# Monsoon-driven biogeochemical dynamics in an equatorial shelf sea: time-series observations in the Singapore Strait

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#### Abstract

Coastal tropical waters are experiencing rapid increases in anthropogenic pressures, yet coastal biogeochemical dynamics in the tropics are poorly studied. We present a multi-year biogeochemical time series from the Singapore Strait in Southeast Asia's Sunda Shelf Sea. Despite being highly urbanised and a major shipping port, the strait harbours numerous biologically diverse habitats, and is a valuable system for understanding how tropical marine ecosystems respond to anthropogenic pressures. Our results show strong seasonality driven by the semi-annual reversal of ocean currents: dissolved inorganic nitrogen (DIN) and phosphorus varied from [?]0.05 µmol l-1 during the intermonsoons to [?]4 µmol l-1 and [?]0.25 µmol l-1, respectively, during the southwest monsoon. Si(OH)4 exceeded DIN year-round. Based on nutrient concentrations, their relationships to salinity and coloured dissolved organic matter, and the isotopic composition of NOx-, we infer that terrestrial input from peatlands is the main nutrient source. This input delivered dissolved organic carbon (DOC) and nitrogen, but was notably depleted in dissolved organic phosphorus. In contrast, particulate organic matter showed little seasonality, and the  $\delta 13C$  of particulate organic carbon (-21.0  $\pm$  1.5autochthonous origin. Diel changes in dissolved O2 varied seasonally with a pattern that suggests that light availability controls primary productivity more than nutrient concentrations. However, diel changes in pH were greater during the southwest monsoon, when remineralisation of terrestrial DOC lowers the seawater buffer capacity. We conclude that terrestrial input results in mesotrophic conditions, and that the strait might be vulnerable to further eutrophication if nutrient inputs increase during seasons when light availability is high. Moreover, the seasonality of diel pH variation suggests that coral reefs exposed to terrestrial organic matter in the Sunda Shelf may be at significant risk from future ocean acidification.

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27 Abstract

28 Coastal tropical waters are experiencing rapid increases in anthropogenic pressures, yet 29 coastal biogeochemical dynamics in the tropics are poorly studied. We present a multi-year 30 biogeochemical time series from the Singapore Strait in Southeast Asia's Sunda Shelf Sea. Despite being highly urbanised and a major shipping port, the strait harbours numerous 31 32 biologically diverse habitats, and is a valuable system for understanding how tropical marine ecosystems respond to anthropogenic pressures. Our results show strong seasonality driven 33 by the semi-annual reversal of ocean currents: dissolved inorganic nitrogen (DIN) and 34 phosphorus varied from  $\leq 0.05 \,\mu\text{mol}\,1^{-1}$  during the intermonsoons to  $\geq 4 \,\mu\text{mol}\,1^{-1}$  and  $\geq 0.25$ 35 µmol 1<sup>-1</sup>, respectively, during the southwest monsoon. Si(OH)<sub>4</sub> exceeded DIN year-round. 36 37 Based on nutrient concentrations, their relationships to salinity and coloured dissolved 38 organic matter, and the isotopic composition of NO<sub>x</sub>, we infer that terrestrial input from 39 peatlands is the main nutrient source. This input delivered dissolved organic carbon (DOC) and nitrogen, but was notably depleted in dissolved organic phosphorus. In contrast, 40 particulate organic matter showed little seasonality, and the  $\delta^{13}$ C of particulate organic 41 carbon (-21.0  $\pm$  1.5‰) is consistent with a primarily autochthonous origin. Diel changes in 42 dissolved O<sub>2</sub> varied seasonally with a pattern that suggests that light availability controls 43 primary productivity more than nutrient concentrations. However, diel changes in pH were 44 45 greater during the southwest monsoon, when remineralisation of terrestrial DOC lowers the seawater buffer capacity. We conclude that terrestrial input results in mesotrophic conditions, 46 and that the strait might be vulnerable to further eutrophication if nutrient inputs increase 47 during seasons when light availability is high. Moreover, the seasonality of diel pH variation 48 suggests that coral reefs exposed to terrestrial organic matter in the Sunda Shelf may be at 49 significant risk from future ocean acidification. 50

## 52 1. Introduction

Tropical shelf seas are ecologically and economically important, but are under increasing 53 anthropogenic pressure from coastal development, land-use change, resource extraction, and 54 55 terrestrial inputs (Jennerjahn, 2012). At the same time, our understanding of the biogeochemistry of tropical shelf seas is more limited than for higher-latitude environments, 56 57 which makes it harder to predict how anthropogenic pressures will affect tropical seas (Lønborg et al., 2021b; Vieillard et al., 2020). 58 59 Tropical coastal waters are usually nutrient-poor because shelf seas exchange large volumes 60 of water with adjacent nutrient-poor open oceans (Brunskill, 2010). However, tropical coastal waters also receive more than half of the global river discharge and nutrient input 61 62 (Jennerjahn, 2012; Mayorga et al., 2010). Nutrient concentrations and ratios delivered by 63 tropical rivers can be different from temperate regions: for example, tropical rivers typically have higher dissolved silicon concentrations (Jennerjahn et al., 2006). While consistently 64 high temperature and sunlight in the tropics allow for fast rates of uptake and biogeochemical 65 66 transformation of nutrients in shelf waters, high input of sediments and dissolved organic matter in the tropics can also attenuate sunlight and potentially slow the rates of nutrient 67 utilisation (Nittrouer et al., 1995). As anthropogenic nutrient input is projected to increase 68 substantially within the next decades, particularly in tropical Asia (Sinha et al., 2019), it is 69 pressing to better understand the biogeochemistry of tropical coastal waters. 70 71 Southeast Asia's Sunda Shelf Sea is one of the largest and most biodiverse shelf seas globally; however, it also has dense human populations along the coast, placing a high degree 72 of pressure on its marine habitats (Jennerjahn, 2012; Veron et al., 2009). This is especially 73 the case in urbanised marine ecosystems that experience high anthropogenic stress (Heery et 74 al., 2018; Todd et al., 2019). The Sunda Shelf Sea receives a large amount of precipitation 75 and river input that deliver freshwater (Lee et al., 2019), terrestrial carbon (Baum et al., 2007; 76

77	Huang et al., 2017; Zhou et al., 2019), and dissolved nutrients (Jennerjahn et al., 2004; Jiang
78	et al., 2019). The climate is driven by the Asian monsoon system, which results in seasonally
79	varying patterns of precipitation across the region and causes a semi-annual reversal in
80	physical ocean circulation across the shelf (Lee et al., 2019; Susanto et al., 2016). While
81	these environmental conditions might be expected to result in dynamic coastal
82	biogeochemistry, the biogeochemistry of Southeast Asia's coastal seas has received
83	comparatively little research attention to date (Partelow et al., 2018). Across the open waters
84	of the Sunda Shelf, chlorophyll- <i>a</i> concentrations are typically $\leq 0.2 \ \mu g \ l^{-1}$ (Kartadikaria et al.,
85	2015; Ke et al., 2014), indicative of oligotrophic waters. Closer to shore and within estuaries,
86	significant levels of eutrophication due to nutrient input have been reported (Chai et al.,
87	2021; Damar et al., 2019; Lim et al., 2021; Lim et al., 2018; Tomascik et al., 1994).
88	However, very few studies have collected multi-year biogeochemical time series in Southeast
89	Asia, and where such time series do exist (Lim et al., 2018), often only a limited number of
90	parameters are available. This limits our understanding of the drivers of coastal
91	biogeochemistry in Southeast Asia.
92	Here, we present time-series data collected over multiple years in the Singapore Strait, an
93	urbanised coastal area in the central Sunda Shelf, to examine the dynamics and drivers of
94	nutrient biogeochemistry, and their potential impacts on planktonic productivity. This study
95	complements our previous analyses of seawater carbonate system and bio-optical variability
96	in the Singapore Strait, which revealed a strong seasonal input of terrigenous dissolved
97	organic matter from regional peatlands (Martin et al., 2021; Zhou et al., 2021).
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99	
100	2. Materials and Methods



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Fig. 1 Map of the study region, modified from Martin et al. (2021), indicating the seasonal
current reversal between southwest (SW) and northeast (NE) monsoons (arrows). Yellow
marker in (a) indicates the Singapore Strait. The two sampling sites, Hantu ("H") and Kusu
("K") are indicated in (b) by the two crossed yellow circles.

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- 108

## 109 2.1 Site description and study design

110 The Singapore Strait is situated in the central part of the Sunda Shelf Sea at 1.2°N 103.8°E (Fig. 1) and is subject to two monsoon seasons (Mayer et al.; Susanto et al.; van Maren & 111 112 Gerritson). During the northeast (NE) monsoon (mid-November to March), the prevailing 113 mean circulation carries water from the open South China Sea across the Sunda Shelf, westand northwards through the Singapore Strait and the Malacca Strait, and southwards into the 114 115 Java Sea. During the southwest (SW) monsoon (mid-May to mid-September), the circulation 116 reverses and water flows northwards from the Java Sea towards the South China Sea, while 117 the flow in the Malacca Strait ceases or flows weakly southwards. Flow through the Singapore Strait is then eastwards and out towards the open South China Sea. The annual 118 mean flow follows the direction of the NE monsoon, forming the South China Sea limb of the 119

120 Indonesian Throughflow. During the two intermonsoon periods (April to mid-May and mid-September to mid-November) the mean residual flow through the Singapore Strait stagnates. 121 Singapore experiences rainfall year-round, but rainfall is highest during the early NE 122 123 monsoon (mid-November to January) and is lowest during the late NE monsoon and early intermonsoon (February and March). Because the seawater chemistry changes considerably 124 125 from early to late NE monsoon, but the late NE monsoon and first intermonsoon are very similar, for the purposes of our analysis we classify March as part of intermonsoon 1, 126 127 consistent with our previous work (Martin et al., 2021; Zhou et al., 2021). We thus define the 128 seasons as: NE monsoon = 15 Nov to end Feb; intermonsoon 1 = 01 Mar to 15 May; SW monsoon = 15 May to 15 Sept; intermonsoon 2 = 15 Sept to 15 Nov. 129 130 Because of the reversing ocean circulation, the Singapore Strait is influenced by considerable 131 river input from Sumatra and the western Malay Peninsula during the SW monsoon, with a notable seasonal decrease in salinity (Tanzil et al., 2019; Zhou et al., 2021) and input of 132 terrestrial dissolved organic matter (DOM) from regional peatlands (Martin et al., 2021; Zhou 133 134 et al., 2021). During the early NE monsoon, there is freshwater input from local rainfall and river flow, with a shorter period of reduced salinity and a small input of terrestrial DOM 135 136 (Martin et al., 2021; Zhou et al., 2021). Here, we present time-series data collected by regular *in-situ* water sampling at two sites in 137 the Singapore Strait, Kusu Island (1.226°N 103.860°E) and Hantu Island (1.227°N 138 139 103.746°E) (Fig. 1). Both sites are small islands with narrow fringing reefs, with diverse communities of hard corals down to approximately 6–8 m depth (Guest et al., 2016; Huang et 140 al., 2009). Below this depth, the seafloor consists largely of soft sediment and slopes down to 141 15-20 m. Sampling started in mid-2015 on an opportunistic basis for inorganic nutrients, and 142

143 was carried out at monthly to bi-weekly frequency from mid-2017 for an increasing number

144 of parameters.

## 145 2.2 Sensor installation

In mid-2015, a Seabird SeaCat 19plusV2 conductivity-temperature-depth sensor (CTD) and a 146 SeaFET pH sensor (previously Satlantic, now Seabird) were installed at approximately 5 m 147 148 depth on the reef slope of Kusu Island, using iron stakes such that the sensors were 149 approximately half a metre above the seafloor. In mid-2017, a PME miniDOT dissolved 150 oxygen sensor was added at the same depth. The SeaFET and the miniDOT were both equipped with copper biofouling guards; the SeaCat had no antifouling protection but was 151 152 operated with the pump running during sampling to prevent sediment accumulation in the 153 conductivity cell. All sensors were installed horizontally (except the miniDOT, which initially faced upwards but was then installed horizontally to prevent sediment accumulation 154 155 between the biofouling guard and the sensor membrane) and measured every 10 min. Sensors 156 were recovered for data download and cleaning every 1-4 months. Gaps in the sensor records 157 occurred as a result of occasional technical problems, the need for maintenance back in the 158 laboratory and factory recalibration, and periods of bad data (see Section 2.5). 159 All salinity data are expressed on the practical salinity scale.

160

161 *2.3 Water sampling* 

Water samples were collected with a Niskin bottle at 5 m depth, and a CTD profile was 162 measured using a Valeport FastCTD with chlorophyll-a fluorometer. Prior to October 2017, 163 164 samples were only collected for dissolved inorganic nutrient analysis, by syringe-filtering (0.2 µm Acrodisc polyethersulfone [PES] filters, 25 mm diameter) water into acid-washed, 165 15 ml polypropylene centrifuge tubes. From October 2017, a larger number of parameters 166 was measured, and sample water was filtered directly from the Niskin bottle with a peristaltic 167 pump and an in-line polycarbonate filter housing (Pall, product 1119) using 0.2 µm PES 168 membranes (47 mm diameter, Supor, Millipore). The filter, tubing, and filter housing were 169

rinsed with 300 ml ultrapure water (18.2 MΩ cm<sup>-1</sup>, hereafter Elga water) and about 100 ml
sample water immediately before samples were collected.

172 Water for  $\delta^{13}$ C of dissolved inorganic carbon ( $\delta^{13}$ C-DIC, 1 ml) was filtered into a syringe without allowing air contact and injected into a He-flushed 12 ml Exetainer (Labco, UK) with 173 174 butyl rubber septum containing 1 ml of 80% H<sub>3</sub>PO<sub>4</sub>. Water for DIC concentration was filled to overflowing into 12 ml Exetainers and capped with minimal headspace with a butyl rubber 175 septum. Water for total alkalinity (TA) was filled into 125 ml acid-washed high-density 176 177 polyethylene (HDPE) bottles. Water for dissolved organic carbon (DOC) and coloured dissolved organic matter (CDOM) was filled into pre-ashed (450°C, 4 hours) 40 ml amber 178 borosilicate vials with PTFE-lined septa. Water for  $\delta^{13}$ C of DOC ( $\delta^{13}$ C-DOC) was filled into 179 50 ml acid-washed polypropylene centrifuge tubes. Water for dissolved organic and 180 inorganic nutrients was filled into acid-washed 15 ml polypropylene centrifuge tubes. Water 181 for nitrate isotopes ( $\delta^{15}$ N- and  $\delta^{18}$ O-NO<sub>x</sub><sup>-</sup>) was filled into acid-washed 125 ml HDPE bottles. 182 183 Samples for dissolved nutrients were immediately frozen in cryogenic dry shippers in the 184 field. All other samples were stored at ambient temperature in the dark until return to the lab (within 2–5 hours). All samples were then stored at +4°C except for dissolved nutrients, 185  $\delta^{15}$ N- and  $\delta^{18}$ O-NO<sub>x</sub><sup>-</sup> (-20°C),  $\delta^{13}$ C-DOC (-20°C), and  $\delta^{13}$ C-DIC (room temperature). 186 Samples for DOC concentration were acidified on the day of collection with 100 µl 50% 187 H<sub>2</sub>SO<sub>4</sub> per 30 ml sample. 188 In addition, unfiltered water was collected in the field into 1 l acid-washed HDPE bottles to 189 measure particulate organic carbon (POC) and particulate nitrogen (PN), particulate 190 phosphorus (PP),  $\delta^{13}$ C of POC ( $\delta^{13}$ C-POC),  $\delta^{15}$ N of PN ( $\delta^{15}$ N-PN), and chlorophyll-a. These 191 samples were stored at ambient temperature in the dark until return to the laboratory, and 192 193 then vacuum-filtered (0.5–1.5 l, depending on date and parameter) onto 25 mm Whatman

194 GF/F filters (nominal pore size 0.7 μm). Except for chlorophyll-*a*, all GF/F filters were pre-

- ashed (450°C 4 hours), and samples were briefly rinsed with Elga water upon filtration. All
- samples were then wrapped in aluminium foil and frozen at -20°C, except chlorophyll
- 197 samples, which were flash-frozen in liquid nitrogen and stored at -80°C.
- 198

199 *2.4 Analyses* 

200 2.4.1 Dissolved nutrients and organic matter

201 Dissolved inorganic nutrients, i.e. nitrate (NO<sub>3</sub><sup>-</sup>), nitrite (NO<sub>2</sub><sup>-</sup>), ammonia (NH<sub>4</sub><sup>+</sup>), phosphate

202 ( $PO_4^{3-}$ ), and silicate (Si(OH)<sub>4</sub>), were analysed on a SEAL AA3 segmented-flow autoanalyser.

203 The methods for  $NO_3^- + NO_2^-$ ,  $NO_2^-$ ,  $PO_4^{3-}$ , and Si(OH)<sub>4</sub> followed the colorimetric techniques

204 outlined in Hansen and Koroleff (1999) according to SEAL methods G172, G173, G297, and

205 G177. NH<sub>4</sub><sup>+</sup> was analysed fluorometrically after reaction with o-phthaldialdehyde according

to SEAL method G327, based on Kérouel and Aminot (1997). Detection limits were 0.05

207  $\mu$ mol l<sup>-1</sup> (NO<sub>3</sub><sup>-</sup> + NO<sub>2</sub><sup>-</sup>), 0.01  $\mu$ mol l<sup>-1</sup> (NO<sub>2</sub><sup>-</sup>), 0.016  $\mu$ mol l<sup>-1</sup> (PO<sub>4</sub><sup>3-</sup>), 0.1  $\mu$ mol l<sup>-1</sup> (Si(OH)<sub>4</sub>),

208 and 0.25  $\mu$ mol l<sup>-1</sup> (NH<sub>4</sub><sup>+</sup>).

209 Dissolved organic nitrogen and phosphorus (DON and DOP) were analysed as for inorganic

 $NO_3^-$  and  $PO_4^{3-}$  following wet oxidation. 4.5 ml of sample water were mixed in glass

centrifuge tubes with 0.5 ml of a solution consisting of 6 g  $K_2S_2O_8$  with 3 g B(OH)<sub>3</sub> in 100

212 ml of 0.42 M NaOH, tightly capped and autoclaved at 120°C for 30 min, and diluted 1:1 with

213 artificial seawater prior to analysis. For DOP analysis, we introduced an additional ascorbic

acid solution with the first reagent line (instead of just surfactant as for inorganic  $PO_4^{3-}$ 

analysis), such that the solution stream on the AA3 had a concentration of 40 mmol  $l^{-1}$ 

ascorbic acid before the colour reagents were introduced. This reduces interference from

chlorine species generated during wet oxidation (Ma et al., 2017). Oxidation efficiency was

218 monitored with ethylenediamine tetraacetic acid (DON) and glucose-6-phosphate (DOP), and

219 was always  $\geq 92\%$ .

220 Dissolved organic carbon (DOC) was analysed on a Shimadzu TOC-L instrument equipped 221 with the manufacturer's high-salt kit, calibrated with potassium hydrogen phthalate 222 standards, and validated using the University of Miami deep-sea certified reference material. 223 Coloured dissolved organic matter (CDOM) was measured on a Thermo Evolution300 dualbeam spectrophotometer against Elga water as the reference using 10-cm pathlength quartz 224 225 cuvettes. Data were baseline corrected (Green and Blough, 1994), smoothed using a loess function, and converted to Napierian absorption coefficients. We use the CDOM absorption 226 coefficient at 350 nm,  $a_{350}$ , as a measure of CDOM concentration. 227

228

229 2.4.2 Particulate C, N, and P

230 Particulate organic carbon (POC) and particulate nitrogen (PN) were analysed together after 231 acid-fuming the filters overnight in a desiccator with concentrated HCl, then drying them overnight at 40°C, and pelleting the samples in tin foil discs (Sercon, SC1032). They were 232 then analysed at the University of Hong Kong on a Eurovector elemental analyser and Nu 233 234 Instruments Perspective isotope ratio mass spectrometer (IRMS) calibrated with acetanilide standards. Particulate phosphorus (PP) was measured by submerging filters in 3 ml of 235 oxidative solution (made as for DOP analysis) in tightly-capped glass centrifuge tubes and 236 autoclaving them for 30 min at 120°C. Samples were then diluted between 1:40 and 1:100 237 with artificial seawater and analysed as for inorganic  $PO_4^{3-}$ ; the high dilution in this case 238 239 eliminates the need for additional ascorbic acid. Oxidation efficiency was monitored with glucose-6-phosphate and was always >88%. 240

241

242 2.4.3 Isotope analyses

243 Stable carbon and nitrogen isotopes of POC and PN ( $\delta^{13}$ C-POC and  $\delta^{15}$ N-PN) were measured 244 with a separate set of filters from POC and PN concentration measurements, for which a

245	larger volume of water was filtered to yield higher instrument signals. These filters were not
246	acid-fumed, because calcifying plankton species are essentially absent from these waters.
247	Samples were otherwise prepared and analysed as for POC/PN analysis, but without using
248	acetanilide concentration standards. Instead, the analysis was calibrated with isotope
249	standards USGS40 and 41a. Analytical precision was assessed with acetanilide standard 1
250	from University of Indiana, and was $\pm 0.2\%$ or better for both $\delta^{13}$ C and $\delta^{15}$ N.
251	$\delta^{15}$ N- and $\delta^{18}$ O-NO <sub>x</sub> <sup>-</sup> was analysed on a subset of samples from Kusu in 2019–2020 for
252	which the NO <sub>3</sub> <sup>-</sup> concentration was sufficiently high. Analysis was performed using an IRMS
253	after converting all $NO_x^-$ into $N_2O$ with the denitrifying bacterium <i>Pseudomonas</i>
254	chlororaphis strain ATCC 13985 (Sigman et al., 2001). During the analysis, the standard
255	reference materials IAEA-NO3 <sup>-</sup> (-1.8‰ vs. air) and USGS 34 (4.7‰ vs. air) were prepared
256	every 8-10 samples to constrain the performance of the bacterial conversion and the stability
257	of the mass spectrometer. The stability of the mass spectrometer was further monitored by a
258	series of prepared $N_2O$ gas vials at the beginning and the end of each run and every 10
259	samples. The average standard deviation of the $\delta^{15}N$ measurements on sample replicates was
260	less than $\pm 0.1\%$ .
261	$\delta^{13}$ C-DIC was analysed partly at the UC Davis Stable Isotope Laboratory and partly at
262	Nanyang Technological University using a Gas Bench connected to a Thermo Delta V IRMS,

as described by Zhou et al. (2021). Analytical precision was ±0.1‰ at UC Davis and ±0.2‰
for our in-house analysis.

265

266 2.4.4 Chlorophyll-a

267 Chlorophyll-*a* was measured on a Horiba Fluoromax4 spectrofluorometer at excitation 436

nm and emission 680 nm (both with bandpass of 5 nm) according to Welschmeyer (1994),

after extracting the samples in 90% acetone at +4°C overnight in the dark. Samples were

- thoroughly mixed and centrifuged at 500 rcf for 10 min prior to analysis. Calibration was
- 271 performed using spinach chlorophyll-*a* (Sigma-Aldrich, C5753).
- 272
- 273 2.5 Sensor data quality control and analysis

The Valeport CTD profiles were used to calculate the mean salinity, temperature, and

chlorophyll-*a* between 4.5 and 5.5 m depth to accompany our water sample data. The

276 chlorophyll fluorometer malfunctioned and returned values consistently below  $0.1 \ \mu g \ l^{-1}$ 

between October 2018 and July 2019 until the fault was repaired; these measurements have

been omitted.

All data from the moored sensors were checked manually to remove spikes and periods with
suspect data, e.g. when heavy biofouling was noted on the sensor parts. For dates when both
SeaCAT and Valeport data were available, the Valeport data were compared to the SeaCAT

282 measurement closest in time; except for two outliers in salinity, the data agreed with root

283 mean squared error (RMSE) of  $\pm 0.07$  (salinity) and  $\pm 0.08^{\circ}$ C (Fig. S1).

284 The SeaFET data were compared to pH calculated from TA and DIC, which were measured

during each sampling date starting in August 2018. pH was calculated using the R package

seacarb (Gattuso et al., 2016) based on the Valeport salinity and temperature and the

287 measured dissolved inorganic nutrient concentrations. We used the dissociation constants

from Lueker et al. (2000) for carbonic acid, from Dickson (1990) for HSO<sub>4</sub>-, and from Perez

and Fraga (1987) for fluoride; total boron concentration followed Uppström (1974). The

290 SeaFET pH data were first reprocessed based on the salinity record from the SeaCAT, and

291 were then compared to the calculated pH based on TA and DIC measurements. For dates

when no SeaCAT data were available, a salinity of 30 was assumed for the SeaFET data

293 processing (note that the salinity correction is too small to impact our results significantly). A

294 direct comparison of our TA+DIC-based calculated pH with the closest matching individual

SeaFET pH measurement for all dates when good-quality SeaFET measurements were
available within 3 hours of the water sampling showed that the data clustered around the 1:1
line with root mean squared error of 0.028 pH units across a pH range of 7.85–8.01 (Figure
S1).

Lab-based measurements of dissolved oxygen concentration are not available for comparison to the miniDOT. Hence, the data were only examined qualitatively to remove periods where either the diel amplitude increased considerably or we observed a clear decrease in daily average concentration together with a large increase in diel amplitude. These cases were suspected to be caused by biofouling and/or accumulation of excessive amounts of suspended particulate matter on the sensor interface, as the variability decreased again after sensor cleaning.

306

307 2.6 Data analysis and previous data use

308 All data analysis and plotting were carried out in R (R Core Team, 2020). To test for seasonal

309 variation, we used non-parametric Kruskal-Wallis tests with post-hoc Dunn tests. All

310 averages are quoted as mean  $\pm$  standard deviation unless specified otherwise.

311 The majority of the data for salinity, temperature, DOC, CDOM, chlorophyll-*a*,  $\delta^{13}$ C-DOC,

312  $\delta^{13}$ C-DIC, and the daily averages of seawater pH were previously used in our analyses of

313 carbonate system variability (Zhou et al., 2021) and bio-optical variability (Martin et al.,

314 2021). The data for dissolved inorganic nitrogen,  $PO_4^{3-}$ , and chlorophyll-*a* are also used in an

analysis of alkaline phosphatase activity in the Singapore Strait (Nichols et al., submitted

316 manuscript).

317

318

319 **3. Results** 

320 *3.1 Hydrographic variability* 

Salinity and temperature ranged typically between 29–33 and 28–31°C and showed 321 pronounced seasonal variation, with highest values during the late NE monsoon and 322 intermonsoon 1 seasons (February to early May), and also during intermonsoon 2 (mid-323 September to mid-November) (Fig. 2). Salinity and temperature decreased during both 324 monsoon seasons, but with distinct patterns: salinity was lowest throughout the SW monsoon 325 326 (mid-May to mid-September), but only decreased for a shorter period during the early NE 327 monsoon (mid-November to January) and not always by as much as during the SW monsoon. 328 Temperature decreased more strongly during the NE monsoon and less during the SW 329 monsoon. While temperature was essentially identical between both sites, the salinity during the SW monsoon was consistently lower at Hantu than at Kusu by an average of  $0.49 \pm 0.22$ . 330 331 Both sites typically showed little vertical density variation without a clear pycnocline (Fig. 332 S2), confirming that the water column is generally well mixed.



Fig. 2. Time series and seasonal boxplots of (a,b) salinity and (c,d) temperature in the Singapore Strait. Grey
shading indicates the southwest (SW) monsoon, blue shading indicates the northeast (NE) monsoon. In the
boxplot x-axis, Int 1 = intermonsoon 1; SW = southwest monsoon; Int 2 = intermonsoon 2; NE = northeast
monsoon. Data from the Seabird SeaCAT moored CTD (at Kusu) are daily mean values; data from the Valeport
FastCTD are from profiling measurements averaged at 5 m. Letters in the boxplots indicate significant
differences between seasons (Kruskal-Wallis with post-doc Dunn test, p<0.05).</li>

## 340 *3.2 Dissolved inorganic nutrients*

Except for NH<sub>4</sub><sup>+</sup>, the dissolved inorganic nutrient concentrations also showed very strong and 341 statistically significant seasonal variation, with elevated concentrations during the SW 342 343 monsoon, a smaller and shorter increase during the early NE monsoon, and mostly very low 344 concentrations (often close to or below detection limits) during both intermonsoon periods (Fig. 3; Table 1). Concentrations of  $NO_3^- + NO_2^-$  reached 4–5 µmol 1<sup>-1</sup> during the SW 345 monsoon, with NO<sub>2</sub><sup>-</sup> typically contributing  $0.5-1.0 \mu$ mol 1<sup>-1</sup> during this time, but NH<sub>4</sub><sup>+</sup> was 346 only sporadically detectable (usually during the NE monsoon), with highest concentrations 347 during 2018 (Fig. 3a-f).  $PO_4^{3-}$  showed very similar seasonal patterns to  $NO_3^- + NO_2^-$ , with 348 values ranging from below detection to around 0.35 µmol 1<sup>-1</sup> (Fig. 3g,h). Si(OH)<sub>4</sub> differed 349 slightly from the other nutrients in never dropping below detection limits, and was >2  $\mu$ mol l<sup>-</sup> 350 351 <sup>1</sup> in all but seven samples, reaching up to 13.8 µmol l<sup>-1</sup> (Fig. 3i,j). Moreover, Si(OH)<sub>4</sub> showed clearer peaks during the NE monsoon than the other nutrients. 352

353



Fig. 3. Time series and seasonal boxplots of dissolved inorganic nutrient concentrations in the Singapore Strait.

**<sup>356</sup>** Colour shading and boxplot labelling are as in Fig. 2.

Parameter		Intermonsoon 1	SW monsoon	Intermonsoon 2	NE monsoon	$\gamma^2$	p
1 41 411000	Min. Max	31.63, 33.32	28.79, 32.97	30.09. 33.17	29.55, 32.79	~	P
Salinity (daily	Mean (SD)	32.63 (0.53)	31.01 (0.85)	32.09 (0.79)	31.44 (0.70)		
mean)	Median	32.74	30.90	32.24	31.49	547	< 0.0001
	Min, Max	28.49, 31.33	28.98, 31.34	29.03, 30.42	27.07, 30.26		
Temperature	Mean (SD)	30.06 (0.66)	30.14 (0.52)	29.64 (0.37)	28.81 (0.75)		
(daily mean)	Median	30.09	30.08	29.53	28.88	662	< 0.0001
	Min, Max	7.942, 7.999	7.821, 7.99	7.859, 8.033	7.865, 8.035		
pH (daily	Mean (SD)	7.968 (0.013)	7.896 (0.037)	7.937 (0.048)	7.980 (0.034)		
mean)	Median	7.964	7.888	7.937	7.987	440	< 0.0001
	Min, Max	155, 193	164, 195	169, 207	155, 198		
Dissolved O <sub>2</sub>	Mean (SD)	181 (9.8)	178 (6.1)	184 (5.8)	180 (11.7)		
(daily mean)	Median	183	179	183	180	43.6	< 0.0001
	Min, Max	0.014, 0.103	0.019, 0.1589	0.017, 0.1444	0.010, 0.162		
Diel change in	Mean (SD)	0.056 (0.020)	0.068 (0.023)	0.059 (0.022)	0.041 (0.019)		0.0001
pH	Median	0.0563	0.0662	0.0556	0.0366	262	< 0.0001
<b>D</b> . 1 1 .	Min, Max	15.3, 78.3	13.5, 80.5	11.8, 69.5	10.0, 63.4		
Diel change in	Mean (SD)	39.5 (13.2)	35.3 (13.8)	32.8 (12.6)	28.3 (10.2)	21.1	-0.0001
dissolved O <sub>2</sub>	Median	40.1	32.2	51.5	27.0	31.1	<0.0001
	Min, Max	<0.05, 2.37	0.015, 5.00	<0.05, 1.80	<0.05, 5.21		
$NO^{-1} + NO^{-1}$	Median	0.805 (0.817)	2.74 (1.10)	0.704 (0.525)	0.755 (0.810)	71.6	<0.0001
1003 + 1002	Min Max	<0.01 0.538	<0.01 1 17	<0.01.0.620	<0.01 1.05	/1.0	<0.0001
	Mean (SD)	0.071 (0.126)	0.451 (0.251)	0.01, 0.020	0.241 (0.292)		
NO <sub>2</sub> -	Median	<0.01	0.404	0.208 (0.201)	0.125	42.9	<0.0001
1102	Min Max	<0.01	<0.25 1.72	<0.122	<0.25.0.719	72.7	<0.0001
	Mean (SD)	0 211 (0 474)	0.075 (0.285)	0 210 (0 575)	0 149 (0 200)		
$NH_4^+$	Median	<0.25	<0.25	<0.25	<0.25	8.78	0.032
	Min. Max	< 0.016. 0.165	0.089. 0.342	<0.016. 0.210	<0.016. 0.193	0.1.0	
	Mean (SD)	0.080 (0.045)	0.206 (0.054)	0.089 (0.041)	0.085 (0.042)		
PO4 <sup>3-</sup>	Median	0.071	0.213	0.083	0.090	82.3	< 0.0001
	Min, Max	0.688, 6.62	2.71, 13.77	1.54, 6.20	2.32, 11.08		
	Mean (SD)	3.89 (1.69)	7.88 (2.57)	3.70 (1.14)	5.60 (2.09)		
Si(OH)4	Median	3.89	8.26	3.79	5.35	61.6	< 0.0001
	Min, Max	8.74, 19.9	6.78, 29.8	8.33, 22.3	7.84, 22.3		
	Mean (SD)	13.5 (3.48)	11.7 (4.21)	14.0 (3.28)	14.2 (3.81)		
POC	Median	13.6	11.2	13.6	13.2	11.9	0.008
	Min, Max	1.41, 3.63	0.97, 5.35	1.49, 3.32	1.23, 4.19		
	Mean (SD)	2.39 (0.75)	2.08 (0.80)	2.46 (0.51)	2.50 (0.80)		
PN	Median	2.18	2.06	2.58	2.16	7.89	0.048
	Min, Max	0.02, 0.19	0.01, 0.16	0.05, 0.20	0.05, 0.22		
	Mean (SD)	0.08 (0.04)	0.07 (0.03)	0.10 (0.04)	0.11 (0.04)		0.0001
РР	Median	0.08	0.07	0.08	0.11	22.6	< 0.0001
	Min, Max	-24.8, -17.1	-24.2, -18.0	-23.2, -19.3	-22.3, -18.0		
d <sup>3</sup> C DOC	Mean (SD)	-20.9 (1.0)	-21.8 (1.4)	-21.0 (1.0)	-20.1 (1.2)	21	0.0001
0 C-rOC	Min Moy	-20.7	-21.9	-20.9	-20.5	21	0.0001
	Mean (SD)	42(13)	40(13)	5.1 (0.7)	48(12)		
S <sup>15</sup> N-PN	Median	4.2 (1.3)	3.8	5.1 (0.7)	5.2	147	0.002
0 11 11	Min. Max	66.0. 85.6	65.9.108	62.6.77.2	55.4.91.1	11.7	0.002
	Mean (SD)	74.8 (4.9)	84.6 (9.7)	69.3 (3.4)	77.9 (7.1)		
DOC	Median	73.6	84.3	69.1	77.9	55.1	< 0.0001
	Min. Max	4.6, 11.7	4, 9.7	2.9.8.9	5.9, 16.6		
	Mean (SD)	7.1 (1.7)	7.1 (1.4)	6.5 (1.5)	8.7 (2.6)		
DON	Median	7.1	7.2	6.6	7.8	12.6	0.0057
	Min, Max	< 0.01, 0.39	< 0.01, 0.13	0.03, 0.42	< 0.01, 0.5		
	Mean (SD)	0.12 (0.08)	0.03 (0.03)	0.13 (0.10)	0.15 (0.09)		
DOP	Median	0.12	0.02	0.11	0.14	49.8	< 0.0001
	Min, Max	6.9, 17.3	7.7, 19.4	7.9, 23.5	3.8, 13		
DOC:DON	Mean (SD)	11.1 (2.47)	12.4 (2.70)	11.6 (4.05)	9.7 (1.98)		
ratio	Median	10.8	12.0	10.1	10.3	16.0	0.0011
	Min, Max	18.6, 681	38.9, 1800	18.1, 146	49.4, 98.9		
DON:DOP	Mean (SD)	111 (150)	309 (366)	63.8 (42.9)	63.9 (15.2)		
ratio	Median	59.6	155	46.3	62.1	26.7	< 0.0001
at 1 (	Min, Max	0.43, 1.72	0.38, 2.55	0.56, 2.60	0.27, 2.39		
Chl-a (CTD-	Mean (SD)	0.89 (0.31)	0.97 (0.46)	1.42 (0.65)	1.17 (0.58)	0.00	0.000
and filter data)	Median	0.84	0.88	1.32	1.01	9.22	0.0266

**357** Table 1. Summary values of physical and biogeochemical properties by season.  $\chi^2$ - and p-values show results of

**358** Kruskal-Wallis tests for differences between seasons (all d.f. = 3).

359 *3.3 Dissolved and particulate organic matter and stable isotope ratios* 

DOC showed a clear seasonal cycle with a typical peak of 80–100 µmol 1<sup>-1</sup> during both the 360 SW and the NE monsoon, and lower values (usually 65–70 µmol 1<sup>-1</sup>) during the intermonsoon 361 362 seasons (Fig. 4a,b). DON showed less clear seasonality, ranging mostly between 4–12 µmol 1<sup>-1</sup>, but was slightly and significantly higher during the NE monsoon (Fig. 4c,d). In contrast, 363 364 DOP had clear seasonal variation, with very low concentrations during the SW monsoon (when DOP was sometimes not detected) and a peak of  $\sim 0.1-0.2 \mu mol l^{-1}$  during the 365 intermonsoon and NE monsoon periods (Fig. 4e,f). 366 367 Unlike the dissolved nutrients, particulate nutrient concentrations had limited seasonal variation, with concentrations ranging mostly between 7–20 µmol l<sup>-1</sup> for POC, 1–4 µmol l<sup>-1</sup> 368 369 for PN, and PP between 0.025–0.2 µmol 1<sup>-1</sup> (Fig. 4g–1). The values of all particulate 370 concentrations were very similar between both sites. However, the concentrations of all three were significantly lower during the SW monsoon and higher during either the intermonsoon 371 or the NE monsoon periods (Fig. 4h,j,l; Table 1). The chlorophyll-a concentration ranged 372 mostly between 0.5–2.5 µg  $l^{-1}$  with an overall mean of  $1.1 \pm 0.52$  µg  $l^{-1}$  (Fig. 4m). Filter-373 based chlorophyll-a concentrations agreed with the Valeport FastCTD fluorometer with root 374 mean squared error =  $0.51 \ \mu g \ l^{-1}$  (Fig. S3). Combining the Valeport data and the filter-based 375 data showed that chlorophyll-a was on average slightly but significantly elevated during 376 intermonsoon 2 (Fig. 4n; Table 1). 377





Fig. 4. Time series and seasonal boxplots of dissolved and particulate organic matter and chlorophyll-*a*concentrations. Colour shading and boxplot labelling are as for previous figures. Panel (m) shows data both
from filter samples measured after acetone extraction and *in-vivo* measurements from the Valeport FastCTD
fluorometer. The boxplot in panel (n) includes the fluorometer data for dates when no filter-based measurements
are available.

386 
$$\delta^{13}$$
C-POC ranged between -24.8‰ to -17.1‰, while  $\delta^{15}$ N-PN ranged between +1.0‰ to  
47.5‰; both showed moderate but significant differences between seasons, with lower values  
388 during the SW monsoon (Fig. 5a–d; Table 1).  $\delta^{13}$ C-DIC showed an extremely clear seasonal  
389 cycle, ranging mostly from -1.5‰ to +0.5‰, with low values during the SW monsoon and  
390 high values during all other seasons (Fig. 5e,f).  $\delta^{15}$ N-NO<sub>x</sub><sup>-</sup> varied between +2.6‰ to +8.5‰  
391 while  $\delta^{18}$ O-NO<sub>x</sub><sup>-</sup> ranged from -0.3‰ to +9.0‰ (Fig. 5g). NO<sub>3</sub><sup>-</sup> concentrations were only  
392 sufficiently high during the SW and early NE monsoon to allow the isotopic composition to  
393 be measured; hence we did not test for seasonality. However, the three measurements from

394 the NE monsoon had the lowest  $\delta^{15}$ N values. There was no significant relationship between

395  $\delta^{18}$ O-NO<sub>x</sub><sup>-</sup> and  $\delta^{15}$ N-NO<sub>x</sub><sup>-</sup>, and the values could be consistent with either marine or terrestrial

**396**  $NO_3^-$  sources (Fig. 6).



397

**398** Fig. 5. Time series and seasonal boxplots of the isotopic composition ( $\delta^{13}$ C and  $\delta^{15}$ N) of (a–d) particulate

399 organic matter, and (e,f) dissolved inorganic carbon. Time series of  $\delta^{15}N$  and  $\delta^{18}O$  of NO<sub>x</sub><sup>-</sup> (measured only at

400 Kusu) is shown in (g). Since  $NO_x^-$  isotopes were only measured for dates with sufficiently high  $NO_3^-$ 

401 concentration, the seasonality was not analysed. Colour shading and boxplot labelling are as for previous

402 figures.



403 404

Fig. 6. Isotopic composition of dissolved  $NO_x^-$  at Kusu Island, together with approximate ranges of the main

405 potential nitrogen sources drawn according to Kendall et al. (2007).

## 407 *3.4 Nutrient stoichiometry and relationships between parameters*

408 Regression statistics between parameters are given in Table 2. Dissolved inorganic nitrogen 409 (DIN) showed a strong relationship to dissolved  $PO_4^{3-}$  that was close to the canonical 410 Redfield ratio of 16:1, but with a tendency towards excess  $PO_4^{3-}$  (Fig. 7a). DIN was also 411 closely related to Si(OH)<sub>4</sub>, but with a considerable excess of silicon: the DIN:Si(OH)<sub>4</sub> ratio 412 was invariably lower than 1, and the regression slope was 0.30 (Fig. 7b). POC and PN also 413 showed a strong relationship that was close to the 6.6:1 Redfield stoichiometry (Fig. 7c),



414

Fig. 7. Scatter plots between parameters to test for relationships and stoichiometric ratios. Solid black lines with
dark-grey dashed lines indicate linear regression slopes with 95% confidence intervals; for regression
parameters, see Table 2. Dotted grey lines in panels a–f indicate the canonical Redfield ratios (C:N:P =
106:16:1, N:Si = 1:1).

420	while PN and PP were less strongly related, with an N:P ratio above Redfield (mean of 33 $\pm$
421	20 mol mol <sup>-1</sup> ; Fig. 7d). There was also no strong relationship between DOC and DON (Fig.
422	7e) or DON and DOP (Fig. 7f); the DOC:DON ratio was enriched in carbon relative to the
423	Redfield value of 6.6, while the DON:DOP ratio was enriched in nitrogen relative to the
424	Redfield value of 16 (Fig. 7e,f). Neither the POC:PN nor the PN:PP ratio showed significant
425	seasonal variation, but both the DOC:DON and the DON:DOP ratio were significantly higher
426	during the SW monsoon than at other times (Table 1). There was no significant relationship
427	between POC and chlorophyll-a concentration, and the POC:chlorophyll-a ratio was on
428	average relatively high (mean of $182 \pm 113$ g g <sup>-1</sup> ).

429

Parameters (y versus x)	Slope estimate (SE)	Intercept estimate (SE)	Statistics
DIN versus PO <sub>4</sub> <sup>3-</sup>	16.0 (0.77)	-0.45 (0.11)	r <sup>2</sup> = 0.753, p<0.0001
DIN versus Si(OH)4	0.304 (0.035)	-0.16 (0.22), NS	r <sup>2</sup> =0.355, p<0.0001
POC versus PN	4.69 (0.22)	2.26 (0.53)	r <sup>2</sup> =0.819, p<0.0001
PN versus PP	6.03 (1.74)	1.80 (0.17)	r <sup>2</sup> =0.111, p<0.001
NO <sub>3</sub> - versus salinity	-0.720 (0.068)	23.7 (2.16)	r <sup>2</sup> =0.461, p<0.0001
PO <sub>4</sub> <sup>3-</sup> versus salinity	-0.047 (0.004)	1.61 (0.139)	r <sup>2</sup> =0.467, p<0.0001
Si(OH)4 versus salinity	-1.71 (0.15)	59.5 (4.80)	r <sup>2</sup> =0.494, p<0.0001
NO2 <sup>-</sup> versus salinity	-0.102 (0.020)	3.48 (0.61)	r <sup>2</sup> =0.176, p<0.0001
DOC versus salinity	-6.31 (0.581)	276 (18.2)	r <sup>2</sup> =0.504, p<0.0001
DOP versus salinity	0.0358 (0.007)	-1.034 (0.221)	r <sup>2</sup> =0.214, p<0.0001
$\delta^{\!$	0.432 (0.132)	-34.6 (4.15)	r <sup>2</sup> =0.102, p<0.01
$\delta^{15}$ N-PN <i>versus</i> salinity	0.336 (0.112)	-6.12 (3.53), NS	r <sup>2</sup> =0.081, p<0.01
$\delta^{15}$ N-NO <sub>x</sub> <sup>-</sup> <i>versus</i> salinity	-0.961 (0.422)	36.1 (13.1)	r <sup>2</sup> =0.302, p<0.05
pH anomaly <i>versus</i> dissolved O <sub>2</sub> anomaly (10-min frequency)	$1.705*10^{-3}$ (7.95*10 <sup>-6</sup> )	-1.883*10 <sup>-5</sup> (5.606*10 <sup>-5</sup> ), NS	r <sup>2</sup> =0.653, p<0.0001
Diel pH change <i>versus</i> diel dissolved O <sub>2</sub> change	$\frac{1.079*10^{-3}}{(1.25*10^{-4})}$	0.0288 (0.0045)	r <sup>2</sup> =0.299, p<0.0001

430

431 Table 2. Results of regression analyses for relationships between key biogeochemical and physical parameters.

432 Intercepts that are not statistically significant are marked NS. p-values refer to the significance of the regression

433 slopes.

434	$NO_3^-$ , $PO_4^{3-}$ , and $Si(OH)_4$ , and to a lesser degree $NO_2^-$ , all showed strong inverse relationships
435	with salinity (Fig. 7g-j). This was also clearly seen for DOC, but not for DON (which
436	seemed to show a unimodal relationship), while DOP was positively related to salinity, but
437	with high variability (Fig. 7k–m). POC, PN, and PP did not show significant relationships to
438	salinity (not shown), but both $\delta^{13}$ C-POC and $\delta^{15}$ N-PN were weakly related to salinity (Fig.
439	7n,o). Consequently, $\delta^{13}$ C-POC and $\delta^{15}$ N-PN were also weakly related to $\delta^{13}$ C-DIC and NO <sub>3</sub> <sup>-</sup>
440	concentrations, respectively (Fig. 7p,q). $\delta^{15}$ N-NO <sub>x</sub> <sup>-</sup> showed a clear inverse relationship to
441	salinity and consequently a positive relationship with NO <sub>3</sub> <sup>-</sup> concentrations (Fig. 7r,s).
442	Parameters that were significantly related to salinity were also significantly related to CDOM
443	(as $a_{350}$ ), mostly with equal or slightly higher r <sup>2</sup> values (Fig. S4; Table S1).

444

#### 445 3.5 Dissolved $O_2$ and pH dynamics

Seawater pH varied mostly between 7.80–8.05, showing appreciable high-frequency 446 447 variability. Moreover, there was a strong seasonal difference in daily mean pH, with lowest values during the SW monsoon (Fig. 8a,b, Table 1). In contrast, dissolved O<sub>2</sub> chiefly showed 448 high-frequency variability between typically 150–210 µmol l<sup>-1</sup> (Fig. 8c). Although seasonal 449 differences in daily mean dissolved O2 were technically significant, their magnitude was too 450 small to be environmentally relevant ( $<5 \mu$ mol l<sup>-1</sup> difference in medians; Fig. 8d, Table 1). 451 Plotting the daily anomaly of pH and dissolved O<sub>2</sub> against time revealed a clear diel cycle 452 with a minimum at 05:30–06:30 local time and a maximum at 14:00–15:00; the average diel 453 change was 0.022 pH units and 14.2 µmol O<sub>2</sub> l<sup>-1</sup> (Fig. 8e,f). There was a strong relationship 454 455 between the pH and dissolved O<sub>2</sub> anomalies at 10-min frequency (Fig. 8g), and a relationship between the diel change in pH and dissolved O<sub>2</sub> (Fig. 8h). The diel variation in both pH and 456 457 of dissolved O<sub>2</sub> showed some evidence of seasonal variability, with diel pH change greatest

- 458 during the SW and lowest during the NE monsoon, and diel dissolved O<sub>2</sub> change greatest
- 459 during intermonsoon 1 and lowest during the NE monsoon (Fig. 8i–l, Table 1).
- 460

461



boxplots of (a,b) seawater pH and (c,d) dissolved O<sub>2</sub> at Kusu. Diel anomalies of (e) seawater pH and (f) dissolved O<sub>2</sub>; grey lines show individual daily data, solid blue and red lines show  $overall\ mean \pm standard$ deviation. Relationships between (g) individual diel anomalies in pH and dissolved O<sub>2</sub> at 10-min frequency, and (h) between the maximum diel change in pH and dissolved O2 (on point for each day). Solid black and dashed grey lines indicate linear regression with 95% confidence interval. Time series and seasonal boxplots of maximum diel change in (i,j) seawater pH and (k,l) dissolved oxygen. Monsoon shading in the time series has been omitted for

Fig. 8. Time series and seasonal

486 clarity; boxplot labelling is as for previous figures.

#### 487 4. Discussion

488

#### 489 *4.1 Seasonality and range in dissolved nutrient concentrations*

490 Dissolved inorganic nutrient concentrations have rarely been reported from the Singapore Strait, and only for shorter time periods and/or with lower measurement frequency. The 491 492 values we measured are broadly consistent with previous studies (Browne et al., 2015; Chénard et al., 2019; Deignan and McDougald, 2021; Gin et al., 2000), which also noted that 493 dissolved nutrient concentrations are typically elevated during the SW monsoon. Our data 494 495 clearly show that the Singapore Strait undergoes strong and consistent seasonal variation from low concentrations typical of oligotrophic waters (especially during and after the late 496 497 NE monsoon) to significantly higher values during the SW monsoon (Fig. 3). Our nutrient 498 concentrations during the late NE monsoon and intermonsoon 1 are similar to reports from the open Sunda Shelf and the South China Sea (Kartadikaria et al., 2015; Liu et al., 2020; 499 Ning et al., 2004). In contrast, nutrient concentrations during the SW monsoon are similar to 500 501 values reported from the Malacca Strait (Lim et al., 2021; Lim et al., 2015). However, chlorophyll-*a* concentrations were above 0.4 µg l<sup>-1</sup> in all but two samples, with an average of 502 about 1  $\mu$ g l<sup>-1</sup> (Fig. 4). This is greater than reported from the open Sunda Shelf Sea 503 (Kartadikaria et al., 2015; Ke et al., 2014; Liu et al., 2020), and indicates that the Singapore 504 Strait does not experience genuinely oligotrophic conditions, even when dissolved inorganic 505 506 nutrients are low. For comparison, eutrophication thresholds for coral reefs are typically 507 considered to be ~1  $\mu$ mol l<sup>-1</sup> DIN, 0.1–0.2  $\mu$ mol l<sup>-1</sup> PO<sub>4</sub><sup>3-</sup>, and 0.2–0.4  $\mu$ g l<sup>-1</sup> chlorophyll-a (Bell, 1992; Bell et al., 2014). 508 The dissolved organic matter pool showed a somewhat different seasonal pattern. While 509

510 DOC showed similar seasonality to the inorganic nutrients, as described previously (Zhou et

al., 2021), the DON concentration showed very limited seasonal changes, and the DOP

512 concentration showed an opposite seasonal pattern, with lowest concentrations during the SW monsoon and highest during the NE and intermonsoon (Fig. 4). The DOC and DON 513 514 concentrations are similar to those in other coastal locations in the tropical Indo-Pacific 515 (Kuwahara et al., 2010; Lønborg et al., 2021a; Martin et al., 2018). The DOP concentrations in Singapore are lower than reported from the Great Barrier Reef by Lønborg et al. (2021a) 516 (average of  $0.21 \pm 0.16 \mu$ mol l<sup>-1</sup>), but similar to recent reports from coastal locations around 517 the Malay Peninsula (Lim et al., 2018) (average of  $0.07 \pm 0.03 \mu$ mol l<sup>-1</sup>). The fact that DOP 518 was sometimes undetectable during the SW monsoon (i.e. the total dissolved P concentration 519 was equal to the dissolved  $PO_4^{3-}$  measurement) might indicate that a refractory DOP fraction 520 was incompletely oxidised, or alternatively that a labile DOP fraction was hydrolysed during 521 dissolved PO<sub>4</sub><sup>3-</sup> measurements. However, the close agreement between our two sites and 522 consistent seasonal patterns between years clearly suggest that at least the relative variation in 523 DOP is accurate. 524

525 Overall, and taken together with the strong seasonality in salinity (Fig. 2), our results confirm 526 that dissolved biogeochemical properties in the Singapore Strait are largely controlled by the 527 regional advection of distinct water masses according to the monsoon-driven changes in 528 ocean currents, as previously described for DOC and for coloured dissolved organic matter 529 (Martin et al., 2021; Zhou et al., 2021). Our data also provide further support for classifying 530 the Singapore Strait as a mesotrophic environment (Lim et al., 2021) despite the seasonally 531 low concentrations of inorganic nutrients.

532

533 *4.2 Sources of nutrients* 

The strong inverse relationships of  $NO_3^-$ ,  $PO_4^{3-}$ , and Si(OH)<sub>4</sub> to salinity (Fig. 7) clearly indicate a terrestrial source from regional river input. Using stable carbon isotopes, Zhou et al. (2021) demonstrated that a large fraction of DOC in the Singapore Strait during the SW

537 monsoon originates from regional peatlands. The fact that all three nutrients were more strongly correlated with CDOM than with salinity (as seen by the higher  $r^2$  values; Fig. S4) 538 539 provides further support for a predominantly terrestrial source of nutrients in the Singapore 540 Strait, as CDOM is a good tracer of terrestrial DOC in the Sunda Shelf Sea (Martin et al., 2018; Martin et al., 2021; Mizubayashi et al., 2013; Siegel et al., 2019). 541 542 The intercepts of our nutrient-salinity regressions can be taken as estimated riverine endmember concentrations. This implies average river concentrations of  $23.7 \pm 2.2 \ \mu mol \ l^{-1}$  for 543  $NO_{3^{-}}$ , 1.61 ± 0.14 µmol 1<sup>-1</sup> for  $PO_{4^{3^{-}}}$ , and 59.5 ± 4.8 µmol 1<sup>-1</sup> for Si(OH)<sub>4</sub> (Fig. 7, Table 2). 544 545 This is at the low end of Si(OH)<sub>4</sub> concentrations in small tropical rivers in Asia (Jennerjahn et al., 2006), and our inferred riverine end-member values of all three nutrients are several-fold 546 547 lower than reported from human-impacted river systems on Java (Damar et al., 2019; 548 Jennerjahn et al., 2004). Tropical peatland-draining rivers carry low nutrient concentrations, often <5 µmol 1<sup>-1</sup> DIN, unless they are affected by anthropogenic nutrient inputs (Alkhatib et 549 550 al., 2007; Baum, 2008), consistent with efficient nutrient retention within the peatland 551 ecosystem (Mishra et al., 2021). However, our inferred riverine end-member concentrations are well within the range reported for peatland-draining rivers with varying degrees of 552 anthropogenic impact from Sumatra and Borneo (Alkhatib et al., 2007; Bange et al., 2019; 553 Baum, 2008; Gandois et al., 2020; Jiang et al., 2019). 554 The fact that  $NO_2^-$  was only weakly related to salinity and CDOM (Fig. 7), while  $NH_4^+$  was 555 556 unrelated to salinity and was consistently low during the SW monsoon (Fig. 3), suggests that 557 these two nitrogen species originate primarily from internal recycling, rather than being derived directly from land. NO<sub>2</sub><sup>-</sup> and NH<sub>4</sub><sup>+</sup> concentrations in peatland rivers have only been 558 reported from the Siak and Rajang rivers, where  $NO_2^-$  is typically <0.5 µmol l<sup>-1</sup> but  $NH_4^+$  is 559 usually 2–15 µmol l<sup>-1</sup> (Baum, 2008; Jiang et al., 2019). Our data therefore suggest that 560

riverine NH<sub>4</sub><sup>+</sup> is rapidly transformed in the estuaries and coastal waters, likely through a

562 combination of phytoplankton uptake and nitrification, as also noted along the salinity gradient of the Rajang delta on Borneo (Jiang et al., 2019). Recycling of organic nitrogen 563 (either terrestrial or aquatic in origin) by ammonification followed by nitrification could also 564 565 act as a source of NO<sub>2</sub><sup>-</sup> in coastal waters. In subtropical coastal waters of North America, temperature-dependent NO<sub>2</sub><sup>-</sup> accumulation can occur when NH<sub>4</sub><sup>+</sup> oxidation and NO<sub>2</sub><sup>-</sup> 566 567 oxidation become uncoupled between 20-30°C, owing to the different temperature sensitivities of the microbial taxa responsible for each of these nitrification steps (Schaefer 568 569 and Hollibaugh, 2017). Whether the permanently high temperatures in tropical coastal waters 570 might promote NO<sub>2</sub><sup>-</sup> accumulation over complete nitrification may be worth testing in future research, especially in the context of increasing tropical surface temperatures. Since the water 571 column at our site was always oxygenated (Fig. 8), it is unlikely that hypoxia was mediating 572 573 nitrification rates (Schaefer and Hollibaugh, 2017).

The  $\delta^{15}$ N-NO<sub>x</sub><sup>-</sup> and  $\delta^{18}$ O-NO<sub>x</sub><sup>-</sup> values are slightly higher compared to values measured in the 574 Rajang River in northwest Borneo (Jiang et al., 2019), but do not provide an unambiguous 575 source fingerprint (Fig 6; (Kendall et al., 2007)). Although the isotopic composition could be 576 577 consistent with marine  $NO_3^-$ , this is only plausible for the NE monsoon period, given the strong inverse relationship of NO3<sup>-</sup> concentration with salinity. For the SW monsoon, the 578 isotopic data would be consistent with soil N, wastewater, or a combination of fertiliser and 579 580 wastewater (Fig. 6). Most of the peatlands on Sumatra are used for agriculture and have synthetic fertilisers applied regularly; Baum (2008) reported that fertilisers and wastewater 581 are the main nutrient sources to the Siak, which is one of the main river systems on Sumatra. 582 Although atmospheric deposition was suggested previously to be a significant source of NO<sub>3</sub><sup>-</sup> 583 to the Singapore Strait (Sundarambal et al., 2010), our isotope data are not consistent with a 584 significant contribution from atmospheric NO<sub>3</sub><sup>-</sup> deposition during any season. The monthly 585 mean  $\delta^{15}$ N- and  $\delta^{18}$ O- NO<sub>3</sub><sup>-</sup> values in rainfall in Singapore are nearly all <2‰ and >50‰, 586

respectively (Li et al., 2020). The fact that  $\delta^{15}$ N-NO<sub>x</sub><sup>-</sup> during the NE monsoon had the lowest 587 values measured, even below typical marine NO<sub>3</sub><sup>-</sup> values (Fig. 6) may point to a significant 588 contribution from N fixation: the shallow subsurface NO<sub>3</sub><sup>-</sup> pool in the South China Sea is 589 590 isotopically depleted due to diazotrophy (Ren et al., 2017; Zhang et al., 2020), and additional N fixation is likely to take place across the Sunda Shelf Sea. For example, N fixation was 591 592 reported from the Singapore Strait even during the DIN-rich SW monsoon, both in the water 593 column and associated with corals, albeit at relatively low rates (Moynihan et al., 2021). 594 In contrast to the main inorganic nutrients and to DOC, neither DON nor DOP appeared to have a predominant terrestrial source, given their different seasonal patterns (Fig. 4). While 595 596 very low DOP concentrations during the SW monsoon might seem surprising, this provides 597 further support for the view that peatlands are the main source of river run-off influencing the 598 Singapore Strait during the SW monsoon (Zhou et al., 2021). Tropical peatlands are 599 ombrotrophic, nutrient-poor systems that retain nutrients efficiently and can become particularly phosphorus-poor, while nitrogen-fixing vegetation continues to provide a 600 nitrogen source even in old peatlands (Mishra et al., 2021; Troxler, 2007). Hence, the most 601 602 likely explanation for the DON and DOP dynamics is that the DOP is predominantly of marine origin (and is hence high during the NE monsoon and intermonsoon months), while 603 604 the DON has both significant marine and terrestrial sources, and hence shows little 605 seasonality. Measurements of both DON and DOP in peatland-draining rivers would be valuable to clarify this further. While disturbed peatlands converted to agricultural use can 606 clearly be a source of inorganic nutrients through fertiliser input, as reflected in our inorganic 607 nutrient data, the dissolved organic matter exported from disturbed peatlands consists of 608 increasingly old soil organic matter (Evans et al., 2014), which would explain the different 609 610 dynamics of the inorganic and the organic nutrients at our site.

611 At present, the bioavailability of DON and DOP in the Sunda Shelf Sea is unknown. In the Great Barrier Reef, DON and DOP contributed more bioavailable N and P than either 612 dissolved inorganic or particulate nutrients (Lønborg et al., 2018), but the DOM pool in that 613 614 study was predominantly of marine origin. In the open South China Sea, isotopic evidence points to active DON cycling with DON production and remineralization rates approximately 615 616 in balance (Zhang et al., 2020). However, peatland-derived DOC in Southeast Asia appears to be relatively refractory to direct remineralisation by heterotrophic microbes, even when 617 inorganic N and P are added (Nichols and Martin, 2021), suggesting that the terrestrial 618 619 organic nutrient pools might also be relatively refractory. Nevertheless, the majority of this peatland DOC is ultimately remineralised before leaving the Sunda Shelf (Wit et al., 2018; 620 621 Zhou et al., 2021), although the biogeochemical processes driving this remineralisation 622 remain unclear. If peatland DON is also remineralised to a similar degree as DOC in the Sunda Shelf, then given the relative lack of DOP, this might lead to an imbalanced N:P ratio 623 in areas receiving peatland run-off. Interestingly, the N:P stoichiometry of the particulate 624 625 pool is typically higher than the canonical Redfield ratio of 16:1 (Fig. 7), although this might also reflect a contribution from detrital organic matter to the particulate pool (see Section 626 4.3). The Singapore Strait also has measurable alkaline phosphatase activity year-round 627 (Nichols et al., submitted manuscript), suggesting that least a fraction of DOP is actively 628 cycled. Resolving the bioavailability of both the terrestrial and marine DON and DOP pools 629 630 will be important both for understanding the patterns of primary productivity in this region, and to reach a more complete understanding of how land use-driven changes in terrestrial 631 DOM fluxes (Moore et al., 2013) affect coastal seas. 632

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634 *4.3 Composition and dynamics of particulate organic matter* 

635 The fact that the particulate organic matter pool and the chlorophyll-a concentration showed 636 only relatively limited seasonality and did not directly follow the seasonal cycle in inorganic 637 nutrients indicates that phytoplankton biomass is not primarily controlled by nutrient 638 availability. Even during the low-nutrient intermonsoon periods, chlorophyll-a was usually  $>0.5 \mu g l^{-1}$ , which suggests that nutrients are efficiently recycled during these periods to 639 640 maintain phytoplankton productivity and standing stock. This is consistent with the observation of year-round measurable levels of alkaline phosphatase activity in the water 641 column, averaging 9 nmol l<sup>-1</sup> h<sup>-1</sup>, most likely from heterotrophic microbial sources (Nichols 642 643 et al., submitted manuscript). However, chlorophyll-a was on average elevated during intermonsoon 2 and partly also during the NE monsoon (Fig. 4). This does suggest that the 644 645 SW monsoon nutrient input stimulates a delayed phytoplankton growth response. The delay 646 might be linked to greater light limitation during the SW monsoon due to the presence of peatland CDOM, which leads to shoaling of the euphotic zone and changes in the spectral 647 quality of light underwater (Martin et al., 2021). Phytoplankton production in tropical and 648 649 subtropical estuaries experiencing episodic nutrient delivery is similarly thought to be modulated by light limitation from high turbidity during flood events (Burford et al., 2012; 650 Eyre, 2000), and depth-integrated phytoplankton productivity along the Great Barrier Reef is 651 consistently greater at offshore stations with greater light availability (Furnas et al., 2005). 652 However, this apparent seasonal increase in chlorophyll-a concentration was small and not 653 654 consistent between years, e.g. no increase was seen in 2019 (Fig. 4). It is probable that grazing, especially by microzooplankton, is also a key factor controlling phytoplankton 655 biomass, as noted, for example, in Darwin Harbour and the Great Barrier Reef (Burford et al., 656 657 2008; Furnas et al., 2005).

658 Although the POC:PN ratio was very close to the Redfield ratio, the PN:PP ratio was higher

659 (Fig. 7), and the POC:chlorophyll-*a* ratio was greater than might be expected for

660	phytoplankton biomass in the relatively low-light environment of the Singapore Strait
661	(Arteaga et al., 2016; Geider et al., 1997). This suggests that a significant part of the
662	particulate organic matter pool was likely detrital. Whether the detrital POM fraction is
663	primarily from marine production or originates from terrestrial input is unclear: the overall
664	mean $\delta^{13}$ C-POC (-21.0 ± 1.5‰) is compatible with a purely marine origin (Fry and Sherr,
665	1989; Verwega et al., 2021), but the small decrease in $\delta^{13}$ C-POC during the SW monsoon
666	(Fig. 5) might indicate a contribution of terrestrial POC during this period. However, the
667	strong decrease in $\delta^{13}$ C-DIC during the SW monsoon, caused by peatland DOC
668	remineralisation (Zhou et al., 2021), means that this might also reflect phytoplankton carbon
669	assimilation from a more isotopically depleted DIC pool (Chanton and Lewis, 1999). The
670	$\delta^{15}$ N-PN data don't help to resolve this question, as $\delta^{15}$ N-PN in Sumatran peatland rivers
671	appears to be mostly in the range of +2‰ to +6‰ (Alkhatib et al., 2007; Baum, 2008),
672	essentially the same as our data.

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## 674 *4.4. Net community metabolism*

Net community metabolism causes correlated diel changes in pH and dissolved O<sub>2</sub>, as seen in 675 Fig. 8. On corals reefs, such variation is driven by a combination of photosynthesis-676 677 respiration and calcification-carbonate dissolution (Albright et al., 2015; DeCarlo et al., 2017; Page et al., 2019). These previous studies were typically conducted on extensive reef 678 flats with limited water exchange, and they consequently observed larger changes, with diel 679 variation in pH mostly  $\geq 0.1$  unit and in dissolved  $O_2 \geq 50 \mu mol l^{-1}$ . In our case, the sensors 680 were installed along a reef slope exposed to the open sea, and the coral reef only extends 681 682 about 20 m from the shoreline. Therefore, the variation in our dataset is most likely dominated by planktonic photosynthesis and respiration rather than by benthic metabolism 683 684 and calcification.

685 The diel change in dissolved O<sub>2</sub> varied by a factor of 3–4 within each season, but was on 686 average highest during intermonsoon 1 and lowest during the NE monsoon (Fig. 8). This 687 pattern suggests that light availability is an important control over primary productivity: 688 Singapore experiences lower rainfall and more solar radiation during the late NE and intermonsoon 1 than in other seasons (Fong, 2012), while CDOM input during the SW 689 690 monsoon (and to a lesser degree during the early NE monsoon) increases the absorption of sunlight underwater, especially at blue wavelengths (Martin et al., 2021). At the same time, 691 692 suspended matter concentrations can vary substantially over short (<1 day) periods on reefs 693 in Singapore (Morgan et al., 2020), further contributing to variation in light attenuation and therefore productivity rates within seasons. 694

695 Our data therefore indicate that phytoplankton productivity in the Singapore Strait is likely 696 more limited by light than by nutrient availability. While this would imply that increases in nutrient input might not trigger phytoplankton blooms, the tendency for chlorophyll-a to 697 increase after the SW monsoon nutrient input (Fig 6) suggests that phytoplankton biomass 698 699 might still respond to increases in nutrients. This could be the case especially during the lownutrient intermonsoon periods, when CDOM concentrations are lower. Increases in nutrient 700 concentrations, such as from future aquaculture expansion (Tan, 2020) or from increased 701 riverine supply, might therefore still cause further eutrophication in the strait. Continued 702 monitoring is hence warranted. Our inorganic nutrient data point towards potential N- rather 703 704 than P-limitation, but also reveal an excess of Si(OH)<sub>4</sub> over N (Fig. 7). This is consistent with observed chlorophyll-*a* increases in experimental incubations of Singapore Strait water upon 705 706 N addition (Gin et al., 2006), and the fact that diatoms are consistently a large fraction of the 707 phytoplankton community (Chénard et al., 2019; Gin et al., 2006).

The fact that the diel change in pH does not follow the same seasonal pattern as dissolved O<sub>2</sub>,
but is on average highest during the SW monsoon (Fig. 8), reflects the seasonal change in the

710 mean state of the carbonate system: the low salinity during the SW monsoon means that total 711 alkalinity is lower than during other seasons, while peatland DOC remineralisation leads to a 712 relative excess of DIC (Zhou et al., 2021). Consequently, the buffering capacity is lowest 713 during the SW monsoon, and so the diel change in pH for a given change in dissolved CO<sub>2</sub> 714 concentration due to metabolic processes is necessarily larger (Pacella et al., 2018). In 715 contrast, the low diel pH variation during the NE monsoon results from both the higher 716 buffering capacity and the lower net community metabolism at this time. Marine ecosystems 717 in this part of the Sunda Shelf might therefore be more vulnerable to future ocean 718 acidification, because the seawater buffering capacity will be depleted both by uptake of atmospheric CO<sub>2</sub> across the South China Sea and further by terrigenous DOC 719 720 remineralisation on the shelf (Zhou et al., 2021). We therefore expect that the diel variation in 721 the carbonate system will increase further, especially during the SW monsoon. Such diel carbonate system variation due to community respiration can lead to periods of net CaCO<sub>3</sub> 722 723 dissolution on reefs, especially from the reef sediment (Stoltenberg et al., 2021). Coral reefs 724 in the Singapore Strait already have relatively low net CaCO<sub>3</sub> accretion rates and low vertical accretion potential even without considering possible sedimentary dissolution (Januchowski-725 726 Hartley et al., 2020). Future ocean acidification of the incoming open-ocean water is therefore an important potential threat to these reefs. 727

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## 730 **5.** Conclusions

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Our results show that terrestrial input is a major source of dissolved inorganic nutrients to the central Sunda Shelf, with coastal waters characterised by  $DIN:PO_4^{3-}$  ratios close to or slightly below the Redfield ratio, and an excess of dissolved Si over DIN. The source of nutrients is

735 likely a combination of natural input from soils together with fertiliser and wastewater input, 736 but atmospheric deposition appears to be at most minor. Rivers additionally provide a major 737 input of peatland-derived dissolved organic matter to coastal waters, although this input is 738 notably poor in DOP. The Singapore Strait experiences strong seasonal variation because the semi-annual current reversal advects either terrestrially influenced water masses or water 739 740 from the open South China Sea through the Strait. The particulate organic matter pool shows far less seasonal variation, suggesting a greater control from local production within coastal 741 742 waters and possibly resuspension from the sediment. While there is likely a significant 743 detrital contribution to the particulate organic matter pool, phytoplankton biomass is higher than would be expected for genuinely oligotrophic tropical waters. Phytoplankton 744 745 productivity is probably limited more by light than by nutrients, but phytoplankton biomass 746 does appear to increase in response to seasonal nutrient inputs, at least in some years. Net community metabolism causes stronger diel variation in pH during the SW monsoon than in 747 748 other seasons, when terrigenous DOC remineralisation depletes the buffering capacity. This 749 metabolic feedback, in combination with the impact of terrigenous DOC remineralisation, may render marine ecosystems in this region of Southeast Asia more vulnerable to the future 750 effects of ocean acidification. 751

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- 763
- 764 Data availability
- All data and analysis codes are archived in the Nanyang Technological University data
- repository and can be accessed at <u>https://doi.org/10.21979/N9/2FQEGW</u>.

- 768 References
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- Albright, R., Benthuysen, J., Cantin, N., Caldeira, K., Anthony, K., 2015. Coral reef
  metabolism and carbon chemistry dynamics of a coral reef flat. Geophys. Res. Lett. 42,
  3980-3988.
- Alkhatib, M., Jennerjahn, T.C., Samiaji, J., 2007. Biogeochemistry of the Dumai River
  estuary, Sumatra, Indonesia, a tropical black-water river. Limnol. Oceanogr. 52, 24102417.
- Arteaga, L., Pahlow, M., Oschlies, A., 2016. Modeled Chl:C ratio and derived estimates of
   phytoplankton carbon biomass and its contribution to total particulate organic carbon in
   the global surface ocean. Glob. Biogeochem. Cycles 30, 1791-1810.
- Bange, H.W., Sim, C.H., Bastian, D., Kallert, J., Kock, A., Mujahid, A., Müller, M., 2019.
  Nitrous oxide (N<sub>2</sub>O) and methane (CH<sub>4</sub>) in rivers and estuaries of northwestern Borneo.
  Biogeosciences 16, 4321-4335.
- 782 Baum, A., 2008. The Siak River in Central Sumatra, Indonesia. University of Bremen.
- Baum, A., Rixen, T., Samiaji, J., 2007. Relevance of peat draining rivers in central Sumatra
  for the riverine input of dissolved organic carbon into the ocean. Estuar. Coast. Shelf
  Sci. 73, 563-570.
- Bell, P.R.F., 1992. Eutrophication and coral reefs—some examples in the Great Barrier Reef
  lagoon. Water Res. 26, 553-568.
- Bell, P.R.F., Elmetri, I., Lapointe, B.E., 2014. Evidence of large-scale chronic eutrophication
  in the Great Barrier Reef: quantification of chlorophyll a thresholds for sustaining coral
  reef communities. Ambio 43, 361-376.
- Browne, N.K., Tay, J.K.L., Low, J., Larson, O., Todd, P.A., 2015. Fluctuations in coral
  health of four common inshore reef corals in response to seasonal and anthropogenic
  changes in water quality. Mar. Environ. Res. 105, 39-52.
- Brunskill, G.J., 2010. Tropical Margins, in: Liu, K.-K., Atkinson, L., Quiñones, R., TalaueMcManus, L. (Eds.), Carbon and Nutrient Fluxes in Continental Margins: A Global
  Synthesis. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 423-493.
- 797 Burford, M.A., Alongi, D.M., McKinnon, A.D., Trott, L.A., 2008. Primary production and
- nutrients in a tropical macrotidal estuary, Darwin Harbour, Australia. Estuar. Coast.
  Shelf Sci. 79, 440-448.

- Burford, M.A., Webster, I.T., Revill, A.T., Kenyon, R.A., Whittle, M., Curwen, G., 2012.
  Controls on phytoplankton productivity in a wet–dry tropical estuary. Estuar. Coast.
  Shelf Sci. 113, 141-151.
- Chai, X., Li, X., Hii, K.S., Zhang, Q., Deng, Q., Wan, L., Zheng, L., Lim, P.T., Tan, S.N.,
  Mohd-Din, M., Song, C., Song, L., Zhou, Y., Cao, X., 2021. Blooms of diatom and
  dinoflagellate associated with nutrient imbalance driven by cycling of nitrogen and
  phosphorus in anaerobic sediments in Johor Strait (Malaysia). Mar. Environ. Res. 169,
  105398.
- Chanton, J.P., Lewis, F.G., 1999. Plankton and dissolved inorganic carbon isotopic
  composition in a river-dominated estuary: Apalachicola Bay, Florida. Estuaries 22,
  575-583.
- 811 Chénard, C., Wijaya, W., Vaulot, D., Lopes dos Santos, A., Martin, P., Kaur, A., Lauro,
  812 F.M., 2019. Temporal and spatial dynamics of Bacteria, Archaea and protists in
  813 equatorial coastal waters. Sci. Rep. 9, 16390.
- Damar, A., Hesse, K.-J., Colijn, F., Vitner, Y., 2019. The eutrophication states of the
  Indonesian sea large marine ecosystem: Jakarta Bay, 2001–2013. Deep Sea Res. II 163,
  72-86.
- B17 DeCarlo, T.M., Cohen, A.L., Wong, G.T.F., Shiah, F.-K., Lentz, S.J., Davis, K.A.,
- Shamberger, K.E.F., Lohmann, P., 2017. Community production modulates coral reef
  pH and the sensitivity of ecosystem calcification to ocean acidification. J. Geophys.
  Res. Oceans 122, 745-761.
- Beignan, L.K., McDougald, D., 2021. Differential Response of the Microbiome of
   *Pocillopora acuta* to Reciprocal Transplantation Within Singapore. Microb. Ecol.
- 823Dickson, A.G., 1990. Standard potential of the reaction:  $AgCl(s) + 12H_2(g) = Ag(s) +$ 824HCl(aq), and and the standard acidity constant of the ion  $HSO_4^-$  in synthetic sea water825from 273.15 to 318.15 K. J. Chem. Thermodyn. 22, 113-127.
- Evans, C.D., Page, S.E., Jones, T., Moore, S., Gauci, V., Laiho, R., Hruška, J., Allott, T.E.H.,
  Billett, M.F., Tipping, E., Freeman, C., Garnett, M.H., 2014. Contrasting vulnerability
  of drained tropical and high-latitude peatlands to fluvial loss of stored carbon. Glob.
  Biogeochem. Cycles 28, 1215-1234.
- Eyre, B.D., 2000. Regional evaluation of nutrient transformation and phytoplankton growth
  in nine river-dominated sub-tropical east Australian estuaries. Mar. Ecol. Prog. Ser.
  205, 61-83.
- Fong, M., 2012. The Weather and Climate of Singapore. Meteorological Service Singapore,
  Singapore.
- Fry, B., Sherr, E.B., 1989. δ<sup>13</sup>C Measurements as Indicators of Carbon Flow in Marine and
  Freshwater Ecosystems, in: Rundel, P.W., Ehleringer, J.R., Nagy, K.A. (Eds.), Stable
  Isotopes in Ecological Research. Springer New York, New York, NY, pp. 196-229.
- Furnas, M., Mitchell, A., Skuza, M., Brodie, J., 2005. In the other 90%: phytoplankton
  responses to enhanced nutrient availability in the Great Barrier Reef Lagoon. Mar.
  Pollut. Bull. 51, 253-265.
- Gandois, L., Hoyt, A.M., Mounier, S., Le Roux, G., Harvey, C.F., Claustres, A., Nuriman,
  M., Anshari, G., 2020. From canals to the coast: dissolved organic matter and trace
  metal composition in rivers draining degraded tropical peatlands in Indonesia.
  Biogeosciences 17, 1897-1909.
- Gattuso, J.P., Epitalon, J.-M., Lavigne, H., 2016. seacarb: Seawater Carbonate Chemistry. R
   package version 3.1.1. <u>https://CRAN.R-project.org/package=seacarb</u>.
- Geider, R.J., MacIntyre, H.L., Kana, T.M., 1997. Dynamic model of phytoplankton growth
  and acclimation: responses of the balanced growth rate and the chlorophyll a:carbon
  ratio to light, nutrient-limitation and temperature. Mar. Ecol. Prog. Ser. 148, 187-200.

- Gin, K.Y.-H., Holmes, M.J., Zhang, S., Lin, X., 2006. Phytoplankton Structure in the
  Tropical Port Waters of Singapore, in: Wolanski, E. (Ed.), The Environment in Asia
  Pacific Harbours. Springer Netherlands, Dordrecht, pp. 347-375.
- Gin, K.Y.-H., Lin, X., Zhang, S., 2000. Dynamics and size structure of phytoplankton in the
  coastal waters of Singapore. J. Plankton Res. 22, 1465-1484.
- Green, S.A., Blough, N.V., 1994. Optical absorption and fluorescence properties of
  chromophoric dissolved organic matter in natural waters. Limnol. Oceanogr. 39, 19031916.
- Guest, J.R., Tun, K., Low, J., Vergés, A., Marzinelli, E.M., Campbell, A.H., Bauman, A.G.,
  Feary, D.A., Chou, L.M., Steinberg, P.D., 2016. 27 years of benthic and coral
  community dynamics on turbid, highly urbanised reefs off Singapore. Sci. Rep. 6,
  36260.
- Hansen, H.P., Koroleff, F., 1999. Determination of nutrients. Methods of Seawater Analysis,
   159-228.
- Heery, E.C., Hoeksema, B.W., Browne, N.K., Reimer, J.D., Ang, P.O., Huang, D., Friess,
  D.A., Chou, L.M., Loke, L.H.L., Saksena-Taylor, P., Alsagoff, N., Yeemin, T.,
  Sutthacheep, M., Vo, S.T., Bos, A.R., Gumanao, G.S., Syed Hussein, M.A., Waheed,
  Z., Lane, D.J.W., Johan, O., Kunzmann, A., Jompa, J., Suharsono, Taira, D., Bauman,
  A.G., Todd, P.A., 2018. Urban coral reefs: Degradation and resilience of hard coral
  assemblages in coastal cities of East and Southeast Asia. Mar. Pollut. Bull. 135, 654681.
- Huang, D., Tun, K.P.P., Chou, L.M., Todd, P.A., 2009. An inventory of zooxanthellate
  scleractinian corals in Singapore, including 33 new records. Raffles Bull. Zool. 22, 6980.
- Huang, T.H., Chen, C.T.A., Tseng, H.C., Lou, J.Y., Wang, S.L., Yang, L., Kandasamy, S.,
  Gao, X., Wang, J.T., Aldrian, E., Jacinto, G.S., Anshari, G.Z., Sompongchaiyakul, P.,
  Wang, B.J., 2017. Riverine carbon fluxes to the South China Sea. J. Geophys. Res.
  Biogeosci. 122, 1239-1259.
- Januchowski-Hartley, F.A., Bauman, A.G., Morgan, K.M., Seah, J.C.L., Huang, D., Todd,
  P.A., 2020. Accreting coral reefs in a highly urbanized environment. Coral Reefs 39,
  717-731.
- Jennerjahn, T.C., 2012. Biogeochemical response of tropical coastal systems to present and
   past environmental change. Earth-Sci. Rev. 114, 19-41.
- Jennerjahn, T.C., Ittekkot, V., Klöpper, S., Adi, S., Purwo Nugroho, S., Sudiana, N., Yusmal,
  A., Prihartanto, Gaye-Haake, B., 2004. Biogeochemistry of a tropical river affected by
  human activities in its catchment: Brantas River estuary and coastal waters of Madura
  Strait, Java, Indonesia. Estuar. Coast. Shelf Sci. 60, 503-514.
- Jennerjahn, T.C., Knoppers, B.A., Souza, W.F.L., Brunskill, G.J., Silva, E.I.L., 2006. Factors
  controlling dissolved silica in tropical rivers, in: Ittekkot, V., Unger, D., Humborg, C.,
  Tac An, N. (Eds.), The Silicon Cycle: Human Perturbations and Impacts on Aquatic
  Systems. Island Press, pp. 29-51.
- Jiang, S., Müller, M., Jin, J., Wu, Y., Zhu, K., Zhang, G., Mujahid, A., Rixen, T., Muhamad,
  M.F., Sia, E.S.A., Jang, F.H.A., Zhang, J., 2019. Dissolved inorganic nitrogen in a
  tropical estuary in Malaysia: transport and transformation. Biogeosciences 16, 28212836.
- Kartadikaria, A.R., Watanabe, A., Nadaoka, K., Adi, N.S., Prayitno, H.B., Soemorumekso,
  S., Muchtar, M., Triyulianti, I., Setiawan, A., Suratno, S., Khasanah, E.N., 2015. CO<sub>2</sub>
  sink/source characteristics in the tropical Indonesian seas. J. Geophys. Res. Oceans
  120, 7842-7856.

- Ke, Z., Tan, Y., Ma, Y., Huang, L., Wang, S., 2014. Effects of surface current patterns on spatial variations of phytoplankton community and environmental factors in Sunda shelf. Cont. Shelf Res. 82, 119-127.
- Kendall, C., Elliott, E.M., Wankel, S.D., 2007. Tracing Anthropogenic Inputs of Nitrogen to
   Ecosystems. Stable Isotopes in Ecology and Environmental Science, 375-449.
- Kérouel, R., Aminot, A., 1997. Fluorometric determination of ammonia in sea and estuarine
   waters by direct segmented flow analysis. Mar. Chem. 57, 265-275.
- Kuwahara, V.S., Nakajima, R., Othman, B.H.R., Kushairi, M.R.M., Toda, T., 2010. Spatial
  variability of UVR attenuation and bio-optical factors in shallow coral-reef waters of
  Malaysia. Coral Reefs 29, 693-704.
- Lee, T., Fournier, S., Gordon, A.L., Sprintall, J., 2019. Maritime Continent water cycle
  regulates low-latitude chokepoint of global ocean circulation. Nat. Commun. 10, 2103.
- Li, C., Li, S.-L., Yue, F.-J., He, S.-N., Shi, Z.-B., Di, C.-L., Liu, C.-Q., 2020. Nitrate sources
  and formation of rainwater constrained by dual isotopes in Southeast Asia: Example
  from Singapore. Chemosphere 241, 125024.
- Lim, J.H., Lee, C.W., Bong, C.W., 2021. Investigating factors driving phytoplankton growth
  and grazing loss rates in waters around Peninsular Malaysia. Journal of Oceanology and
  Limnology 39, 148-159.
- Lim, J.H., Lee, C.W., Bong, C.W., Affendi, Y.A., Hii, Y.S., Kudo, I., 2018. Distributions of
  particulate and dissolved phosphorus in aquatic habitats of Peninsular Malaysia. Mar.
  Pollut. Bull. 128, 415-427.
- Lim, J.H., Lee, C.W., Kudo, I., 2015. Temporal variation of phytoplankton growth and
  grazing loss in the west coast of Peninsular Malaysia. Environ. Monit. Assess. 187,
  246.
- Liu, H., Wu, C., Xu, W., Wang, X., Thangaraj, S., Zhang, G., Zhang, X., Zhao, Y., Sun, J.,
  2020. Surface Phytoplankton Assemblages and Controlling Factors in the Strait of
  Malacca and Sunda Shelf. Front. Mar. Sci. 7, 33.
- 926 Lønborg, C., Álvarez–Salgado, X.A., Duggan, S., Carreira, C., 2018. Organic matter
  927 bioavailability in tropical coastal waters: The Great Barrier Reef. Limnol. Oceanogr.
  928 63, 1015-1035.
- Lønborg, C., McKinna, L.I.W., Slivkoff, M.M., Carreira, C., 2021a. Coloured dissolved
  organic matter dynamics in the Great Barrier Reef. Cont. Shelf Res. 219, 104395.
- 931 Lønborg, C., Müller, M., Butler, E.C.V., Jiang, S., Ooi, S.K., Trinh, D.H., Wong, P.Y., Ali,
  932 S.M., Cui, C., Siong, W.B., Yando, E.S., Friess, D.A., Rosentreter, J.A., Eyre, B.D.,
  933 Martin, P., 2021b. Nutrient cycling in tropical and temperate coastal waters: Is latitude
  934 making a difference? Estuar. Coast. Shelf Sci. 262, 107571.
- Lueker, T.J., Dickson, A.G., Keeling, C.D., 2000. Ocean pCO<sub>2</sub> calculated from dissolved
  inorganic carbon, alkalinity, and equations for K<sub>1</sub> and K<sub>2</sub>: validation based on
  laboratory measurements of CO<sub>2</sub> in gas and seawater at equilibrium. Mar. Chem. 70,
  105-119.
- Ma, J., Yuan, Y., Zhou, T., Yuan, D., 2017. Determination of total phosphorus in natural
  waters with a simple neutral digestion method using sodium persulfate. Limnol.
  Oceanogr. Methods 15, 372-380.
- Martin, P., Cherukuru, N., Tan, A.S.Y., Sanwlani, N., Mujahid, A., Müller, M., 2018.
  Distribution and cycling of terrigenous dissolved organic carbon in peatland-draining rivers and coastal waters of Sarawak, Borneo. Biogeosciences 15, 6847-6865.
- Martin, P., Sanwlani, N., Lee, T.W.Q., Wong, J.M.C., Chang, K.Y.W., Wong, E.W.S., Liew,
  S.C., 2021. Dissolved organic matter from tropical peatlands reduces shelf sea light
  availability in the Singapore Strait, Southeast Asia. Mar. Ecol. Prog. Ser. 672, 89-109.

- Mayorga, E., Seitzinger, S.P., Harrison, J.A., Dumont, E., Beusen, A.H.W., Bouwman, A.F.,
  Fekete, B.M., Kroeze, C., Van Drecht, G., 2010. Global Nutrient Export from
  WaterSheds 2 (NEWS 2): Model development and implementation. Environ. Model.
  Software 25, 837-853.
- Mishra, S., Page, S.E., Cobb, A.R., Lee, J.S.H., Jovani-Sancho, A.J., Sjögersten, S., Jaya, A.,
  Aswandi, Wardle, D.A., 2021. Degradation of Southeast Asian tropical peatlands and
  integrated strategies for their better management and restoration. J. Appl. Ecol. 58,
  1370-1387.
- Mizubayashi, K., Kuwahara, V.S., Segaran, T.C., Zaleha, K., Effendy, A.W.M., Kushairi,
  M.R.M., Toda, T., 2013. Monsoon variability of ultraviolet radiation (UVR) attenuation
  and bio-optical factors in the Asian tropical coral-reef waters. Estuar. Coast. Shelf Sci.
  126, 34-43.
- Moore, S., Evans, C.D., Page, S.E., Garnett, M.H., Jones, T.G., Freeman, C., Hooijer, A.,
  Wiltshire, A.J., Limin, S.H., Gauci, V., 2013. Deep instability of deforested tropical
  peatlands revealed by fluvial organic carbon fluxes. Nature 493, 660-663.
- Morgan, K.M., Moynihan, M.A., Sanwlani, N., Switzer, A.D., 2020. Light Limitation and
  Depth-Variable Sedimentation Drives Vertical Reef Compression on Turbid Coral
  Reefs. Front. Mar. Sci. 7, 931.
- Moynihan, M.A., Goodkin, N.F., Morgan, K.M., Kho, P.Y.Y., Lopes dos Santos, A., Lauro,
  F.M., Baker, D.M., Martin, P., 2021. Coral-associated nitrogen fixation rates and
  diazotrophic diversity on a nutrient-replete equatorial reef. The ISME Journal.
- 969 Nichols, R.S., Martin, P., 2021. Low biodegradability of dissolved organic matter from
  970 Southeast Asian peat-draining rivers. J. Geophys. Res. Biogeosci. 126,
  971 e2020JG006182.
- 972 Ning, X., Chai, F., Xue, H., Cai, Y., Liu, C., Shi, J., 2004. Physical-biological oceanographic
  973 coupling influencing phytoplankton and primary production in the South China Sea. J.
  974 Geophys. Res. Oceans 109, C10005.
- 975 Nittrouer, C.A., Brunskill, G.J., Figueiredo, A.G., 1995. Importance of tropical coastal
  976 environments. Geo-Mar. Lett. 15, 121-126.
- Pacella, S.R., Brown, C.A., Waldbusser, G.G., Labiosa, R.G., Hales, B., 2018. Seagrass
  habitat metabolism increases short-term extremes and long-term offset of CO<sub>2</sub> under
  future ocean acidification. Proc. Natl. Acad. Sci. 115, 3870.
- Page, H.N., Courtney, T.A., De Carlo, E.H., Howins, N.M., Koester, I., Andersson, A.J.,
  2019. Spatiotemporal variability in seawater carbon chemistry for a coral reef flat in
  Kāne'ohe Bay, Hawai'i. Limnol. Oceanogr. 64, 913-934.
- Partelow, S., Schlüter, A., von Wehrden, H., Jänig, M., Senff, P., 2018. A Sustainability
  Agenda for Tropical Marine Science. Conservation Letters 11, e12351.
- Perez, F.F., Fraga, F., 1987. Association constant of fluoride and hydrogen ions in seawater.
  Mar. Chem. 21, 161-168.
- 987 Ren, H., Sigman, D.M., Martínez-García, A., Anderson, R.F., Chen, M.-T., Ravelo, A.C.,
  988 Straub, M., Wong, G.T.F., Haug, G.H., 2017. Impact of glacial/interglacial sea level
  989 change on the ocean nitrogen cycle. Proc. Natl. Acad. Sci. 114, E6759.
- Schaefer, S.C., Hollibaugh, J.T., 2017. Temperature Decouples Ammonium and Nitrite
   Oxidation in Coastal Waters. Environ. Sci. Technol. 51, 3157-3164.
- Siegel, H., Gerth, M., Stottmeister, I., Baum, A., Samiaji, J., 2019. Remote Sensing of
  Coastal Discharge of SE Sumatra (Indonesia), in: Barale, V., Gade, M. (Eds.), Remote
  Sensing of the Asian Seas. Springer International Publishing, Cham, pp. 359-376.
- Sigman, D.M., Casciotti, K.L., Andreani, M., Barford, C., Galanter, M., Böhlke, J.K., 2001.
  A Bacterial Method for the Nitrogen Isotopic Analysis of Nitrate in Seawater and
  Freshwater. Anal. Chem. 73, 4145-4153.

- Sinha, E., Michalak, A.M., Calvin, K.V., Lawrence, P.J., 2019. Societal decisions about
  climate mitigation will have dramatic impacts on eutrophication in the 21st century.
  Nat. Commun. 10, 939.
- Stoltenberg, L., Schulz, K.G., Lantz, C.A., Cyronak, T., Eyre, B.D., 2021. Late Afternoon
  Seasonal Transition to Dissolution in a Coral Reef: An Early Warning of a Net
  Dissolving Ecosystem? Geophys. Res. Lett. 48, e2020GL090811.
- Sundarambal, P., Tkalich, P., Balasubramanian, R., 2010. Impact of biomass burning on
   ocean water quality in Southeast Asia through atmospheric deposition: eutrophication
   modeling. Atmos. Chem. Phys. 10, 11337-11357.
- Susanto, R.D., Zexun, W., Adi, T.R., Guohong, F., Bin, F., Agus, S., Teguh, A., Shujiang, L.,
  Mukti, T., Agus, S., 2016. Oceanography Surrounding Krakatau Volcano in the Sunda
  Strait, Indonesia. Oceanography 29, 264-272.
- 1010 Tan, A., 2020. As some fish farms in Johor Strait near maximum production levels,
  1011 authorities eye southern expansion, The Straits Times, Singapore.
- 1012 Tanzil, J.T.I., Goodkin, N.F., Sin, T.M., Chen, M.L., Fabbro, G.N., Boyle, E.A., Lee, A.C.,
  1013 Toh, K.B., 2019. Multi-colony coral skeletal Ba/Ca from Singapore's turbid urban
  1014 reefs: Relationship with contemporaneous in-situ seawater parameters. Geochim.
  1015 Cosmochim. Acta 250, 191-208.
- Team, R.C., 2020. R: A language and environment for statistical computing. R Foundation
   for Statistical Computing, Vienna, Austria.
- Todd, P.A., Heery, E.C., Loke, L.H.L., Thurstan, R.H., Kotze, D.J., Swan, C., 2019. Towards
  an urban marine ecology: characterizing the drivers, patterns and processes of marine
  ecosystems in coastal cities. Oikos 128, 1215-1242.
- Tomascik, T., Suharsono, Mah, A., 1994. Case histories: a historical perspective of the
  natural and anthropogenic impacts in the Indonesian Archipelago with a focus on the
  Kepulauan Seribu, Java Sea. Colloquium on Global Aspects of Coral Reefs: Health,
  Hazard and History.
- 1025Troxler, T.G., 2007. Patterns of phosphorus, nitrogen and  $\delta^{15}N$  along a peat development1026gradient in a coastal mire, Panama. J. Trop. Ecol. 23, 683-691.
- 1027 Uppström, L.R., 1974. The boron/chlorinity ratio of deep-sea water from the Pacific Ocean.
   1028 Deep Sea Research and Oceanographic Abstracts 21, 161-162.
- Veron, J.E.N., Devantier, L.M., Turak, E., Green, A.L., Kininmonth, S., Stafford-Smith, M.,
  Peterson, N., 2009. Delineating the Coral Triangle. Galaxea 11, 91-100.
- 1031 Verwega, M.T., Somes, C.J., Schartau, M., Tuerena, R.E., Lorrain, A., Oschlies, A., Slawig,
  1032 T., 2021. Description of a global marine particulate organic carbon-13 isotope data set.
  1033 Earth Syst. Sci. Data 13, 4861-4880.
- 1034 Vieillard, A.M., Newell, S.E., Thrush, S.F., 2020. Recovering From Bias: A Call for Further
  1035 Study of Underrepresented Tropical and Low-Nutrient Estuaries. J. Geophys. Res.
  1036 Biogeosci. 125, e2020JG005766.
- Welschmeyer, N.A., 1994. Fluorometric analysis of chlorophyll *a* in the presence of
   chlorophyll *b* and pheopigments. Limnol. Oceanogr. 39, 1985-1992.
- Wit, F., Rixen, T., Baum, A., Pranowo, W.S., Hutahaean, A.A., 2018. The Invisible Carbon
  Footprint as a hidden impact of peatland degradation inducing marine carbonate
  dissolution in Sumatra, Indonesia. Sci. Rep. 8, 17403.
- Zhang, R., Wang, X.T., Ren, H., Huang, J., Chen, M., Sigman, D.M., 2020. Dissolved
  Organic Nitrogen Cycling in the South China Sea From an Isotopic Perspective. Glob.
  Biogeochem. Cycles 34, e2020GB006551.
- 1045 Zhou, Y., Evans, C.D., Chen, Y., Chang, K.Y.W., Martin, P., 2021. Extensive
- 1046 Remineralization of Peatland-Derived Dissolved Organic Carbon and Ocean

- Acidification in the Sunda Shelf Sea, Southeast Asia. J. Geophys. Res. Oceans 126,
  e2021JC017292.
- Zhou, Y., Martin, P., Müller, M., 2019. Composition and cycling of dissolved organic matter
   from tropical peatlands of coastal Sarawak, Borneo, revealed by fluorescence
   spectroscopy and parallel factor analysis. Biogeosciences 16, 2733-2749.

# **Supplementary Material**

P. Martin *et al.* Monsoon-driven biogeochemical dynamics in an equatorial shelf sea: timeseries observations in the Singapore Strait

Table S1. Relationships between biogeochemical parameters and CDOM  $a_{350}$ . Slope and intercept estimates are given together with their respective standard errors; non-significant intercepts are marked "NS". P-values refer to the regression slopes.

Parameter	Slope estimate (SE)	Intercept estimate (SE)	Statistics
NO <sub>3</sub> -	1.79 (0.13)	-0.05 (0.10), NS	r <sup>2</sup> =0.612, p<0.0001
PO4 <sup>3-</sup>	0.118 (0.008)	0.048 (0.007)	r <sup>2</sup> =0.611, p<0.0001
Si(OH) <sub>4</sub>	4.20 (0.33)	2.98 (0.26)	r <sup>2</sup> =0.563, p<0.0001
NO <sub>2</sub> -	0.234 (0.044)	0.010 (0.035)	r <sup>2</sup> =0.186, p<0.0001
DOC	14.3 (1.18)	68.6 (0.95)	r <sup>2</sup> =0.540, p<0.0001
DOP	-0.097 (0.015)	0.160 (0.013)	r <sup>2</sup> =0.311, p<0.0001
$\delta^{13}$ C-POC	-1.24 (0.31)	-20.2 (0.23)	r <sup>2</sup> =0.143, p<0.0001
$\delta^{15}$ N-PN	-0.907 (0.241)	5.01 (0.19)	r <sup>2</sup> =0.116, p<0.001
$\delta^{15}$ N-NO <sub>x</sub> -	2.59 (0.96)	4.42 (0.75)	r <sup>2</sup> =0.376, p<0.05



Fig. S1. Comparison of (a) salinity and (b) temperature measured by Seabird SeaCAT moored CTD at Kusu and by Valeport FastCTD profiler at Kusu. The RMSE in (a) excludes the two outliers indicated in grey. (c) Comparison of seawater pH measured by SeaFET pH sensor at Kusu and pH calculated from laboratory measurements of total alkalinity and dissolved inorganic carbon concentration. Solid lines show 1:1 relationships.



Fig. S2. Vertical profiles of potential density anomaly calculated from Valeport FastCTD profile data (calculated by subtracting the mean potential density of each profile). Note that there is typically no clear pycnocline, indicating little consistent water column stratification.



Fig. S3. Comparison of chlorophyll-*a* as measured *in-vivo* by the fluorometer on the Valeport FastCTD *versus* measurements from filtered water samples that were extracted in acetone and measured in the laboratory. Solid black and dashed dark grey lines indicate linear regression and 95% confidence interval. Dotted grey line in the 1:1 relationship.



Fig. S4. Relationships between parameters that showed significant relationships to salinity and coloured dissolved organic matter (measured as absorption coefficient at 350 nm;  $a_{350}$ ). Solid black and dashed dark grey lines indicate linear regressions and 95% confidence intervals.