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Spatial and temporal variability of carbon dioxide and methane fluxes over semi-diurnal and spring–neap–spring timescales in a mangrove creek

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Abstract

Automated in situ instrumentation captured high-resolution surface water $p\mathrm{CO_2}$, CH_4 and ^{222}Rn data at the creek mouth, and ~500 m upstream in a sub-tropical mangrove ecosystem (Southern Moreton Bay, Australia, S27.78°, E153.38°) over a spring-neap-spring tidal cycle (~15 days) during November 2013. The partial pressure of CO_2 ($p\mathrm{CO_2}$) ranged from 385 to 26,106 µatm, CH_4 from 1.8 to 889 nM, and ^{222}Rn from 280 to 108,172 dpm m^{-3}. Average surface water $p\mathrm{CO_2}$, CH_4 and ^{222}Rn were 4-fold higher at the upstream station. Surface water fluxes of CO_2 and CH_4 ranged from 9.4 to 629.2 mmol CO_2 m^{-2} d^{-1} and 13.1 to 632.9 µmol CH_4 m^{-2} d^{-1} depending upon the gas transfer model used and station location. Creek $p\mathrm{CO_2}$, CH_4 and ^{222}Rn displayed changes over both semi-diurnal and spring–neap–spring tidal scales. Semi-diurnally, all gases had a significant inverse relationship with water depth. Over the spring–neap–spring cycle, all gases exhibited an inverse relationship with tidal amplitude, with higher values during neap tides than spring tides. Estimated fluxes, porewater observations, and the significant positive relationship between surface water $p\mathrm{CO_2}$ and CH_4, and ^{222}Rn suggests groundwater exchange (i.e., tidal pumping) drives $p\mathrm{CO_2}$ and CH_4 within the mangrove creek. We hypothesize that a combination of hourly and weekly groundwater–surface water exchange processes drive surface water $p\mathrm{CO_2}$ and CH_4 in mangrove creeks. Semi-diurnally, flushing of crab burrows leads to high $p\mathrm{CO_2}$ and CH_4 concentrations at low tide. During the spring–neap–spring cycle, older groundwater enriched in CO_2, CH_4 and ^{222}Rn seeps into the creek as tidal amplitude decreases, leading to higher concentrations at neap tides.

1. INTRODUCTION

Carbon cycling in mangrove systems has received considerable attention in recent years, resulting in a better understanding of the processes associated with the major export pathways (Bouillon et al., 2008; Kristensen et al., 2008a; Alongi, 2014). Based on limited data, previous global mangrove carbon budgets underestimated the various carbon sinks and were unable to account for approximately 50% of mangrove net primary productivity (NPP, 112–160 Tg C yr^{-1}) (Bouillon et al., 2008; Alongi, 2009). This "missing carbon" is likely linked to underestimates of sediment-air CO_2 fluxes (Chen et al., 2012; Leopold et al., 2013; Lovelock et al., 2014), and lateral carbon export by groundwater previously being unaccounted for (Maher et al., 2013a). For example, recent evidence suggests belowground respiration has been greatly underestimated and that the majority of the "missing carbon" is exported as dissolved inorganic carbon (DIC, 86 Tg C yr^{-1}; Alongi, 2014) via

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tidally mediated exchange of interstitial porewater with surface waters (Bouillon et al., 2008; Alongi, 2009; Maher et al., 2013a).

The tidally mediated exchange of porewater between sediments and surface waters via the ebb and flow of tides is known as "tidal pumping" (Robinson et al., 2007; Li et al., 2009; Santos et al., 2012a; Gleeson et al., 2013). The structural complexity of the aerial mangrove tree roots creates a low energy environment allowing for fine-grained particles to settle out, creating a relatively impermeable substrate (Bouillon, 2011). However, crabs create abundant burrows in most mangrove sediments, which enhance hydraulic connectivity and increase the surface area of the sediment–water interface (Stieglitz et al., 2000) where exchange of the by-products of subterranean respiration can occur during tidal inundation (Kristensen et al., 2008b). Thus, metabolic solutes derived from sub-surface mineralisation of organic matter may be continuously exported from mangrove ecosystems via tidal pumping.

Tidal pumping is a potential source of solutes to mangrove waters, but the process has only recently been quantified and directly linked to the export of carbon and nutrients (Bouillon et al., 2007a; Gleeson et al., 2013; Maher et al., 2013a). Borges et al. (2003) first suggested the potential importance of tidal pumping on $p\mathrm{CO_2}$ in mangrove creeks and Koné and Borges (2008) attributed high DIC and total alkalinity in mangrove creek waters to the influx of porewaters, based on stoichiometric relationships that showed anaerobic processes controlled these solutes. Linto et al. (2014) relied on the negative correlation of $p\mathrm{CO_2}$, $\mathrm{CH_4}$, total alkalinity and DIC concentrations with tidal height to link tidal pumping with high concentrations of $\mathrm{CO_2}$ and $\mathrm{CH_4}$ in creek waters. However, ecosystem scale quantification of the carbon and nutrient exports via tidal pumping in mangroves has only recently been determined through the use of natural radioisotope tracers (Gleeson et al., 2013; Maher et al., 2013a).

Radon-222 (^{222}Rn) is a radioactive isotope produced continuously by the decay of Radium-226 (^{226}Ra), which is a product of the naturally occurring Uranium-238 (^{238}U) decay series present in most sediment matrices. Radon-222 is often highly enriched in porewater or groundwater relative to surface water and its short half-life (3.84 d) is comparable to mixing time scales in many coastal systems. Gleeson et al. (2013) quantified groundwater–surface water exchange in a mangrove tidal creek at the ecosystem scale, revealing that 5–12% of the tidal prism volume infiltrated the sediments and drained back to the creek at low tide. Stieglitz et al. (2013) quantified the volume of groundwater exchange in a mangrove creek to be ~30 $\mathrm{L\,m^{-2}\,d^{-1}}$, which is equivalent to 16–22% of the total annual river discharge within the study area. In both cases, crab burrows, particularly the construction of new burrows, were considered to be a major facilitator of groundwater and porewater exchange.

Maher et al. (2013a) used ^{222}Rn and carbon stable isotope ratios (δ^{13}C) to directly measure and model the export of DIC and dissolved organic carbon (DOC) via tidal pumping in a sub-tropical mangrove ecosystem. It was estimated that DIC exported via tidal waters averaged 3 $\mathrm{g\,C\,m^{-2}\,d^{-1}}$ which was an order of magnitude greater than DOC export and similar to estimates of the unaccounted mangrove NPP (~1.7–2.7 $\mathrm{g\,C\,m^{-2}\,d^{-1}}$). Tidal pumping was responsible for 89–92% of the DOC and 93–99% of the DIC exported. The magnitude of groundwater-derived DIC export from mangroves implies that tidal pumping may drive other important processes, particularly groundwater–surface water exchange of $\mathrm{CO_2}$ and $\mathrm{CH_4}$.

This paper builds on previous studies by using ^{222}Rn to assess the influence of tidal pumping on surface water $p\mathrm{CO_2}$ and $\mathrm{CH_4}$ concentrations over a spring–neap–spring cycle. An automated in situ system was used to measure $p\mathrm{CO_2}$ and $\mathrm{CH_4}$ at 1 Hz and ^{222}Rn at 10 min intervals at two locations within the creek (creek mouth and ~500 m upstream) over a 16-day period. We hypothesise that tidal pumping will control surface water $p\mathrm{CO_2}$ and $\mathrm{CH_4}$ concentrations and that there will be significant spatial (i.e., between the creek mouth and upstream station) and temporal variability (i.e., semi-diurnal and spring–neap–spring time scales) in surface water $p\mathrm{CO_2}$, $\mathrm{CH_4}$ and associated estimates of the water to atmosphere fluxes of these gases.

2. METHODS

2.1. Study site

The study was conducted in a tidal mangrove creek located on Kangaroo Island within Southern Moreton Bay, Queensland, Australia. The small, well-defined creek has been used in previous studies by Eyre et al. (2011), Maher et al. (2013a) and Gleeson et al. (2013). The creek is approximately 800 m long and receives no upstream freshwater inputs. The creek is well mixed vertically and horizontally as determined by depth and cross-creek profiles of temperature, salinity and oxygen (data not shown). The tidal regime is semi-diurnal with neap and spring tide amplitude of ~1 and 1.5 m, respectively. Moreton Bay is a sub-tropical estuary with annual rainfall of 1346 mm. Rainfall is typically highest from December to March (158 $\mathrm{mm\,month^{-1}}$) and lowest from July to September (57 $\mathrm{mm\,month^{-1}}$). Temperature ranges from a mean of 31.4 °C in December to 18.3 °C in July. Rainfall during the sampling period (3rd to 19th November 2013) totalled 64.4 mm, with 56.4 mm occurring after 14th November. An intense storm event on 18th November included hail.

2.2. Surface water sampling

Water column $p\mathrm{CO_2}$ and $\mathrm{CH_4}$ were measured at two sites (creek mouth and ~500 m upstream) within the mangrove creek at ~1 Hz during a spring-tide to spring-tide tidal cycle, commencing 3rd November 2013 (new moon) and concluding 19th November 2013 (full moon). At the creek mouth station (hereafter termed "creek mouth"), a small vessel was moored in the middle of the creek to be used as a platform. Water was pumped from a depth of ~20 cm below the surface at ~3 $\mathrm{L\,min^{-1}}$ using a submersible bilge pump (Rule™ 600 G.P.H) into two showerhead air–water equilibrators (General Oceanics) as described by Pierrot et al. (2009). Headspace air was then pumped at ~30 $\mathrm{mL\,min^{-1}}$