mentioned are U.S. eastern standard times (EST).
208 Water flow data before and after the hurricanes were compared using the Students' t-tests
209 (95% confidence limits). The period of hurricane influence was arbitrarily defined as the
210 time period characterized by sustained wind speeds of at least 10 m/s, which was rarely
211 found during non-hurricane conditions.

212

213 **5. Results**

214 **5.1 Hurricane Katrina**

215 During Hurricane Katrina, the estimated wind speeds at GL and SL first increased over
216 10 m/s at 19:45 25 August, 2005, and were oriented toward the southeast. The wind
217 direction started to deflect clockwise at 22:30, and moved toward the northwest (277°) at
218 22:45 with a speed of 7 m/s. The wind speed in the northwest direction reached a
219 maximum of 17.3 m/s at 3:15 on 26 August, 2005, and then decreased to less than 10 m/s
220 after 7:45 on 26 August, 2005. The wind speeds as measured at TE and CH did not reach
221 hurricane strength (33 m/s) as these stations were located just north of the hurricane track
222 on the weaker side of the hurricane.

223 During the peak storm conditions, the magnitude of water flow in the horizontal
224 plane decreased at both GL and SL, but continued to flow primarily southward (Figure 2).
225 After the wind shifted from a southeastward to northwestward direction, the water flow
226 direction at GL also was deflected toward the west. During peak wind conditions, both

227 the wind and water flow direction exhibit a strong westerly component. Interestingly,
228 water flow was still essentially southward even though the strongest winds were blowing
229 toward the north.

230 The mean values of variables measured by the fixed ADVs before and after Katrina
231 are shown in Table 1. The time periods before and after the hurricane correspond to 4
232 days before the winds reached 10 m/s and 4 days after the winds receded from 10 m/s.
233 This time frame was chosen since it also corresponds to a period when gate discharges,
234 ambient temperature, and water depths were comparable before and after hurricane
235 passage, thereby providing a baseline upon which hurricane impacts could be compared.
236 Mean horizontal water speed significantly increased at both GL ($p < 0.01$) and SL ($p <$
237 0.01) during the four day period immediately following Hurricane Katrina. The mean
238 horizontal water speed increased by 30% above pre-storm values at GL (1.30 to 1.69
239 cm/s) and by 10% at SL (1.89 to 2.07 cm/s). In spite of these apparent increases, these
240 values are comparable to mean water speeds measured at GL and SL during the previous
241 wet season (Bazante et al., 2006). The results also showed a sinusoidal flow pattern at GL
242 after the storm showing higher flows during the late night and early morning hours and
243 lower flows during the middle of the day. This pattern may have been related to
244 changes in evapo-transpiration rates throughout the day. The same was not readily
245 observed for SL. Gate flow through upstream stations remained relatively constant
246 before, during, and after Hurricane Katrina. The precipitation was recorded at NP 201,
247 202, and 203 during the hurricane (Figure 3). The highest hourly rainfall occurred at NP

248 202 and was as much as 51.5 cm/hr, much greater than 7.9 and 13.7 cm/hr recorded at NP
249 201 and NP 203, respectively. In response to rainfall, water elevations at NP 201, 202 and
250 203 increased by 6, 10, and 20 cm, respectively. Over the five following days, these
251 elevated water levels did not return to the levels observed before the hurricane.

252 The hourly hydraulic gradients between these sites were characterized by short-term
253 fluctuations associated with storm passage (Figure 3). The gradient was steeper between
254 NP 202 and NP 203 in comparison to the gradients between NP 201 and NP 202 and
255 between NP 201 and 203 during the 8-day period. During Hurricane Katrina, the largest
256 change in hydraulic gradient occurred between NP 202 and NP 203; increasing from 5.5
257 to 6.0 cm/km and then decreasing to 5.0 cm/km. Change in hydraulic gradient was less
258 pronounced between NP 201 to 203, decreasing from 4.6 to 4.0 cm/km and then returning
259 to 4.4 cm/km. The smallest change in hydraulic gradient was observed between 202 and
260 203, decreasing from 3.5 to 3.0 cm/km and then returning to 3.5 cm/km. These changes
261 in hydraulic gradient are coincident with the larger peak rainfall measured at NP 202
262 which resulted in larger fluctuations in hydraulic gradient.

263 The horizontal water speeds at GL and SL apparently responded to the changes in
264 these gradients during the hurricane (Figure 3). At SL, the water speed was roughly
265 synchronized with the hydraulic gradient between NP201 and NP202, since the site was
266 the geographically closest to NP 202. Similarly at GL, water speed followed a very
267 similar pattern as the gradient curve between NP202 and NP203 since GL is closer to NP
268 203. The minimum water speeds were also coincident with the peak wind speed, because

269 the wind direction was roughly in a direction opposite to flow.

270

271 **5.2 Hurricane Wilma**

272 During Hurricane Wilma, estimated wind speeds at GL and SL increased to over 10 m/s
273 at 0:30 on 24 October 2005 (Figure 4). The wind direction was initially to the northwest,
274 and gradually rotated towards the northeast after 7:15 when wind speeds peaked at 31 m/s.
275 The wind speed gradually declined to less than 10 m/s by 17:15. Although Hurricane
276 Wilma made landfall in South Florida as a category 3 hurricane, the wind speeds
277 measured in the study area were below the minimum value of a category 3 storm (54 m/s)
278 because the study area was 75 km south of the hurricane center. Compared to Hurricane
279 Katrina, however, Wilma generated wind speeds that were 2-fold higher at GL and SL.

280 The directions of water flow at GL and SL were deflected clockwise following the
281 clockwise rotation of the wind during the passage of peak storm conditions (Figure 4). As
282 the storm crossed to the north, the direction of water flow at SL was first deflected to the
283 north (308°). This deflection in flow direction from almost west to the NNW began when
284 the wind speed exceeded 24 m/s (6:30 on Oct. 24). Flow direction remained toward the
285 north, and in opposition to the ambient flow direction, over the next three hours until
286 wind speed returned to less than 24 m/s (6:30 on 10/24/05, Figure 4). After this time,
287 flow returned to a southerly direction. The maximum water speed recorded at SL (5.3
288 cm/s) occurred during the peak of the hurricane when both flow direction and wind
289 direction were oriented to the north. The flow direction at GL also was deflected

290 clockwise following the clockwise rotation of the wind, however, not to the extent as
291 observed at SL. Northerly flow occurred only briefly at approximately 7:15 on Oct. 24
292 when peak wind (31 m/s) conditions existed. As observed for SL, the water flow direction
293 observed at GL during this time represents almost a complete reversal of the natural flow
294 direction.

295 The mean values of variables measured by the fixed ADVs before and after
296 Hurricane Wilma are shown in Table 1. Significant differences in mean horizontal water
297 speeds and water flow direction were observed at both stations ($p < 0.01$). Following
298 Hurricane Wilma, the mean horizontal water speed decreased to 50% (1.80 to 0.90 cm/s)
299 of the pre-storm mean at GL. In contrast at SL, mean horizontal water speed increased
300 above the pre-storm mean by more than 2 times (0.59 to 1.32 cm/s). Of note, the flow
301 pattern after Hurricane Wilma for both stations showed a daily sinusoidal pattern again
302 with higher velocities during late night and early morning and lower velocities during
303 mid-day. After the storm, wind speeds were very low and could not explain this pattern.
304 The reason for this pattern is not known, but, as mentioned earlier, may be related to daily
305 evapotranspiration cycles. Further, the flow direction was changed from 214° to 211° at
306 GL and from 154° to 215° at SL. Of note, the water flow direction at SL was variable
307 before Hurricane Wilma, but was relatively constant after the hurricane.

308 The sum of discharges (S-12C, S-12D and S-333) was not appreciably altered by the
309 hurricane although gate discharge was slightly higher following the storm and gradually
310 increased (Figure 5). Water elevations at NP 201, 202 and 203, however, displayed abrupt

311 increases in response to high precipitation during the hurricane. This was particularly the
312 case at NP 201 where the water elevation increased from 273.1 cm to 284.7 cm when
313 Hurricane Wilma crossed the station. After storm passage, the water elevation at NP 202
314 and 203 quickly decreased to levels comparable to those observed before the hurricane,
315 but at NP 201 water elevation did not return to its initial level until approximately three
316 days after the hurricane. The dissimilarity in the water elevation variations at the three
317 sites may be ascribed to the localized variations in amounts and rates of the local rainfall.

318 During Hurricane Wilma, the hydraulic gradient from NP 201 to 202 increased from
319 a pre-storm gradient of 3.60 cm/km to a maximum of 4.9 cm/km. After storm passage, it
320 gradually decreased to the pre-storm level (3.6 cm/km). Finally, the hydraulic gradient
321 stabilized at 2.90 cm/km by 8:00 on Oct. 27 which was lower than prior to the hurricane.
322 The hydraulic gradient between NP 201 and NP 203 had a similar trend, increasing from
323 4.5 cm/km to 5.2 cm/km during the hurricane and decreasing back to the pre-storm level
324 within 2 days. Interestingly, the hydraulic gradient between NP 202 and NP 203
325 decreased from 5.8 cm/km before Hurricane Wilma to 4.8 cm/km during storm passage.
326 It then quickly returned to the pre-storm level of 5.8 cm/km at 10:00 on Oct. 28. This
327 response contrasts with the NP201 to 202 gradient and also with the hydraulic gradients
328 observed during Hurricane Katrina.

329 As for Hurricane Katrina, water speed at SL during Hurricane Wilma showed an
330 increase in speed when the gradient increased between NP201 and NP202. At GL the
331 speed increased, but not as much. The diminished response at GL is likely associated

332 with the reversal of hydraulic gradient between NP202 and NP203, and the smaller
333 increase in water levels at NP203 as GL is closer to this station.

334

335 **6.0 Discussion and Conclusion**

336

337 *Comparisons Between Hurricanes:* The maximum mean wind speeds at GL and SL
338 during Hurricane Wilma (31 m/s) were almost twice that during Katrina (ca. 17 m/s), and,
339 accordingly, the water flow was much more strongly affected in magnitude and direction
340 by Hurricane Wilma than by Hurricane Katrina. Thus, critical wind strengths appeared to
341 exist, above which the water flow was altered, with stronger winds causing greater
342 impacts on water flow. Moreover, the characteristics of water flow after the two
343 hurricanes were significantly different. Hurricane Katrina with relatively low strength did
344 not cause a large sustained alternation of the mean speed (10 to 50%) and mean direction
345 (up to 2°) at GL and SL (Table 1). However, after Hurricane Wilma, a stronger hurricane,
346 the mean magnitude of water flow sustained after the event at GL was decreased by a half,
347 but the magnitude at SL doubled. Overall the impacts of the hurricanes on flow speed
348 were larger at SL as compared to GL. The differences observed between the two
349 stations is likely due to depth effects, as SL is located at the edge of Shark River Slough
350 in shallower water (about 30 cm), whereas GL is located in deeper water (between 84 and
351 87 cm) within the center of the slough.

352 *Short Term Alterations in Flow:* The hurricanes, in particular the larger one, Wilma,

353 caused both short term (during hurricane conditions) and longer term (days after the
354 storm) alterations in flow characteristics. The short term alterations coincided with high
355 wind speeds, localized variations in rainfall, changes in water depth, and changes in
356 hydraulic gradients (as observed from figures 3 and 5). He et al. (2010) found that
357 hydraulic gradient, water depth, and vegetative resistance could explain about 70% of the
358 variation in water flow within these same sites during non-hurricane conditions. The
359 short term variations observed during hurricane conditions were consistent with the
360 significance of hydraulic gradients and water depths, as identified by He et al. (2010).

361 The observations from the current study are consistent with those from Harvey et al.
362 (2009) as observed during Hurricane Wilma at a surface water monitoring site located
363 about 20 km to the north of our sites. Maximum wind speeds observed by Harvey et al.
364 (2009) were at about $\frac{1}{2}$ (14 m/s) those observed in the current study. Flow responded in
365 our study in a similar fashion as documented by Harvey et al. (2009) with maximum
366 velocities of 5 cm/s, as compared to a maximum at SL of 5 cm/s and at GL of 3 cm/s,
367 during this same storm. In the wet season of 2005, the mean water velocities at SL and
368 GL were 1.90 cm/s and 1.29 cm/s, respectively (He et al., 2010). Obviously, the
369 maximum velocities at the two sites during Hurricane Wilma were greater than mean
370 levels. Bazante et al. (2006) proposed 7 cm/s to be a critical water speed for
371 re-suspension of the particles (3.3 μm) in the Shark River Slough. Larsen et al. (2009)
372 measured a critical bed shear stress of 0.01 Pa to re-suspend the flocculated particles (100
373 μm) collected from the Everglades, corresponding to a critical water speed of 2.5 cm/s. In

374 the current study, the maximum measured water speeds during Hurricane Wilma were
375 over or close to the estimated critical rates, suggesting that at least a part of the particles
376 in the slough were re-suspended. Of note, such re-suspension rarely occurs in the slough
377 during non-hurricane conditions. Thus hurricanes have the potential to resuspend
378 particulates within this wetland, a process required for the formation of a ridge and
379 slough topography, an important component of Everglades restoration.

380

381 Harvey et al. (2009) reported a large spike in water level during the hurricane (up to
382 22 cm above the pre-hurricane level), and attributed the changes in water speed and
383 direction to an inverse barometric effect. Our interpretation of the cause of the shift in
384 flow speed and direction is somewhat different, as we attribute the changes to the
385 combined effects of wind shear, differential rainfall, shift in hydraulic gradients, and
386 changes in the structure of submerged vegetation. We recognize that barometric effects
387 can also serve as a factor and we cannot disregard this effect as contributing to the
388 changes in flow that were observed.

389 Another factor that played an important role during hurricane conditions was wind
390 speed. Wind did not notably affect the water flow in the study wetland at depth for wind
391 speeds less than 10 m/s, as shown in Figures 2 and 4. During hurricane conditions wind
392 impacts were observed with an obvious alteration of water flow direction which followed
393 the direction of the wind (as observed in figure 4). During Hurricane Wilma, the
394 clockwise rotation of water flow direction followed the clockwise rotation of wind

395 direction. The wind can cause a deviation from the preferential flow path through forces
396 applied at the surface of the water plus forces placed on vegetation that is emerging above
397 the surface of the water. The emergent vegetation would likely bend in the direction of
398 the wind perhaps facilitating the shift in water flow direction.

399

400 Moreover local vegetation likely played another role, by minimizing the extreme
401 changes in velocity during peak wind conditions. For open water, the impacts of
402 hurricanes are greater. During Hurricane Frances and Jeanne in 2004, greater current
403 velocities and large surface seiches occurred in Lake Okeechobee (a shallow lake, with
404 the mean depth of 3 m, located in Florida, USA) (James et al., 2008). Even, the slope of
405 the water surface reversed itself as wind direction changed during the both hurricanes
406 (Chimney, 2005). In 1999, when the Hurricane Irene passed over the Lake Okeechobee,
407 the local wind speed was increased to 25 m/s, causing a great increase in the surface
408 water speed from 5 cm/s to 100 cm/s (Haven et al., 2001). In contrast, our maximum
409 water speed at SL was 5 cm/s during Hurricane Wilma and the maximum wind speeds
410 observed in our study was 31 m/s, greater than the speeds observed over Lake
411 Okeechobee during Hurricane Irene. The dissimilarity in the water velocity increase
412 caused by the hurricanes over open water such as Lake Okeechobee versus highly
413 vegetated wetlands is likely due to the emergent vegetation shielding the wetland surface
414 from strong wind conditions.

415

416

417 *Long Term Alterations in Flow:* One would expect that once the water levels receded
418 and hydraulic gradients returned back to their normal state, flow would resume as before;
419 however, our observations suggest a longer time-scale for changes in flow (on the order
420 of days). For example a shift in water flow direction at SL was observed after Hurricane
421 Wilma. Before Hurricane Wilma the flow direction at SL considerably varied from
422 northwards to southwards (standard deviation of direction = 94°); after the hurricane the
423 flow (mean flow direction 215°) was characterized by a more constant average flow
424 direction (standard deviation of direction = 11°). We hypothesize that these longer
425 time-scale changes are likely due to the effects of the hurricanes on vegetation structure.

426 Vegetative structure is considered to be a significant factor controlling water velocity
427 (Harvey et al., 2009). Typically, the flow velocity increases with the fourth power of stem
428 diameter, and decreases in direct proportion with the increasing frontal area of vegetation.
429 Under a strong storm, destruction in vegetative structure is typically significant. Doyle et
430 al. (2009) correlated observed plantfall and destruction patterns with wind speed and
431 direction in the Everglades using a hurricane simulation model. They found mangrove
432 forests within the storm's eyepath and in the right-side (forewind) quadrants suffered
433 whole or partial blowdowns. Smith et al. (2009) also studied cumulative impacts of
434 hurricanes on Florida wetland mangrove ecosystem, and reported immediate effects of
435 the hurricanes including changes to stem size-frequency distributions and to species
436 relative abundance and density. Immediately after Hurricane Wilma, our reconnaissance

437 of the area showed *Cladium jamaicense* (sawgrass) stands blown down along with
438 underwater vegetation pushed up against these stands, suggesting that the vegetation was
439 blown into water under the strong winds. These changes in vegetative structure might
440 explain some of the changes in velocity that were observed after hurricane conditions.

441

442 *Summary and Recommendations:* In summary, results from the current study suggest
443 that baseline wind conditions (< 10 m/s) were not a major factor influencing water flow
444 at depth. Extreme wind events, such as those during hurricanes, can influence water
445 flow with larger hurricane events causing larger impacts. During the brief hurricane
446 period (on the order of an hour) flow speed and direction can be radically altered due to
447 the combined alterations in wind speed, water depth, rainfall variations, hydraulic
448 gradients, and possibly barometric effects; emergent vegetation also likely plays a role
449 during hurricane conditions by shielding the water surface from wind shear but also
450 influencing underwater vegetation structure through the wind's influence on the
451 movement of emergent vegetation. The longer lasting effects of hurricanes (time scale
452 of a few days) resulted in altered flow speeds that changed by 50% or less with flow
453 directions very close to those observed during non-hurricane conditions. These longer
454 lasting changes in flow characteristics, although not extreme for the study watershed,
455 may be due to the redistribution of emergent vegetation causing an alteration in flow
456 resistance and preferential flow paths.

457 Our observations in this study were relatively qualitative in nature as quantitative

458 relationships between the various factors could not be established. Future work is
459 highly recommended to disaggregate the different factors that influence water flow
460 during hurricane conditions through improvements in wind measurements (including the
461 installation of wind meters immediately above the point of water flow measurements).
462 Wind measurements and water velocity measurements should also be taken at various
463 points in the vertical to evaluate the distribution of wind as the emergent vegetation is
464 approached and also to evaluate the impact of this wind with water depth.

465

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476

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639 availability and microbial communities in a subtropical wetland-estuary transition zone.

641 **Table 1** Mean values of variables measured by the fixed ADVs before and after
 642 Hurricanes Katrina and Wilma. The time periods corresponded to 4 days before the
 643 winds reached 10 m/s and 4 days after the winds receded from 10 m/s. For Hurricane
 644 Katrina the “before” data corresponded to 0:00 on 21 Aug. to 23:45 on 24 Aug. 2005; the
 645 “after” data corresponded to 0:00 on 27 Aug. to 23:45 on 30 Aug. 2005. For Hurricane
 646 Wilma the “before” data corresponded to 0:00 on 19 Oct. to 23:45 on 22 Oct. 2005; the
 647 “after” data corresponded to 0:00 on 25 Oct. 25 to 23:45 on 28 Oct. 2005.
 648
 649

Parameters	GL		SL	
	Before	After	Before	After
Hurricane Katrina				
Mean horizontal water speed (cm/s)	1.30	1.69	1.89	2.07
Standard deviation	0.29	0.26	0.21	0.17
Direction of horizontal flow, degrees from magnetic north	209	209	188	186
Standard deviation	16	8	9	3
Hurricane Wilma				
Mean horizontal water speed (cm/s)	1.80	0.90	0.59	1.32
Standard deviation	0.32	0.22	0.54	0.63
Direction of horizontal flow, degrees from magnetic north	214	211	154	215
Standard deviation	6	6	94	11

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Figure 1 Hurricane tracks and locations of fixed Acoustical Doppler Velocity meters (ADV) and wind measurement stations. These locations include the fixed ADVs (GL and SL) and two closest wind measurement stations (TE and CH). Inset figure shows locations of gates and water level stations maintained by Everglades National Park.

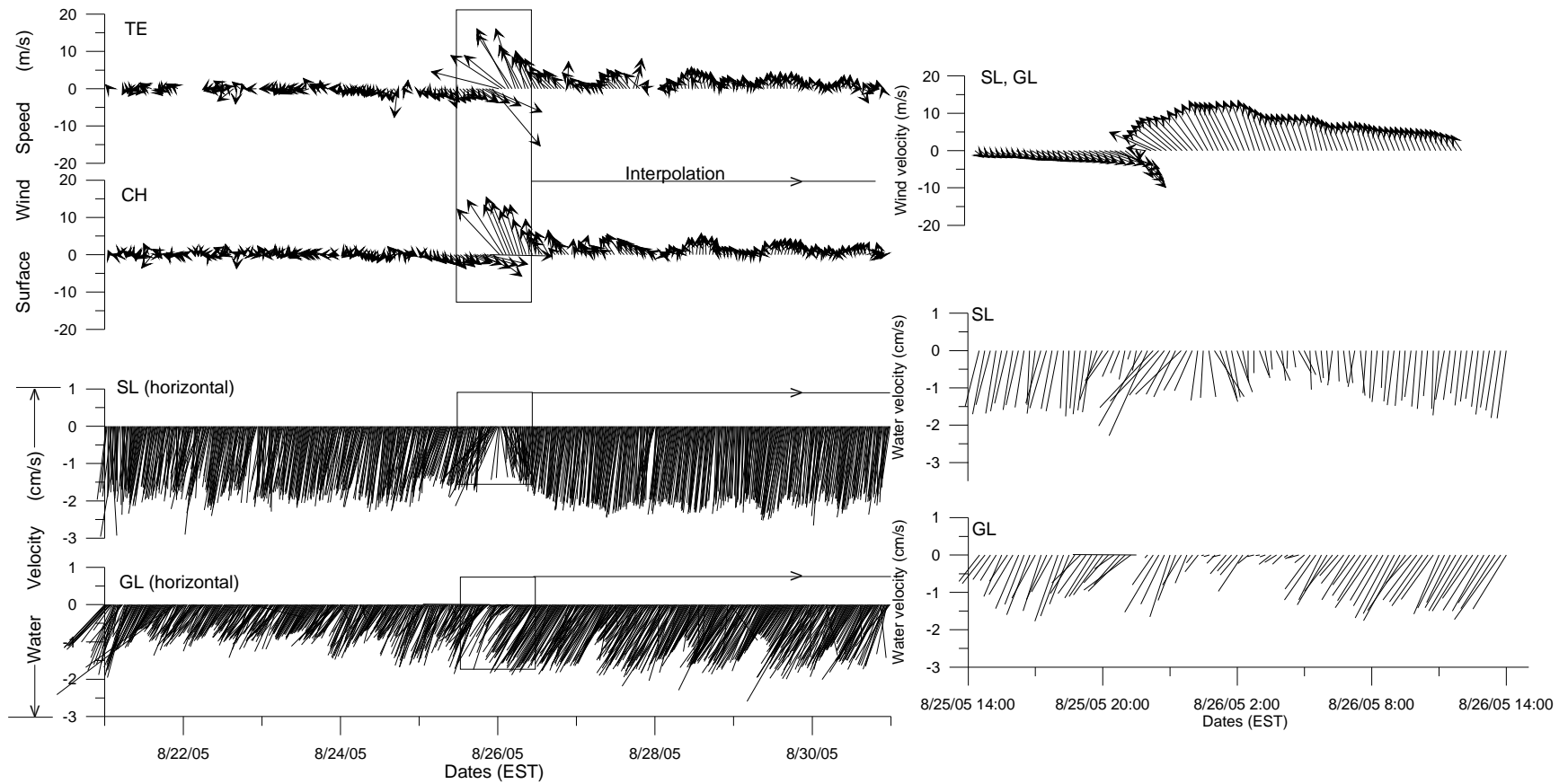


Figure 2 Water flow vs. wind speed during Hurricane Katrina. Top two plots correspond to wind speed and direction at the TE and CH stations. Inset plot to the right corresponds to interpolated wind speed and direction at SL and GL. Bottom two plots indicate horizontal water speed and direction at SL and GL, and inset two plots to the right correspond to horizontal water flow during the Hurricane Katrina period, respectively. Vertical scale on vector plots provides wind or water speed magnitude corresponding to the full length of the vector. Up direction indicates magnetic north.

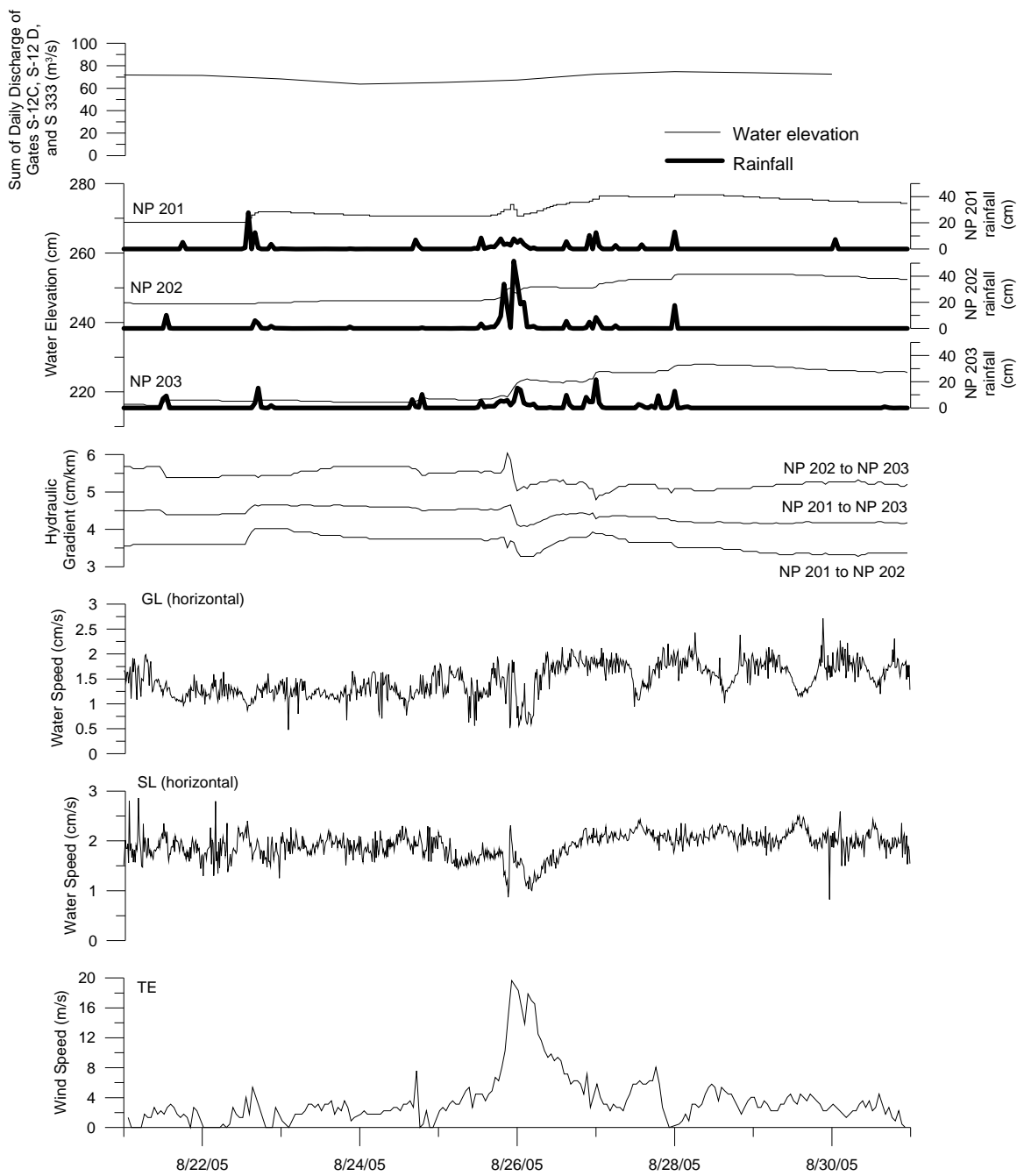


Figure 3 Upstream gate discharge, water elevations (NP 201, NP 202, and NP 203), hydraulic gradients, versus horizontal flow (GL and SL) and wind speed during Hurricane Katrina

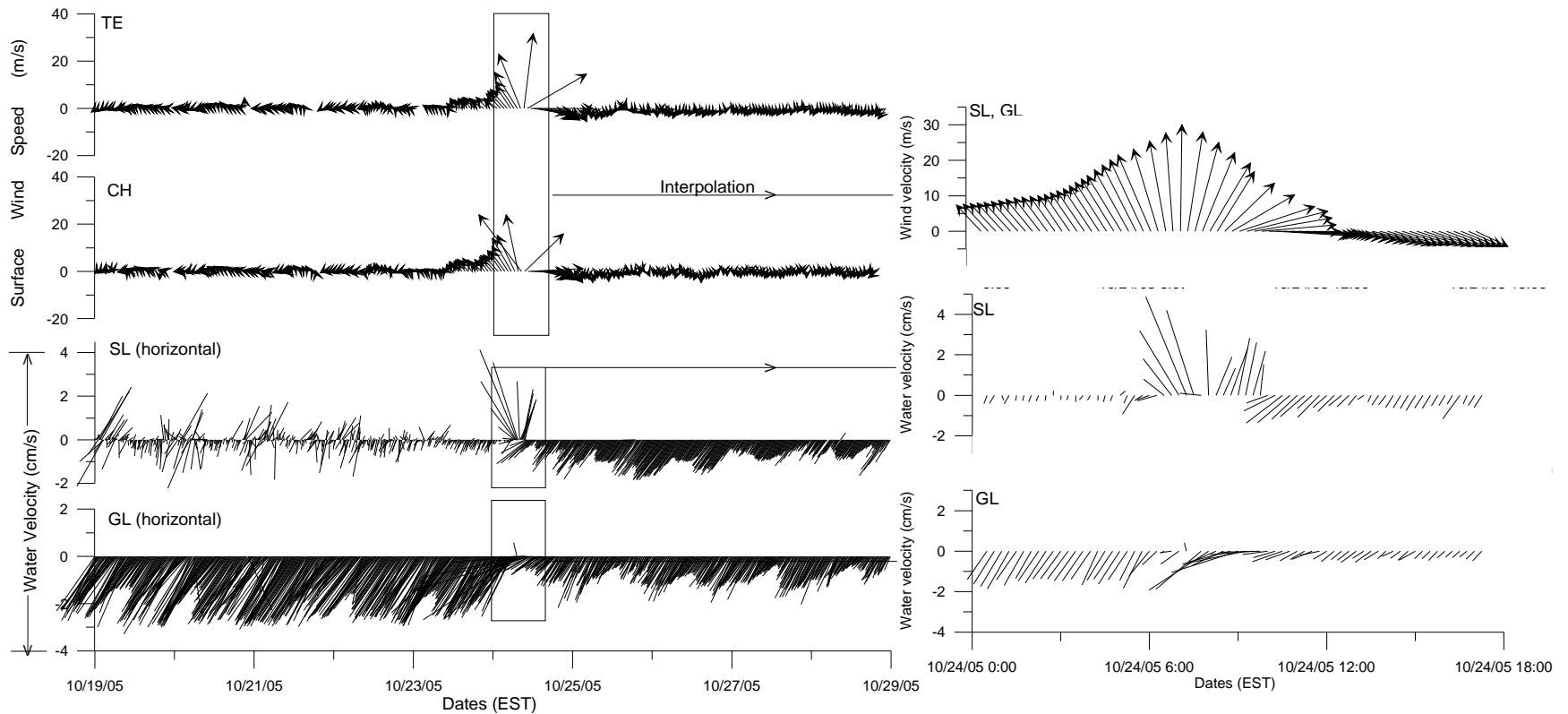


Figure 4 Water flow vs. wind speed during Hurricane Wilma. Top two plots correspond to wind speed and direction at the TE and CH stations. Inset plot to the right corresponds to interpolated wind speed and direction at SL and GL. Bottom two plots indicate horizontal water speed and direction at SL and GL, and inset two plots to the right correspond to horizontal water flow during the Hurricane Wilma period, respectively. Vertical scale on vector plots provides wind or water speed magnitude corresponding to the full length of the vector. Up direction indicates magnetic north.

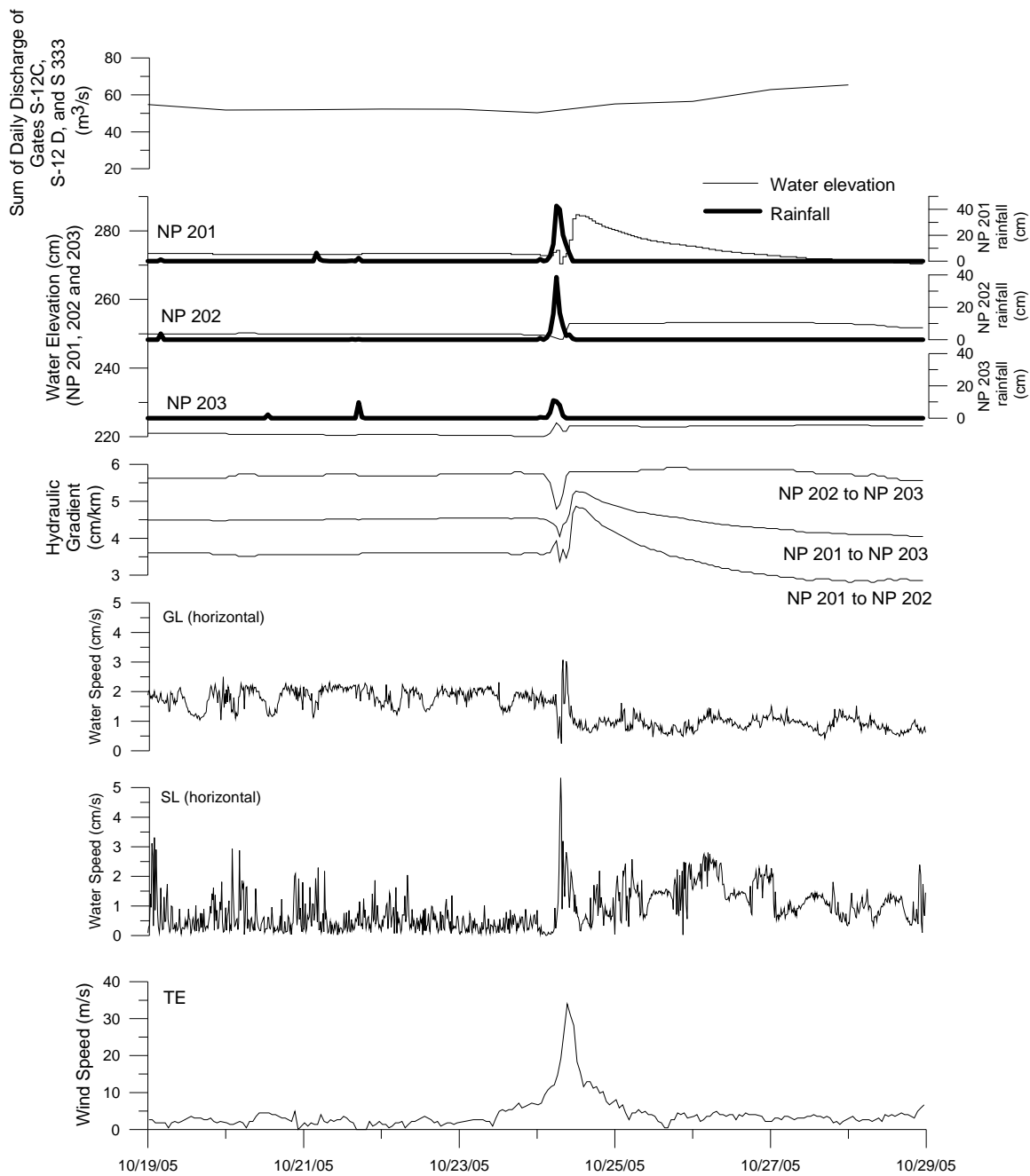


Figure 5 Upstream gate discharge, water elevations (NP 201, NP 202, and NP 203), hydraulic gradients, versus horizontal flow (GL and SL) and wind speed during Hurricane Wilma.