



Tracer studies of sheet flow in the Florida Everglades

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[1] Information on sheet flow patterns in the marsh ridge and slough habitat of the Florida Everglades is scarce, primarily because of difficulty in taking measurements across large enough spatial scales in such a heterogeneous environment. As part of the Everglades Tracer Release Experiment (EverTREx), two SF₆ tracer releases were conducted to measure sheet flow in relatively intact ridge and slough habitats. The first was a pilot experiment that allowed the analytical equipment to be tested in the Everglades, and yielded some preliminary, coarse-scale measurements of advection and dispersion in multiple sloughs. In the second experiment, higher-resolution measurements of tracer distributions in a single slough showed that the mean advection ranged from 0.08 to 0.15 cm s⁻¹, while longitudinal dispersion ranged from 3.7 × 10² to 2.6 × 10³ cm² s⁻¹. **Citation:** Ho, D. T., V. C. Engel, E. A. Variano, P. J. Schmieder, and M. E. Condon (2009), Tracer studies of sheet flow in the Florida Everglades, *Geophys. Res. Lett.*, 36, L09401, doi:10.1029/2009GL037355.

1. Introduction

[2] Coherent vegetation patterns often develop in relation to surface and groundwater flow fields [Rietkerk and van de Koppel, 2008]. Vegetation bands that are oriented perpendicular to flow vectors are relatively common in patterned ecosystems, and the biological and hydrological processes leading to their formation have been examined in numerous field studies and modeling approaches [e.g., Klausmeier, 1999; Sherratt and Lord, 2007]. However, the processes leading to vegetation bands that are parallel to the prevailing flow vectors are not as well understood. These patterns occur in several major wetland ecosystems around the world [e.g., San Jose et al., 2001; Ellery et al., 2003], including the Florida Everglades [Ogden, 2005], and they exhibit a wide range of characteristic wavelengths.

[3] In the heavily-studied Everglades, hydrodynamics, differential peat accretion rates, nutrient dynamics, plant physiological properties, and sediment transport are all thought to play a role in the formation of the parallel vegetation bands [Saiers et al., 2003; Ross et al., 2006;

Larsen et al., 2007; Givnish et al., 2008], though the precise set of mechanisms in relation to flow patterns have not yet been demonstrated empirically or reproduced in eco-hydrologic simulation models. In order to improve understanding of the processes that both lead to and result from vegetation patterning, synoptic measurements of large-scale flow patterns are necessary.

[4] The goal of the Everglades Tracer Release Experiment (EverTREx) is to develop a method to measure large scale sheet flow patterns in the ridge and slough habitat, and allow improved understanding of how large-scale advection and dispersion patterns in the Everglades reflect controlling factors such as water depths, vegetation, and hydrologic management. This information, in turn, will be useful for generating restoration targets and for estimating how hydrologic management may impact the Everglades marshes.

[5] EverTREx represents the first application of sulfur hexafluoride (SF₆) in a shallow-water vegetated environment. SF₆, a gas tracer that has been applied previously in investigations of transport processes in estuarine and coastal waters [e.g., Clark et al., 1996; Ho et al., 2002; Caplow et al., 2003], has advantages over fluorescent dyes (e.g., Rhodamine WT, Fluorescein) in that its concentration can be measured over a greater dynamic range, is considerably less expensive, and does not suffer from photodegradation, thus enabling longer experiments to be conducted over larger areas and over a longer time period [Ho et al., 2006]. Using a tracer that is not subject to photodegradation is especially important in the Everglades, since the water depth is shallow and light penetrates throughout the water column.

2. Study Locations

[6] The greater Everglades ecosystem of south Florida once extended from the shores of Lake Okeechobee to Florida Bay, and was characterized by wide expanses of slow moving surface water (i.e., sheet flow) with depths that fluctuated seasonally with rainfall. Beginning in the late 1800s, major portions of the ecosystem were drained for agriculture and impounded for flood control and water supply [Light and Dineen, 1994].

[7] The two tracer release experiments (EverTREx 1 and 2) were conducted in the interior of the remnant Everglades called Water Conservation Area 3A (WCA 3A; auxiliary material), in a habitat characterized by parallel and slightly elevated sawgrass ridges separated by deeper sloughs (ridge and slough).¹ The study sites were selected based on several factors, including accessibility, habitat

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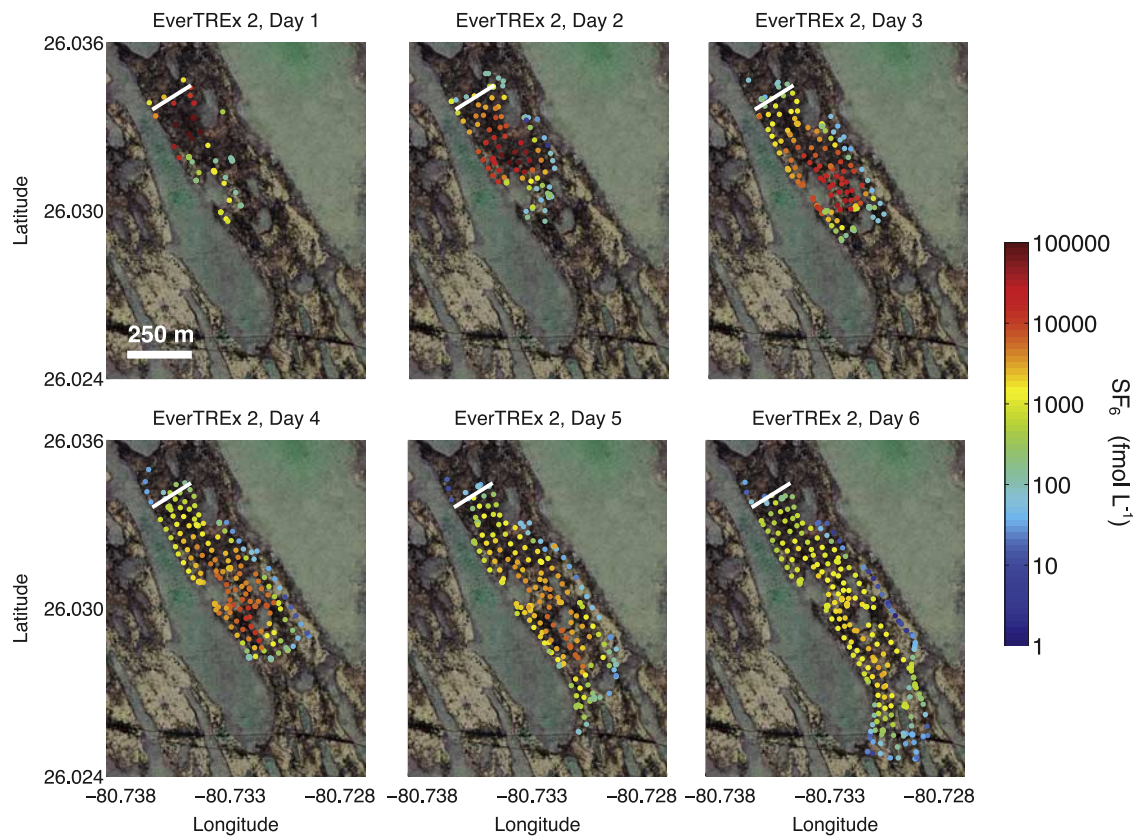


Figure 1. SF₆ tracer evolution in a well-preserved slough in central WCA 3A during EverTREx 2. Sawgrass ridges and islands appear as solid green features in the images, and sloughs appear black and tan. The tracer was released along a 177 m track indicated by the white lines on Day 0 (Nov 29, 2006), and measured for 6 consecutive days.

quality, water depths and clarity, and low visitation rates from recreational users.

3. EverTREx 1

[8] EverTREx 1 was a pilot experiment whose primary aim was to field-test the continuous SF₆ system (described below) in the Everglades, and to examine coarse-scale flow patterns in several sloughs that are differentiated by somewhat variable morphology. These sloughs were relatively narrow (30–100 m in width), and separated by ridges up to 150 m wide. The habitat of the study area was well preserved, with distinct and continuous sawgrass ridges and deep sloughs exhibiting clear parallel patterning. There were few airboat trails or natural deep-water areas connecting adjacent sloughs, and water depths in the individual sloughs were approximately equal (ca. 31 cm). The results of this pilot experiment are presented as auxiliary material.

4. EverTREx 2

[9] EverTREx 2 focused on high-resolution measurements of flow patterns within one large slough approximately 200–225 m in width and 1.25 km long, with the objective of analysing the large-scale flow patterns, as well as the localized effects of vegetation on advection and dispersion.

[10] The study area was characterized as well-preserved habitat with clear parallel patterning and long, contiguous ridges. Sawgrass density in this area was relatively high (auxiliary material) and did not allow airboat access. The

slough vegetation was comprised mostly of *Nymphaea spp.* and *Eleocharis spp.*, with large, scattered patches of *Panicum spp.* Large floating mats of periphyton were also present, though they were not ubiquitous in the slough and were generally absent in the deepest zones.

5. Tracer Injection and Measurement

[11] A propeller-driven airboat was used to access the study sites and to perform the tracer injection and measurement. At each site, marsh water was pumped into a 20 L container, and then saturated with SF₆ by bubbling through a length of diffuser tubing. After saturation, the SF₆-infused water was injected into the water at mid-depth with a peristaltic pump while the airboat traversed a predefined path. After injection, the tracer distribution was sampled each day using the continuous SF₆ analysis system mounted on an airboat. Navigation was accomplished using high-resolution aerial images (USGS Digital Orthophoto Quarter Quadrangle; <http://edc.usgs.gov/>) on a portable personal computer equipped with a GPS.

[12] For EverTREx 2, the tracer was released along a 177 m line that crossed approximately half the width of the slough near its northern terminus on Nov 29, 2006, and surveyed for six days from Nov 30 to Dec 5, 2006 (Figure 1). The multiple transects within the slough were spaced 10–15 m apart, and the maximum distance traveled by the tracer, its lateral extent, and its distribution in and around prominent sawgrass patches along the main slough axis were defined to ensure adequate resolution of tracer dynamics.

[13] The uncertainty in the location of a measurement was mainly due to residence time distribution of tracer in the pumping and gas extraction units (see below). This uncertainty is proportional to the vessel speed, and of order ± 30 m for EverTREx 1 and ± 5 m for EverTREx 2 (see auxiliary material). Uncertainties on derived quantities (e.g., flow velocity) are computed by standard propagation of errors and from the uncertainty in least squares fitting parameters (when relevant) [Taylor, 1996].

6. Continuous SF₆ Analysis System

[14] The basic principle and design of the high-resolution continuous SF₆ measurement system used during EverTREx has been described in detail by Ho *et al.* [2002]. The system consists of 3 main units: The pumping unit, the gas extraction unit, and the gas separation and analysis unit.

[15] The system, which employed a gas chromatograph equipped with an electron capture detector (GC/ECD) for SF₆ detection, was mounted on an airboat and had a measurement interval of ca. one minute and a detection limit for SF₆ of 1×10^{-14} mol L⁻¹. A sample loop size of 0.354 ml was used during EverTREx, and the analytical precision, based on repeated measurements of the standard, was $\pm 2\%$. Data are recorded on a portable personal computer, and includes the output from the GC/ECD, GPS, water flow meter, and dissolved oxygen meters. Auxiliary field data included periodic measurements of water depths, and qualitative observations of vegetation and water column characteristics.

[16] For EverTREx, the pumping unit and the gas separation and analysis unit were modified from the original design to accommodate the challenging conditions in the Everglades. Because of the shallow water and the large amount of particulate matter in the water, the typical pumping setup used in previous experiments would have resulted in clogged filters in less than one minute. The modified pumping unit consisted of a flexible impeller pump, which delivered water from the Everglades into a custom-made 100 ml tangential flow filter on the airboat at a flow rate of 20 L min⁻¹. Most of this water, filled with particulates, was bypassed and drained back into the Everglades directly. A diaphragm pump took a split of the water from the tangential flow filter at a rate of 4 L min⁻¹ and delivered it to the gas extraction unit. This setup allowed most of the particulates and organic matter to be flushed out of the pumping system at a high rate, enabling a continuous delivery of water to the gas extraction unit.

[17] Unlike previous experiments on boats where there were cabins to shelter the sensitive valves and electronics of the gas separation and analysis unit, the airboat was completely exposed and susceptible to rain associated with the thunderstorms that are prevalent in the Everglades, and to extreme heat caused by direct exposure to the sun. Hence, a weatherproofed housing was designed for the unit, and equipped with a thermoelectric cooler to maintain a constant internal temperature.

7. Advection and Dispersion

[18] Advection was determined from the EverTREx 2 data by examining the movement of the center of mass of

the tracer patch. Also, two-dimensional Gaussians were fitted to SF₆ distributions from each day to estimate advection and dispersion. Because the location of SF₆ data were referenced to the Universal Transverse Mercator (UTM) coordinate system, whereas the plume length and widths σ_x and σ_y were referenced with respect to the major (x') and minor (y') axes of the tracer patch, the following formula was used:

$$C(x, y) = A \exp\left(-\alpha(x - x_0)^2 - \beta(x - x_0)(y - y_0) - \gamma(y - y_0)^2\right)$$

$$\alpha \equiv (\cos(\theta)/\sigma_x)^2 + (\sin(\theta)/\sigma_y)^2;$$

$$\beta \equiv -\sin(2\theta)/\sigma_x^2 + \sin(2\theta)/\sigma_y^2;$$

$$\gamma \equiv (\sin(\theta)/\sigma_x)^2 + (\cos(\theta)/\sigma_y)^2; \quad (1)$$

where θ is the heading of the main axis of the tracer patch with respect to the UTM coordinate axes (e.g., north = 0°; east = 90°, etc.). Advection was estimated from the change in the location of the plume center (x_0 , y_0), and longitudinal and lateral dispersion coefficients K_x and K_y were determined from changes in $\sigma_x^2(t)$ and $\sigma_y^2(t)$, respectively, as follows:

$$K_x = \frac{1}{2} \left(\frac{d\sigma_x^2}{dt} \right) \approx \frac{1}{2} \frac{\sigma_x^2(t_2) - \sigma_x^2(t_1)}{t_2 - t_1} \quad (2)$$

where $\sigma_x^2(t_1)$ and $\sigma_x^2(t_2)$ are the second moments of the tracer distribution at times t_1 and t_2 , respectively.

[19] Over the course of EverTREx 2, the leading edge of the tracer (defined as the 50 fmol L⁻¹ contour) traveled on the order of ~ 150 – 270 m day⁻¹, a rate equivalent to an average downstream velocity of ~ 0.25 cm s⁻¹. Advection calculated from the daily movement of the SF₆ center of mass and peak of Gaussian were comparable, and averaged 0.11 ± 0.04 cm s⁻¹ over the entire experiment (Figure 2a). Peclet number (Pe) calculated from this experiment (characteristic length scale = 1000 m) ranged from 3 to 40, suggesting that advection had a slightly higher influence on the system, but longitudinal dispersion also played an important role.

[20] Temporal variability was apparent in the flow. The mean advection over the first 3 days of the experiment was 0.15 ± 0.001 cm s⁻¹, and then dropped to 0.08 ± 0.004 cm s⁻¹ over the final 3 days (Figure 2b). Correspondingly, K_x was $3.7 \pm 1.0 \times 10^2$ cm² s⁻¹ for the first 3 days of EverTREx 2, and increased to $2.6 \pm 0.3 \times 10^3$ cm² s⁻¹ for the final 3 days (Figure 2c). The fact that K_x did not remain constant with time is a commonly observed behavior in tracer studies and is sometimes called “anomalous diffusion” [e.g., Fischer *et al.*, 1979; Young and Jones, 1991].

[21] The “anomalous” growth in longitudinal dispersion during EverTREx 2 can be parameterized by a power law fit: $\sigma_x^2 \sim t^{2\beta}$, where $\beta = 1.47$ ($r^2 = 0.99$; Figure 2c), while a compilation of dye experiments from North American rivers yield $\beta \approx 0.7$ [Nordin and Sabol, 1974]. To relate this nonlinear growth rate to measurable environmental quantities, the EverTREx 2 SF₆ data should be examined with a model that includes transient storage effects [e.g., Bencala and Walters, 1983], in which some tracer is held back in slow-flowing regions and slowly leaches back into the main

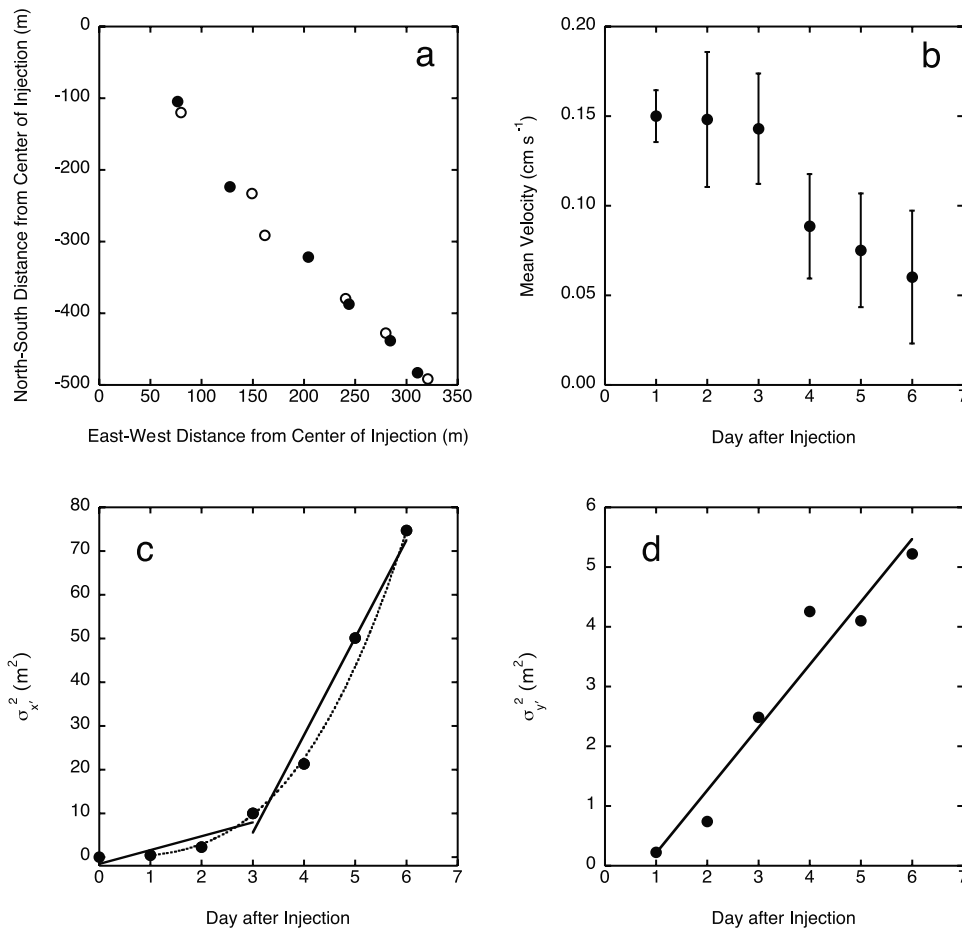


Figure 2. Plots for EverTREx 2 showing (a) daily movement of tracer patch as estimated from the center of mass (solid circles) and from the peak of the 2D Gaussian fit (open circles); (b) the mean velocity calculated from the change in location of center of mass. The uncertainty in the mean velocity is a result of the uncertainty in the location of the patch center; (c) second moments of the tracer distribution in the longitudinal direction, $\sigma_x^2(t)$; and (d) second moments of the tracer distribution in the transverse direction, $\sigma_y^2(t)$. $\sigma_x^2(t)$ is best parameterized by a power law fit (dotted line), while $\sigma_y^2(t)$ increased linearly with time (solid line).

flow. Transient storage effects could induce a shift in the center of mass of the tracer towards upstream locations, and may have influenced the velocity estimates derived from the tracer data, especially during the latter portion of study periods. Implementation of such a model is beyond the scope of the present contribution and will be presented in a forthcoming paper.

[22] Lateral dispersion, calculated to be $1.2 \pm 0.2 \times 10^2 \text{ cm}^2 \text{ s}^{-1}$ over the entire study period (Figure 2d), was low compare to longitudinal dispersion. The maximum width of the tracer plume was only slightly greater than the length of the release line, although isolated sawgrass patches encountered downstream resulted in non-uniform tracer concentrations across the slough later in the study period (Figure 1).

8. Flow Patterns in the Ridge and Slough Habitat

[23] The EverTREx data showed that significant variability in flow velocity occurs across short distances in the marsh (see auxiliary material). In EverTREx 2, the intensive tracer measurements showed that small-scale differences in

vegetation density and the presence of isolated sawgrass patches were correlated with the observed patterns in tracer distributions. Concentrations downstream of these features were generally lower than the maximum values observed along the open slough channels (Figure 1). Retention of the tracer behind these patches and by submerged vegetation probably played a role in longitudinal dispersion and resulted in long “tails” of low tracer concentrations along the main slough axis following the passage of the highest plume concentrations. These observations are consistent with previous small-scale experiments examining effect of vegetation on dispersion [e.g., Nepf *et al.*, 1997; Huang *et al.*, 2008]. As shown in Figure 1, the tracer traveled more quickly down the center of the slough in slightly meandering, preferential flow paths which were unobstructed by sawgrass patches. The influence of these features on advection and dispersion and their effect on observed tracer distribution during EverTREx 2 will be examined in a forthcoming modeling paper. This interaction between flow and vegetation patterns has important implications for sediment and nutrient dynamics across the ridge-slough interfaces, factors

which are thought to influence the formation and maintenance of this habitat [e.g., *Larsen et al.*, 2007].

9. Comparisons With Previous Experiments

[24] Advection rates during EverTREx 1 and 2 were comparable to past studies in the Everglades. In these earlier studies, advection rates ranged from 0.15 to 0.63 cm s⁻¹ using chemical and particle tracers in 3 m wide field flumes that restricted lateral transport [*Saiers et al.*, 2003; *Harvey et al.*, 2005], and 0.23 to 0.76 cm s⁻¹ in open water conditions using an acoustic Doppler velocimeter [*Leonard et al.*, 2006]. A series of experiments conducted with fluorescent particles in another flume found advection rates of 1.5 to 3.2 cm s⁻¹, but pumps were used in these experiments to create a water level gradient [*Huang et al.*, 2008].

[25] K_x derived from EverTREx 1 and 2 were considerably higher than previous chemical and particle tracer experiments in field flumes located in the Everglades, which range from 0.2 to 48.4 cm² s⁻¹ [*Saiers et al.*, 2003; *Harvey et al.*, 2005; *Huang et al.*, 2008]. The higher K_x is from a flume experiment that employed pumps, and the higher velocities in that study may not represent natural conditions. The fact that K_x from a large scale experiment like EverTREx is higher than those from smaller scale flume studies is not surprising, since larger tracer patches experience a wider range of local velocities [e.g., *Okubo*, 1980]. An experiment conducted over the scale of a few meters in a salt marsh in Massachusetts yielded K_x of 4 to 27 cm s⁻¹, but theoretical considerations indicate that K_x could be at least 5.4×10^2 cm² s⁻¹ in a typical wetland [*Lightbody and Nepf*, 2006], comparable to K_x from the initial days of EverTREx 2.

[26] Most of the previous tracer experiments conducted in the Everglades on small scales (i.e., in field flumes) are heavily influenced or even dominated by advection, with Pe ranging from 23 to 3167 [*Saiers et al.*, 2003; *Harvey et al.*, 2005; *Huang et al.*, 2008], whereas a dye experiment conducted on a similar scale as EverTREx had a Pe of 0.8, possibly due to retention of dye along the multiple flow paths in the study area [*Dierberg et al.*, 2005].

10. Environmental Controls on Sheet Flow

[27] In addition to the localized resistances presented by vegetation and landscape patterns, advection and dispersion in the Everglades are governed by spatially variable hydraulic gradients that change with depth, basin-scale engineered water controls, groundwater exchange, rainfall events, and wind [e.g., *Lee et al.*, 2004; *Bazante et al.*, 2006; *Leonard et al.*, 2006]. As a result, many studies have not been able to identify simple and direct relationships between point measurements of flow velocities and the larger-scale controlling factors. The mesoscale measurements presented here integrate the effects of all those factors, and provide calibration and validation data for the nonlinear and hierarchical numerical models that are needed to determine relationships between local-scale flow dynamics and large-scale controlling factors, and to connect basin-scale water budgets to flow dynamics.

[28] Tracer flow patterns in these two experiments showed some correspondence to the magnitude and direction (south-southeast) of larger-scale surface water elevation

gradients derived from the USGS EDEN water levels in this area (see auxiliary material). The magnitudes of surface water elevation gradients were similar during the two experiments (~ 1 cm km⁻¹) and corresponded to the similar advection rates measured during the first part of the two experiments. These gradients showed only minor variation during the course of the experiments, so cannot explain the decreases in southward advection rates observed during the latter portions of the experiments. As mentioned above, the gradual decreases in advection rates observed during these experiments could be due to trapping effects of vegetation, and in the case of EverTREx 1, uncertainty in the measurement location. Groundwater exchange and transient pressure gradients caused by localized rainfall events are two other factors controlling flow patterns in this region which were not accounted for in this study. Wind direction did not correlate with the observed patterns.

[29] Higher flow velocities were expected during EverTREx 2 given the deeper water conditions. However, the differences in basin-scale hydrologic budgets during the two experiments may have influenced the stage-velocity relationships at the study sites. EverTREx 1 took place during a period of generally rising water levels in WCA 3A, while water levels were in recession during EverTREx 2. These opposing trends suggest the differences in large-scale advection patterns and water management in WCA 3A may have influenced flow patterns at the study sites independently of local water depth.

11. Conclusions

[30] EverTREx shows that SF₆ tracer release experiments can be an effective way to quantify flow and transport in patterned wetlands like the Everglades. Future experiments in the Everglades should be detailed, like EverTREx 2, and should: 1) investigate flow patterns in degraded ridge and slough habitats; 2) be conducted in the well-preserved areas with concurrent studies of nutrient biogeochemistry and vegetation patterning, which will provide important guidelines for ridge and slough flow restoration targets; 3) be timed to coincide with planned water management operations to provide more information on linkages between structural discharges and flow velocities in the central marsh areas; and 4) examine flow dynamics in parts of the Everglades that will likely be impacted by climate change-induced sea-level rise.

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