

An autonomous self-orienting catamaran (SOCa) for measuring air-water fluxes and forcing

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Abstract. An instrumented, Self-Orienting Catamaran (SOCa) has been developed to measure air-water mass, heat and momentum exchange, as well as physical properties just above and below the air-water interface. The autonomous capabilities of SOCa include an atmospheric CO₂ profiling and air-water flux (F_{CO₂}) measurement system, surface-following measurements of water velocity and turbulent energy dissipation, and rotational orientation of water sensors into a surface current to avoid flow distortion. The gradient flux technique (GFT) is used with simplified assumptions of atmospheric eddy diffusivity to estimate F_{CO₂}. Using field data from the Hudson River estuary, SOCa is shown to orient properly to direct water measurements into the current for different combinations of wind and water velocity, up to mean wind speeds of at least 10 m s⁻¹. Water velocity and turbulence data are validated with instrument comparisons and a turbulent energy budget. Uncertainty and biases in F_{CO₂} estimates are quantified using null tests. This paper describes procedures for building a similar platform, and data processing methods that will be useful for a variety of autonomous platforms designed to study air-water interaction. Key Words: Carbon dioxide, air-water flux, autonomous platforms, turbulence, Hudson River

1. Introduction

Air-water gas exchange in rivers, estuaries and the continental shelf is of growing interest due to the potentially important role of these regions in the global carbon budgets (*Borges* 2005), and growing concerns over hypoxia (e.g., *Dai et al.* 2006). Studies at the ocean's margins are particularly useful for improving our understanding of air-water interaction, due to their convenient access, and diverse characteristics (e.g. fetch, depth) and processes (e.g. winds, tides). Also, large air-water CO₂ partial pressure differences ($\Delta p\text{CO}_2$; *Borges* 2005) lead to larger air-water gas fluxes that are easier to measure.

The design of a dual-purpose instrument platform that measures both air-water exchanges

and turbulence just below the air-water interface is motivated by recent studies that have demonstrated fundamental links and feedbacks between these processes (e.g., *McGillis et al.* 2004; *Moog and Jirka* 1999; *Nimmo-Smith et al.* 1999; *Zappa et al.* 2007). Air-water gas exchange is fundamentally an interfacial turbulent process in all but the most quiescent conditions, whether forced by tidal currents, wind, rain (*Zappa et al.* 2007) or diurnally-forced convection and shear instability in the surface ocean (*McGillis et al.* 2004). A catamaran that is attached to a boom alongside a boat has recently been used for field studies of estuarine air-water gas exchange and turbulence, but requires carefully timed manual profiling to collect vertical profiles of wind, temperature, humidity and CO₂ (*Zappa et al.* 2007; *Zappa et al.* 2003). The observations collected from that platform have been highly valuable, and a goal of the present research is to collect data over a much wider range of conditions and locations using an autonomous platform and atmospheric profiling system.

This paper describes the construction and capabilities of the Self-Orienting Catamaran (SOCa) and its automated CO₂ profiling and air-water flux measurement system. SOCa is a versatile, shallow-draft instrument platform that is deployed at anchor and has properties assuring that its water velocity measurements and atmospheric profile measurements are made without structural flow interference. The gradient flux technique (GFT) is utilized to estimate air-water gas fluxes with a small spatial footprint, useful for studying small-scale aquatic systems or localized features in the coastal ocean. In the sections that follow, we: (a) describe SOCa construction, instrumentation, and measurement techniques; (b) assess SOCa behavior, instrument performance, and uncertainty using data from two field campaigns on the Hudson River estuary; and (c) discuss how SOCa can help broaden our understanding of air-water interaction processes.

2. Materials and methods

The primary desired attributes for designing SOCa were autonomy, mobility, and low labor and materials expenses. These were achieved by constructing a simple lightweight catamaran that can be transported and deployed on short notice at a wide range of possible locations. The catamaran has a low deck for minimal windage and a keel that "vanes" or steers it into the current so that near-surface currents are measured without obstruction (**Figure 1**). A 15 m long bridle is fed through the front crossbar to avoid anchor-line flow interference in front of the water velocity sensors. The catamaran's pontoons are lightweight, have a draft of only ~0.15 m, and allow waves to pass under the vessel unimpeded. Additional details on materials, power and data logging are given in a Ph.D. dissertation (*Orton* 2010, p.66). The materials and labor costs of the platform itself are relatively low, due in part to using commercially available components – below US\$1000 and one day of assembly.

Atmospheric measurements are also collected in such a way as to minimize problems with structural flow interference. "High" atmospheric wind velocity measurements and pumped air samples are taken at the top of a 2.25 m mast, located high enough that platform flow interference is negligible. "Low" atmospheric air intakes are located on both sides of SOCa so that there is always a sample taken on the upwind side, undisturbed by structural flow interference (**Figure 1**). Optimally, a second wind measurement is made either on the windward

side (see photograph, Orton 2010, p.101) or at a height high enough to avoid structural flow interference.

2.1 Sensors and locations

SOCa is fitted with physical and chemical sensors for observing air-water gas fluxes and processes that directly influence these fluxes – wind velocity, water velocity and turbulence, water temperature, salinity and stratification, CO₂ concentrations in surface water and at two heights in the lower atmospheric surface boundary layer, and H₂O concentrations in the atmosphere. Water velocity is recorded at 25 Hz with an acoustic Doppler velocimeter (10 MHz Sontek ADV) with beams oriented downward to sample at a depth just below the sea surface (0.1–0.5 m), with the sensor head 0.2 m forward of the vessel's pontoons. The turbulent kinetic energy dissipation rate is estimated using the inertial dissipation method (described below). An inertial sensor (Crossbow VG400MA-100) samples at 25 Hz to monitor vessel motion to assist in the turbulence data processing. One or two 2-D sonic anemometers (Gill Wind Observer II) continuously record wind velocity and air temperature above the platform. Instruments and their locations used in one particular field study are given in **Table 1**.

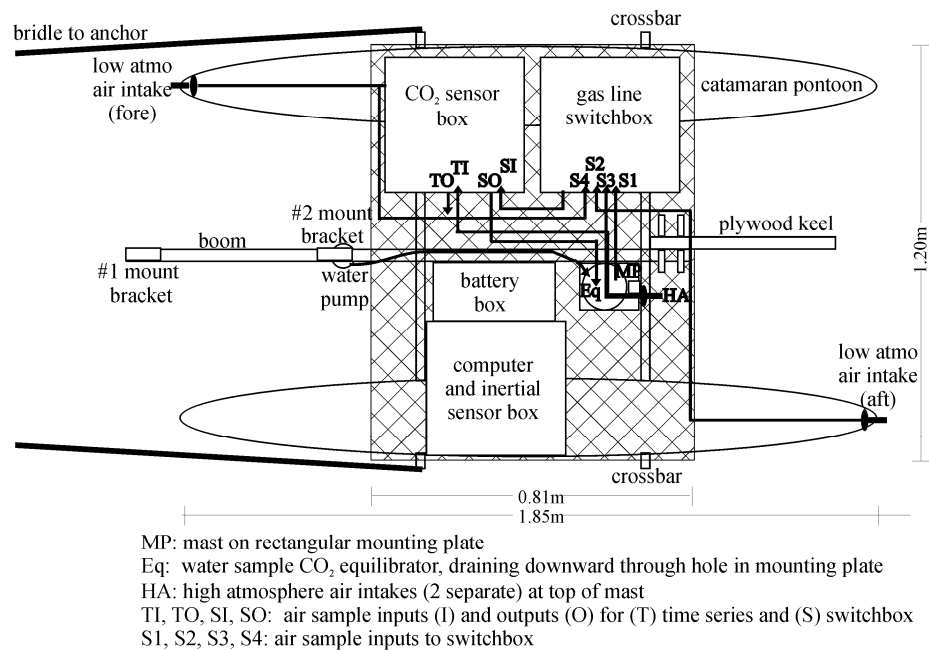


Figure 1: Plan view of SOCa with the autonomous atmosphere and water CO₂ profiling system, focusing on basic structural components and the air sampling lines. The keel "vaness" (spins) the float so that the water velocity sensor on mount bracket #1 is always oriented into the current. The bracket holds one or more acoustic Doppler velocimeters (ADV) at user-selectable depths, typically 10–50 cm. Photos of the platform are given in Orton (2010).

Table 1: Sensors, their vertical locations, and sample rates on SOCa during the CASsIE study

Model / description	Variables	z^a (m)	Location	Rate (Hz)
Gill Wind Observer II	temperature, wind velocity	1.2	mast top	2
Sontek 10 MHz ADV	water u, v, w, ϵ	-0.5	forward	25
Licor LI-840 (switchbox)	equilibrator (water) $[CO_2]$	-0.2	forward	1
	air $[CO_2], [H_2O]$	0.4	forward ^b	1
	air $[CO_2], [H_2O]$	2.25	mast top	1
Licor LI-840 (timeseries)	air $[CO_2], [H_2O]$	2.25	mast top	1
RBR chain of TR-1050s	water temperature	profile.	anchor line	0.02
Crossbow VG400MA-100	angular rates, linear accels.	0.3	on deck	25

a: shows measurement height (depths negative), or gas intake height for Licor sensors

b: both intakes were at the front for a residual moisture test throughout CASsIE (see **Section 3.3**)

The automated atmosphere and water CO_2 profiling system is described here, and the Gradient Flux Technique (GFT) is utilized to estimate air-water fluxes (see sections below). Two closed path infrared CO_2/H_2O concentration sensors (Licor, LI-840) in the CO_2 box (**Figure 1**) are used for measuring (sensor 1) air samples from a gas valve switchbox, and (sensor 2) a stationary atmospheric timeseries from one height. The switchbox was built in collaboration with Fathom Research, Inc., and combines an electronically switched 4-port valve actuator (VICI Valco, model ECMT) with a computer controller, and reports its position via serial communication. The switchbox is used so that atmospheric and air-water gradients are measured using the same LI-840 sensor, avoiding problems with instrument inter-calibration. The stationary timeseries is collected so that the temporal change that occurs while a vertical profile is sampled can be removed before computing the vertical CO_2 gradient (McGillis *et al.* 2001b). Miniature pumps pull air through each sensor. Air for the first LI-840 (**Figure 1**; S1) is routed through the switchbox in 10-minute increments from four channels: (S1) the headspace of an equilibrator that processes surface water pumped from below the front of the vessel, with pump intake at 20 cm depth (7 L min^{-1}), (S2) 0.4 m height atmosphere at the back of the vessel, (S3) 2.25 m height atmosphere, (S4) 0.4 m height atmosphere at the front of the vessel. All air sample nozzles have filters to prevent water droplets or other particles from being pulled into the switchbox and LI-840s. Gradients in CO_2 or H_2O are computed using two-point "profiles" taken between channels 2 and 3 (wind from aft) or 3 and 4 (wind from fore).

The equilibrator is a smaller version of the design used to measure seawater pCO_2 by Broecker and Takahashi (1966), with a water volume of 0.8 L and air volume of 2.0 L, fashioned from off-the-shelf parts (Newberger 2004). Water is drawn with an immersion pump from a water depth of 20 cm and sprayed into the equilibrator. Air is drawn from the headspace through the LI-840 at a rate of 1.0 L min^{-1} , then routed back into the equilibrator to form a closed loop (**Figure 1**; SO), allowing equilibration of $[CO_2]$ in the water and headspace air to occur gradually.

2.2 Field study

A study called Carbon and Air-Sea Interaction in an Estuary (CASSIE) was conducted in fall, 2007 (Orton 2010; Orton *et al.* 2010; Orton *et al.* in press). SOCa was frequently anchored at a shallow (5 m) site in the Hudson River estuary, during the period 23 September through 2 November, 2007 (year-days 265–303), with instrumentation summarized in **Table 1**. The platform was anchored at this site collecting extensive datasets for periods as long as 11 days (year-day 269.5–280.5). A total of 19 complete days of wind and ADV data, and 14 days of CO₂ data were collected. The study site had a cross-channel wind fetch of 1.8 km in each direction and along-channel fetch of >10 km (it is a long straight estuary), resulting in significant wave heights estimated at 0–0.5 m. Nearby, a bottom-mounted acoustic Doppler current profiler measured vertical profiles of velocity and acoustic backscatter at 1 Hz, with a Seabird SBE-37 CTD on its frame. Also, a meteorological station on a pier 8 km to the south included measurements of atmospheric pressure.

2.3 ADV estimates of turbulent energy dissipation

The Inertial Dissipation Method (IDM) was applied to velocity data with the frozen field assumption to estimate 10-minute averages of the dissipation (ε) rate of turbulent energy (Orton *et al.* in press). A keel rotated SOCa so that the boom was oriented into the current to avoid wake biases. Periods with a wave orbital speed greater than 40% of mean flow speed were omitted to avoid biases from aliasing wave energy into the inertial subrange (Lumley and Terray 1983).

2.4 Autonomous application of the Gradient Flux Technique (GFT)

A simple and robust method for estimating air-water exchanges from a free-floating platform is GFT, which has the advantage of requiring only measurements of mean vertical gradients, often much easier to measure than the eddy covariance. Flux estimates computed with GFT compare favorably with other, more direct flux measurements (Businger *et al.* 1971; McGillis *et al.* 2001b; Zappa *et al.* 2003). GFT utilizes the fact that a constituent's air-water exchange is proportional to its vertical gradient in the atmospheric surface layer (ASL), and corrects for the smearing of the gradient by turbulent mixing. A shortcoming of the method is its reliance on a parameterization to represent this mixing, but theory for ASL mixing is well-developed and has been validated extensively (e.g., Edson *et al.* 2004; Edson *et al.* 2007).

The water-to-air flux of CO₂ (F_{CO_2}) is defined with GFT as (Edson *et al.* 2004; McGillis *et al.* 2001b; McGillis *et al.* 2004):

$$F_{CO_2} = -K_C(z) \frac{\partial C(z)}{\partial z} \quad (1)$$

Here, K_C is the eddy diffusivity for CO₂, $C(z)$ is the CO₂ number density (moles per m³ dry air) at height z . For the CASSIE datasets, GFT was applied following an approach similar to that of McGillis *et al.* (2001b), described in detail in Orton (2010, p.72). The parameterization for K_C is from the Monin-Obukhov Similarity Theorem (Edson *et al.* 2004), and permits an analytical solution to Eq. 1 to be used to compute F_{CO_2} from the observed two-height vertical gradient in C . The required air-water heat and momentum fluxes and parameterization of turbulent diffusivity were all computed using the Matlab COARE 3.0 bulk flux toolbox (Fairall *et al.* 2003).

Average [CO₂] and [H₂O] are computed over 10-minute periods, following the switchbox

schedule. Average $[\text{CO}_2]$ data are corrected for dilution by water vapor, and then these data are converted to C using the ideal gas law with observed atmospheric pressure. Computation of the average $\Delta p\text{CO}_2$ is performed for every 40-minute switchbox cycle by computing partial pressure from observed molar ratio concentration and atmospheric pressure (McGillis and Wanninkhof 2006), assuming ideal gas behavior and estimating saturation water vapor pressure from water temperature and air pressure. The CO_2 solubility K_0 is computed as a function primarily of water temperature, but also secondarily of salinity (McGillis and Wanninkhof 2006; Wanninkhof 1992), both measured in situ.

The air-water CO_2 flux is related to the gas transfer velocity (k) through the empirical parameterization (e.g., McGillis and Wanninkhof 2006):

$$k = F_{\text{CO}_2} / K_0(p\text{CO}_{2,\text{water}} - p\text{CO}_{2,\text{air}}) = F_{\text{CO}_2} / K_0 \Delta p\text{CO}_2 \quad (2)$$

Here, the solubility K_0 is assumed to be constant across the aqueous mass boundary layer, and $p\text{CO}_{2,\text{water}}$ and $p\text{CO}_{2,\text{air}}$ are the partial pressures of CO_2 in water and air. Calculations of F_{CO_2} , K_0 and $\Delta p\text{CO}_2$ are used compute k . The Schmidt number is the ratio of momentum to mass diffusivity, and depends on the gas of interest as well as the temperature and salinity of the water. The gas exchange velocity k is normalized to a Schmidt number for CO_2 (Sc) of 660 (the value for a temperature of 20 °C and salinity of 35 psu) using observed salinity and temperature timeseries (Wanninkhof 1992), and hereafter referred to as k_{660} . A normalization exponent of -0.5 was used, for gas exchange at a clean, wavy water surface (e.g., Jähne *et al.* 1984).

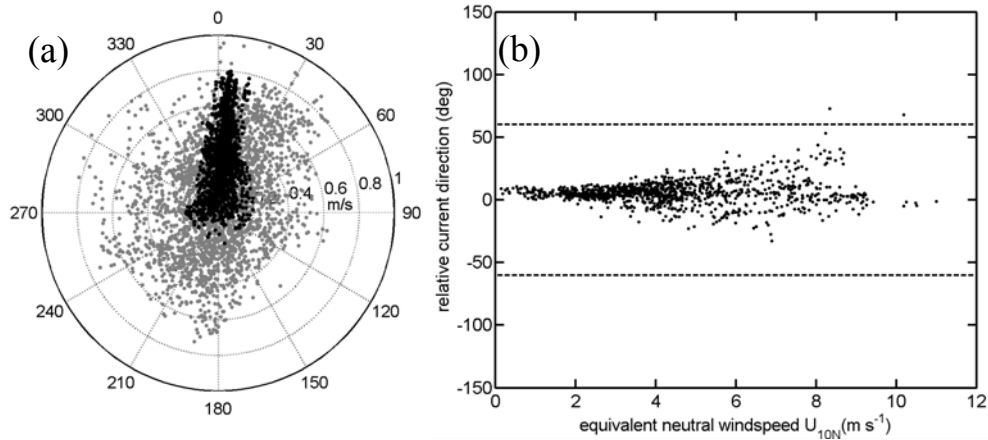


Figure 2: (a) SOCa rotational orientation, with each black point representing a 10-minute mean water velocity vector emanating from the point and aiming toward the target center (direction of fluid movement), relative to the direction SOCa is pointing (0°). Observed wind velocity (U) vectors divided by 10 are also shown as grey points. (b) SOCa orientation as a function of wind speed, for water speeds above 0.2 m s^{-1} . Dashed lines show -60° and $+60^\circ$, conservative cutoffs beyond which flow interference from the pontoons could bias velocity or turbulence estimates.

3. Results

SOCa measurements of water velocity, turbulence, and gas exchange are assessed below using the CASsIE study field data. In situ system tests and comparisons between different instruments are used to validate the measurements and quantify uncertainty. Additional validation is sought using comparisons of field observations with those from prior studies.

3.1 Platform orientation

SOCa oriented properly to direct the ADV into the surface current for different combinations of wind and water flow direction, up to mean wind speeds of at least 10 m s^{-1} (**Figure 2a**). There was a small mean heading angle of $\sim 4^\circ$, relative to water velocity, likely due to something about the platform or instruments (e.g. the ADV, or the anchor line bridle) that is not laterally symmetric about the centerline. The angle was small for low wind speeds, but its magnitude was sometimes larger for higher wind speeds. However, when water speed was at least 0.20 m s^{-1} , the water flowed into the ADV from an acceptable angle ($\pm 60 \text{ deg}$) 99.8% of the time, avoiding current measurement biases due to wake effects (**Figure 2b**). Pitching of the vessel moves the velocity sensor vertically, impacting vertical and potentially also stream-wise velocity measurements. Dissipation measurements are made possible, however, by the separation of wave-induced velocities from the inertial subrange in wavenumber space. Wave-induced variability in platform tilt was generally small but increased with wind speed, with standard deviations in pitch and roll of $\sim 4^\circ$ for winds of 10 m s^{-1} (Orton 2010, p.106).

3.2 Velocity and turbulence validation

The range in ADV ϵ estimates for CASsIE was from 5×10^{-8} to $8 \times 10^{-4} \text{ W kg}^{-1}$ (Orton 2010, p.103), with detection of lower values generally prevented by the ADV noise floor. During low energy periods, ADV sampling noise led to white (flat) velocity spectra at high wavenumbers. The velocity range was maximized during this experiment, and this may generally be necessary with a moving platform in wavy conditions. In environments with small waves, it would likely be possible to observe lower ϵ values with a lower range setting – instrument noise is proportional to the velocity range (Voulgaris and Trowbridge 1998).

Validation for the ADV surface water speed measurements is provided by a comparison with ADCP data, with good agreement at all times (Orton 2010, p.107). Validation for the ϵ estimates was accomplished on two fronts, though only for low-wind conditions (Orton *et al.* in press): (1) agreement typically within a factor of two in a comparison between the ADV and a fine-scale (2.6 cm resolution) spatial velocity profiler that does not require Taylor's assumption, and (2) closed turbulent kinetic energy (TKE) budgets based on ADV estimates of ϵ and ADCP estimates of TKE, TKE shear production, TKE time variation, and TKE turbulent transport.

The ϵ data also show reasonable trends with wind and water speed (**Figure 3**). Dissipation increases with increasing winds, regardless of current velocity, and increases with the water speed when winds are weak. These results are similar to those found by Zappa *et al.* (2007) for a relatively shallow and unstratified system, the Parker River estuary. However, with the SOCa data, there is no suggestion that ϵ increases with water speed when winds are moderate ($3 \leq U_{10N} \leq 6 \text{ m s}^{-1}$). This suggests that currents play less of a role in controlling ϵ at the CASsIE site, likely due to stratification and a deeper water column over which bottom-generated turbulence decays.

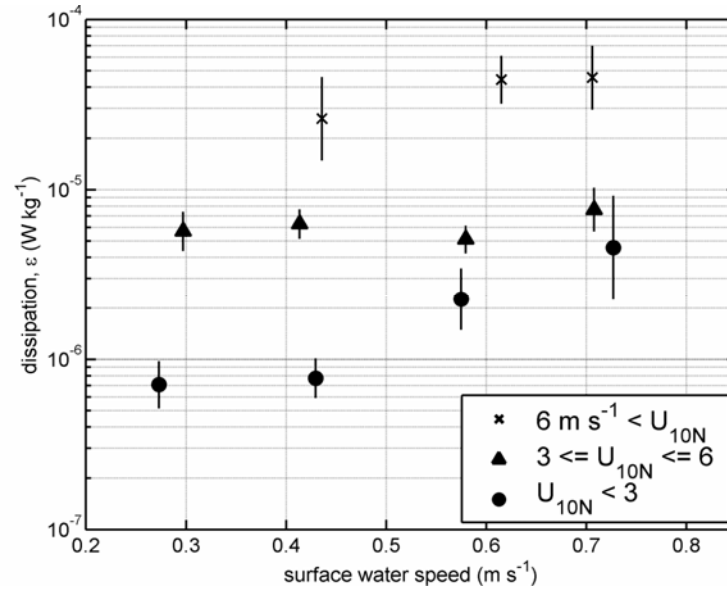


Figure 3: Dissipation bin-averages for different wind and water speeds, with errorbars showing 95% confidence intervals. At least five 10-minute average ϵ estimates were required in a bin to compute an average for display on the plot. Wind speed bins are shown in the legend, and water speed bins were 0.20–0.35, 0.35–0.50, 0.50–0.65, and 0.65–0.80 m s⁻¹.

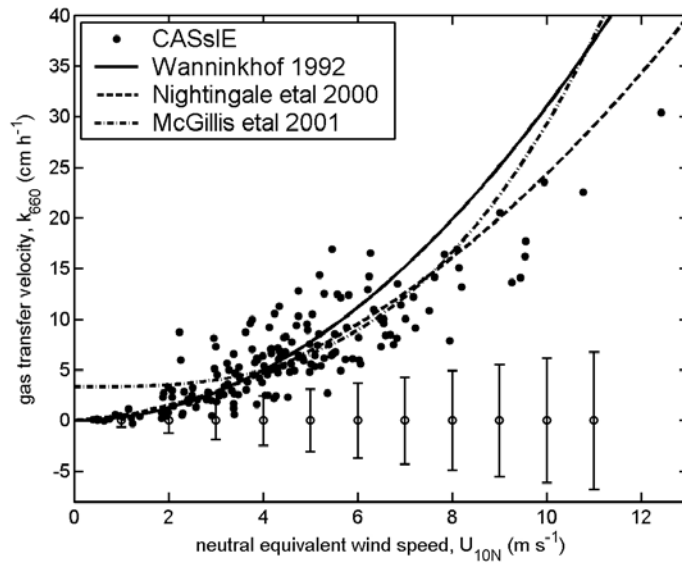


Figure 4: The relationship between observed wind speed and gas transfer velocity, compared with three well-known parameterizations, for CASsIE. Errorbars show how the estimated 95% confidence in ΔC from null tests propagates into k_{660} .

3.3 CO₂ validation and uncertainty tests

Here, the unique autonomous CO₂ profiling and GFT approach used during CASSIE is evaluated with tests of system functionality, an examination of uncertainty, and with comparisons of the Hudson measurements with other studies. The performance of the equilibrator was examined at the beginning of the study, when it was verified that the sampling time of 10 minutes was sufficient for equilibration to occur (the switchbox has adjustable timing). The pCO₂ rapidly changed from the atmospheric value to the (much higher) value for the equilibrator headspace, with an equilibration rate for the water pCO₂ measurement of 2–3 minutes. An initial abrupt change over ~10 seconds matches the time it takes for completely flushing the tubing and switchbox hardware, which we have observed in the laboratory when testing with tanks of known [CO₂]. The more gradual, 2–3 minute adjustment appears to correspond to the equilibration of [CO₂] in the recirculating headspace air with the surface estuarine water flowing through the system. Rapid (2–3 hour) decreases in pCO₂ of as much as 32% are observed from early-to-mid afternoon on sunny days, consistent with formation of a warm shallow stratified layer with high primary productivity. The sea breeze arrives in mid-afternoon, and wind- or tide-driven mixing of the stratified layer is associated with a rapid return of pCO₂ to near the original levels (Orton *et al.* 2010).

Figure 4 shows a comparison of SOCa observations of the gas exchange velocity as a function of wind speed, versus a set of parameterizations (McGillis *et al.* 2001a; Nightingale *et al.* 2000; Wanninkhof 1992). Observed values are similar to the parameterizations, but frequently higher (double) for low and moderate wind speeds, yet generally lower for high wind speeds. The enhanced gas transfer at low winds could be a result of many factors, including rain (which will be quantified in future studies) or tidal currents. The weaker gas transfer at high winds is likely due to fetch limitation, because a fully developed sea state with frequent whitecapping was not observed to develop over a fetch as low as 1.8 km during high wind periods. The use of wind-based bulk heat flux parameterizations biases the results and likely improves the fit of the estimated k_{660} values to the wind-based parameterization, and solutions for this problem are discussed in **Section 4**. However, near-surface turbulence drives gas exchange at this range of wind speeds, and this turbulence was driven more by wind than by tidal currents during this study (Orton *et al.* in press).

A "residual moisture bias test" was conducted throughout CASSIE to check whether there was any bias in CO₂ flux estimates made using different switchbox channels, due to residual moisture droplets in the switchbox, sample lines or LI-840. Both of the low height atmospheric sample intakes (Ch. 2, Ch. 4) were placed at the front of the vessel for this test. After channel 1 samples the water-saturated air from the equilibrator's headspace, then channels 2–4 sample relatively low humidity atmospheric air in 10-minute intervals. Residual moisture was confirmed to be present – the "switcher LI-840" samples at 2.25 m (Ch. 3) often have higher [H₂O] levels than the "stationary timeseries LI-840", which always samples air from 2.25 m. Vertical C gradient estimates computed using Ch. 2 ($\Delta C = C(z_2) - C(z_1) = C_{Ch.3} - C_{Ch.2}$) and Ch. 4 ($\Delta C = C_{Ch.3} - C_{Ch.4}$) were very similar, and no significant difference was found between their means ($\alpha > 0.33$). However, for cases with low ΔC , ΔC from Ch. 4 was typically larger (more negative) than ΔC from Ch. 2. Flux results presented in the paper were computed using the average concentration from Ch. 2 and Ch. 4 for the low height atmosphere C. A useful protection against

sample-line moisture that we are now using is to install vials of air sample drying agent (e.g. magnesium perchlorate) to dry the air samples without causing any biases to the CO₂ measurements.

Two different null tests were used to verify system functionality and quantify uncertainty: (1) with the switchbox sampling air from only one channel for several days interspersed through the study, and (2) with the switchbox cycling through the four channels, with all atmospheric air intakes located at the same height (~30 cm) for over one day. The first test showed how noise in LI-840 sampling led to uncertainty in the atmospheric CO₂ vertical concentration difference, ΔC . The observed mean ΔC was 0.00010 with a standard deviation of 0.00266 mmol m⁻³. This is nearly identical to the expected standard error for a mean concentration difference, based on the manufacturer estimated measurement uncertainty. The resulting 95% confidence intervals in k_{660} are shown in **Figure 4**. The second test showed how measurements using different sample lines impact ΔC . A mean ΔC of -0.0029 with a standard deviation of 0.00250 mmol m⁻³, indicated that there was a bias towards a negative concentration difference (and therefore a very small positive F_{CO_2} and k_{660}). The reasons for this bias are unknown, but could be caused by sample line length differences or valve obstructions that lead to flow rate differences that are not corrected for by the LI-840. This bias in ΔC was subtracted prior to computing fluxes.

4. Discussion and conclusions

The positive attributes of SOCa are not replicated in any other existing platform, and it provides a valuable new perspective for studies of air-water gas exchange and turbulence in coastal, estuarine and freshwater systems. Below, we discuss the benefits of the wider temporal and spatial coverage that can be sampled, the longer deployment durations (and prospects for extending battery life), and the unobstructed surface-following measurements of turbulence. We also suggest some simple approaches for improving the air-water exchange and turbulence measurements.

The low expense and relative ease of deploying one or more SOCa in different locations for autonomous measurements make it a useful tool for obtaining data with broad temporal and spatial coverage. The shallow-draft SOCa may be valuable for studies of air-water gas transfer in shallow coastal regions that are inaccessible for normal research vessel based sampling, yet may be highly important for local biogeochemistry or global carbon budgets (*Borges* 2005). The CASSIE deployments captured the passage of fall season storm systems with mean along-estuary winds as high as 11.0 m s⁻¹ (1.2 m height) gusting as high as 19 m s⁻¹. These periods exhibited very high air-water CO₂ fluxes (100–200 mmol m⁻² d⁻¹), air-water temperature differences as large as -12 °C, extreme upward net air-water heat fluxes as high as 500 W m⁻², and strong turbulent mixing (*Orton et al.* in press) and deepwater ventilation.

Another strength is longevity – because all the onboard measurements are relatively insensitive to calibration drift, long-term deployments are possible. The acoustic measurements of water velocity (and turbulence) and wind velocity have negligible calibration drift. The CO₂ flux algorithm relies on air-water pCO₂ differences and vertical gradients in the lower atmosphere, and since these are made with a single sensor, the flux measurement is also relatively insensitive to calibration drift. Deployments during CASSIE were as long as 11 days, and much longer durations are possible; SOCa was only towed in for equipment upgrades. This

is a substantial improvement upon prior sampling that required a boat and personnel for manual profiling (e.g. Zappa et al., 2003). Batteries were taken out for daily replacements, and looking ahead, use of a commercial long-term pCO₂ monitoring system (e.g., SAMI-CO₂, Sunburst Sensors; DeGrandpre et al. 1995) and low-power data loggers (instead of an onboard computer) would be useful improvements.

A shortcoming with the CASSIE SOCa measurements was that use of the bulk heat and momentum fluxes in the processing likely obscured some detail of the CO₂ flux variability and forcing. One relatively simple improvement to address this issue has already been made in a more recent experiment, by adding a second sonic anemometer (see photograph, Orton 2010, p.101). Sonic anemometers have virtually no calibration drift, so collecting a two-point wind profile with an additional wind velocity sensor at a different height can provide accurate atmospheric gradients and improved estimates of air-water momentum fluxes. An additional relatively simple improvement would be to add thermocouples for highly accurate atmospheric temperature gradients, improving estimates of the air-water sensible heat flux. An additional or separate option is to use eddy covariance for all the air-sea flux measurements (McGillis et al. 2001a), but as mentioned earlier, this can be difficult on a moving platform in wavy seas.

SOCa self-orients and provides undisturbed turbulence measurements near the water surface, which are rarely made because free-falling micro-scale sensors typically begin their profile at 2–3 m depth (e.g., Peters and Bokhorst 2000). Turbulent mixing of constituents in the upper meter of the water column is relatively poorly understood, yet can be highly important for surface oriented pollutants, surface-oriented biological constituents, or air-water exchanges (Nimmo-Smith et al. 1999). A potential weakness of the platform is applicability in cases with steep or breaking waves, when the turbulence measurements become difficult due either to (1) orbital velocities being larger than mean velocities, violating Taylor's assumption, and (2) pitching of the vessel. Currently, data is masked during wavy conditions, but field testing during windy conditions with multiple instruments would be useful to better understand the impact of winds and waves on measurement accuracy.

Our goal in the ongoing research with SOCa and similar platforms is to make observations under a wide range of conditions at several sites and provide the research community with improved, multi-parameter gas exchange and turbulence models. More broadly, methods presented in this paper may be useful for any autonomous study of air-water mass, heat or momentum exchange. These studies are becoming more common due to interest in climate change and the movement toward construction of a complete Earth observation system.

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