



HAL
open science

Biogeochemical River Runoff Drives Intense Coastal Arctic Ocean CO₂ Outgassing

C. Bertin, D. Carroll, D. Menemenlis, S. Dutkiewicz, H. Zhang, A. Matsuoka, S. Tank, M. Manizza, C E Miller, M. Babin, et al.

► **To cite this version:**

C. Bertin, D. Carroll, D. Menemenlis, S. Dutkiewicz, H. Zhang, et al.. Biogeochemical River Runoff Drives Intense Coastal Arctic Ocean CO₂ Outgassing. *Geophysical Research Letters*, 2023, 50 (8), pp.e2022GL102377. 10.1029/2022GL102377 . hal-04074930

HAL Id: hal-04074930

<https://hal.science/hal-04074930>

Submitted on 19 Apr 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

Geophysical Research Letters[®]




RESEARCH LETTER

10.1029/2022GL102377

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

C. Bertin¹ , D. Carroll^{2,3} , D. Menemenlis³ , S. Dutkiewicz⁴ , H. Zhang³, A. Matsuoka⁵ , S. Tank⁶ , M. Manizza⁷ , C. E. Miller³ , M. Babin⁸ , A. Mangin⁹, and V. Le Fouest¹ 

¹Littoral ENvironnement et Sociétés (LIENSs) – UMR 7266, Bâtiment ILE, La Rochelle, France, ²Moss Landing Marine Laboratories, San José State University, Moss Landing, CA, USA, ³Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA, ⁴Department of Earth Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA, ⁵Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, NH, USA, ⁶Department of Biological Sciences, University of Alberta, Edmonton, AB, Canada, ⁷Geosciences Research Division, Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, USA, ⁸Takuvik Joint International Laboratory, Université Laval and CNRS, Québec, QC, Canada, ⁹ACRI-ST, Sophia Antipolis, France

Supporting Information:

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

Correspondence to:

C. Bertin,
clement.bertin1@univ-lr.fr

Citation:

Bertin, C., Carroll, D., Menemenlis, D., Dutkiewicz, S., Zhang, H., Matsuoka, A., et al. (2023). Biogeochemical river runoff drives intense coastal Arctic Ocean CO₂ outgassing. *Geophysical Research Letters*, 50, e2022GL102377. <https://doi.org/10.1029/2022GL102377>

Received 9 DEC 2022

Accepted 9 MAR 2023

Author Contributions:

Conceptualization: D. Carroll, D. Menemenlis, S. Dutkiewicz, H. Zhang, V. Le Fouest

Formal analysis: D. Carroll, D. Menemenlis, S. Dutkiewicz, M. Manizza, V. Le Fouest

Funding acquisition: C. E. Miller, M. Babin, A. Mangin, V. Le Fouest

Investigation: V. Le Fouest

Methodology: D. Carroll, D. Menemenlis, S. Dutkiewicz, H. Zhang, V. Le Fouest

Resources: A. Matsuoka, S. Tank

Software: H. Zhang

Supervision: V. Le Fouest

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

© 2023 The Authors.

This is an open access article under the terms of the [Creative Commons Attribution-NonCommercial License](https://creativecommons.org/licenses/by/4.0/), which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.

Validation: D. Carroll, D. Menemenlis, H. Zhang, A. Matsuoka, V. Le Fouest
Writing – review & editing: D. Carroll, D. Menemenlis, S. Dutkiewicz, A. Matsuoka, S. Tank, M. Manizza, C. E. Miller, V. Le Fouest

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”

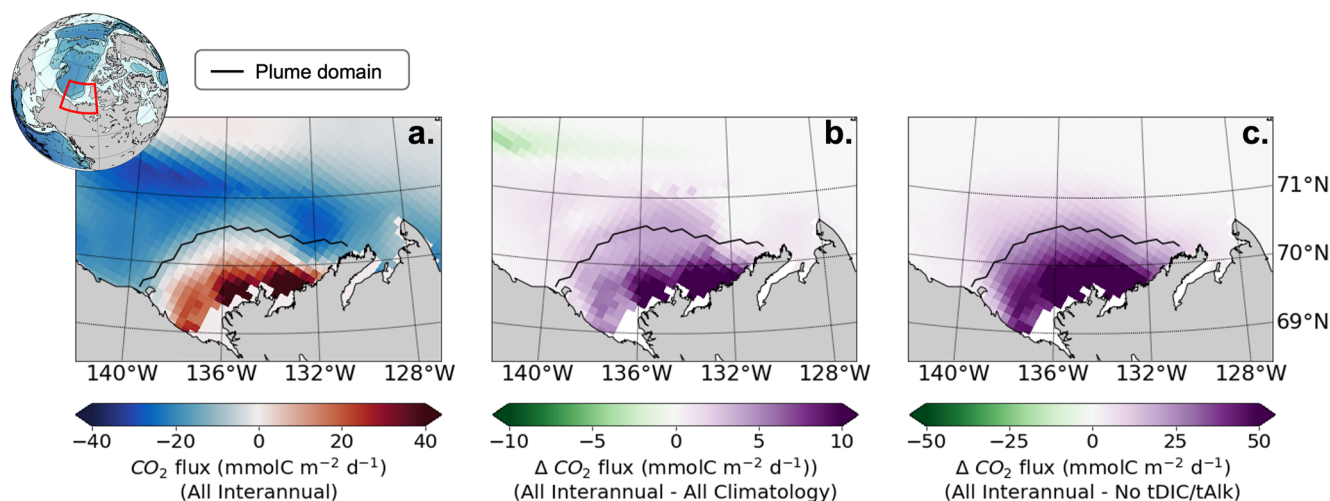


Figure 1. (a) Net air-sea CO_2 flux simulated by the “All Interannual” run during the 23 August 2007 outgassing event and difference with (b) “All Climatology” and (c) “No tDOC” runs. Positive (negative) values indicate CO_2 outgassing (ingassing). Top left inset shows the ED-SBS model region in a global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

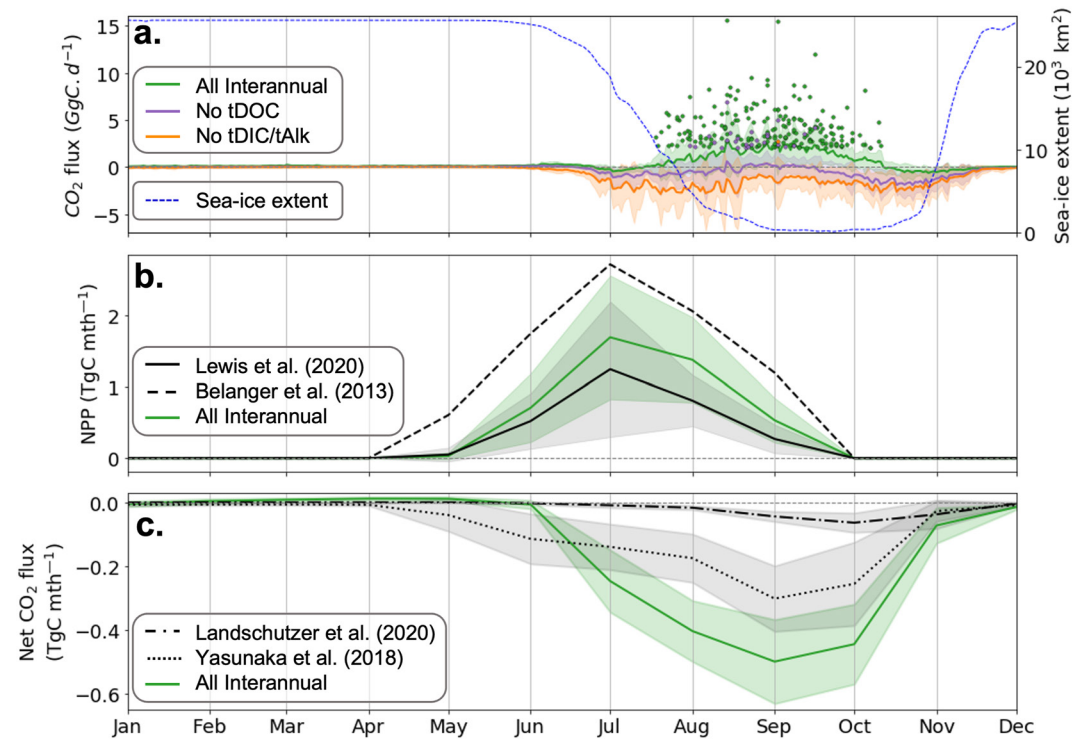


Figure 2. (a) 2000–2019 daily net CO₂ flux (TgC d⁻¹) simulated by the “All Interannual” run (green solid line), “No tDOC” run (purple solid line) and “No terrestrial dissolved inorganic carbon (tDIC)/tAlk” run (orange solid line) in the plume domain (see Figure S1 in Supporting Information S1). Green, 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

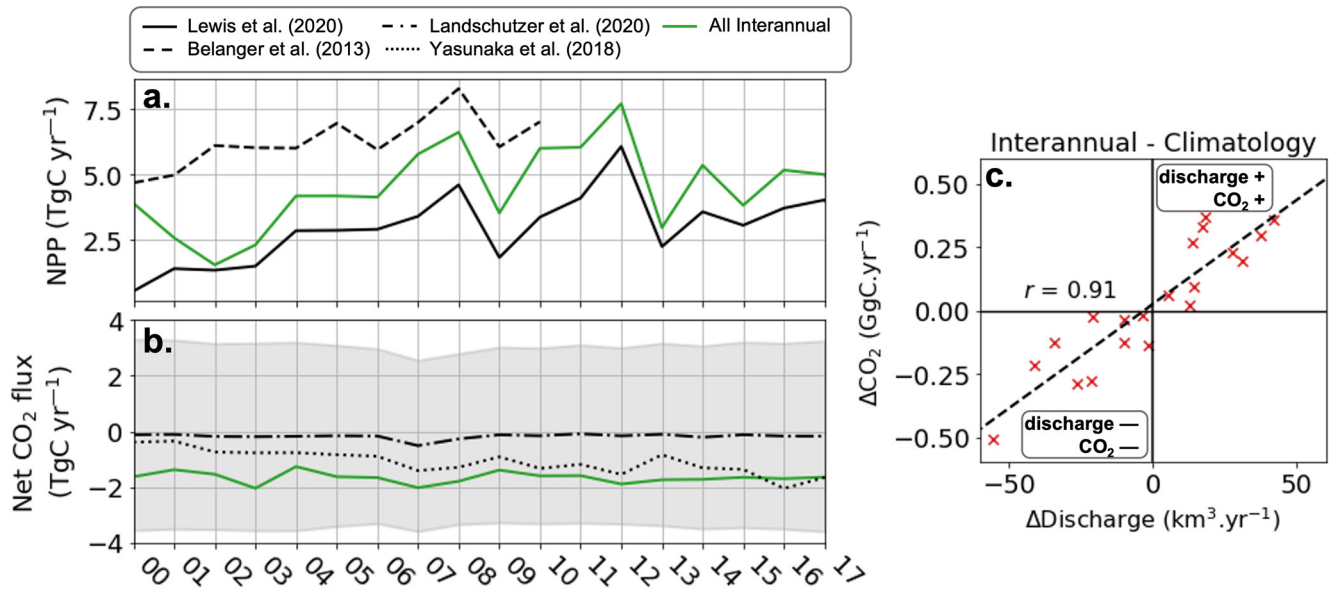


Figure 3. Interannual (a) NPP and (b) net CO₂ flux (TgC yr⁻¹) in the “All Interannual” run (green solid line) and observed by satellite (solid black line, Lewis et al. (2020); dashed black line, Bélanger et al. (2013); dash-dotted black line, (Landschützer et al., 2020) and dotted black line, Yasunaka 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.

References

- Aarnos, H., Gélinais, Y., Kasurinen, V., Gu, Y., Puupponen, V.-M., & Vähätalo, A. V. (2018). Photochemical mineralization of terrigenous DOC to dissolved inorganic carbon in ocean. *Global Biogeochemical Cycles*, 32(2), 250–266. <https://doi.org/10.1002/2017GB005698>
- Ahmed, R., Prowse, T., Dibike, Y., Bonsal, B., & O’Neil, H. (2020). Recent trends in freshwater influx to the Arctic Ocean from four major Arctic-draining rivers. *Water*, 12(4), 1189. <https://doi.org/10.3390/w12041189>
- AMAP (2021). Arctic climate change update 2021: Key trends and impacts. Summary for policy-makers. In *Arctic Monitoring and Assessment Programme (AMAP)*.
- Ardyna, M., & Arrigo, K. R. (2020). Phytoplankton dynamics in a changing Arctic Ocean. *Nature Climate Change*, 10(10), 892–903. <https://doi.org/10.1038/s41558-020-0905-y>
- Arrigo, K. R., Pabi, S., van Dijken, G. L., & Maslowski, W. (2010). Air-sea flux of CO₂ in the Arctic Ocean, 1998–2003. *Journal of Geophysical Research*, 115(G4), G04024. <https://doi.org/10.1029/2009JG001224>
- Bates, N., & Mathis, J. (2009). The Arctic Ocean marine carbon cycle: Evaluation of air-sea CO₂ exchanges, ocean acidification impacts and potential feedbacks. *Biogeosciences*, 6(11), 2433–2459. <https://doi.org/10.5194/bg-6-2433-2009>
- Bélanger, S., Babin, M., & Tremblay, J.-É. (2013). Increasing cloudiness in Arctic dampens the increase in phytoplankton primary production due to sea ice receding. *Biogeosciences*, 10(6), 4087–4101. <https://doi.org/10.5194/bg-10-4087-2013>
- Bélanger, S., Xie, H., Krotkov, N., Larouche, P., Vincent, W. F., & Babin, M. (2006). Photomineralization of terrigenous dissolved organic matter in Arctic coastal waters from 1979 to 2003: Interannual variability and implications of climate change. *Global Biogeochemical Cycles*, 20(4), GB4005. <https://doi.org/10.1029/2006GB002708>
- Bertin, C., Matsuoka, A., Mangin, A., Babin, M., & Le Fouest, V. (2022). Merging satellite and in situ data to assess the flux of terrestrial dissolved organic carbon from the Mackenzie River to the coastal Beaufort Sea. *Frontiers of Earth Science*, 10, 66. <https://doi.org/10.3389/feart.2022.694062>
- Box, J. E., Colgan, W. T., Christensen, T. R., Schmidt, N. M., Lund, M., Parmentier, F.-J. W., et al. (2019). Key indicators of Arctic climate change: 1971–2017. *Environmental Research Letters*, 14(4), 045010. <https://doi.org/10.1088/1748-9326/aafc1b>
- Brown, K. A., Holding, J. M., & Carmack, E. C. (2020). Understanding regional and seasonal variability is key to gaining a pan-Arctic perspective on Arctic Ocean freshening. *Frontiers in Marine Science*, 7, 606. <https://doi.org/10.3389/fmars.2020.00606>
- Bruhn, A. D., Stedmon, C. A., Comte, J., Matsuoka, A., Speetjens, N. J., Tanski, G., et al. (2021). Terrestrial dissolved organic matter mobilized from eroding permafrost controls microbial community composition and growth in Arctic coastal zones. *Frontiers of Earth Science*, 9, 640580. <https://doi.org/10.3389/feart.2021.640580>
- Carmack, E. C., Barber, D., Christensen, J., Macdonald, R. W., Rudels, B., & Sakshaug, E. (2006). Climate variability and physical forcing of the food webs and the carbon budget on panarctic shelves. *Progress in Oceanography*, 71(2–4), 145–181. <https://doi.org/10.1016/j.pocean.2006.10.005>
- Carmack, E. C., & Macdonald, R. W. (2002). Oceanography of the Canadian shelf of the Beaufort Sea: A setting for marine life. *Arctic*, 55(5), 29–45. <https://doi.org/10.14430/arctic733>
- Carmack, E. C., Macdonald, R. W., & Jasper, S. (2004). Phytoplankton productivity on the Canadian shelf of the Beaufort Sea. *Marine Ecology Progress Series*, 277, 37–50. <https://doi.org/10.3354/meps277037>
- Carroll, D., Menemenlis, D., Adkins, J., Bowman, K., Brix, H., Dutkiewicz, S., et al. (2020). The ECCO-Darwin data-assimilative global ocean biogeochemistry model: Estimates of seasonal to multidecadal surface ocean pCO₂ and air-sea CO₂ flux. *Journal of Advances in Modeling Earth Systems*, 12(10), e2019MS001888. <https://doi.org/10.1029/2019MS001888>
- Carroll, D., Menemenlis, D., Dutkiewicz, S., Lauderdale, J. M., Adkins, J. F., Bowman, K. W., et al. (2022). Attribution of space-time variability in global-ocean dissolved inorganic carbon. *Global Biogeochemical Cycles*, 36(3), e2021GB007162. <https://doi.org/10.1029/2021GB007162>
- Chadburn, S. E., Burke, E. J., Cox, P. M., Friedlingstein, P., Hugelius, G., & Westermann, S. (2017). An observation-based constraint on permafrost loss as a function of global warming. *Nature Climate Change*, 7(5), 340–344. <https://doi.org/10.1038/nclimate3262>
- Coltriano, D., Tran, P. Q., Guéguen, C., Williams, W. J., Lovejoy, C., & Walsh, D. A. (2018). Genomic evidence for the degradation of terrestrial organic matter by pelagic Arctic Ocean Chloroflexi bacteria. *Communications biology*, 1(1), 90. <https://doi.org/10.1038/s42003-018-0086-7>

Acknowledgments

CB was supported by a Ph.D. fellowship from the French Ministry of Higher Education, Research and Innovation. This work is part of the Nunataryuk project; the project has received funding under the European Union’s Horizon 2020 Research and Innovation Programme under grant agreement no. 773421. This work was also funded by the Centre National de la Recherche Scientifique (CNRS, LEFE program). Part of this research was supported by Japan Aerospace Exploration Agency (JAXA) Global Change Observation Mission-Climate (GCOM-C) to AM (contract #19RT000542). This work was also supported by the NASA Earth Science Division’s Interdisciplinary Science (IDS) program through an award to the Jet Propulsion Laboratory, California Institute of Technology, under contract with National Aeronautics and Space Administration (80NM0018D0004). Part of this research was supported by the Arctic Great River Observatory (ArcticGRO) to ST (contract NSF 1913888). We are grateful to S. Bélanger and S. Yasunaka for sharing their satellite-derived primary production and air-sea CO₂ flux data. Finally, we also thank the two anonymous reviewer, the editor and the two informal reviewers for their feedback which contributed greatly to improve the manuscript.

- Dai, M., Su, J., Zhao, Y., Hofmann, E. E., Cao, Z., Cai, W.-J., et al. (2022). Carbon fluxes in the Coastal Ocean: Synthesis, boundary processes, and future trends. *Annual Review of Earth and Planetary Sciences*, 50(1), 593–626. <https://doi.org/10.1146/annurev-earth-032320-090746>
- Dittmar, T., & Kattner, G. (2003). The biogeochemistry of the river and shelf ecosystem of the Arctic Ocean: A review. *Marine Chemistry*, 83(3–4), 103–120. [https://doi.org/10.1016/S0304-4203\(03\)00105-1](https://doi.org/10.1016/S0304-4203(03)00105-1)
- Dittmar, T., Lennartz, S. T., Buck-Wiese, H., Hansell, D. A., Santinelli, C., Vanni, C., et al. (2021). Enigmatic persistence of dissolved organic matter in the ocean. *Nature Reviews Earth & Environment*, 2(8), 570–583. <https://doi.org/10.1038/s43017-021-00183-7>
- Drake, T. W., Guillemette, F., Hemingway, J. D., Chanton, J. P., Podgorski, D. C., Zimov, N. S., & Spencer, R. G. (2018). The ephemeral signature of permafrost carbon in an Arctic fluvial network. *Journal of Geophysical Research: Biogeosciences*, 123(5), 1475–1485. <https://doi.org/10.1029/2017JG004311>
- Emmert, C. A., Lesack, L. F. W., & Vincent, W. F. (2008). Mackenzie River nutrient delivery to the Arctic Ocean and effects of the Mackenzie Delta during open water conditions. *Global Biogeochemical Cycles*, 22(1), GB1024. <https://doi.org/10.1029/2006GB002856>
- Evans, W., Mathis, J. T., Cross, J. N., Bates, N. R., Frey, K. E., Else, B. G., et al. (2015). Sea–air CO₂ exchange in the western Arctic coastal ocean. *Global Biogeochemical Cycles*, 29(8), 1190–1209. <https://doi.org/10.1002/2015GB005153>
- Feng, D., Gleason, C. J., Lin, P., Yang, X., Pan, M., & Ishitsuka, Y. (2021). Recent changes to Arctic river discharge. *Nature Communications*, 12(1), 6917. <https://doi.org/10.1038/s41467-021-27228-1>
- Forest, A., Coupel, P., Else, B., Nahavandian, S., Lansard, B., Raimbault, P., et al. (2014). Synoptic evaluation of carbon cycling in the Beaufort Sea during summer: Contrasting river inputs, ecosystem metabolism and air–sea CO₂ fluxes. *Biogeosciences*, 11(10), 2827–2856. <https://doi.org/10.5194/bg-11-2827-2014>
- Galeron, M.-A., Radakovitch, O., Charrière, B., Vaultier, F., Volkman, J. K., Bianchi, T. S., et al. (2018). Lipoxigenase-induced autoxidative degradation of terrestrial particulate organic matter in estuaries: A widespread process enhanced at high and low latitude. *Organic Geochemistry*, 115, 78–92. <https://doi.org/10.1016/j.orggeochem.2017.10.013>
- Gelfan, A., Gustafsson, D., Motovilov, Y., Arheimer, B., Kalugin, A., Krylenko, I., & Lavrenov, A. (2017). Climate change impact on the water regime of two great Arctic rivers: Modeling and uncertainty issues. *Climatic Change*, 141(3), 499–515. <https://doi.org/10.1007/s10584-016-1710-5>
- Good, S., Fiedler, E., Mao, C., Martin, M. J., Maycock, A., Reid, R., et al. (2020). The current configuration of the OSTIA system for operational production of foundation sea surface temperature and ice concentration analyses. *Remote Sensing*, 12(4), 720. <https://doi.org/10.3390/rs12040720>
- Hilborn, A., & Devred, E. (2022). Delineation of Eastern Beaufort Sea sub-regions using self-organizing maps applied to 17 years of MODIS-Aqua data. *Frontiers in Marine Science*, 1061. <https://doi.org/10.3389/fmars.2022.912865>
- Hill, V. J. (2008). Impacts of chromophoric dissolved organic material on surface ocean heating in the Chukchi Sea. *Journal of Geophysical Research*, 113(C7), C07024. <https://doi.org/10.1029/2007JC004119>
- Holmes, R. M., McClelland, J. W., Peterson, B. J., Tank, S. E., Bulygina, E., Eglinton, T. I., et al. (2012). Seasonal and annual fluxes of nutrients and organic matter from large rivers to the Arctic Ocean and surrounding seas. *Estuaries and Coasts*, 35(2), 369–382. <https://doi.org/10.1007/s12237-011-9386-6>
- Hoppe, C. J. M. (2022). Always ready? Primary production of Arctic phytoplankton at the end of the polar night. *Limnology and Oceanography Letters*, 7(2), 167–174. <https://doi.org/10.1002/lol2.10222>
- Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J. W., Schuur, E., Ping, C.-L., et al. (2014). Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. *Biogeosciences*, 11(23), 6573–6593. <https://doi.org/10.5194/bg-11-6573-2014>
- Irrgang, A. M., Bendixen, M., Farquharson, L. M., Baranskaya, A. V., Erikson, L. H., Gibbs, A. E., et al. (2022). Drivers, dynamics and impacts of changing Arctic coasts. *Nature Reviews Earth & Environment*, 3(1), 39–54. <https://doi.org/10.1038/s43017-021-00232-1>
- Jong, D., Bröder, L., Tanski, G., Fritz, M., Lantuit, H., Tesi, T., et al. (2020). Nearshore zone dynamics determine pathway of organic carbon from eroding permafrost coasts. *Geophysical Research Letters*, 47(15), e2020GL088561. <https://doi.org/10.1029/2020GL088561>
- Juhs, B., Stedmon, C. A., Morgenstern, A., Meyer, H., Hölemann, J., Heim, B., et al. (2020). Identifying drivers of seasonality in Lena River biogeochemistry and dissolved organic matter fluxes. *Frontiers in Environmental Science*, 8, 53. <https://doi.org/10.3389/fenvs.2020.00053>
- Kipp, L. E., Henderson, P. B., Wang, Z. A., & Charette, M. A. (2020). Deltaic and estuarine controls on Mackenzie River solute fluxes to the Arctic Ocean. *Estuaries and Coasts*, 43(8), 1992–2014. <https://doi.org/10.1007/s12237-020-00739-8>
- Kirchman, D. L., Morán, X. A. G., & Ducklow, H. (2009). Microbial growth in the polar oceans—Role of temperature and potential impact of climate change. *Nature Reviews Microbiology*, 7(6), 451–459. <https://doi.org/10.1038/nrmicro2115>
- Lacroix, F., Ilyina, T., & Hartmann, J. (2020). Oceanic CO₂ outgassing and biological production hotspots induced by pre-industrial river loads of nutrients and carbon in a global modeling approach. *Biogeosciences*, 17(1), 55–88. <https://doi.org/10.5194/bg-2019-152>
- Lacroix, F., Ilyina, T., Laruelle, G. G., & Regnier, P. (2021). Reconstructing the preindustrial coastal carbon cycle through a global ocean circulation model: Was the global continental shelf already both autotrophic and a CO₂ sink? *Global Biogeochemical Cycles*, 35(2), e2020GB006603. <https://doi.org/10.1029/2020GB006603>
- Lacroix, F., Zaehle, S., Caldararu, S., Schaller, J., Stimmler, P., Holl, D., et al. (2022). Mismatch of N release from the permafrost and vegetative uptake opens pathways of increasing nitrous oxide emissions in the high Arctic. *Global Change Biology*, 28(20), 5973–5990. <https://doi.org/10.1111/gcb.16345>
- Landschützer, P., Laruelle, G. G., Roobaert, A., & Regnier, P. (2020). A uniform pCO₂ climatology combining open and coastal oceans. *Earth System Science Data*, 12(4), 2537–2553. <https://doi.org/10.5194/essd-12-2537-2020>
- Langer, M., Nitzbon, J., Groenke, B., Assmann, L.-M., Schneider von Deimling, T., Stuenzi, S. M., & Westermann, S. (2022). The evolution of Arctic permafrost over the last three centuries. *EGU Sphere*. <https://doi.org/10.5194/egusphere-2022-473>
- Le Fouest, V., Babin, M., & Tremblay, J.-É. (2013). The fate of riverine nutrients on Arctic shelves. *Biogeosciences*, 10(6), 3661–3677. <https://doi.org/10.5194/bg-10-3661-2013>
- Lewis, K., Van Dijken, G., & Arrigo, K. R. (2020). Changes in phytoplankton concentration now drive increased Arctic Ocean primary production. *Science*, 369(6500), 198–202. <https://doi.org/10.1126/science.aay8380>
- Li, M., Peng, C., Wang, M., Xue, W., Zhang, K., Wang, K., et al. (2017). The carbon flux of global rivers: A re-evaluation of amount and spatial patterns. *Ecological Indicators*, 80, 40–51. <https://doi.org/10.1016/j.ecolind.2017.04.049>
- Lin, P., Pickart, R. S., Fissel, D., Ross, E., Kasper, J., Bahr, F., et al. (2020). Circulation in the vicinity of Mackenzie Canyon from a year-long mooring array. *Progress in Oceanography*, 187, 102396. <https://doi.org/10.1016/j.pocean.2020.102396>
- Louchard, D., Gruber, N., & Münnich, M. (2021). The impact of the Amazon on the biological pump and the air–sea CO₂ balance of the Western Tropical Atlantic. *Global Biogeochemical Cycles*, 35(6), e2020GB006818. <https://doi.org/10.1029/2020GB006818>
- Macdonald, R. W., Carmack, E. C., McLaughlin, F., Iseki, K., Macdonald, D., & O'Brien, M. (1989). Composition and modification of water masses in the Mackenzie shelf Estuary. *Journal of Geophysical Research*, 94(C12), 18057–18070. <https://doi.org/10.1029/JC094iC12p18057>

- Manizza, M., Follows, M., Dutkiewicz, S., McClelland, J., Menemenlis, D., Hill, C., et al. (2009). Modeling transport and fate of riverine dissolved organic carbon in the Arctic Ocean. *Global Biogeochemical Cycles*, 23(4), GB4006. <https://doi.org/10.1029/2008GB003396>
- Manizza, M., Follows, M., Dutkiewicz, S., Menemenlis, D., Hill, C., & Key, R. (2013). Changes in the Arctic Ocean CO₂ sink (1996–2007): A regional model analysis. *Global Biogeochemical Cycles*, 27(4), 1108–1118. <https://doi.org/10.1002/2012GB004491>
- Manizza, M., Follows, M. J., Dutkiewicz, S., Menemenlis, D., McClelland, J. W., Hill, C., et al. (2011). A model of the Arctic Ocean carbon cycle. *Journal of Geophysical Research*, 116(C12), C12020. <https://doi.org/10.1029/2011JC006998>
- Manizza, M., Menemenlis, D., Zhang, H., & Miller, C. E. (2019). Modeling the recent changes in the Arctic Ocean CO₂ sink (2006–2013). *Global Biogeochemical Cycles*, 33(3), 420–438. <https://doi.org/10.1029/2018GB006070>
- Mann, P. J., Strauss, J., Palmtag, J., Dowdy, K., Ogneva, O., Fuchs, M., et al. (2022). Degrading permafrost river catchments and their impact on Arctic Ocean nearshore processes. *Ambio*, 51(2), 439–455. <https://doi.org/10.1007/s13280-021-01666-z>
- Massicotte, P., Amon, R. M., Antoine, D., Archambault, P., Balzano, S., Bélanger, S., et al. (2021). The MALINA oceanographic expedition: How do changes in ice cover, permafrost and UV radiation impact biodiversity and biogeochemical fluxes in the Arctic Ocean? *Earth System Science Data*, 13(4), 1561–1592. <https://doi.org/10.5194/essd-2020-252>
- Mathis, M., Logemann, K., Maerz, J., Lacroix, F., Hagemann, S., Chegini, F., et al. (2022). Seamless integration of the coastal ocean in global marine carbon cycle modeling. *Journal of Advances in Modeling Earth Systems*, 14(8), e2021MS002789. <https://doi.org/10.1029/2021ms002789>
- Matsuoka, A., Babin, M., & Vonk, J. E. (2022). Decadal trends in the release of terrigenous organic carbon to the Mackenzie delta (Canadian arctic) using satellite ocean color data (1998–2019). *Remote Sensing of Environment*, 283, 113322. <https://doi.org/10.1016/j.rse.2022.113322>
- Matsuoka, A., Boss, E., Babin, M., Karp-Boss, L., Hafez, M., Chekalyuk, A., et al. (2017). Pan-Arctic optical characteristics of colored dissolved organic matter: Tracing dissolved organic carbon in changing Arctic waters using satellite ocean color data. *Remote Sensing of Environment*, 200, 89–101. <https://doi.org/10.1016/j.rse.2017.08.009>
- Mayorga, E., Seitzinger, S. P., Harrison, J. A., Dumont, E., Beusen, A. H., Bouwman, A., et al. (2010). Global nutrient export from Watersheds 2 (NEWS 2): Model development and implementation. *Environmental Modelling & Software*, 25(3), 837–853. <https://doi.org/10.1016/j.envsoft.2010.01.007>
- McClelland, J., Holmes, R., Dunton, K., & Macdonald, R. (2012). The Arctic Ocean estuary. *Estuaries and Coasts*, 35(2), 353–368. <https://doi.org/10.1007/s12237-010-9357-3>
- McClelland, J., Holmes, R., Peterson, B., Raymond, P., Striegl, R., Zhulidov, A., et al. (2016). Particulate organic carbon and nitrogen export from major Arctic rivers. *Global Biogeochemical Cycles*, 30(5), 629–643. <https://doi.org/10.1002/2015GB005351>
- McGuire, A. D., Koven, C., Lawrence, D. M., Klein, J. S., Xia, J., Beer, C., et al. (2016). Variability in the sensitivity among model simulations of permafrost and carbon dynamics in the permafrost region between 1960 and 2009. *Global Biogeochemical Cycles*, 30(7), 1015–1037. <https://doi.org/10.1002/2016GB005405>
- Menemenlis, D., Fukumori, I., & Lee, T. (2005). Using Green's functions to calibrate an ocean general circulation model. *Monthly Weather Review*, 133(5), 1224–1240. <https://doi.org/10.1175/MWR2912.1>
- Mol, J., Thomas, H., Myers, P. G., Hu, X., & Mucci, A. (2018). Inorganic carbon fluxes on the Mackenzie shelf of the Beaufort Sea. *Biogeosciences*, 15(4), 1011–1027. <https://doi.org/10.5194/bg-15-1011-2018>
- Mulligan, R. P., & Perrie, W. (2019). Circulation and structure of the Mackenzie River plume in the coastal Arctic Ocean. *Continental Shelf Research*, 177, 59–68. <https://doi.org/10.1016/j.csr.2019.03.006>
- Nguyen, A. T., Pillar, H., Ocaña, V., Bigdeli, A., Smith, T. A., & Heimbach, P. (2021). The Arctic Subpolar Gyre State Estimate: Description and Assessment of a data-constrained, dynamically consistent ocean-sea ice estimate for 2002–2017. *Journal of Advances in Modeling Earth Systems*, 13(5), e2020MS002398. <https://doi.org/10.1029/2020MS002398>
- Nielsen, D. M., Pieper, P., Barkhordarian, A., Overduin, P., Ilyina, T., Brovkin, V., et al. (2022). Increase in Arctic coastal erosion and its sensitivity to warming in the twenty-first century. *Nature Climate Change*, 12(3), 263–270. <https://doi.org/10.1038/s41558-022-01281-0>
- Odériz, I., Mori, N., Shimura, T., Webb, A., Silva, R., & Mortlock, T. (2022). Transitional wave climate regions on continental and polar coasts in a warming world. *Nature Climate Change*, 12(7), 662–671. <https://doi.org/10.1038/s41558-022-01389-3>
- Ortega-Retuerta, E., Jeffrey, W., Babin, M., Bélanger, S., Benner, R., Marie, D., et al. (2012). Carbon fluxes in the Canadian Arctic: Patterns and drivers of bacterial abundance, production and respiration on the Beaufort Sea margin. *Biogeosciences*, 9(9), 3679–3692. <https://doi.org/10.5194/bg-9-3679-2012>
- Ouyang, Z., Li, Y., Qi, D., Zhong, W., Murata, A., Nishino, S., et al. (2021). The changing CO₂ sink in the western Arctic Ocean from 1994 to 2019. *Global Biogeochemical Cycles*, 36(1), e2021GB007032. <https://doi.org/10.1029/2021GB007032>
- Overeem, I., Nienhuis, J. H., & Piliouras, A. (2022). Ice-dominated Arctic deltas. *Nature Reviews Earth & Environment*, 3(4), 225–240. <https://doi.org/10.1038/s43017-022-00268-x>
- Pefanis, V., Losa, S. N., Losch, M., Janout, M. A., & Bracher, A. (2020). Amplified Arctic surface warming and sea ice loss due to phytoplankton and colored dissolved material. *Geophysical Research Letters*, 47(21), e2020GL088795. <https://doi.org/10.1029/2020GL088795>
- Randelhoff, A., Lacour, L., Marec, C., Leymarie, E., Lagunas, J., Xing, X., et al. (2020). Arctic mid-winter phytoplankton growth revealed by autonomous profilers. *Science Advances*, 6(39), eabc2678. <https://doi.org/10.1126/sciadv.abc2678>
- Rawlins, M. A., Connolly, C. T., & McClelland, J. W. (2021). Modeling terrestrial dissolved organic carbon loading to western Arctic rivers. *Journal of Geophysical Research: Biogeosciences*, 126(10), e2021JG006420. <https://doi.org/10.1029/2021JG006420>
- Roobaert, A., Laruelle, G. G., Landschützer, P., Gruber, N., Chou, L., & Regnier, P. (2019). The spatiotemporal dynamics of the sources and sinks of CO₂ in the global coastal ocean. *Global Biogeochemical Cycles*, 33(12), 1693–1714. <https://doi.org/10.1029/2019GB006239>
- Saito, K., Walsh, J. E., Bring, A., Brown, R., Shiklomanov, A., & Yang, D. (2021). Future trajectory of Arctic system evolution. In *Arctic hydrology, permafrost and ecosystems* (pp. 893–914). Springer. https://doi.org/10.1007/978-3-030-50930-9_30
- Schuur, E. A., McGuire, A. D., Schädel, C., Grosse, G., Harden, J. W., Hayes, D. J., et al. (2015). Climate change and the permafrost carbon feedback. *Nature*, 520(7546), 171–179. <https://doi.org/10.1038/nature14338>
- Schwab, M. S., Hilton, R. G., Raymond, P. A., Haghypour, N., Amos, E., Tank, S. E., et al. (2020). An abrupt aging of dissolved organic carbon in large Arctic rivers. *Geophysical Research Letters*, 47(23), e2020GL088823. <https://doi.org/10.1029/2020GL088823>
- Serreze, M. C., Barrett, A. P., Slater, A. G., Woodgate, R. A., Aagaard, K., Lammers, R. B., et al. (2006). The large-scale freshwater cycle of the Arctic. *Journal of Geophysical Research*, 111(C11), C11010. <https://doi.org/10.1029/2005JC003424>
- Shiklomanov, A., Holmes, R., McClelland, J., Tank, S., & Spencer, R. (2021). ArcticGRO discharge dataset (technical report). Version 2021-05-27. Retrieved from <https://arcticgreatrivers.org/data/>
- Slater, A. G., & Lawrence, D. M. (2013). Diagnosing present and future permafrost from climate models. *Journal of Climate*, 26(15), 5608–5623. <https://doi.org/10.1175/JCLI-D-12-00341.1>
- Soppa, M. A., Pefanis, V., Hellmann, S., Losa, S. N., Hölemann, J., Martynov, F., et al. (2019). Assessing the influence of water constituents on the radiative heating of Laptev Sea shelf waters. *Frontiers in Marine Science*, 6, 221. <https://doi.org/10.3389/fmars.2019.00221>

- Spencer, R. G., Mann, P. J., Dittmar, T., Eglinton, T. I., McIntyre, C., Holmes, R. M., et al. (2015). Detecting the signature of permafrost thaw in Arctic rivers. *Geophysical Research Letters*, *42*(8), 2830–2835. <https://doi.org/10.1002/2015GL063498>
- Tank, S. E., Raymond, P. A., Striegl, R. G., McClelland, J. W., Holmes, R. M., Fiske, G. J., & Peterson, B. J. (2012). A land-to-ocean perspective on the magnitude, source and implication of DIC flux from major Arctic rivers to the Arctic Ocean. *Global Biogeochemical Cycles*, *26*(4), GB4018. <https://doi.org/10.1029/2011GB004192>
- Tank, S. E., Striegl, R. G., McClelland, J. W., & Kokelj, S. V. (2016). Multi-decadal increases in dissolved organic carbon and alkalinity flux from the Mackenzie drainage basin to the Arctic Ocean. *Environmental Research Letters*, *11*(5), 054015. <https://doi.org/10.1088/1748-9326/11/5/054015>
- Terhaar, J., Lauerwald, R., Regnier, P., Gruber, N., & Bopp, L. (2021). Around one third of current Arctic Ocean primary production sustained by rivers and coastal erosion. *Nature Communications*, *12*(1), 169. <https://doi.org/10.1038/s41467-020-20470-z>
- Terhaar, J., Orr, J., Ethé, C., Regnier, P., & Bopp, L. (2019). Simulated Arctic Ocean response to doubling of riverine carbon and nutrient delivery. *Global Biogeochemical Cycles*, *33*(8), 1048–1070. <https://doi.org/10.1029/2019GB006200>
- Tokuda, D., Kim, H., Yamazaki, D., & Oki, T. (2019). Development of a global river water temperature model considering fluvial dynamics and seasonal freeze-thaw cycle. *Water Resources Research*, *55*(2), 1366–1383. <https://doi.org/10.1029/2018WR023083>
- Wunsch, C., Heimbach, P., Ponte, R. M., Fukumori, I., & MEMBERS, E.-G. C. (2009). The global general circulation of the ocean estimated by the ECCO-consortium. *Oceanography*, *22*(2), 88–103. <https://doi.org/10.5670/oceanog.2009.41>
- Yasunaka, S., Siswanto, E., Olsen, A., Hoppema, M., Watanabe, E., Fransson, A., et al. (2018). Arctic Ocean CO₂ uptake: An improved multi-year estimate of the air–sea CO₂ flux incorporating chlorophyll a concentrations. *Biogeosciences*, *15*(6), 1643–1661. <https://doi.org/10.5194/bg-15-1643-2018>

References From the Supporting Information

- Dutkiewicz, S., Follows, M. J., & Bragg, J. G. (2009). Modeling the coupling of ocean ecology and biogeochemistry. *Global Biogeochemical Cycles*, *23*(4), GB4017. <https://doi.org/10.1029/2008GB003405>
- Dutkiewicz, S., Hickman, A., Jahn, O., Gregg, W., Mouw, C., & Follows, M. (2015). Capturing optically important constituents and properties in a marine biogeochemical and ecosystem model. *Biogeosciences*, *12*(14), 4447–4481. <https://doi.org/10.5194/bg-12-4447-2015>
- Follows, M. J., & Dutkiewicz, S. (2011). Modeling diverse communities of marine microbes. *Annual Review of Marine Science*, *3*(1), 427–451. <https://doi.org/10.1146/annurev-marine-120709-142848>
- Follows, M. J., Ito, T., & Dutkiewicz, S. (2006). On the solution of the carbonate chemistry system in ocean biogeochemistry models. *Ocean Modelling*, *12*(3–4), 290–301. <https://doi.org/10.1016/j.ocemod.2005.05.004>
- Holmes, R. M., McClelland, J., Tank, S., Spencer, R., & Shiklomanov, A. (2021). ArcticGRO water quality dataset (technical report). Version 2021-05-27. Retrieved from <https://arcticgreatrivers.org/data/>
- Holmes, R. M., McClelland, J. W., Raymond, P. A., Frazer, B. B., Peterson, B. J., & Stieglitz, M. (2008). Lability of DOC transported by Alaskan rivers to the Arctic Ocean. *Geophysical Research Letters*, *35*(3), L03402. <https://doi.org/10.1029/2007GL032837>
- Lizotte, M., Juhls, B., Matsuoka, A., Massicotte, P., Mével, G., Anikina, D. O. J., et al. (2022). Nunataryuk field campaigns: Understanding the origin and fate of terrestrial organic matter in the coastal waters of the Mackenzie Delta region. In *Earth system science data discussions* (pp. 1–46). <https://doi.org/10.5194/essd-2022-163>
- Lønborg, C., Carreira, C., Jickells, T., & Álvarez-Salgado, X. A. (2020). Impacts of global change on ocean dissolved organic carbon (DOC) cycling. *Frontiers in Marine Science*, *7*, 466. <https://doi.org/10.3389/fmars.2020.00466>
- Marshall, J., Adcroft, A., Hill, C., Perelman, L., & Heisey, C. (1997). A finite-volume, incompressible Navier Stokes model for studies of the ocean on parallel computers. *Journal of Geophysical Research*, *102*(C3), 5753–5766. <https://doi.org/10.1029/96JC02775>
- Runkel, R. L., Crawford, C. G., & Cohn, T. A. (2004). *Load estimator (LOADEST): A FORTRAN program for estimating constituent loads in streams and rivers (technical report)*. U.S. Geological Survey (USGS).
- Zhang, H., Menemenlis, D., & Fenty, I. (2018). *ECCO LLC270 ocean-ice state estimate (technical report)*. Jet Propulsion Laboratory, California Institute of Technology.