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RESEARCH LETTER

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Biogeochemical River Runoff Drives Intense Coastal Arctic Ocean CO₂ Outgassing

Key Points:

- Mackenzie River biogeochemical discharge decreases the southeastern Beaufort Sea carbon sink
- Terrestrial dissolved inorganic carbon (DIC) is the primary driver of outgassing events in the SBS, followed by terrestrial DOC
- Interannual variability in river discharge modulates localized air-sea CO₂ flux

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Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Arctic warming alters land-to-sea fluxes of nutrients and organic matter, which impact air-sea carbon exchange. Here we use an ocean-biogeochemical model of the southeastern Beaufort Sea (SBS) to investigate the role of Mackenzie River biogeochemical discharge in modulating air-sea CO₂ fluxes during 2000–2019. The contribution of six biogeochemical discharge constituents leads to a net CO₂ outgassing of 0.13 TgC yr⁻¹, with a decrease in the coastal SBS carbon sink of 0.23 and 0.4 TgC yr⁻¹ due to riverine dissolved organic and inorganic carbon, respectively. Years with high (low) discharge promote more CO₂ outgassing (uptake) from the river plume. These results demonstrate that the Mackenzie River modulates the capacity of the SBS to act as a sink or source of atmospheric CO₂. Our work suggests that accurate model representation of land-to-sea biogeochemical coupling can be critical for assessing present-day Arctic coastal ocean response to the rapidly changing environment.

Plain Language Summary We modeled the discharge of freshwater and six biogeochemical constituents from the Mackenzie River into the southeastern Beaufort Sea to study their impact on ocean-atmosphere carbon dioxide (CO₂) fluxes during 2000–2019. We find that biogeochemical constituents from river runoff promote CO₂ outgassing to the atmosphere in the river plume region. Dissolved inorganic carbon is the main contributor to this phenomenon, with river discharge events driving pulses of intense CO₂ outgassing during ice-free periods. Our results show that the capacity of the SBS to act as an atmospheric CO₂ sink or source is strongly related to interannual variability in biogeochemical river discharge. Our results highlight the increased coupling of Arctic land-ocean biogeochemical systems under rapid environmental changes.

1. Introduction

The Arctic Ocean (AO) is estimated to be a carbon sink of roughly 118 to 180 TgC yr⁻¹ (Arrigo et al., 2010; Manizza et al., 2019; Yasunaka et al., 2018). Its net contribution to global CO₂ uptake is massive relative to its surface area (Bates & Mathis, 2009). However, whether the coastal periphery, which occupies approximately 50% of the AO (e.g., Carmack et al., 2006), acts as a net atmospheric CO₂ source or sink, remains poorly understood (Forest et al., 2014; Roobaert et al., 2019). For example, warming-induced changes in land-to-sea fluxes of freshwater associated with biogeochemical variables (Mann et al., 2022; Tank et al., 2012, 2016) can drive CO₂ outgassing rather than CO₂ uptake (Lacroix et al., 2021; Roobaert et al., 2019). An improved understanding of the effect of freshwater-biogeochemical discharge from Arctic rivers is therefore critical for accurately estimating AO air-sea CO₂ exchange.

Arctic rivers transport 11% of global freshwater to the world's ocean (McClelland et al., 2012) and contribute half of the net freshwater input to the AO (Brown et al., 2020). Additionally, these rivers transport significant amounts of inorganic nutrients and organic matter into the coastal zone (Dittmar & Kattner, 2003; Holmes et al., 2012; Juhls et al., 2020; Le Fouest et al., 2013; Rawlins et al., 2021), with part of the organic matter signal originating from thawing of northern permafrost and peatlands (Hugelius et al., 2014; Schuur et al., 2015). While riverine inorganic nutrients promote phytoplankton growth and enhance nearshore CO₂ uptake, fluxes of terrestrial

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organic matter and in particular dissolved organic carbon (tDOC), support favorable conditions for CO₂ production (Kirchman et al., 2009). Once in coastal waters, tDOC is reprocessed by mechanisms such as flocculation (Kipp et al., 2020), photodegradation (Aarnos et al., 2018; Bélanger et al., 2006), or bacterial degradation (Bruhn et al., 2021; Colatrisano et al., 2018; Ortega-Retuerta et al., 2012). The latter two mechanisms produce dissolved inorganic carbon (DIC) that increases the partial pressure of CO₂ ($p\text{CO}_2$), which in turn can promote CO₂ outgassing if seawater $p\text{CO}_2$ exceeds atmospheric $p\text{CO}_2$.

Since the 1970s, the Arctic has warmed three times faster than anywhere else on Earth (AMAP, 2021), inducing large changes in its hydrological cycle (Box et al., 2019; Brown et al., 2020; Saito et al., 2021). This warming has dramatically altered Arctic watersheds and rivers, which play an important role in shaping the physical and biogeochemical setting of the coastal AO. Along with a 0.22% yr⁻¹ intensification of river discharge since 1984 (Feng et al., 2021), accelerated permafrost thaw (Chadburn et al., 2017; Langer et al., 2022; McGuire et al., 2016; Slater & Lawrence, 2013) (a) changes the quantity and the quality (i.e., sources, compositions, and bioavailability) of tDOC exported to the AO (Mann et al., 2022; Matsuoka et al., 2022) and (b) increases connectivity between watersheds and marine ecosystems. Recent work shows that permafrost-driven carbon in the Mackenzie River mouth was observed even in early spring/summer, typically when only modern (i.e., young) organic matter has been observed (Schwab et al., 2020), highlighting the ongoing, rapid Arctic warming. In addition to tDOC, pan-Arctic rivers also act as large conveyor belts of terrestrial dissolved inorganic carbon (tDIC) to the ocean (Tank et al., 2012). While DIC upwelled from depth is known to trigger outgassing in coastal regions (Mol et al., 2018), quantification of tDIC release and associated CO₂ outgassing driven by Arctic river plumes has received far less attention and remains highly uncertain.

The sparse observational record in Arctic coastal waters has led to large uncertainty estimates of coastal CO₂ flux (Landschützer et al., 2020; Yasunaka et al., 2018). Although the impact of riverine input to the AO has already been considered in a few modeling studies (Manizza et al., 2019; Mathis et al., 2022; Terhaar et al., 2019, 2021), these previous studies either lack nearshore data constraints or do not include realistic representation of dissolved carbon river runoff. Additionally, the strong differences between individual Arctic river systems (Brown et al., 2020) motivates the need to investigate regional land-to-sea coupling in order to infer its effects at the AO scale. In the context of rapid watershed modification, it is also timely to gain understanding on the ecosystem response to seasonal-to-interannual variability in riverine discharge (Brown et al., 2020; Gelfan et al., 2017).

Here we use a regional ocean-ice-biogeochemistry model (ECCO-Darwin) to understand how freshwater and matter transported by Arctic rivers modulate air-sea CO₂ fluxes in the coastal AO. We focus on the southeastern Beaufort Sea (SBS), where outflow from the Mackenzie River makes this region, with the Siberian shelf (McClelland et al., 2012), one of the most riverine-influenced of all pan-Arctic shelves with respect to its size and river runoff (Carmack et al., 2004; Macdonald et al., 1989). The remainder of the paper is organized as follows. First, we describe the regional model set-up and simulation of the SBS carbon cycle. Second, we quantify the contribution of Mackenzie constituents to coastal air-sea CO₂ flux. Third, we characterize intense outgassing events that develop under specific discharge conditions and quantify the interannual variability in coastal air-sea CO₂ fluxes driven by land-to-sea export. Finally, we conclude by highlighting the critical processes that drive AO land-to-sea coupling of carbon and make recommendations for future modeling efforts.

2. Methods

The SBS model is a regional set-up adapted from the global-ocean ECCO-Darwin biogeochemistry state estimate described in Carroll et al. (2020, 2022). ECCO-Darwin assimilates both physical (Wunsch et al., 2009) and biogeochemical (Menemenlis et al., 2005) observations and is used for generating initial, open, and surface boundary conditions. The general set-up of the regional model (hereafter referred to as ED-SBS) is detailed in Text S1 in Supporting Information S1. In the following section, we provide the specific details required for the regional Arctic set-up.

The biogeochemical component of the model explicitly simulates cycling of carbon, nitrogen, phosphorus, silica, iron, and oxygen as they transition between inorganic, living, and dead organic pools; the model also simulates the carbonate cycle. In addition, the ED-SBS has four key plankton functional types (PFTs) characteristic of the western AO: diatoms, large eukaryotes, and small and large zooplankton. To represent the observed phytoplankton biomass that is maintained under sea ice in winter, no mortality or grazing occur when phytoplankton biomass is below 0.05 mmolC m⁻³ (Hoppe, 2022; Randelhoff et al., 2020).

ED-SBS also includes terrestrial inputs from the Mackenzie River. We prescribed daily freshwater discharge, river temperature, and six biogeochemical components (Table S1 and Text S2 in Supporting Information S1) at

Table 1
Net Air-Sea CO₂ Fluxes and Net Primary Production (NPP) During 2000–2019 Calculated in the River Plume Area ($S < 27$)

Model run	Net CO ₂ flux (TgC yr ⁻¹)	NPP (TgC yr ⁻¹)
No river	-0.20 ± 0.06 (-51%) ^a	0.51 ± 0.08 (-12%) ^a
Q	-0.42 ± 0.05 (1%) ^a	0.57 ± 0.06 (-1%) ^a
Q + Temp	-0.41 ± 0.06	0.58 ± 0.07
All Interannual	0.13 ± 0.10 (-132%) ^a	0.70 ± 0.06 (+21%) ^a
No Nutrients	0.21 ± 0.10	0.58 ± 0.07
No tDOC	-0.10 ± 0.06	0.70 ± 0.06
No tDIC-tAlk	-0.27 ± 0.06	0.70 ± 0.06
All Climatology	0.13 ± 0.08	0.70 ± 0.06

^aValues in brackets indicates difference with “Q + Temp” simulation.

the three major outlets of the Mackenzie Delta: Shallow Bay, Beluga Bay, and Kugmallit Bay (Figure S1 in Supporting Information S1). Freshwater and biogeochemical river fluxes were distributed over a group of grid cells located within Shallow Bay (29.8%), Beluga Bay (37.6%), and Kugmallit Bay (32.6%) (Bertin et al., 2022). Freshwater discharge and river temperature were forced by daily gauge measurements of the Water Survey of Canada (WSC) from the Arctic Great River Observatory (Figure S2 in Supporting Information S1; Shiklomanov et al., 2021) and by the Tokuda et al. (2019) data set, respectively. Riverine biogeochemical components include tDOC, terrestrial dissolved organic nitrogen (tDON), phosphorus (tDOP), tDIC, alkalinity (tAlk), and inorganic silica (tDSi). tDIC and tDOC were computed based on chemodynamic relationships between discharge and concentration (Bertin et al., 2022; Tank et al., 2012) using a nonlinear load estimation method (Text S2 in Supporting Information S1). tAlk was computed using a Alk:DIC ratio of 0.93 (Tank et al., 2012) and tDOC was split into to semi-labile (DOC_{sl}) and semi-refractory (DOC_{sr}) pools. DOC_{sl} and DOC_{sr} were implicitly remineralized into DIC at rates of 1 month and 10 years (Manizza et al., 2009, 2011),

respectively. tDON, tDOP, and tDSi concentrations were computed using the GlobalNEWS2 annual climatology (Mayorga et al., 2010).

A suite of eight simulations were integrated and analyzed for the 2000–2019 period (Table S2 in Supporting Information S1). The run “Q + Temp” included only freshwater discharge (Q) and river temperature and served as a reference run. The runs “All Interannual” and “All Climatology” included all riverine physical and biogeochemical inputs calculated, respectively, with interannual and climatological forcing; climatologies were estimated by averaging daily time series. The effect of each group of riverine biogeochemical components was analyzed by removing one by one the associated inputs: run “No tDOC” included all but tDOC, run “No tDIC” included all but tDIC and tAlk, and run “No Nutrients” included all but tDON, tDOP, and tDSi. Finally, two runs were designed to assess model sensitivity to zero biogeochemical input; The “No river” run did not included any riverine inputs from the Mackenzie River and the “Q” run included only the freshwater discharge with river temperature set to the sea-surface temperature (SST) value of the wet grid cell. A plume region delimited by Mulligan and Perrie (2019) observations at isohaline $S = 27$ was computed to evaluate the contribution of the Mackenzie plume to CO₂ fluxes and net primary production (NPP) in the SBS. The plume region was coherent with the Mackenzie inner-shelf sub-region determined by a neural network (not shown), which combined 17 years of satellite data acquired by the Aqua-MODIS sensor (Hilborn & Devred, 2022).

3. Contribution of River Components to Mackenzie Plume Air-Sea CO₂ Flux

For the 2000–2019 period, using all river inputs in the ED-SBS model (“All Interannual”) results in an annual-mean CO₂ outgassing of 0.13 ± 0.10 TgC yr⁻¹ within the plume region (Table 1 and Figure 1). This estimate falls outside the range reported in previous studies (-0.9 ± 0.5 to -4.3 ± 2.5 TgC yr⁻¹; Evans et al., 2015; Manizza et al., 2013, 2019; Ouyang et al., 2021) that categorize the SBS as a weak-to-moderate CO₂ sink (see also Dai et al., 2022; Roobaert et al., 2019). However, the lack of nearshore data (which do not cover a large part of the river plume) or lack of terrestrial inputs (missing tDIC-tAlk input or poorly-resolved tDOC remineralization), can explain this discrepancy. With no riverine biogeochemistry in the river plume (“Q + Temp” run), the plume region transitions to a CO₂ sink (-0.41 TgC yr⁻¹, Table 1), highlighting the key role of the Mackenzie river in modulating air-sea CO₂ flux. We estimate that the biogeochemical plume ventilates 0.54 ± 0.16 TgC yr⁻¹ to the atmosphere, which corresponds to about 7% of the annual-mean riverine input of both tDIC and tDOC (Table S1 in Supporting Information S1).

Including riverine nutrients (tDON, tDOP, and tDSi) increases NPP by 21%, resulting in an uptake of 0.08 TgC yr⁻¹ by the coastal AO (“All Interannual” run and “No Nutrients” run, Table 1). The riverine nutrient contribution to NPP is comparable to previously reported values in the region (>9.8%; Terhaar et al., 2021) and also in Arctic (Lena River, 34%; Lacroix et al., 2020) and non-Arctic (Amazon River, 21%; Louchard et al., 2021) river systems. However, as a caveat the riverine tDON and tDOP used in ED-SBS may be overestimated relative to other observations (Table S1 in Supporting Information S1). In the absence of riverine nutrients (“No Nutrients”

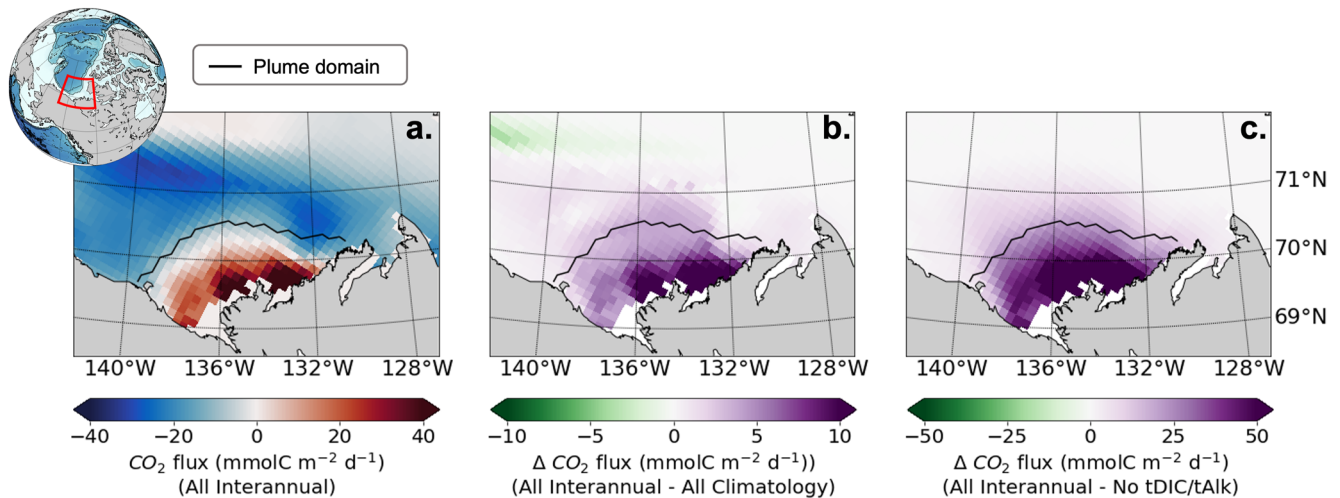


Figure 1. (a) Net air-sea CO_2 flux simulated by the “All Interannual” run during the 23 August 2007 outgassing event and difference with (b) “All Climatology” and (c) “No tDOC” runs. Positive (negative) values indicate CO_2 outgassing (ingassing). Top left inset shows the ED-SBS model region in a global context. Black solid lines indicate the plume region ($S < 27$).

run), the coastal Beaufort Sea's net CO_2 flux to the atmosphere is strengthened due to weaker biological uptake. In ED-SBS, riverine tDIC drives an outgassing of 0.40 TgC yr^{-1} in the coastal AO, which is ~ 2 times higher than the tDOC contribution (0.23 TgC yr^{-1}). This results from higher tDIC supply in the Mackenzie River compared to tDOC (Table S1 in Supporting Information S1), demonstrating that tDIC plays a crucial role in carbon cycling on the Mackenzie Shelf.

In Arctic river waters, tDOC originating from permafrost thaw can exhibit fast remineralization rates (7 days; Spencer et al., 2015), depending on the season and soil characteristics in various watersheds (Bruhn et al., 2021). Additionally, tDOC lability varies significantly according to the soil type, to which marine microbes respond differently (Bruhn et al., 2021; Drake et al., 2018). tDOC is thus a complex pool of molecules characterized by a large spectrum of lifetimes (Dittmar et al., 2021) that makes it challenging to represent in biogeochemical models. In this study, we represent tDOC based on our best knowledge of the Mackenzie River system by separating it into fast-reacting (50%) and slow-reacting (50%) pools. According to this parameterization, the model was able to correctly reproduce the DOC concentrations retrieved by satellite (Figure S4 in Supporting Information S1, $r = 0.65$; Matsuoka et al., 2017, 2022). In our simulations, tDIC plays a greater role than tDOC in the air-sea CO_2 balance in the Beaufort Sea (see Mol et al., 2018; Tank et al., 2012). This contrasts with results from Terhaar et al. (2019) that assumed the immediate remineralization of all tDOC into DIC and predicted a greater effect of tDOC compared to tDIC on air-sea CO_2 flux. Our results emphasize the critical role of tDOC remineralization in ocean-atmosphere carbon exchange, highlighting the importance of accurately representing the fate of riverine carbon in models.

Turning off all Mackenzie River inputs (“No river”) results in a 51% weaker net CO_2 sink, along with a 12% decrease in NPP (Table 1). This response results from (a) higher CO_2 solubility in less-saline waters and (b) enhanced DIC uptake by phytoplankton blooms promoted by increased upper-ocean stratification (Ardyna & Arrigo, 2020; Carmack & Macdonald, 2002) in the “Q + Temp” run. In contrast, the effect of river temperature on air-sea CO_2 exchange is negligible. We find that ED-SBS underestimates observed SST (OSTIA; Good et al., 2020), especially in the coastal zone influenced by the Mackenzie River plume (Figure S5 in Supporting Information S1; Nguyen et al., 2021). This mismatch can be explained by two primary reasons. First, the uppermost vertical layer in ED-SBS is 10-m thick, which does not fully resolve the fine-scale vertical stratification driven by the river plume, which has been observed to be roughly 2–3 m deep (Mulligan & Perrie, 2019). Second, ED-SBS does not include thermal effects from the colored and optically-active tDOC fraction (Hill, 2008; Matsuoka et al., 2017; Pefanis et al., 2020; Soppa et al., 2019) which likely influenced SST in this region.

4. Biogeochemically-Induced Outgassing Events in the SBS

“All Interannual” and “All Climatology” simulate a general sink of carbon in the SBS (blue colors, Figure 1a), balanced by short lived intense outgassing as a result of riverine input (red colors, Figure 1a). In this study, an

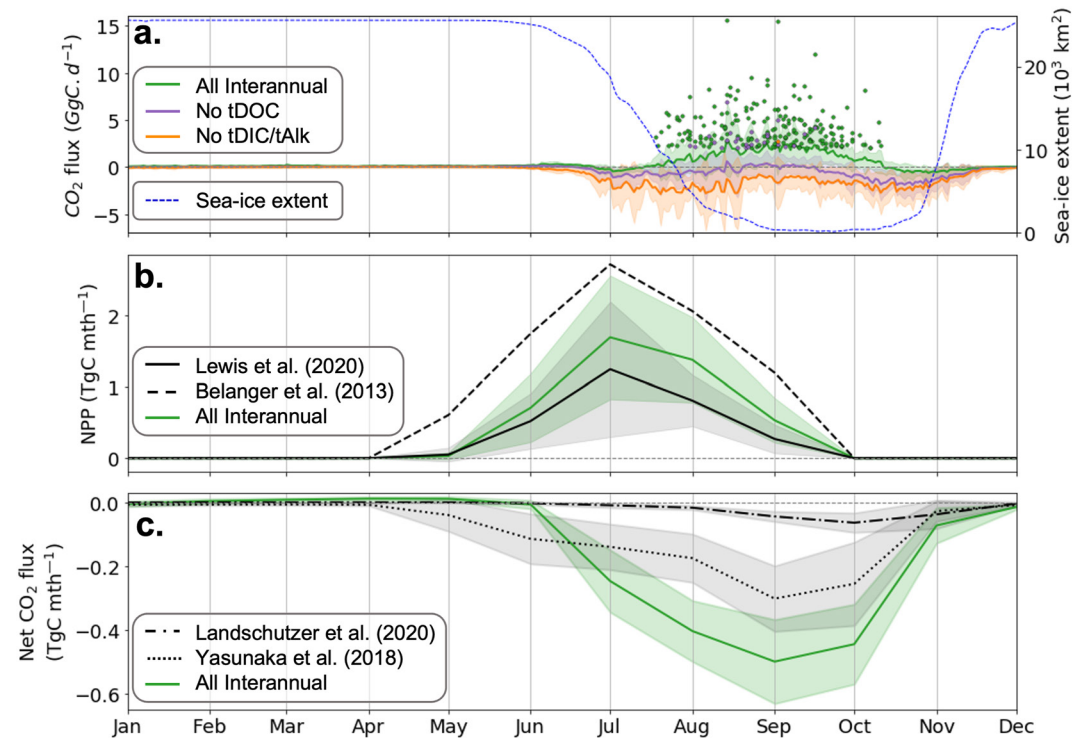


Figure 2. (a) 2000–2019 daily net CO₂ flux (TgC d⁻¹) simulated by the “All Interannual” run (green solid line), “No tDOC” run (purple solid line) and “No terrestrial dissolved inorganic carbon (tDIC)/tAlk” run (orange solid line) in the plume domain (see Figure S1 in Supporting Information S1). Green, purple and orange dots show the net CO₂ flux driven by individual outgassing events simulated in “All Interannual,” “No tDOC” and “No tDIC/tAlk” runs, respectively. Positive (negative) values indicate CO₂ outgassing (ingassing). The simulated sea ice extent (10³ km²) is overlaid (blue dashed line). 2000–2017 seasonal (b) NPP and (c) net CO₂ flux (TgC mth⁻¹) from “All Interannual” run (green solid line) and observed by satellite (solid black line, Lewis et al. (2020); dashed black line, Bélanger et al. (2013); dash-dotted black line, Landschützer et al. (2020), and dotted black line, Yasunaka et al. (2018)) over the full model domain (see Figure S1 in Supporting Information S1). For all panels, the shaded envelop indicates the standard deviation computed for every seasonal cycles.

outgassing event is defined as a net CO₂ flux to the atmosphere exceeding 2 GgC d⁻¹ within the river plume region. While both runs exhibit similar net CO₂ fluxes (Table 1), specifically in terms of the number of outgassing events (191–192) and net carbon ventilated (787–815 GgC), disparities occur at seasonal and interannual timescales (Figure 1b). In July, after the peak of discharge, the “All Interannual” run increases CO₂ outgassed by discrete events by 31%. From year to year, the number of events and carbon outgassed also strongly differs between the two runs (Figure S6 in Supporting Information S1). This highlights the influence of riverine interannual variability in modulating the frequency and intensity of plume-driven CO₂ outgassing in the SBS.

We find that the absence of tDIC and tAlk input (“No tDIC-tAlk” run), and tDOC (“No tDOC” run) to a lesser extent, strongly limits CO₂ outgassing events, (Figures 1c and 2a). Coastal waters deprived of these inputs become a net CO₂ sink over the two decades, with the number of outgassing events decreasing from 192 (“All Interannual”) to 26 in “No tDOC” and to only 1 event in “No tDIC-tAlk” (Figure 2a). Therefore, including tDIC, tAlk and tDOC forcing is necessary for accurately simulating seasonal carbon dynamics in the SBS between July to October (Table S3 in Supporting Information S1). We find that outgassing events start in mid-July, which coincides with the decline in near-shore sea-ice (Figure 2; Carmack et al., 2004) that confines the river plume and dampens the intensity of outgassing hotspots. 85% of the outgassing events occur in August and September, when phytoplankton decline (Figure 2b) and tDIC/tDOC inputs are maintained by high discharge rates (Figure S2 in Supporting Information S1), promoting air-sea CO₂ exchange in ice-free waters with low productivity. Finally, outgassing declines in October, following seasonal decline in river's carbon supply.

We find that ED-SBS exhibits broad-scale consistency in both time and space with the observed circulation patterns (Figure S3 in Supporting Information S1, Lin et al., 2020) and NPP and net CO₂ flux products. Over the

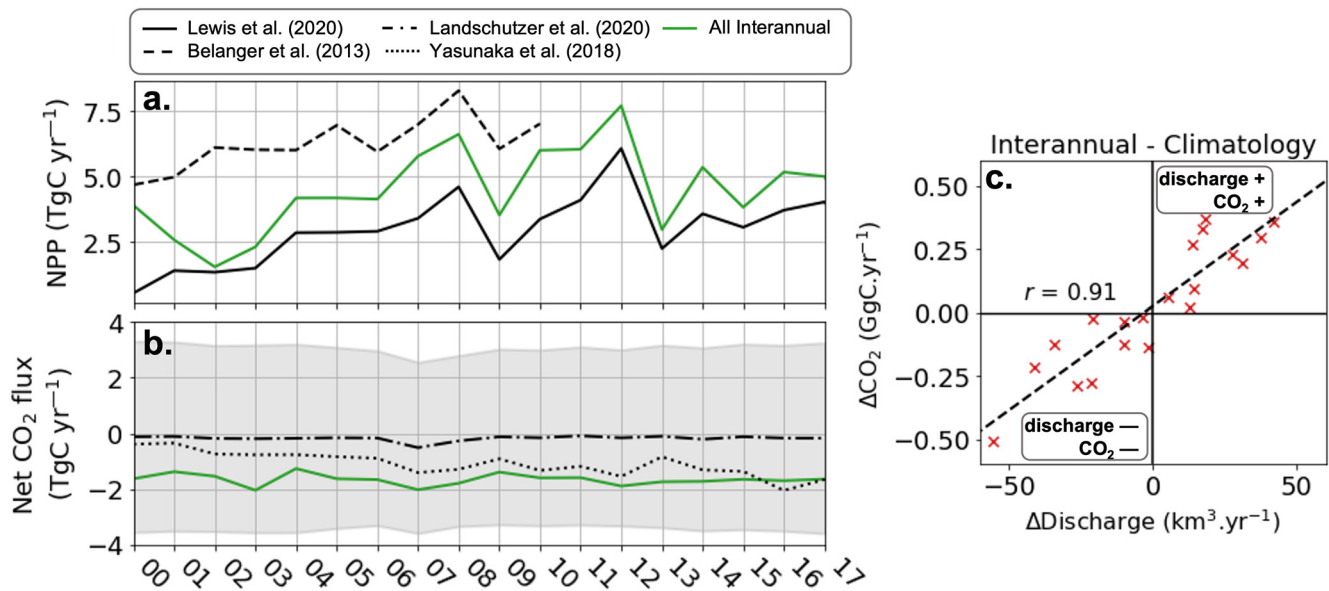


Figure 3. Interannual (a) NPP and (b) net CO₂ flux (TgC yr⁻¹) in the “All Interannual” run (green solid line) and observed by satellite (solid black line, Lewis et al. (2020); dashed black line, Bélanger et al. (2013); dash-dotted black line, (Landschützer et al., 2020) and dotted black line, Yasunaka et al. (2018)) over the full model domain (see Figure S1 in Supporting Information S1). Positive (negative) values indicate CO₂ outgassing (ingassing). The shaded envelop indicates the net CO₂ flux error associated to Yasunaka et al. (2018) data. (c) Relationship between net annual CO₂ flux versus annual Mackenzie discharge interannual variability.

2000–2017 period, the “All Interannual” run is able to accurately simulate both seasonal and interannual variability within the range of mean product amplitude and bloom phenology (Figures 2a and 3a, Bélanger et al., 2013; Lewis et al., 2020). In terms of net CO₂ flux, ED-SBS simulates higher CO₂ uptake compared to Yasunaka et al. (2018) and Landschützer et al. (2020) (Figure 2c). We note that these interpolated-based products lack near-shore observations which prevents a more robust comparison along the coastal periphery and does not indicate a model discrepancy. On interannual timescales, ED-SBS net CO₂ flux falls within the Yasunaka et al. (2018) error bounds (Figure 3b).

We observe a positive linear relationship ($r = 0.91$) between interannual variability in Mackenzie River discharge and net annual CO₂ flux (“All Interannual”–“All Climatology” values). This result suggests that low discharge promotes CO₂ uptake and high discharge drives CO₂ outgassing (Figure 3c). Interannual variability in river discharge is thus an important driver of the capacity of the coastal AO to capture or release CO₂ to the atmosphere. In a recent study, Ouyang et al. (2021) simulated interannual variability in CO₂ uptake across the western Arctic using a data-driven box model, but without including Mackenzie River discharge. Ouyang et al. (2021) obtained a better fit between their model and the observations in the Canada Basin and Chukchi Sea compared to Beaufort Shelf that is highly influenced by the Mackenzie River. Our results suggest that excluding the effect of the pan-Arctic river systems and their biogeochemical constituents in an ocean biogeochemistry model might hamper complete assessment of coastal air-sea CO₂ fluxes on interannual timescales.

5. Conclusion and Future Directions

We investigated how the Mackenzie River plume modulates the capacity of the SBS to act as a sink or source of CO₂ to the atmosphere. ED-SBS compares well to both time-coincident satellite and observation products and provides key mechanistic insight on the contribution of riverine freshwater and biogeochemistry to air-sea CO₂ fluxes in this rapidly-changing region. We have several critical results:

1. During the 2000–2019 period, the Mackenzie River plume drives net CO₂ outgassing (0.13 ± 0.10 TgC yr⁻¹), resulting from tDIC and tDOC inputs that ventilate 0.40 and 0.23 TgC yr⁻¹ to the atmosphere, respectively.
2. tDIC riverine discharge contributes twice as much as tDOC in driving outgassing conditions; we identified 192 discrete CO₂ outgassing events, which mainly occur during ice-free periods.
3. Interannual variability of the Mackenzie River discharge strongly modulates air-sea CO₂ flux, with more outgassing occurring when discharge is high and more uptake when discharge is low.

Despite the tiny scale of the plume outgassing relative to the entire Arctic shelf (Dai et al., 2022), this study improves the mechanistic understanding of the processes controlling the seasonal air-sea CO₂ fluxes in the Mackenzie shelf and provides a set of new software tools that can help refine the pan-Arctic coastal carbon budget. We suggest that tDIC can be a key driver of ocean outgassing, which might be relevant to other tDIC-dominated river systems (Li et al., 2017). As suggested by recent observational-based coastal air-sea CO₂ flux estimates (Landschützer et al., 2020; Roobaert et al., 2019), we also demonstrate that large spatial heterogeneity exists near river mouths, such as the Mackenzie Delta (Figure 1), which indicates that localized outgassing along the Arctic coastal periphery may result in a weaker AO CO₂ sink than previously expected (Dai et al., 2022). These results also stress the importance of including all river freshwater and biogeochemical discharge constituents in AO numerical ocean simulations and highlight that previous studies which do not include these processes may overestimate the AO CO₂ sink (Manizza et al., 2019; Ouyang et al., 2021). Pan-Arctic rivers are important contributors to the budget of freshwater (Serreze et al., 2006) and inorganic and organic matter in the coastal AO (Holmes et al., 2012; Tank et al., 2012). Fluxes from these large river system are projected to increase in the future with the intensification of the Arctic hydrologic cycle (Brown et al., 2020; Saito et al., 2021), river discharge (Ahmed et al., 2020; Feng et al., 2021), and permafrost thaw (McGuire et al., 2016; Schuur et al., 2015). As suggested by our study, representing the large interannual variability in riverine export of tDIC and tDOC to the coastal AO is critical for predicting how these changes may alter future carbon cycling on Arctic shelves. This requires quantifying the quantity, type, and lability of riverine nutrients, as well as the timing with which they are delivered to coastal waters. Measurements of nutrient distributions are needed as close as possible to the mouths of large deltas and estuaries, which could prevent biases due to removal/addition processes taking place upstream in watersheds (Emmerton et al., 2008; Schwab et al., 2020). This is particularly true for tDOC originating from thawing permafrost, which has a much older ¹⁴C age and is more labile than tDOC from contemporary sources. Furthermore, we report significant outgassing in late summer, which is coincident with maximum seasonal depth of the permafrost active layer (Lacroix et al., 2022; Schuur et al., 2015). Future soil warming (Slater & Lawrence, 2013) could promote the release of permafrost-derived tDOC in coastal waters (Matsuoka et al., 2022), potentially increasing river-driven outgassing. However, the actual amount of permafrost tDOC exported into the ocean still remains highly uncertain (Schwab et al., 2020). Recent autonomous systems (Juhls et al., 2020) and methods which merge in-situ and remotely-sensed data (Bertin et al., 2022) provide a new AO monitoring frameworks, but they are still unable to track seasonal-to-interannual changes in tDOC lability in response to rapid changes in permafrost conditions. We stress that knowledge of the riverine tDOC signal and how it will change in time and space is pivotal, as this determines remineralization pathways and key timescales within the carbon cycle. Concerning tDIC, concentrations are indirectly estimated from ions present in river water (Tank et al., 2012), whose monitoring primarily relies on the ArcticGRO pan-Arctic program (Holmes et al., 2012). Such a database and continuity in monitoring programs are essential for tracking seasonal-to-interannual variations of tDIC alongside those of tDOC. This is important as the riverine tDIC:tDOC ratio exhibits large variations at the pan-Arctic scale (Figure S7 in Supporting Information S1).

In the Eurasian AO, the tDIC:tDOC ratio falls between 1.0 and 1.5, while it is as high as 4.5 on the North American side (Holmes et al., 2012; Tank et al., 2012). There is far more tDOC delivered by large rivers in the Eurasian shelf seas, so outgassing events might not be driven by the processes we have identified in the SBS. With ongoing Arctic warming, an improved understanding of seasonal-to-interannual variability in tDOC concentrations and fluxes are thus required to improve the ability of AO simulations to quantify the relative contribution of tDOC and tDIC to air-sea CO₂ fluxes in these productive shelf regions.

We find that the CO₂ outgassing signal is sensitive to the choice of vertical model resolution. Additional experiments (not shown) demonstrate that with finer vertical resolution in the upper layer, CO₂ fluxes are increased and tend to promote more outgassing. Therefore, we recommend that future models use coastal observations to optimize their land-to-sea boundary conditions. This is also critical for the implementation of riverine fluxes of particulate matter, which are subject to vertical sedimentation. The Mackenzie shelf receives as much terrestrial particulate organic carbon (tPOC) as tDOC (1.6 TgC yr⁻¹; Bertin et al., 2022) from both the river (0.7 TgC yr⁻¹; McClelland et al., 2016) and coastal erosion (0.9 TgC yr⁻¹; Nielsen et al., 2022). Once in shallow waters, tPOC is resuspended from bottom sediments to the water column (Jong et al., 2020) and transported farther offshore (Forest et al., 2014). Resuspension cycles constantly bring tPOC back to surface waters where it can be oxidized (Galeron et al., 2018; Massicotte et al., 2021) and degraded by bacteria to be ultimately outgassed as CO₂ (Jong et al., 2020). However, representing tPOC in regional models is not trivial as it requires coupling with bottom

sediments and fine grid resolution in order to resolve the physical (i.e., tides, waves) and biogeochemical processes that drive tPOC dynamics.

Both tPOC and tDOC also produce a browning of shelf waters, with potential consequences for near-surface light penetration. Therefore, future models will need to include this process as it will impact the delicate balance between CO₂ uptake through NPP and regeneration through bacterial respiration. Finally, we suggest that future efforts focus more on the role of tPOC in driving air-sea CO₂ flux. Since the 2000s, coastal erosion has reached high rates (up to -1.8 m yr^{-1} along the US Beaufort Sea coast; Irrgang et al., 2022) expected to rise in the future (more than -3 m yr^{-1} ; Nielsen et al., 2022) in the North American Arctic. An explicit representation of terrestrial POC may be required to produce a more holistic view on how land-to-sea connectivity would drive carbon flows in an Arctic “green belt,” which is already facing rapid and drastic environmental changes. Furthermore, Arctic deltas are projected to become less ice-dominated and more exposed to wave erosion in the future (Odériz et al., 2022; Overeem et al., 2022), bringing more uncertainty to the projected AO carbon cycle.

Data Availability Statement

Model code and instructions for running ED-SBS simulations are available at <https://doi.org/10.5281/zenodo.7417828>. ED-SBS forcing files are available at https://ecco.jpl.nasa.gov/drive/files/ECCO2/LLC270/Mac_Delta. Each user must first register for an Earthdata account at <https://urs.earthdata.nasa.gov/users/new> in order to access these files in NASA Earthdata.

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