Variations of suspended particulate matter concentrations of the Mackenzie River plume (Beaufort Sea, Arctic Ocean) over the last two decades

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Abstract:	This work addresses the last 20 years' evolution of the suspended particulate matter (SPM) concentrations in the Beaufort Sea (Canadian Arctic Ocean) directly influenced by the Mackenzie River discharge. The SPM variations in the coastal zone are highlighted and related to the freshwater and solid discharges of the river measured in situ at the Arctic Red River station (150 km upstream of the river delta). The correlation between the variations of the river discharge and SPM concentration within the surface layer of the coastal waters is obvious. Rather unexpectedly, both have been slightly but significantly decreasing from 2003 to 2018-2019 and started to increase very recently (2019-2022). This change of regime could be explained by changing patterns of precipitation (especially in winter), groundwater distribution and wind_induced mixing in the coastal area.
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We would like to thank the reviewer for his/her work, valuable comments and suggestions. Below we answer to each of them separately.

Reviewers' comments:

"The work is another study concerning the inflow of various substances (SPM, organic carbon) into the Arctic Ocean from the Mackenzie River. Due to distinct trends in air temperature in these regions and the overall ecosystem sensitivity, this topic is of significant importance. The study encompasses recent years (up to 2022), which is crucial. The paper includes all necessary elements and is clearly written. The figures are appropriate, but authors are recommended to include:

boxplots for SPM and annual discharge sums."

The annual discharge sums were indeed not indicated in text (no number were provided explicitly), but we used them for the Pearson correlation matrix (Fig. 1 in Appendix). We added the annual discharge sums to the **legend box** of Fig.1 for each year (see below).

As for the boxplots for the SPM, we would appreciate to implement it, but unfortunately, could not understand what figure was referred. In case of Fig.1d, there are too few datapoints to add the boxplots, and in case of Fig. 2(b, d, f), there is too many datapoints, as they are daily means (Fig;2.d, f).

"My general comments are listed below.

The conducted reevaluation and use of new regression analysis methods provide a fresh perspective on the phenomena. However, the change in trend based on 3 years raises evident doubts and it might be worth discussing its significance further (especially considering that the only other study pertains to medical data)."

Thank you for this comment.

We have to add that although we do not cite other works using a segmented regression analysis, the method suggested by Muggeo, 2003 was also applied to various geophysical datasets (there are about 1900 citations of this work mentioned at https://scholar.google.com/scholar?cites=16460629970310398020&as_sdt=2005&sciodt=0,5&hl=fr), e.g.:

Zhang, S., Gan, T. Y., Bush, A. B., Liu, J., Zolina, O., & Gelfan, A. (2023). Changes of the streamflow of northern river basins of Siberia and their teleconnections to climate patterns. International Journal of Climatology.

Lee, E., Epstein, J. M., & Cohen, M. J. (2023). Patterns of Wetland Hydrologic Connectivity Across Coastal-Plain Wetlandscapes. Water Resources Research, e2023WR034553.

Börgel, F., Neumann, T., Rooze, J., Radtke, H., Barghorn, L., & Meier, H. E. (2023). Deoxygenation of the Baltic Sea during the last millennium. Frontiers in Marine Science.

Indeed, the positive trends for the last three years are not statistically significant, and the monitoring should be continued. We discussed the significance of trends in section 3, and mentioned that the positive trends for the river discharge are not significant in paragraph #6:

> "The positive trend from 2019 to the present, $slope2_Q = 640.05x + const$, **although not statistically significant**, can indicate a progressive increase in the minimum flow impacted by a "mobilization of ground waters" as discussed by Yang et al. 2015."

And in paragraph #7 of section 3 we say that the SPM (in situ and satellite) positive trends are questionable:

> "The breakpoint of SPM_{isitu} trends is slightly shifted to 2018, and CIs contain zero, thus indicating that the *segmented* model is **less reliable** for this dataset. <…>
>
> The positive trends $slope2_{sat}$ and $slope2_{sat200}$ **are not statistically significant**, and their SEs are of the order of the estimated coefficient of linear regression (Tab.1). Nevertheless, this result is interesting for further discussion"

We added in the last paragraph of the conclusion an additional indication about statistical significance of the positive trend.

I also have reservations about the presentation of the hypothetical mechanism explaining the observed negative trend in river discharge and SPM concentration, which suddenly switches to a rapid positive trend. Since this is an original aspect of the study, the discussion should be supported by literature describing the mentioned mechanisms.

Thank you for this comment. We discussed the results with our colleagues hydrologists, and indeed changed the optics for the possible explanation of observed trends. Please, see the last three paragraphs of the results and discussion section, together with the updated Conclusions section.

The authors should include a discussion on the dynamics of the coastal zone. For instance, storms could influence the determined concentrations in the coastal area. Perhaps some seasons were more dynamic, while others were less so?

Thank you for this suggestion, we added to the analysis the wind data from ERA5 (marine area similar to that chosen for the MODIS study box).

The hypothesis that the wind stress will induce the vertical mixing and affect the SPM concentration in water is clear and reasonable. Nevertheless, there is one fundamental limitation for this analysis due to the nature of ocean color data retrieval from satellite: the highest wind speed (and thus mixing events) will mostly occur under the cloud cover with the passage of cyclones, and SPM concentrations cannot be retrieved from ocean color satellite under such conditions (presence of clouds).

To include the effect of storms to the Pearson correlation matrix (where the yearly parameters are compared), we included the *number of days of storms per year* as a new parameter (ndays_storm in Fig. 1Appendix). The day was considered stormy if over the study area there was a wind vector with a wind speed over 15 m/s. The negative correlation between days of storm and cumulative annual SPM is weak (-0.19), any conclusion can hardly be done based on this result.

Then we took the *wind speed* (the absolute value of wind vector) for each moment of time, when SPM retrieved from MODIS satellite data was available, and *averaged for the whole study area* both *Uwind_mean* and *SPM_MODIS_mean (Fig. R2).* The linear fit between the spatially averaged SPM and wind speed was low as well: *y = 0.24x + 10.71 (where x is wind speed and y is SPM concentration).*

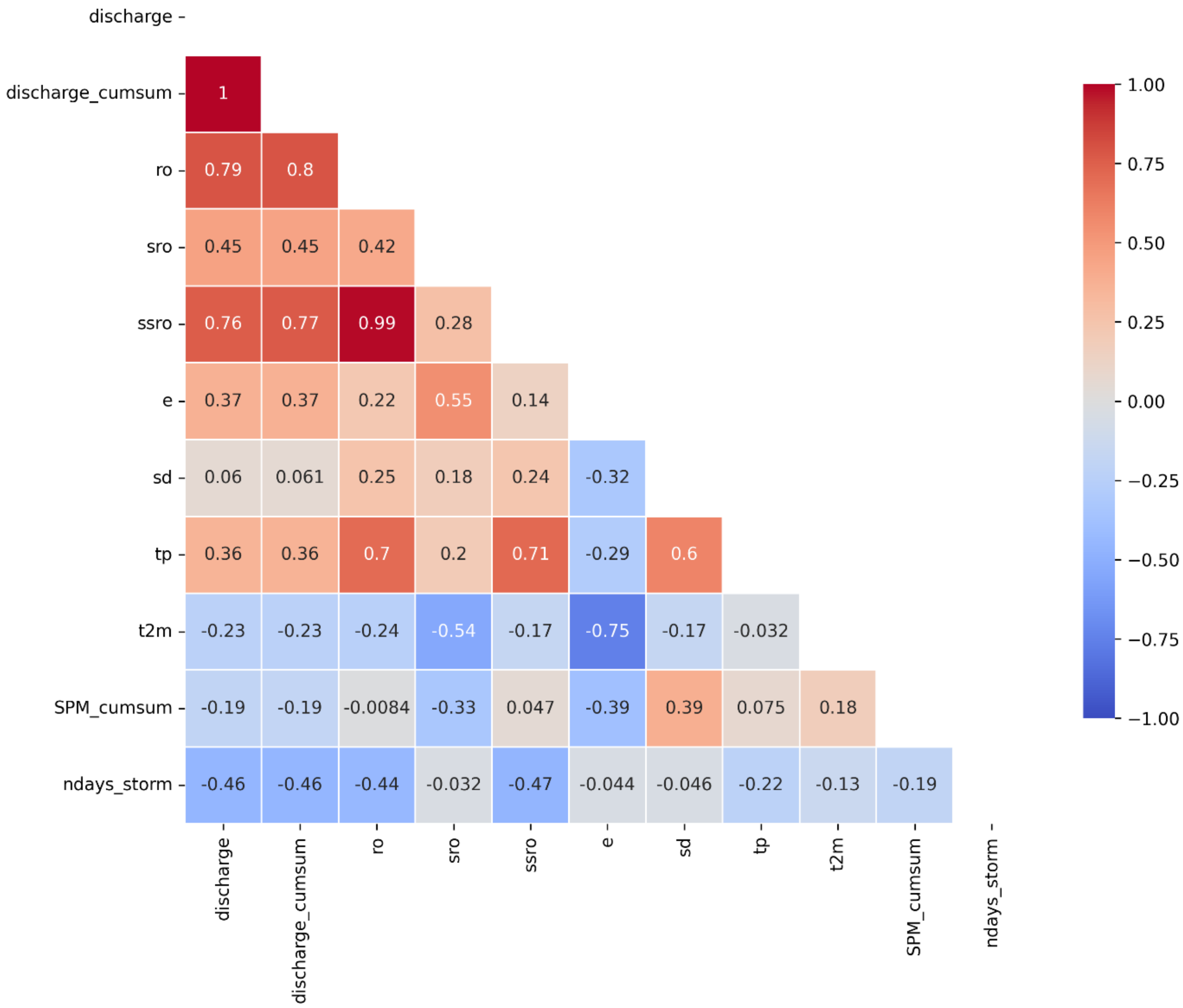


Fig.R1 Pearson correlation matrix with a new parameter referring to wind (ndays_storm).

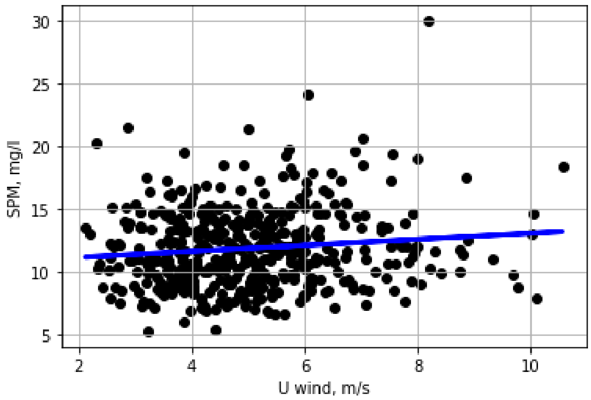
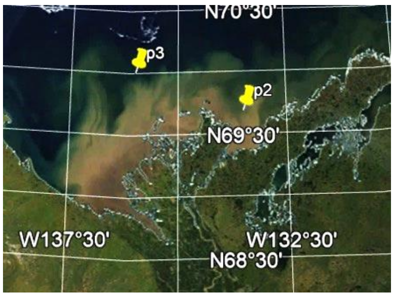


Fig.R2 Wind speed and SPM MODIS averaged over the study area for each moment of time. The blue line shows the fit

Then we tried to apply the segmented correlation method to the wind data over two sample points close to the regular river plume frontal position: *69.7°N, -133.5°W and 70°N, 136W.*



The mean wind speed force varies from 8.5 to 10.5 m/s overall, and there is no distinguishable particular pattern (Fig. R3, red line shows the linear fit).

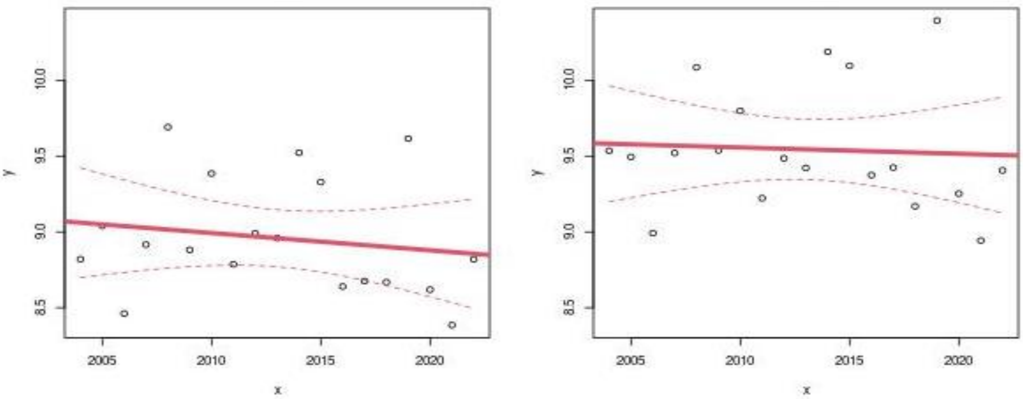


Fig. R3. Regression analysis applied to the wind force in 2 study points (left: 69.7°N, -133.5°W, right: 70°N, 136W). The x axis is time, y axis is wind force in m/s

The only parameter that changes slightly over the 2004-2022 period is the wind direction (Fig. R4): According to linear fits, in both points, from 2004 to ~2020 the wind direction turned from SWW to SSW (from -100° to -130° from north).

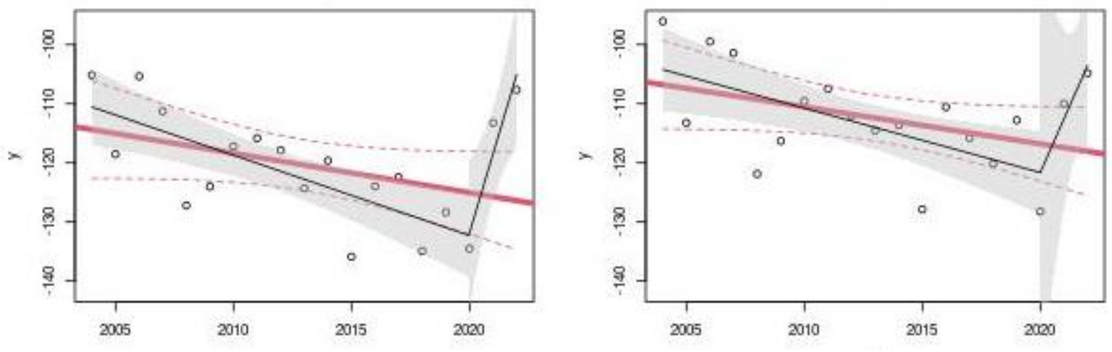
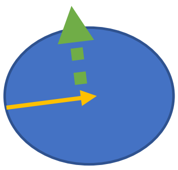


Fig. R4. Regression analysis applied to the wind direction in 2 study points (left: 69.7°N, -133.5°W, right: 70°N, 136W). The x axis is time, y axis is wind direction in degrees from North. Red line is a linear regression result, black line is segmented regression method

-110°

(2004)



-130°

(2020)

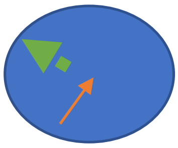


Fig. R5. Illustration of possible effect of wind direction change (yellow and orange arrows), and the Ekman effect (green arrow).

This change in direction suggests rather complex consequences because of the coastal system of currents.

While the SWW wind direction (Fig.R5, left) is changing to SSW (Fig.R5; right), the Ekman effect might:

(a) bring the river plume into a small coastal vortex in the Mackenzie bay. In this case the SPM has more chances to recirculate within the delta area (higher SPM concentration?), but also be sedimented on the floor (lower SPM concentration)
(b) bring the SPM further offshore into the westward or eastward system of currents. In both cases, the SPM concentration reduces.

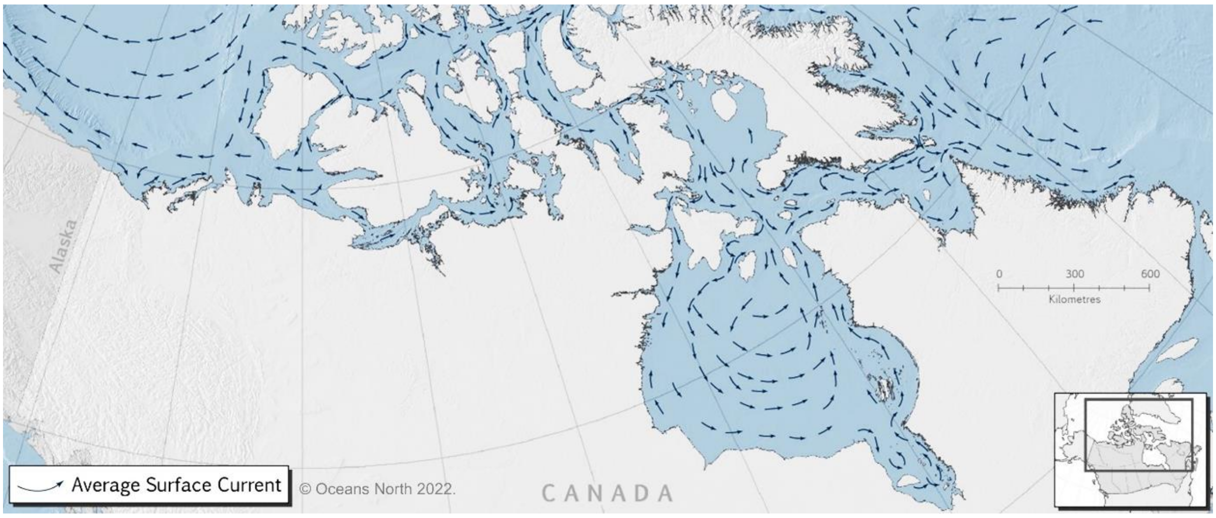


Fig. R6. Surface currents in Canadian Arctic basin (from https://www.oceansnorth.org/wp-content/uploads/2018/07/en-02-canadas-arctic-marine-atlas-chapter-two-physical-oceanography.pdf)

After this analysis, we conclude that understanding the impact of wind on the SPM concentration is beyond the focus of this study and should be investigated additionally.

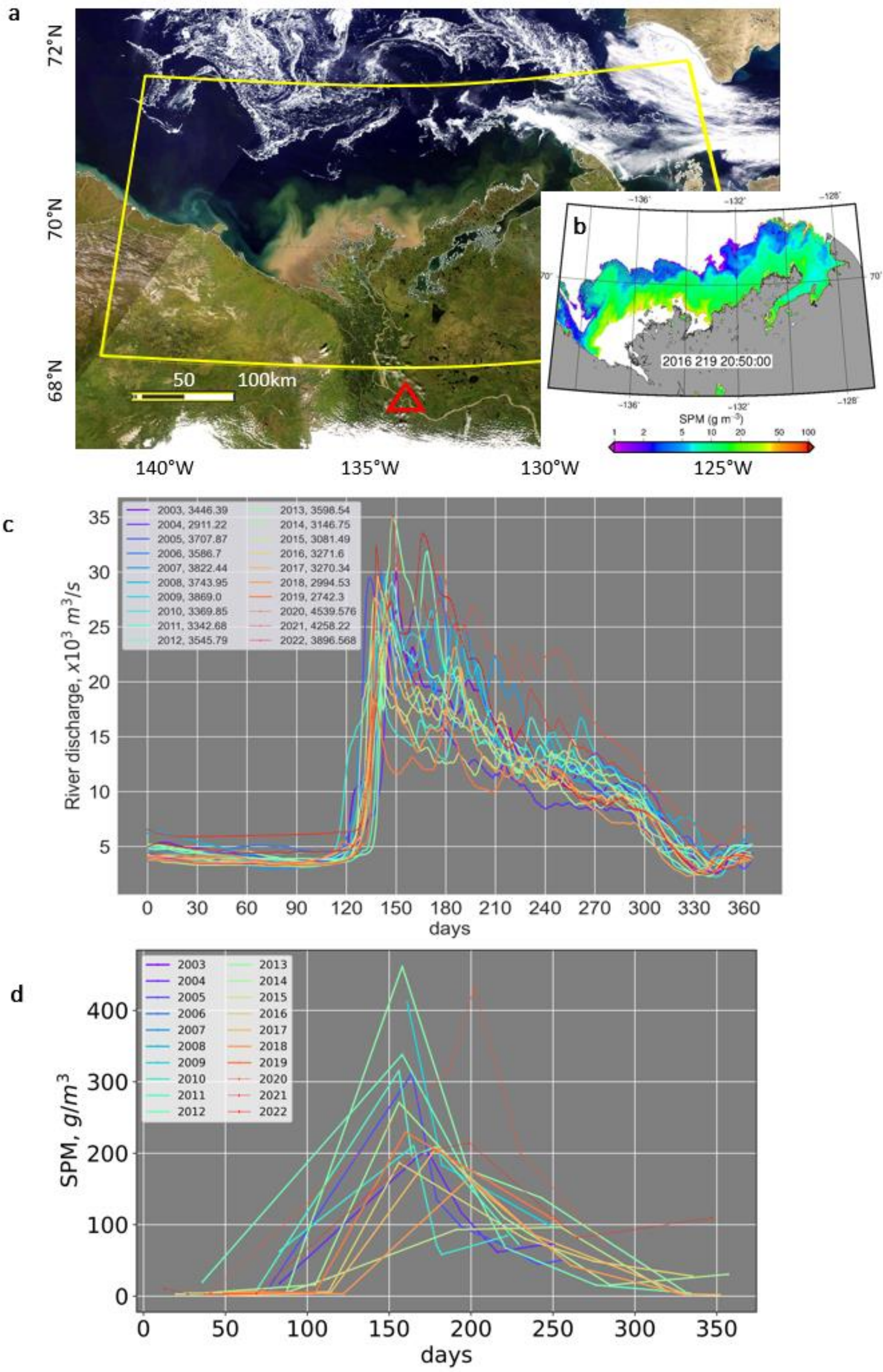
We included the updated Pearson correlated matrix in the Appendix, and added this resumé to the methods and discussion sections:

> Section 2:
>
> “To have idea of the large-scale estimates of the wind impact on the annual cumulated SPM, we included the number of days of storms parameter.
>
> Section 3:
>
> “Another question that was not addressed in our study is the impact of the wind-induced mixing on the offshore SPM concentration. The simple hypothesis proposes that the higher is the wind speed, the more mixing occurs in a shallow area, which reduces the surface SPM concentrations. At the same time, an additional hypothesis may suggest that more mixing means more re-suspension of particulate matter from the bottom sediments (increasing the SPM concentration). To verify these controversial hypotheses, we have to compare quasi simultaneous wind and SPM observations. In case of this study, this problem faces a fundamental limitation due to the nature of a satellite-retrieved SPM dataset: the highest wind speeds are observed during the cyclone passage, and SPM concentrations cannot be retrieved from satellite data under the clouds (as clouds mask the water-leaving signal).
>
> We found a weak negative correlation (correlation coefficient is -0.19) between the number of days of storm and annual cumulated SPM, which confirms the first simple hypothesis (more mixing, less SPM), but this question should be addressed additionally with other tools, like modeling.”

In conclusion, the issue is quite complex, and the statistical significance of the (linear) regressions is not very strong. As for the detailed comments:

1. Fig. 1: The map and satellite image should have a scale.

Thank you, we added a scale in Fig.1a:



2. The link to ERA5-LAND is incorrect (it should end with "...documentation").

Thank you for your suggestion, the new link was changed to https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation and https://confluence.ecmwf.int/display/CKB/ERA5-Land%3A+data+document

We were following the instruction found at https://confluence.ecmwf.int/display/CKB/How+to+acknowledge+and+cite+a+Climate+Data+Store+%28CDS%29+catalogue+entry+and+the+data+published+as+part+of+it

3. Fig. 2: Subfigures c and e, as well as d and f, have the same subtitle, but they describe different things. This is explained in the figure caption, but it's a bit confusing - please revise.

The titles were changes, thank you for your suggestions.

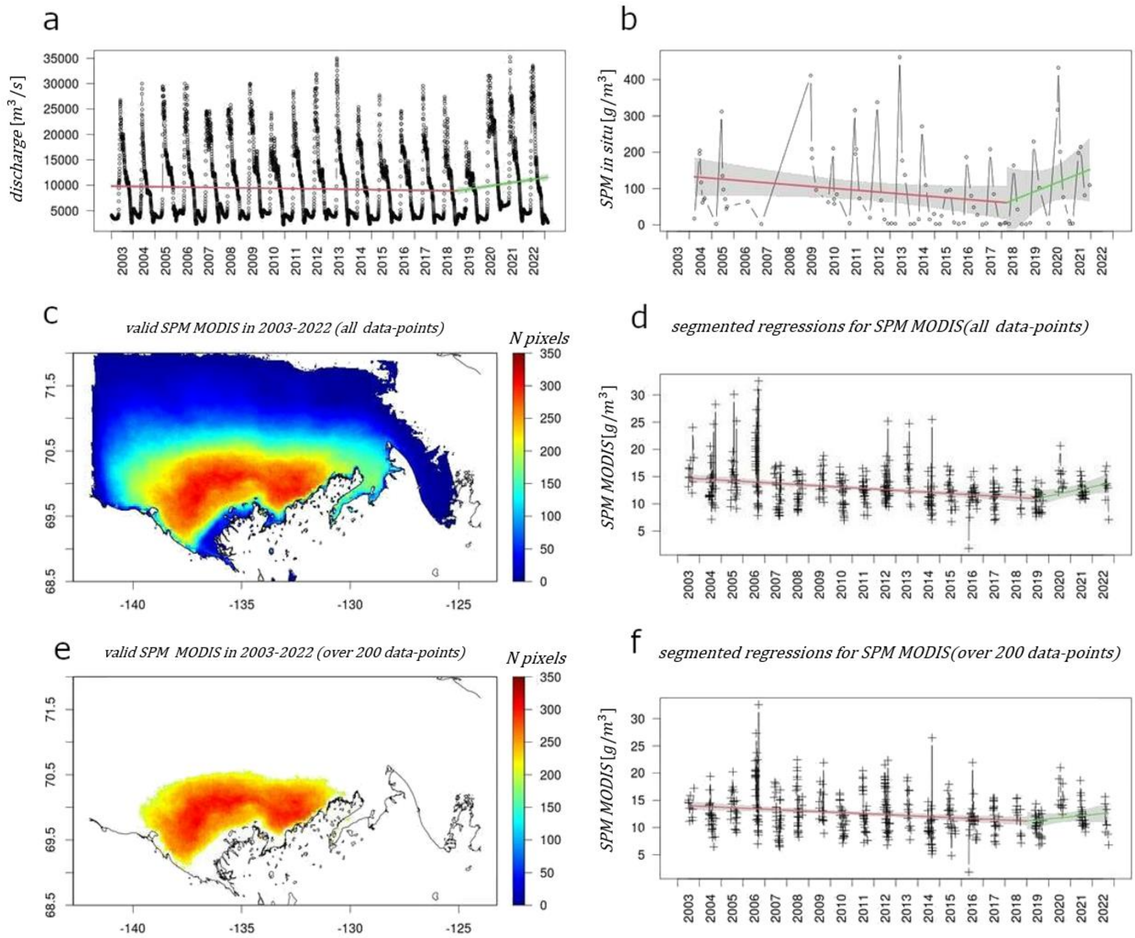


Fig.2

Highlights

Variations of suspended particulate matter concentrations of the Mackenzie River plume (Beaufort Sea, Arctic Ocean) over the last two decades

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- Interannual variations of suspended particulate matter (SPM) in coastal waters influenced by the Mackenzie River were investigated over the last 20 years (2003-2022) using MODIS/Aqua satellite data

- The offshore SPM variations are related to the Mackenzie River hydrological regime, air temperature, amount of snow, and permafrost state over its draining basin

- Over the last twenty years, a statistically significant negative trend was highlighted over the period 2003-2018 for both SPM and river discharge, with a positive trend starting from 2019 up to present

Graphical Abstract

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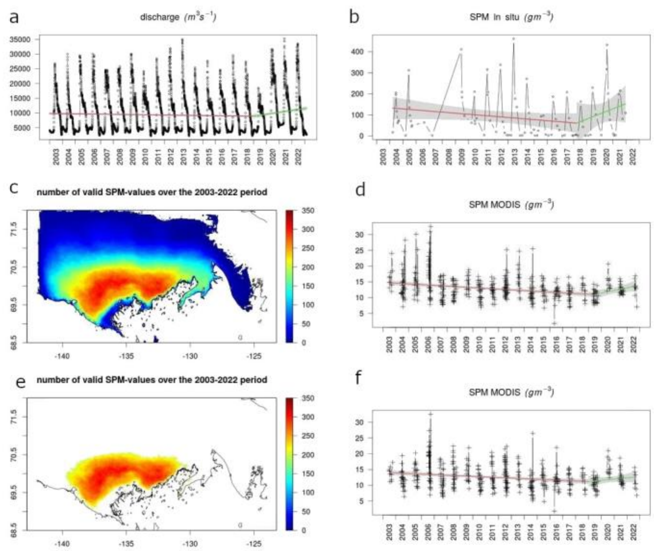

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Abstract

This work addresses the last 20 years' evolution of the suspended particulate matter (SPM) concentrations in the Beaufort Sea (Canadian Arctic Ocean) directly influenced by the Mackenzie River discharge. The SPM variations in the coastal zone are highlighted and related to the freshwater and solid discharges of the river measured in situ at the Arctic Red River station (150 km upstream of the river delta). The correlation between the variations of the river discharge and SPM concentration within the surface layer of the coastal waters is obvious. Rather unexpectedly, both have been slightly but significantly decreasing from 2003 to 2018-2019 and started to increase very recently (2019-2022). This change of regime could be explained by changing winter precipitation and groundwater distribution, progressively accumulating sediments within the thawing permafrost layer and its recent release into the groundwater together with thermokarst lakes' rapid drainage.

Keywords: suspended particulate matter, ocean optics, Arctic Ocean, MODIS

1. Introduction

Climate change occurs faster in polar regions than at lower latitudes Arias et al. (2021). Global warming is usually associated in high latitudes with rising air temperature, precipitations, and permafrost thaw Miner et al. (2022); Pörtner et al. (2022). Consequently, the freshwater discharged by rivers into the Arctic Ocean is expected to increase, so as the discharge of terrestrial substances with enhanced erosion along drainage basins Doxaran et al. (2015); Matsuoka et al. (2022); Juhls et al. (2022). This would result in increasing water turbidity in coastal areas directly affected by river inputs but also boosted primary production due to higher nutrient loads and reduced sea ice cover (i.e., increasing solar light within the water column).

The Mackenzie River is the fourth largest Arctic river in terms of river discharge (7% of freshwater inflow to the Arctic Ocean) and is the primary source of sediment discharge Carson et al. (1998); Wagner et al. (2011); Yang et al. (2015), so the changes in the Mackenzie River regime will have a significant impact on the whole Arctic region Juhls et al. (2022). The Mackenzie has a prominent seasonal cycle with winter lows and a summer maximum of river discharge, which is related to the water cycle over its large basin with its 75% permafrost area and the importance of snowmelt in spring Yang et al. (2015); Grotheer et al. (2020). The delta of the Mackenzie River is a complex area where the freshwater massively inflows into the southern Beaufort Sea, highly impacted by a long presence of sea ice. The southern Beaufort Sea is frozen most part of the year; the polynia between the fast ice of the delta starts opening in May, then the water surface stays mostly icefree from July to October. Over the last two decades, the sea ice conditions have become softer, and the sea ice concentration (SIC) has diminished by -4-8% per decade from 2003 to 2019 Hilborn and Devred (2022).

The open discussion of the Mackenzie River regime and its adaptation to climate change depends on the studied period Woo and Thorne (2003); Doxaran et al. (2015); Yang et al. (2015); Matsuoka et al. (2022); Zolkos et al. (2022). Doxaran et al. 2015 claimed a 22% increase of the river discharge from 2003 to 2013. Yang et al. 2015 showed that over the 19732011 period, the positive linear trend for the Mackenzie discharge was very weak ($y = 17.21x + 8947.4$), and Woo and Thorne 2003 found no significant trend for the annual discharge over the period 1968-1999, nor did Matsuoka et al. 2022 for the 1992-2018 period. Meanwhile, several studies agreed that the yearly amount of river discharge has changed its seasonal distribution: cold season discharge becomes slightly higher, but spring flows are lower (as higher air temperatures shift the snowmelt earlier) Woo and Thorne (2003); Yang et al. (2015). The question of the river water discharge, thus, should be regularly reevaluated.

In such a remote and changing environment, satellite observations have been proven to be an efficient tool to monitor the evolution of Arctic coastal zones, and compensate the lack of field measurements Doxaran et al. (2012); Hill et al. (2013); Juhls et al. (2022). SPM field measurements, although extremely valuable, are usually too sparse for the long-term variability analysis, as most of them are associated with specific summer expeditions (e.g. the recent MALINA Massicotte et al. (2021) and Nunataryuk Lizotte et al. (2023) field campaigns). Overall, during the ice-free season, satellite-derived suspended particulate matter (SPM) concentrations typically vary from 30 g/m^3 in the delta region to 0.5 g/m^3 offshore over the Canada Basin Hilborn and Devred (2022).

Several studies analyzed satellite-derived SPM concentration variability in the southern Beaufort Sea for long time periods (over 10 years), and their results are rather controversial. From 2003 to 2013, Doxaran et al. 2015 found a linear trend with a significant increase in monthly- averaged SPM concentrations at the mouth of Mackenzie River (+46% in 10 years over the river mouth area and +71% in the river delta south to 70°N). Hilborn and Devred 2022 applied *self-organizing maps* method to identify six different regions in the eastern Beaufort Sea using 17 years of MODIS (Moderate Resolution Imaging Spectroradiometer) data and found only one statistically significant trend (negative) for the annual SPM concentration in the deepwater Canada basin area, far offshore the Mackenzie delta. At the same time, Matsuoka et al. 2022 showed a statistically significant increase of dissolved and particulate organic matter concentrations (but not fluxes) in late summer: 0.019 g/m^3 *per year* and 0.069 g/m^3 *per year*, accordingly).

The present study is a continuation of Doxaran et al.2015, where we analyze the evolution of the SPM concentration in the Beaufort Sea directly influenced by the discharge of the Mackenzie River over the last two decades (2003-2022), using the methodology developed by Doxaran et al. (2012, 2015), this time excluding the complex river delta zone.

2. Materials and Methods

Fig.1a shows the limits of the study area (yellow rectangular) on a quasitrue color daily MODIS composite for August 8, 2016. In this image, the SPM-rich Mackenzie River plume propagates along the coast and northward, partly into the MIZ (marginal ice zone). The variations of SPM concentrations (Fig.1b) from the delta to offshore waters are obvious, which highlights complex processes along this land-sea interface. The field and satellite datasets used in this study, so as the methods used to retrieve and analyze time series of river discharge and SPM concentrations, are detailed hereafter.

2.1. Field data sets

In situ measurements of the river water discharge (2003-2022) were provided by the Water Survey of Canada via the ArcticGRO project McClelland et al. (2023) at the Arctic Red River gauge station (station ID: 10LC014, 67.45°N 133.74°W, red triangle in Fig.1a). River discharge measurements, Q, are available daily (Fig.1c). The measurements of suspended matter are distributed by the ArcticGRO as *total suspended solids (TSS)* concentrations, which is the same as SPM, so hereafter we will refer to in situ *TSS* as the SPM_{insitu}. The SPM_{insitu} data were collected at most once per month, but not during all months (on average, 4 to 6 measurements per year, Fig.1d). Over the studied period, some years are poorly represented (one measurement per year in 2003, 2006, and 2007; no SPM measurement in 2008). The lack of SPM in situ data implies the necessity to use satellite data.

The ArcticGRO in situ datasets pass the quality control procedure and indicate less reliable measurements as ”provisional data”. Over the 2003-2022 period, it corresponds to river discharge data in 2020-2022 and SPM_{insitu} data in 2019–2022 (shown with thinner lines in Fig.1c, d).

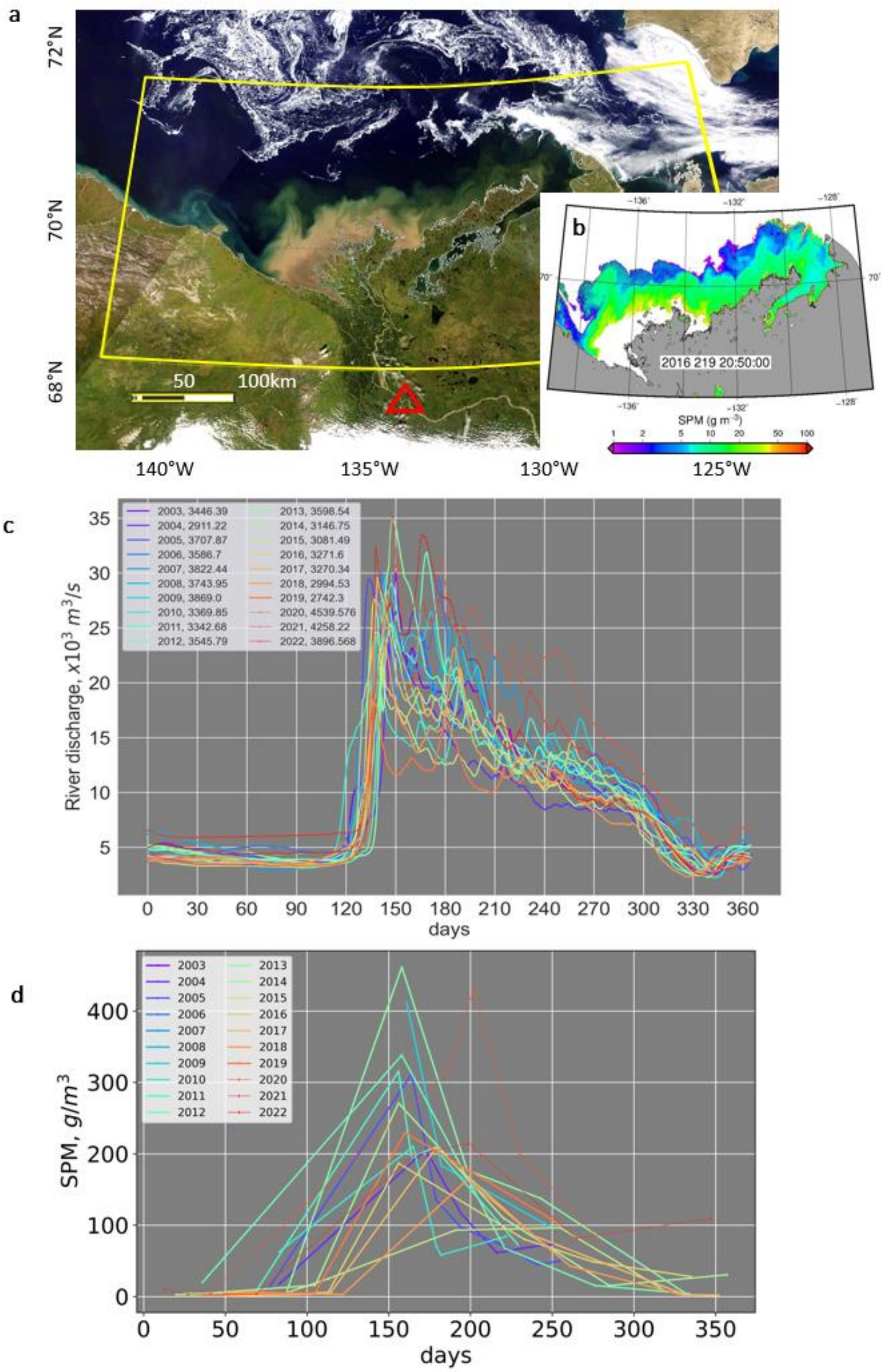

Figure 1: (a) MODIS image (August 6, 2016) locating the Arctic Red River gauge station (Tsiigehtchic) where in situ measurements are carried out (red triangle) and the coastal waters studied using satellite data (yellow rectangle); (b) SPM concentrations: Interannual variations of water discharge (the year of measument and the annual cumulative sum of discharge is indicated in legend), (c) and SPM concentrations (d) at the Arctic Red River station. The inserted SPM color map shows the result of MODIS satellite data processing

2.2. *Ocean color satellite data*

As in Doxaran et al. 2015, a single satellite sensor (MODIS/Aqua) was considered for this study in order to avoid any bias between different sensor products when detecting temporal trends. Since 2003, MODIS provides high-quality ocean color observations at a good temporal resolution: several images per day of the study area during the Arctic summer months Doxaran et al. (2012, 2015); Hilborn and Devred (2022); Matsuoka et al. (2022). The region of interest was defined as 68.5°N-72°N, 142°W - 124°W (yellow rectangle in Fig.1a). The initial dataset contained 10608 swaths collected between May 1 and October 31 each year over the 2003-2022 period.

Processing of satellite data. MODIS L1A satellite data were processed using the SeaWiFS Data Analysis System (SeaDAS 8.1.0) software (http://seadas.gsfc.nasa.gov/) and its l2gen function. The atmospheric correction was performed using the NIR–SWIR algorithm of Wang and Shi 2007); this method was proved to be the most appropriate for the highly turbid waters at the mouth of the Mackenzie River to the less turbid waters offshore Doxaran et al. (2012).

SeaDAS l2gen flags were used to mask clouds and glint. In the work of Doxaran et al. 2015, two techniques were used to mask clouds: the default one in the coastal waters and an increased cloud albedo threshold value (0.4 instead of 0.027) over the specific area of the river delta zone to avoid masking the highly turbid water pixels. This procedure was time-consuming and required an additional inspection of every image in the river delta zone. Here, the cloud-masking method preconized by Ody et al. 2022 for river mouths was used to process each satellite image only once: the 2130 nm shortwave-infrared waveband was used with a cloud threshold of 0.018. The sea ice mask was computed from daily sea ice concentration (SIC) data at 3.125°spatial resolution distributed by the University of Bremen Spreen et al. (2008). This dataset contains AMRS-E and AMSR2 (Advanced Microwave Scanning Radiometer -for Eos and -2) images. Due to several gaps in data acquisition over the 2003-2022 time period, the dataset was completed with the sea ice concentration from the SSMIS (Special Sensor Microwave Imager/Sounder) instrument. The ice mask was created using the SIC above 0%.

All satellite data (Rayleigh-corrected reflectances and masks) were reprojected on a regular 250 m grid. The following criteria were then applied to exclude potentially contaminated images:

- the number of valid pixels should exceed 15% of the marine area of the study area in the downloaded MODIS image;

- the distance between the central point of the study area and that of the MODIS image should be less than 1000 km to avoid aberrations on the border of the image;

- only areas with a zenith solar angle lower than 74°were conserved.

This automatic filtering reduced the MODIS collection to 700 images. Finally, all images were inspected visually to filter out the remaining contaminated images because of not detected MIZ, clouds or cloud shadows, etc.; 651 MODIS images remained after this last quality check step.

The SPM concentrations were computed from the ratio (in %) between the remote sensing reflectance signals, Rrs (in sr^{-1}) in the near-infrared and green wavebands using the set of relationships established based on field measurements Doxaran et al. (2012, 2015):

$$SPM_{sat} = 0.8386 \times R_{RS}(748:555) \quad (1)$$

if $R_{RS}(748:555) < 87\%$

$$SPM_{sat} = 70+0.1416\times R_{RS}(748:555)+2.9541\times e^{0.2092\times(R_{RS}(748:555)-87)} \quad (2)$$ if $87\% \leq R_{RS}(748:555) \leq 94\%$

$$SPM_{sat} = 3.922 \times R_{RS}(748:555) - 285.4 \quad (3)$$

if $94\% < R_{RS}(748:555)$, where SPM_{sat} is the SPM concentration in g/m^3 and $R_{RS}(748:555)$ is the ratio of remote-sensing reflectances at 748 and 555 nm.

Negative $R_{RS}(555)$ and $R_{RS}(748)$ values were discarded before computing SPM, as well as computed SPM concentrations higher than 1000 g/m^3, to remove atmospheric correction failures and residual contaminations (typically encountered along borders of clouds or sea ice).

The processed SPM images were averaged as daily, monthly, and yearly composites as simple mean averages for every pixel. Only daily composites and their mean values were used further, as monthly composites were sometimes computed using only 1 to 3 cloud-free images, which is not representative of mean monthly concentrations.

2.3. Reanalysis data

A dataset from ERA5 Land reanalysis was extracted to better understand how environmental factors did impact the Mackenzie River discharge and SPM concentrations in the adjacent coastal waters. This dataset was selected as the most suitable tool for the studies of river discharge variability Winkelbauer et al. (2022). ERA5 Land has a monthly temporal resolution and 9-km spatial resolution and is provided by Copernicus data center Munõz-Sabater et al. (2021). The area of extraction approximately corresponds to the Mackenzie drainage basin (52-70°N, 100-140°W). The following parameters were used: river runoff (ro), surface river runoff (sro), evaporation (e), total precipitation (tp), snow depth (sd), and air temperature at 2m (t2m), (see detailed description at https://confluence.ecmwf.int/display/CKB/ERA5-Land%3A+data+document The

Pearson correlation matrix for the mean annual values of all described parameters (Fig.A.3).

To include a possible effect of storms on the SPM concentrations, we added to the analysis the wind data from ERA5 (marine area similar to that chosen for the MODIS study box). The Pearson correlation matrix (where the yearly parameters are compared) contains an additional parameter ”the number of days of storms per year” (*ndays_storm* in Fig. A.3). The day was considered stormy if over the study area there was a wind vector with a wind speed over 15 m/s.

2.4. Temporal variability

As previous works have shown, the linear regression model provides relatively little information on interannual variability of river water discharge and related parameters, such as SPM, because, over the long term, the discharge appears as stable Yang et al. (2015); Matsuoka et al. (2022). Over the last 20 years, the linear trend for the in situ Mackenzie discharge time series calculated with the Ordinary Least Squares (OLS) model is $y = 17.1x+9554$ with a standard error (SE) of 63.6 m^3/s, and confidence intervals (CI) [0.025 0.975] equal to -107.5 and 141.7 m^3/s for the coefficient term. Although these results are very close to that of Yang et al. 2015, the statistical metrics confirm that the OLS model is not suitable for the analysis in this case.

For this reason, we used an estimating regression model with unknown break-points, which allows describing several temporal trends Muggeo (2003). To apply this model to our datasets, we used the *segmented* function in the R package *segmented*.

To compute the trends, the in situ data time series of daily river discharge (Q_{insitu}) and SPM concentration (SPM_{insitu}) described above were used (Fig.2a, b). For the satellite data, the spatial sparsity of observations was taken into account. Thus, to obtain SPM_{sat} time series, we calculated: • one daily spatial mean SPM value for all available SPM pixels over the study area, which resulted in SPM_{sat} time series (Fig.2 c-d); • one daily spatial mean SPM value for the area with the highest data density (where valid satellite pixels appear more than 200 times over the 2003-2022 period), which resulted in SPM_{sat200} (Fig.2 e-f)

Then the segmented regression analysis technique was applied to all time series: Q_{insitu}, SPM_{insitu}, SPM_{sat}, and SPM_{sat200}. After several tests, the most statistically significant results were obtained with one breaking point and two segment slopes. The following statistical parameters were computed for each segment: estimated coefficient of linear regression (Est.), standard error, lower and upper 95% confidence intervals (CI(95%).l, CI(95%).u, respectively) (Tab.1).

3. Results and Discussion

The seasonal cycles of both the river discharge, Q, and SPM_{insitu} are very pronounced, with high summer and low winter values (Fig.1c,d). These parameters also have a strong interannual variability. During the 2003-2022 period, the river discharge varied from $2.2\times10^3\ m^3/s$ (winter) to $35.2\times10^3\ m^3/s$ (summer), with a mean value of $9.5\pm6.8\times10^3\ m^3/s$. Typically, the discharge increases very rapidly in 2 weeks from 5 to $25\times10^3\ m^3/s$ in late May, when the main summer peak occurs, then slowly decreases to its winter values by November.

The years 2013 and 2021 were exceptional with extreme *yearly maxima* of river discharge over $35\times10^3\ m^3/s$ on May 28 (both), while the lowest yearly maximum river discharge, $18\times10^3\ m^3/s$, was registered on May 18, 2019. Previously, Yang et al. 2015 also observed similar prominent interannual variations in the river discharge during the summer (e.g., in 1992 and 1995 for the 1972-2011 period). They concluded that a negative anomaly in precipitation-evaporation balance over the river basin in summer (hot and dry weather) usually results in a lower discharge the next year with an earlier maximum, while the opposite (cold and wet) weather is responsible for a higher discharge. This statement does not explain the extreme peak of discharge recorded in 2013: in 2012 the summer was "hot and dry", so 2013 should have been a year of extremely low summer river discharge. Overall, calculated correlations between in situ river discharge and ERA5 Land total precipitation, as well as air temperature were weak (0.36 and -0.23, respectively).
However, the river discharge is well correlated with snow depth cover (correlation coefficient between Q_{insitu} and *sd* is 0.67): the 2011-12 and 2012-13 winters were snowy (+10% and +3% *sd* anomaly compared to 20years median values), as well as the 2020 winter (+7% *sd* anomaly), but 2018-19 snow cover was weak (-7% *sd* anomaly). Interestingly, in 2013 the yearly means of river discharge and air temperature were close to their 20years median values, indicating the overall stability of the system during this period.

The river discharge regime in 2006-2008 and 2012 was special with two summer Q maxima, the first one in late May and the second between the end of June and mid-July. The reason for this change in river regime might be related to the precipitation seasonal pattern and the river ice opening (several ice jams crushes, creating the second peak). To investigate these particularities, a higher temporal resolution reanalysis data should be used. We also observe local maxima (values higher than the previous year) in SPM_{sat} in 2006, 2008, and 2012.

As explained in section 2.4, the OSL model does not highlight a statistically significant trend in the river discharge time series, but the *segmented* model does. Fig.2 and Table 1 present the results of calculated segmented regressions, where the river discharge and SPM concentrations demonstrate very similar trends: a negative trend from 2003 to 2018, then a recent positive trend from 2019 (2018 for SPM_{insitu}) to 2022 (Fig.2). Based on the confidence intervals, we conclude that negative trends for $slope1_{Q}$, $slope1_{SPMsat}$, and $slope1_{SPMsat200}$ are statistically significant (CIs [0.025 0.975] are all negative).

This negative trend of $slope1_{Q} = -57.21x + const$ in river discharge for the 2003-2018 period is opposite to that of Doxaran et al. 2015 for the 20032013 period, but the latter study slightly overestimated the river discharge in 2013 (as the data was not yet fully quality-checked) resulting in an erroneous positive (+22%) trend. As already mentioned, other studies, e.g. Yang et al. (2015); Matsuoka et al. (2022) which used an OSL model did not find any significant trend in the Mackenzie River discharge. The positive trend from 2019 to the present, $slope2_{Q} = 640.05x + const$, although not statistically significant, can indicate a progressive increase in the minimum flow impacted by a "mobilization of ground waters" as discussed by Yang et al. 2015.

In situ data show that the SPM seasonal cycle generally follows the river discharge cycle, with the summer maxima in late May - beginning of June. The SPM_{sat} values vary from 0.8 to 461 g/m^3 with a median value of 67.7±11 g/m^3. The breakpoint of SPM_{isitu} trends is slightly shifted to 2018, and CIs contain zero, thus indicating that the *segmented* model is less reliable for this dataset. At the same time, the SPM_{isitu} time series has the fewest amount of data, which is not homogeneous in time and is mainly available in summer. It makes it more difficult to interpret with any statistical model. SPM_{sat} and SPM_{sat200} trend analyses show similar results: their negative *slope*1 values and corresponding SE are close to each other, which gives confidence in the observed SPM negative trend. The positive trends $slope2_{sat}$ and $slope2_{sat200}$ are not statistically significant, and their SEs are of the order of the estimated coefficient of linear regression (Tab.1). Nevertheless, this result is interesting for further discussion.

Over the 2003-2019 period, Hilborn and Devred 2022 obtained results in good agreement with a negative trend (although not significant) for SPM concentrations over the southern Beaufort Sea (from -0.16 to -0.46 g/m^3 per decade) except for the Mackenzie River delta, where they found an increase of SPM of 0.36 g/m^3 per decade. The difference in negative coefficients' values obtained in the present study and that of Hilborn and Devred (2022) comes from (1) the difference of SPM-retrieval methods and different MODIS bands used; and (2) the regions: our study region of SPM_{sat200} corresponds to 3 regions over the shelf identified by Hilborn and Devred (2022).

In the Mackenzie delta zone, Doxaran et al. 2015 also found a significant increase of SPM (+71% from 2003 to 2013) over the "Mackenzie River delta" region of Hilborn and Devred (2022). The delta zone seems to play an important role of "SPM filter" between the river and the coastal waters. Based on satellite observations, SPM apparently settles massively in this shallow area, resulting in the formation of temporary maximum turbidity zones where resuspension of bottom sediments may occur depending on the river discharge, tidal currents, and wind stress (Wegner et al., 2005; Grotheer et al., 2020). Observations at high spatial and temporal resolutions are required to further investigate SPM dynamics in this delta zone.

However, how to explain the negative trends in both river discharge and SPM concentrations in the riverbed and offshore delta zone over the 2003-2018 period? Based on the correlation matrix (Fig. A.3), we recognize that the river runoff and, thus, river discharge variability depend mostly on the amount of total precipitation (r = 0.7) and the snow depth (r = 0.63, which is another estimate of solid precipitation in winter) parameters. This trivial conclusion leads us to a simple suggestion that the Mackenzie River discharge slightly declined while the precipitation pattern has changed over this period.

As for the SPM, the recent study of Zolkos et al. 2022 reveals a similar decrease in SPM loads in most of the Siberian rivers between 1970 and 2010 and explains it by natural and anthropogenic factors. The ”natural factors” of sediments erosion over the river basin are the physical and chemical denudation. For the Mackenzie River, the physical denudation rates exceed the chemical denudation about several orders of time: mechanical denudation rate at the Arctic Great River was reported as $844\ t * km{-}2 * y{-}1$ in 1997, while the chemical weathering occurs at a rate of 25 mm∗ky−1 with a transport time of 10-400 ky−1 (Vigier et al. (2001); DePaolo et al. (2006)). On the order of two decades, it is, thus, physical or mechanical factors related to the river discharge and the atmospheric conditions in the delta-adjacent areas that control SPM concentrations. A simultaneous decline of *Q_insitu* and *SPM_insitu* in 2003–2018 means that the lower the river discharge, the less suspended particulate matter it transports.

Another source of variability for the “marine” SPM might be the wind mixing. The simple hypothesis proposes that the higher the wind speed, the more mixing occurs in a shallow area, which reduces the surface SPM concentrations. At the same time, an additional hypothesis may suggest that more mixing means more re-suspension of particulate matter from the bottom sediments (increasing the SPM concentration). To verify these controversial hypotheses, we must compare quasi simultaneous wind and SPM observations. In the framework of this study there is yet one fundamental limitation for this analysis due to the nature of ocean color data retrieval from satellite: the highest wind speed (and thus mixing events) will mostly occur under the cloud cover with the passage of cyclones, and SPM concentrations cannot be retrieved from ocean color satellite under such conditions (presence of clouds). We found a weak negative correlation (correlation coefficient is $r=-0.19$) between the number of days of storm and annual cumulated SPM, which confirms the first simple hypothesis (more mixing, less SPM), but this question should be addressed additionally with other tools, like modeling.

There is yet a question about the recent positive trends in *Q* and *SPM* over the last 3-5 years of observations. Although the trends are statistically not significant, can we suggest any important processes that might have impacted the river discharge and sedimentation transport recently?

The presence of permafrost over the river basin was considered as ”precluding” for the groundwater’s contribution to general river discharge, as it prevented the water infiltration through the permafrost layer, but might have helped to create underground cavities filled with non-communication water reservoirs (Vigier et al. (2001)). With a progressive permafrost thawing, this neglected role might be re-evaluated. Matsuoka et al. 2022 observed an increase of thaw depth and precipitation, but a decrease in river discharge, which is probably explained by the contribution of ground waters, also suggested by Connolly et al. (2020). The permafrost thaw also likely affects the drainage of lakes located in the permafrost area Webb and Liljedahl (2023). A recent work of Nitze et al. 2020 described, e.g., a series of extremely quick thermokarst lakes drainage in 2018 in northwestern Alaska after the unprecedented warm (with air temperature close to 0°C) and wet winter of 2017-2018. This drainage "exceeded the average drainage rate by a factor of 10", and is supposed to continue and increase the liquid and solid discharges of Arctic rivers. This situation suggests that in the Canadian Arctic, where "large areas are susceptible to hillslope thermokarst activity" (Zolkos et al. (2022)), the permafrost thawing will progressively change chemical denudation and induce the downstream redistribution of sediments over the next millennial(s).

Table 1: Statistics for the segmented linear regression analysis of in situ river discharge (Fig.2a) - $slope_Q$; trends of SPM_{insitu}: $slope_{insitu}$ (Fig.2b); trends of SPM_{sat} for all available points: $slope_{sat}$ (Fig.2d); and trends for SPM_{sat} for the area with over 200 pixels available: $slope_{sat200}$ (Fig.2f). Negative trend parameters are described with *slope*1, positive with *slope*2

	Est.	Standard error	CI(95%).l	CI(95%).u
$slope1_Q$	-57.21	19.14	-94.73	-19.68
$slope2_Q$	640.05	142.91	359.88	920.19
$slope1_{insitu}$	-5.08	3.04	-11.13	0.96
$slope2_{insitu}$	24.46	21.86	-19.02	67.93
$slope1_{sat}$	-0.23	0.04	-0.32	-0.15
$slope2_{sat}$	0.84	0.43	-0.01	1.70
$slope1_{sat200}$	-0.18	0.04	-0.27	-0.09
$slope2_{sat200}$	0.39	0.40	-0.40	1.18

4. Conclusion

Twenty years (2003-2022) of in situ measurements (river discharge and SPM concentration at the Arctic Red River station) and satellite-derived SPM concentrations were analyzed to describe the evolution of SPM inputs in the Beaufort Sea by the Mackenzie River and its impact on the adjacent coastal waters. Using the segmented regression model, we showed two opposite trends over the last 20 years for both the river freshwater discharge and SPM concentration. Over the studied period, we observe statistically significant negative trends from 2003 to 2018-2019, then a positive trend from 2019 to 2022 for both river discharge and SPM concentrations. Our results extend previous estimations of Doxaran et al. 2015 and tend to confirm other long-term observations showing a rather stable freshwater discharge of the Mackenzie River, increasing SPM concentrations in the delta zone and a significant decrease in SPM concentration in adjacent coastal waters Feng et al. (2021); Hilborn and Devred (2022); Matsuoka et al. (2022).

We suggest that the observed variability indicates a simultaneous decline of water discharge and, thus, suspended particulate matter transport due to changing precipitation pattern, especially the amount of snow over the river basin with a possible role of wind-induced mixing in the marine area. We also discuss along-term effects of climate change and permafrost thawing on the sediment transport rate in the Mackenzie River.

These processes of SPM release into the Arctic Ocean should be studied next on a pan-Arctic scale: can we expect a similar behavior based on the regional variations of river discharges reported by ArcticGRO? A recent study of Zolkos et al. 2022 used only in situ data, and further analysis of SPM distribution into the Arctic Ocean with satellite data will be beneficial. Studying the seasonal variability for specific years (e.g., 2006-2008, 2012) is also required using higher resolution data, including satellite imagery, to better understand changing river regimes in Arctic regions.

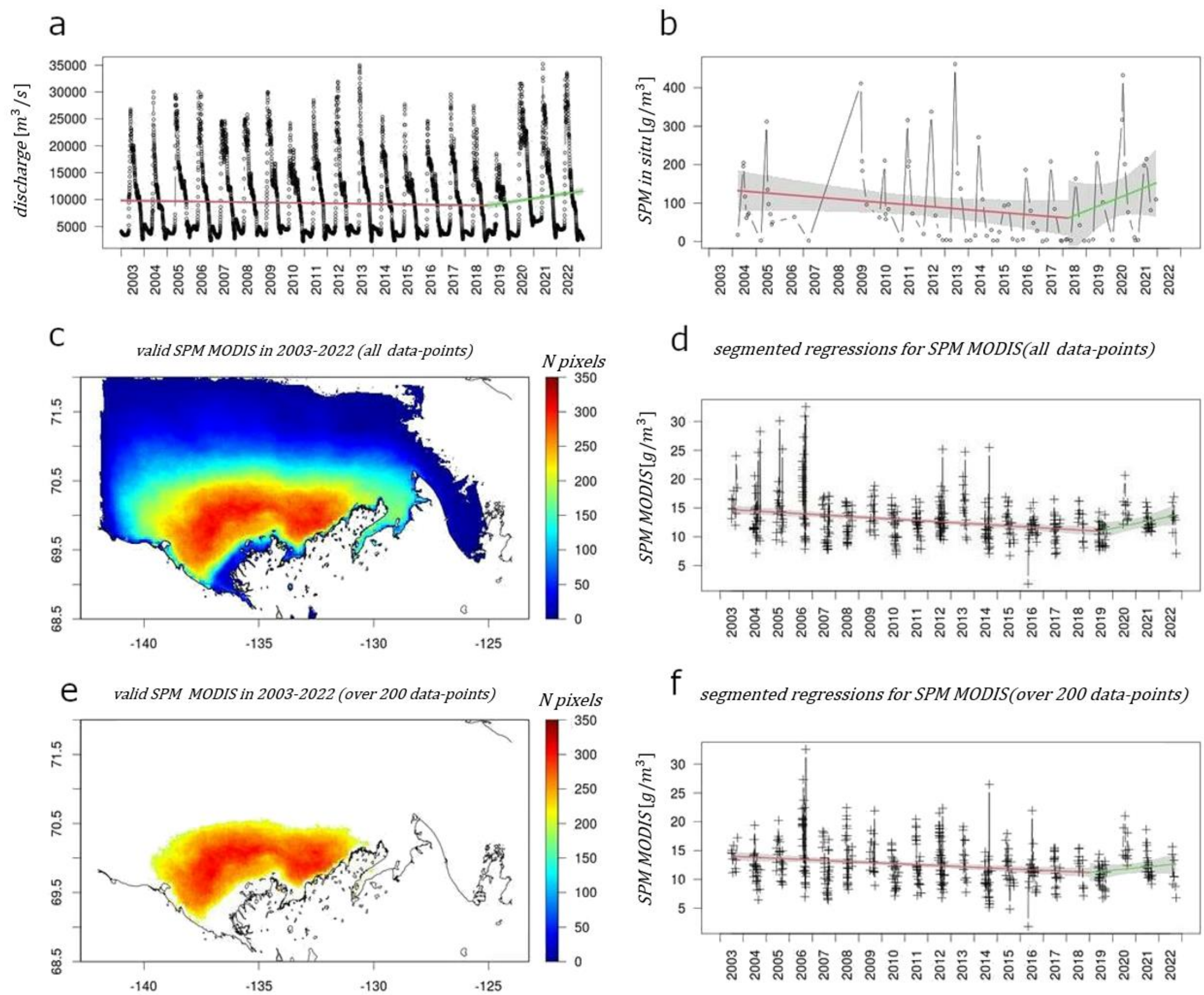

Figure 2: Interannual variations of in situ and satellite data (river discharge and SPM) with their segmented linear regression slopes (red and green colors show negative and positive regressions, respectively): (a) river discharge Q_{insitu}, (b) SPM_{insitu} time series; (c) maximum number of valid SPM_{sat} pixels in 2003-2022 (d) satellite SPM_{sat} time series;
(e-f) similar to (c-d), but for the area with at least 200 valid pixels

5. Data availability

In situ measurements described in section 1 (river water discharge and TSS) are provided at https://arcticgreatrivers.org/data/. MODIS data is accessible from the NASA website https://oceancolor.gsfc.nasa.gov. Sea ice concentrations are available at https://seaice.uni-bremen.de/data-archive/. ERA5 LAND reanalysis data can be found at https://doi.org/10.24381/cds.68d2bb30 with a detailed description at https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation, and ERA5 wind data is available at https://doi.org/10.24381/cds.adbb2d47 with a detailed description at

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No conflict of interest is stated.

Appendix A. ERA5-Land

The appendix contains Fig.A.3 illustrating correlation between ERA5 parameter, the Mackenzie discharge from the Arctic GRO dataset, and in situ and satellite SPM concentrations.

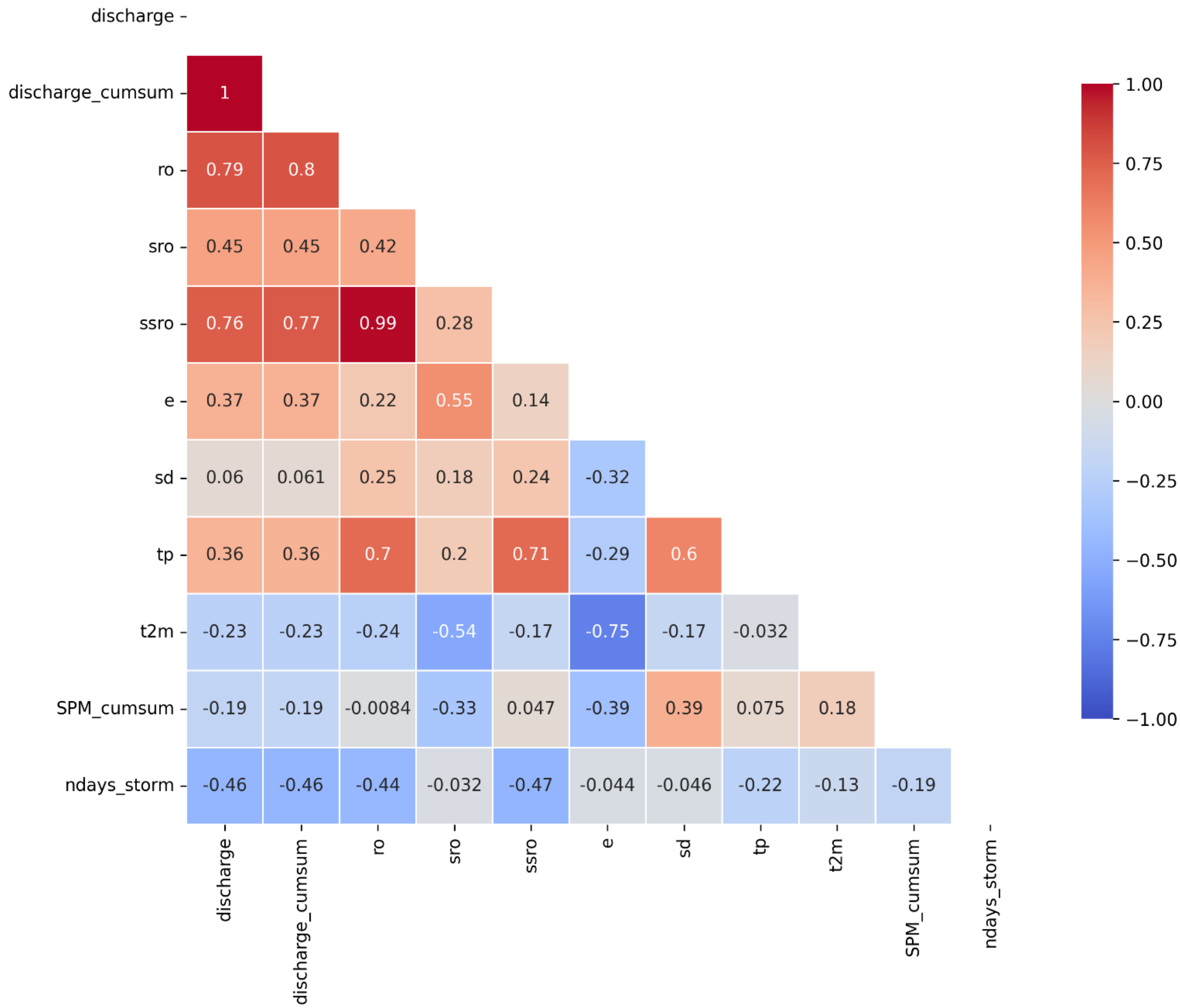

Figure A.3: Correlation matrix of all mean yearly reanalysis (ERA5 LAND) parameters over the Mackenzie basin and in situ (Arctic GRO) discharge for Mackenzie (Arctic Red station). ERA5 Land parameters are described in main text (ro - total runoff, sro surface runoff, ssro - subsurface runoff (ssro = ro-sro), e - evaporation, sd - snow depth, tp - total precipitation, t2m - air temperature at 2 m, SPM_{cumsum} - annual cumulated SPM concentrations, discharge - Arctic GRO in situ discharge).

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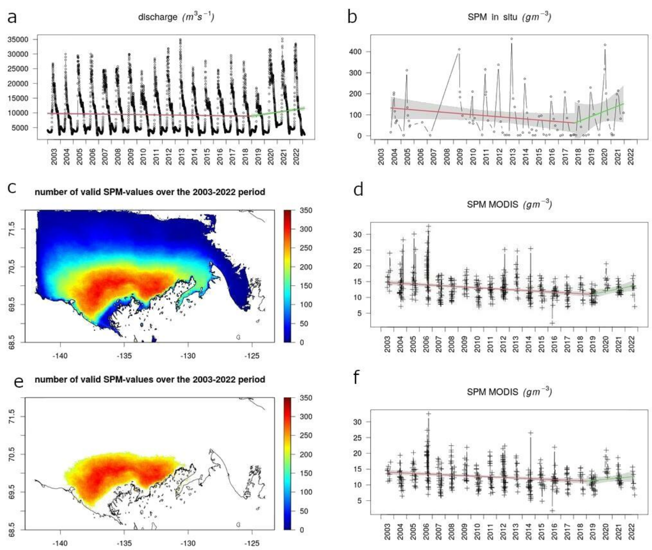
Graphical Abstract

Variations of suspended particulate matter concentrations of the Mackenzie River plume (Beaufort Sea, Arctic Ocean) over the last two decades

Anastasia Tarasenko, David Doxaran, Bernard Gentili



Highlights

Variations of suspended particulate matter concentrations of the Mackenzie River plume (Beaufort Sea, Arctic Ocean) over the last two decades

Anastasia Tarasenko, David Doxaran, Bernard Gentili

- Interannual variations of suspended particulate matter (SPM) in coastal waters influenced by the Mackenzie River were investigated over the last 20 years (2003-2022) using MODIS/Aqua satellite data
- The offshore SPM variations are related to the Mackenzie River hydrological regime, air temperature, amount of snow, and permafrost state over its draining basin
- Over the last twenty years, a statistically significant negative trend was highlighted over the period 2003-2018 for both SPM and river discharge, with a positive trend starting from 2019 up to present

Variations of suspended particulate matter concentrations of the Mackenzie River plume (Beaufort Sea, Arctic Ocean) over the last two decades

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Abstract

This work addresses the last 20 years' evolution of the suspended particulate matter (SPM) concentrations in the Beaufort Sea (Canadian Arctic Ocean) directly influenced by the Mackenzie River discharge. The SPM variations in the coastal zone are highlighted and related to the freshwater and solid discharges of the river measured in situ at the Arctic Red River station (150 km upstream of the river delta). The correlation between the variations of the river discharge and SPM concentration within the surface layer of the coastal waters is obvious. Rather unexpectedly, both have been slightly but significantly decreasing from 2003 to 2018-2019 and started to increase very recently (2019-2022). This change of regime could be explained by changing winter precipitation and groundwater distribution, progressively accumulating sediments within the thawing permafrost layer and its recent release into the groundwater together with thermokarst lakes' rapid drainage.

Keywords: suspended particulate matter, ocean optics, Arctic Ocean, MODIS

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1. Introduction

Climate change occurs faster in polar regions than at lower latitudes Arias et al. (2021). Global warming is usually associated in high latitudes with rising air temperature, precipitations, and permafrost thaw Miner et al. (2022); Pörtner et al. (2022). Consequently, the freshwater discharged by rivers into the Arctic Ocean is expected to increase, so as the discharge of terrestrial substances with enhanced erosion along drainage basins Doxaran et al. (2015); Matsuoka et al. (2022); Juhls et al. (2022). This would result in increasing water turbidity in coastal areas directly affected by river inputs but also boosted primary production due to higher nutrient loads and reduced sea ice cover (i.e., increasing solar light within the water column).

The Mackenzie River is the fourth largest Arctic river in terms of river discharge (7% of freshwater inflow to the Arctic Ocean) and is the primary source of sediment discharge Carson et al. (1998); Wagner et al. (2011); Yang et al. (2015), so the changes in the Mackenzie River regime will have a significant impact on the whole Arctic region Juhls et al. (2022). The Mackenzie has a prominent seasonal cycle with winter lows and a summer maximum of river discharge, which is related to the water cycle over its large basin with its 75% permafrost area and the importance of snowmelt in spring Yang et al. (2015); Grotheer et al. (2020). The delta of the Mackenzie River is a complex area where the freshwater massively inflows into the southern Beaufort Sea, highly impacted by a long presence of sea ice. The southern Beaufort Sea is frozen most part of the year; the polynia between the fast ice of the delta starts opening in May, then the water surface stays mostly icefree from July to October. Over the last two decades, the sea ice conditions have become softer, and the sea ice concentration (SIC) has diminished by -4-8% per decade from 2003 to 2019 Hilborn and Devred (2022).

The open discussion of the Mackenzie River regime and its adaptation to climate change depends on the studied period Woo and Thorne (2003); Doxaran et al. (2015); Yang et al. (2015); Matsuoka et al. (2022); Zolkos et al. (2022). Doxaran et al. 2015 claimed a 22% increase of the river discharge from 2003 to 2013. Yang et al. 2015 showed that over the 19732011 period, the positive linear trend for the Mackenzie discharge was very weak ($y = 17.21x + 8947.4$), and Woo and Thorne 2003 found no significant trend for the annual discharge over the period 1968-1999, nor did Matsuoka et al. 2022 for the 1992-2018 period. Meanwhile, several studies agreed that the yearly amount of river discharge has changed its seasonal distribution: cold season discharge becomes slightly higher, but spring flows are lower (as higher air temperatures shift the snowmelt earlier) Woo and Thorne (2003); Yang et al. (2015). The question of the river water discharge, thus, should be regularly reevaluated.

In such a remote and changing environment, satellite observations have been proven to be an efficient tool to monitor the evolution of Arctic coastal zones, and compensate the lack of field measurements Doxaran et al. (2012); Hill et al. (2013); Juhls et al. (2022). SPM field measurements, although extremely valuable, are usually too sparse for the long-term variability analysis, as most of them are associated with specific summer expeditions (e.g. the recent MALINA Massicotte et al. (2021) and Nunataryuk Lizotte et al. (2023) field campaigns). Overall, during the ice-free season, satellite-derived suspended particulate matter (SPM) concentrations typically vary from 30 g/m^3 in the delta region to 0.5 g/m^3 offshore over the Canada Basin Hilborn and Devred (2022).

Several studies analyzed satellite-derived SPM concentration variability in the southern Beaufort Sea for long time periods (over 10 years), and their results are rather controversial. From 2003 to 2013, Doxaran et al. 2015 found a linear trend with a significant increase in monthly- averaged SPM concentrations at the mouth of Mackenzie River (+46% in 10 years over the river mouth area and +71% in the river delta south to 70°N). Hilborn and Devred 2022 applied *self-organizing maps* method to identify six different regions in the eastern Beaufort Sea using 17 years of MODIS (Moderate Resolution Imaging Spectroradiometer) data and found only one statistically significant trend (negative) for the annual SPM concentration in the deepwater Canada basin area, far offshore the Mackenzie delta. At the same time, Matsuoka et al. 2022 showed a statistically significant increase of dissolved and particulate organic matter concentrations (but not fluxes) in late summer: 0.019 g/m^3 *per year* and 0.069 g/m^3 *per year*, accordingly).

The present study is a continuation of Doxaran et al.2015, where we analyze the evolution of the SPM concentration in the Beaufort Sea directly influenced by the discharge of the Mackenzie River over the last two decades (2003-2022), using the methodology developed by Doxaran et al. (2012, 2015), this time excluding the complex river delta zone.

2. Materials and Methods

Fig.1a shows the limits of the study area (yellow rectangular) on a quasitrue color daily MODIS composite for August 8, 2016. In this image, the SPM-rich Mackenzie River plume propagates along the coast and northward, partly into the MIZ (marginal ice zone). The variations of SPM concentrations (Fig.1b) from the delta to offshore waters are obvious, which highlights complex processes along this land-sea interface. The field and satellite datasets used in this study, so as the methods used to retrieve and analyze time series of river discharge and SPM concentrations, are detailed hereafter.

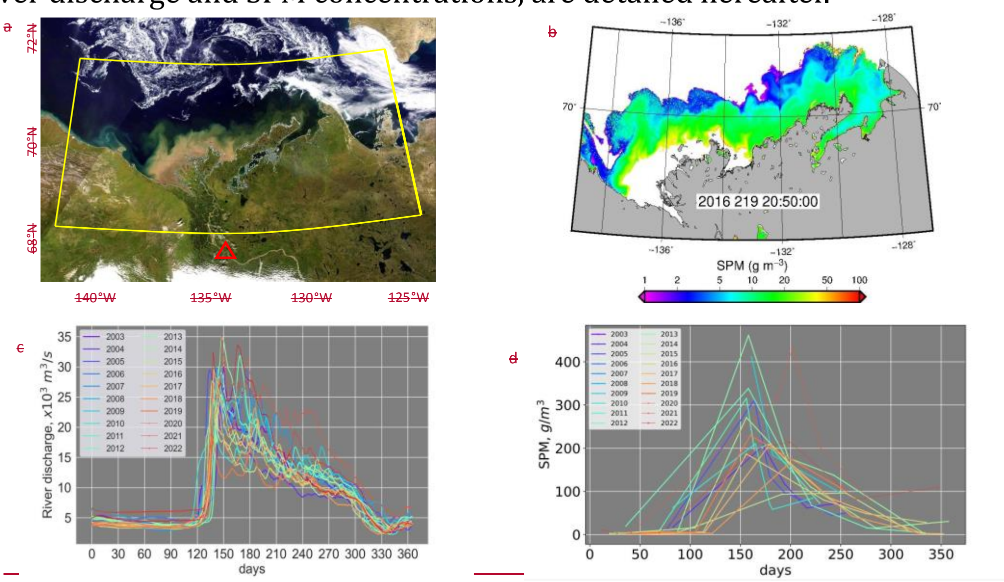


Figure 1: (a) MODIS image (August 6, 2016) locating the Arctic Red River gauge station (Tsiigehtchic) where in situ measurements are carried out (red triangle) and the coastal waters studied using satellite data (yellow rectangle); (b) SPM concentrations: Interannual variations of liquid discharge (c) and SPM concentrations (d) at the Arctic Red River station. The inserted SPM color map shows the result of MODIS satellite data processing

2.1. Field data sets

In situ measurements of the river water discharge (2003-2022) were provided by the Water Survey of Canada via the ArcticGRO project McClelland et al. (2023) at the Arctic Red River gauge station (station ID: 10LC014, 67.45°N 133.74°W, red triangle in Fig.1a). River discharge measurements, Q, are available daily (Fig.1c). The measurements of suspended matter are distributed by the ArcticGRO as *total suspended solids (TSS)* concentrations, which is the same as SPM, so hereafter we will refer to in situ *TSS* as the

SPM_{insitu}. The SPM_{insitu} data were collected at most once per month, but not during all months (on average, 4 to 6 measurements per year, Fig.1d). Over the studied period, some years are poorly represented (one measurement per year in 2003, 2006, and 2007; no SPM measurement in 2008). The lack of SPM in situ data implies the necessity to use satellite data.

The ArcticGRO in situ datasets pass the quality control procedure and indicate less reliable measurements as ”provisional data”. Over the 2003-2022 period, it corresponds to river discharge data in 2020-2022 and SPM_{insitu} data in 2019–2022 (shown with thinner lines in Fig.1c, d).

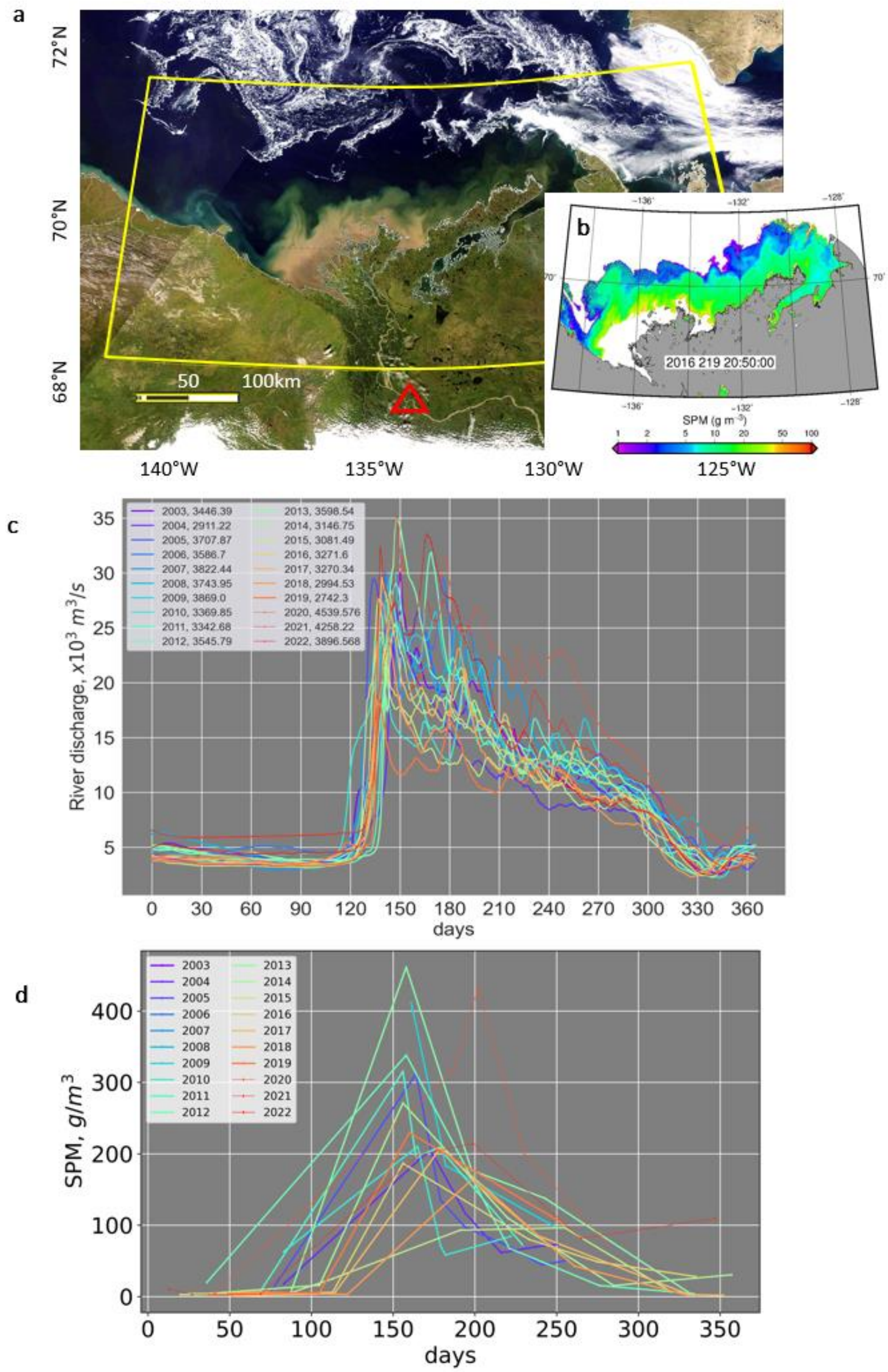


Figure 1: (a) MODIS image (August 6, 2016) locating the Arctic Red River gauge station (Tsiigehtchic) where in situ measurements are carried out (red triangle) and the coastal waters studied using satellite data (yellow rectangle); (b) SPM concentrations: Interannual variations of water discharge (the year of measument and

the annual cumulative sum of discharge is indicated in legend), (c) and SPM concentrations (d) at the Arctic Red River station. The inserted SPM color map shows the result of MODIS satellite data processing

2.2. *Ocean color satellite data*

As in Doxaran et al. 2015, a single satellite sensor (MODIS/Aqua) was considered for this study in order to avoid any bias between different sensor products when detecting temporal trends. Since 2003, MODIS provides high-quality ocean color observations at a good temporal resolution: several images per day of the study area during the Arctic summer months Doxaran et al. (2012, 2015); Hilborn and Devred (2022); Matsuoka et al. (2022). The region of interest was defined as 68.5°N-72°N, 142°W - 124°W (yellow rectangle in Fig.1a). The initial dataset contained 10608 swaths collected between May 1 and October 31 each year over the 2003-2022 period.

Processing of satellite data. MODIS L1A satellite data were processed using the SeaWiFS Data Analysis System (SeaDAS 8.1.0) software (http://seadas.gsfc.nasa.gov/) and its l2gen function. The atmospheric correction was performed using the NIR–SWIR algorithm of Wang and Shi 2007); this method was proved to be the most appropriate for the highly turbid waters at the mouth of the Mackenzie River to the less turbid waters offshore Doxaran et al. (2012).

SeaDAS l2gen flags were used to mask clouds and glint. In the work of Doxaran et al. 2015, two techniques were used to mask clouds: the default one in the coastal waters and an increased cloud albedo threshold value (0.4 instead of 0.027) over the specific area of the river delta zone to avoid masking the highly turbid water pixels. This procedure was time-consuming and required an additional inspection of every image in the river delta zone. Here, the cloud-masking method preconized by Ody et al. 2022 for river mouths was used to process each satellite image only once: the 2130 nm shortwave-infrared waveband was used with a cloud threshold of 0.018. The sea ice mask was computed from daily sea ice concentration (SIC) data at 3.125°spatial resolution distributed by the University of Bremen Spreen et al. (2008). This dataset contains AMRS-E and AMSR2 (Advanced Microwave Scanning Radiometer -for Eos and -2) images. Due to several gaps in data acquisition over the 2003-2022 time period, the dataset was completed with the sea ice concentration from the SSMIS (Special Sensor Microwave Imager/Sounder) instrument. The ice mask was created using the SIC above 0%.

All satellite data (Rayleigh-corrected reflectances and masks) were reprojected on a regular 250 m grid. The following criteria were then applied to exclude potentially contaminated images:

- the number of valid pixels should exceed 15% of the marine area of the study area in the downloaded MODIS image;

- the distance between the central point of the study area and that of the MODIS image should be less than 1000 km to avoid aberrations on the border of the image;
- only areas with a zenith solar angle lower than 74°were conserved.

This automatic filtering reduced the MODIS collection to 700 images. Finally, all images were inspected visually to filter out the remaining contaminated images because of not detected MIZ, clouds or cloud shadows, etc.; 651 MODIS images remained after this last quality check step.

The SPM concentrations were computed from the ratio (in %) between the remote sensing reflectance signals, Rrs (in sr^{-1}) in the near-infrared and green wavebands using the set of relationships established based on field measurements Doxaran et al. (2012, 2015):

$$SPM_{sat} = 0.8386 \times R_{RS}(748:555) \qquad (1)$$

if $R_{RS}(748:555) < 87\%$

$$SPM_{sat} = 70+0.1416\times R_{RS}(748:555)+2.9541\times e^{0.2092\times(R_{RS}(748:555)-87)} \qquad (2)$$

if $87\% \leq R_{RS}(748:555) \leq 94\%$

$$SPM_{sat} = 3.922 \times R_{RS}(748:555) - 285.4 \qquad (3)$$

if $94\% < R_{RS}(748:555)$, where SPM_{sat} is the SPM concentration in g/m^3 and $R_{RS}(748:555)$ is the ratio of remote-sensing reflectances at 748 and 555 nm.

Negative $R_{RS}(555)$ and $R_{RS}(748)$ values were discarded before computing SPM, as well as computed SPM concentrations higher than 1000 g/m^3, to remove atmospheric correction failures and residual contaminations (typically encountered along borders of clouds or sea ice).

The processed SPM images were averaged as daily, monthly, and yearly composites as simple mean averages for every pixel. Only daily composites and their mean values were used further, as monthly composites were sometimes computed using only 1 to 3 cloud-free images, which is not representative of mean monthly concentrations.

2.3. Reanalysis data

A dataset from ERA5 Land reanalysis was extracted to better understand how environmental factors did impact the Mackenzie River discharge and SPM concentrations in the adjacent coastal waters. This dataset was selected as the most suitable tool for the studies of river discharge variability Winkelbauer et al. (2022). ERA5 Land has a monthly temporal resolution and 9-km spatial resolution and is provided by Copernicus data center ~~Mun˜oz~~Munõz-Sabater et al. (2021). The area of extraction approximately corresponds to the Mackenzie drainage basin (52-70°N, 100-140°W). The following parameters were used: river runoff (ro), surface river runoff (sro), evaporation (e), total precipitation (tp), snow depth (sd), and air temperature at 2m (t2m), (see de-detailed description at https://confluence.ecmwf.int/display/CKB/ERA5-Land%3A+data+document The Pearson correlation matrix for the mean annual values of all described parameters (Fig.A.3).

tailed description at https://confluence.ecmwf.int/display/CKB/ERA5-Land%3A+data+document The similarity between the ERA5-LAND river runoff and the Arctic GRO river discharge are shown in the Supplementary Information section (Fig.), as well as a correlation matrix for the mean annual values of all described parameters (Fig.SI2).

To include a possible effect of storms on the SPM concentrations, we added to the analysis the wind data from ERA5 (marine area similar to that chosen for the MODIS study box). The Pearson correlation matrix (where the yearly parameters are compared) contains an additional parameter ”the number of days of storms per year” (*ndays storm* in Fig. A.3). The day was considered stormy if over the study area there was a wind vector with a wind speed over 15 m/s.

2.4. Temporal variability

As previous works have shown, the linear regression model provides relatively little information on interannual variability of river water discharge and related parameters, such as SPM, because, over the long term, the discharge appears as stable Yang et al. (2015); Matsuoka et al. (2022). Over the last 20 years, the linear trend for the in situ Mackenzie discharge time series calculated with the Ordinary Least Squares (OLS) model is y = 17.1x+9554 with a standard error (SE) of 63.6 m^3/s, and confidence intervals (CI) [0.025 0.975] equal to -107.5 and 141.7 m^3/s for the coefficient term. Although these results are very close to that of Yang et al. 2015, the statistical metrics confirm that the OLS model is not suitable for the analysis in this case.

For this reason, we used an estimating regression model with unknown break-points, which allows describing several temporal trends Muggeo (2003). To apply this model to our datasets, we used the *segmented* function in the R package *segmented*.

To compute the trends, the in situ data time series of daily river discharge (Q_{insitu}) and SPM concentration (SPM_{insitu}) described above were used (Fig.2a, b). For the satellite data, the spatial sparsity of observations was taken into account. Thus, to obtain SPM_{sat} time series, we calculated: • one daily spatial mean SPM value for all available SPM pixels over the study area, which resulted in SPM_{sat} time series (Fig.2 c-d); • one daily spatial mean SPM value for the area with the highest data density (where valid satellite pixels appear more than 200 times over the 2003-2022 period), which resulted in SPM_{sat200} (Fig.2 e-f)

Then the segmented regression analysis technique was applied to all time series: Q_{insitu}, SPM_{insitu}, SPM_{sat}, and SPM_{sat200}. After several tests, the most statistically significant results were obtained with one breaking point and two segment slopes. The following statistical parameters were computed for each segment: estimated coefficient of linear regression (Est.), standard error, lower and upper 95% confidence intervals (CI(95%).l, CI(95%).u, respectively) (Tab.1).

3. Results and Discussion

The seasonal cycles of both the river discharge, *Q*, and SPM_{insitu} are very pronounced, with high summer and low winter values (Fig.1c,d). These parameters also have a strong interannual variability. During the 2003-2022 period, the river discharge varied from 2.2×10^3 m^3/s (winter) to 35.2×10^3 m^3/s (summer), with a mean value of $9.5\pm6.8\times10^3$ m^3/s. Typically, the discharge increases very rapidly in 2 weeks from 5 to 25×10^3 m^3/s in late May, when the main summer peak occurs, then slowly decreases to its winter values by November.

The years 2013 and 2021 were exceptional with extreme *yearly maxima* of river discharge over 35×10^3 m^3/s on May 28 (both), while the lowest yearly maximum river discharge, 18×10^3 m^3/s, was registered on May 18, 2019. Previously, Yang et al. 2015 also observed similar prominent interannual variations in the river discharge during the summer (e.g., in 1992 and 1995 for the 1972-2011 period). They concluded that a negative anomaly in precipitation-evaporation balance over the river basin in summer (hot and dry weather) usually results in a lower discharge the next year with an earlier maximum, while the opposite (cold and wet) weather is responsible for a higher discharge. This statement does not explain the extreme peak of discharge recorded in 2013: in 2012 the summer was "hot and dry", so 2013 should have been a year of extremely low summer river discharge. Overall, calculated correlations between in situ river discharge and ERA5 Land total precipitation, as well as air temperature were weak (0.36 and -0.23, respectively).

However, the river discharge is well correlated with snow depth cover (correlation coefficient between Q_{insitu} and *sd* is 0.67): the 2011-12 and ~~201213~~2012-13 winters were ~~very~~ snowy (+10% and +3% *sd* anomaly compared to 20years median values), as well as the 2020 winter (+7% *sd* anomaly), but 2018-19 snow cover was weak (-7% *sd* anomaly). Interestingly, in 2013 the yearly means of river discharge and air temperature were close to their 20years median values, indicating the overall stability of the system during this period.

The river discharge regime in 2006-2008 and 2012 was special with two summer *Q* maxima, the first one in late May and the second between the end of June and mid-July. The reason for this change in river regime might be related to the precipitation seasonal pattern and the river ice opening (several ice jams crushes, creating the second peak). To investigate these particularities, a higher temporal resolution reanalysis data should be used. We also observe local maxima (values higher than the previous year) in SPM_{sat} in 2006, 2008, and 2012.

As explained in section 2.4, the OSL model does not highlight a statistically significant trend in the river discharge time series, but the *segmented* model does. Fig.2 and Table 1 present the results of calculated segmented regressions, where the river discharge and SPM concentrations demonstrate very similar trends: a negative trend from 2003 to 2018, then a recent positive trend from 2019 (2018 for SPM_{insitu}) to 2022 (Fig.2). Based on the confidence intervals, we conclude that negative trends for $slope1_Q$, $slope1_{SPMsat}$, and $slope1_{SPMsat200}$ are statistically significant (CIs [0.025 0.975] are all negative).

This negative trend of $slope1_Q = -57.21x + const$ in river discharge for the 2003-2018 period is opposite to that of Doxaran et al. 2015 for the 20032013 period, but the latter study slightly overestimated the river discharge in 2013 (as the data was not yet fully quality-checked) resulting in an erroneous positive (+22%) trend. As already mentioned, other studies, e.g. Yang et al. (2015); Matsuoka et al. (2022) which used an OSL model did not find any significant trend in the Mackenzie River discharge. The positive trend from 2019 to the present, $slope2_Q = 640.05x + const$, although not statistically significant, can indicate a progressive increase in the minimum flow impacted by a ”mobilization of ground waters” as discussed by Yang et al. 2015.

In situ data show that the SPM seasonal cycle generally follows the river discharge cycle, with the summer maxima in late May - beginning of June. The SPM_{sat} values vary from 0.8 to 461 g/m^3 with a median value of 67.7±11 g/m^3. The breakpoint of SPM_{isitu} trends is slightly shifted to 2018, and CIs contain zero, thus indicating that the *segmented* model is less reliable for this dataset. At the same time, the SPM_{isitu} time series has the fewest amount of data, which is not homogeneous in time and is mainly available in summer. It makes it more difficult to interpret with any statistical model. SPM_{sat} and SPM_{sat200} trend analyses show similar results: their negative $slope1$ values and corresponding SE are close to each other, which gives confidence in the observed SPM negative trend. The positive trends $slope2_{sat}$ and $slope2_{sat200}$ are not statistically significant, and their SEs are of the order of the estimated coefficient of linear regression (Tab.1). Nevertheless, this result is interesting for further discussion.

Over the 2003-2019 period, Hilborn and Devred 2022 obtained results in good agreement with a negative trend (although not significant) for SPM concentrations over the southern Beaufort Sea (from -0.16 to -0.46 g/m^3 per decade) except for the Mackenzie River delta, where they found an increase of SPM of 0.36 g/m^3 per decade. The difference in negative coefficients' values obtained in the present study and that of Hilborn and Devred (2022) comes from (1) the difference of SPM-retrieval methods and different MODIS bands used; and (2) the regions: our study region of SPM_{sat200} corresponds to 3 regions over the shelf identified by Hilborn and Devred (2022).

In the Mackenzie delta zone, Doxaran et al. 2015 also found a significant increase of SPM (+71% from 2003 to 2013) over the ”Mackenzie River delta” region of Hilborn and Devred (2022). The delta zone seems to play an important role of “SPM filter” between the river and the coastal waters. Based on satellite observations, SPM apparently settles massively in this shallow area, resulting in the formation of temporary maximum turbidity zones where resuspension of bottom sediments may occur depending on the river discharge, tidal currents, and wind stress (Wegner et al., 2005; Grotheer et al~~. (~~., 2020). Observations at high spatial and temporal resolutions are required to further investigate SPM dynamics in this delta zone.

However, how to explain the negative trends in both river discharge and SPM concentrations ~~(~~in the riverbed and offshore ~~the~~ delta zone~~) derived from field and satellite observations~~ over the 2003-2018 period? ~~The~~ Based on the correlation matrix (Fig. A.3), we recognize that the river runoff and, thus, river discharge variability depend mostly on the amount of total precipitation (r = 0.7) and the snow depth (r = 0.63, which is another estimate of solid precipitation in winter) parameters. This trivial conclusion leads us to a simple suggestion that the Mackenzie River discharge slightly declined while the precipitation pattern has changed over this period.

As for the SPM, the recent study of Zolkos et al. 2022 reveals a similar decrease in SPM loads in most of the ~~Russian Arctic~~ Siberian rivers between 1970 and 2010~~,~~ and explains it by natural and anthropogenic factors. ~~At the same time, the rivers' discharge (mean and peak values)~~The ”natural factors” of sediments erosion over the river basin are the physical and chemical denudation. For the Mackenzie River, the physical denudation rates exceed the chemical denudation about several orders of time: mechanical denudation rate at the Arctic Great River was reported as $844\ t * km^{-2} * y^{-1}$ in 1997, while the chemical weathering occurs at a rate of $25\ mm * ky^{-1}$ with a transport time of 10-400 ky^{-1} (Vigier et al. (2001); DePaolo et al. (2006)). On the order of two decades, it is, thus, physical or mechanical factors related to the river discharge and the atmospheric conditions in the delta-adjacent areas that control SPM concentrations. A simultaneous decline of Q_{insitu} and SPM_{insitu} in 2003–2018 means that the lower the river discharge, the less suspended particulate matter it transports.

Another source of variability for the “marine” SPM might be the wind mixing. The simple hypothesis proposes that the higher the wind speed, the more mixing occurs in a shallow area, which reduces the surface SPM concentrations. At the same time, an additional hypothesis may suggest that more mixing means more re-suspension of particulate matter from the bottom sediments (increasing the SPM concentration). To verify these controversial hypotheses, we must compare quasi simultaneous wind and SPM observations. In the framework of this study there is yet one fundamental limitation for this analysis due to the nature of ocean color data retrieval from satellite: the highest wind speed (and thus mixing events) will mostly occur under the cloud cover with the passage of cyclones, and SPM concentrations cannot be retrieved from ocean color satellite under such conditions (presence of clouds). We found a weak negative correlation (correlation coefficient is *r=-0.19*) between the number of days of storm and annual cumulated SPM, which confirms the first simple hypothesis (more mixing, less SPM), but this question should be addressed additionally with other tools, like modeling.

There is yet a question about the recent positive trends in *Q* and *SPM* over the last 3-5 years of observations. Although the trends are statistically not significant, can we suggest any important processes that might have impacted the river discharge and sedimentation transport recently?

The presence of permafrost over the river basin was considered mostly stable, so the link between the river discharge and SPM load is not straightforward. Zolkos et al. suggest that the decrease of SPM is due to the decrease of the sediments input "and/or increased sedimentation within the fluvial network". Nonetheless, the Kolyma yearly SPM flux has doubled over the same period, which was associated with the geological stratification of more erodible quaternary sediments altering with ice. In the Canadian Arctic "where large areas are susceptible to hillslope thermokarst activity", the permafrost thaw can induce the downstream redistribution of particular sediments over the next "centuries or millennial". We might observe the effect of the sediment accumulation duringas "precluding" for the groundwater's contribution to general river discharge, as it prevented the water infiltration through the permafrost layer, but might have helped to create underground cavities filled with non-communication water reservoirs (Vigier et al. (2001)). With a progressive permafrost thawing and its recent release in SPM measurements.

The permafrost thaw likely controls as well the drainage of lakes located in the permafrost area Webb and Liljedahl (2023)., this neglected role might be re-evaluated. Matsuoka et al. 2022 observed an increase of thaw depth and precipitation, but a decrease in river discharge, which is probably explained by the contribution of ground waters, also suggested by Connolly et al. (2020). Finally,The permafrost thaw also likely affects the drainage of lakes located in the permafrost area Webb and Liljedahl (2023). A recent work of Nitze et al. 2020 described, e.g., a series of extremely quick thermokarst lakes drainage in 2018 in northwestern Alaska after the unprecedented warm (with air temperature close to 0°C) and wet winter of 2017-2018. This drainage "exceeded the average drainage rate by a factor of 10", and is supposed to continue and increase the liquid and solid discharges of Arctic rivers. This situation suggests that in the Canadian Arctic, where "large areas are susceptible to hillslope thermokarst activity" (Zolkos et al. (2022)), the permafrost thawing will progressively change chemical denudation and induce the downstream redistribution of sediments over the next millennial(s).

Based on these results, we conclude that the following mechanism ex-

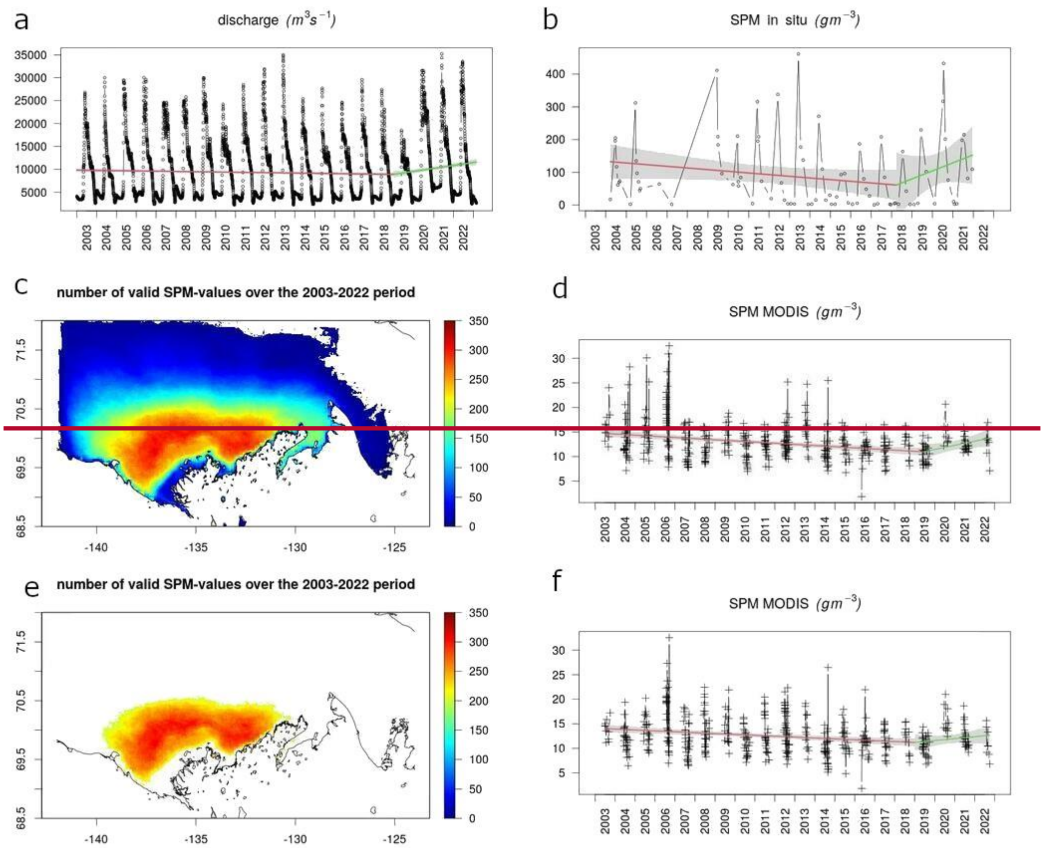
Table 1: Statistics for the segmented linear regression analysis of in situ river discharge (Fig.2a) - $slope_Q$; trends of SPM_{insitu}: $slope_{insitu}$ (Fig.2b); trends of SPM_{sat} for all available points: $slope_{sat}$ (Fig.2d); and trends for SPM_{sat} for the area with over 200 pixels available: $slope_{sat200}$ (Fig.2f). Negative trend parameters are described with *slope*1, positive with *slope*2

	Est.	Standard error	CI(95%).l	CI(95%).u
$slope1_Q$	-57.21	19.14	-94.73	-19.68
$slope2_Q$	640.05	142.91	359.88	920.19
$slope1_{insitu}$	-5.08	3.04	-11.13	0.96
$slope2_{insitu}$	24.46	21.86	-19.02	67.93
$slope1_{sat}$	-0.23	0.04	-0.32	-0.15
$slope2_{sat}$	0.84	0.43	-0.01	1.70
$slope1_{sat200}$	-0.18	0.04	-0.27	-0.09
$slope2_{sat200}$	0.39	0.40	-0.40	1.18

plains the observed negative trend in river discharge and SPM concentrations switched by a rapid positive trend: the progressive thaw of the permafrost helped to accumulate sediments in the ground inner impermeable layers up to the certain moment (appr. 2018), then these additional sediments arrived into the groundwater, and together with the drainage of lakes, the accumulated sediments started its quick release with groundwater into the main surface flow and the Beaufort Sea.

4. Conclusion

Twenty years (2003-2022) of in situ measurements (river discharge and SPM concentration at the Arctic Red River station) and satellite-derived SPM concentrations were analyzed to describe the evolution of SPM inputs in the Beaufort Sea by the Mackenzie River and its impact on the adjacent coastal waters. Using the segmented regression model, we showed two opposite trends over the last 20 years for both the river freshwater discharge and SPM concentration. Over the studied period, we observe a statistically significant negative trendtrends from 2003 to 2018-2019, then a positive trend from 2019 to 2022 for both river discharge and SPM concentrations. Our results extend previous estimations of Doxaran et al. 2015 and tend to confirm other long-term observations showing a rather stable freshwater discharge of the Mackenzie River, increasing SPM concentrations in the delta zone and a significant decrease in SPM concentration in adjacent



~~Figure 2: Interannual variations of in situ and satellite data (river discharge and SPM) with their segmented linear regression slopes (red and green colors show negative and positive regressions, respectively): (a) river discharge Q_{insitu}; (b) SPM_{insitu} time series; (c) maximum number of valid SPM_{sat} pixels in 2003-2022 (d) satellite SPM_{sat} time series;~~

~~(e-f) similar to (c-d), but for the area with at least 200 valid pixels~~

coastal waters Feng et al. (2021); Hilborn and Devred (2022); Matsuoka et al. (2022).

We suggest that the observed variability indicates a ~~recent progressive accumulation of sediments during the permafrost thaw, its further release into the drainage system, Mackenzie flow, and finally into the Beaufort Sea since 2018. An important snow accumulation followed by a spring thawing with extreme air temperatures aggravates the drainage and sediment accumulation and release on the medium-term timescale.~~ simultaneous decline of water discharge and, thus, suspended particulate matter transport due to changing precipitation pattern, especially the amount of snow over the river basin with a possible role of wind-induced mixing in the marine area. We also discuss along-term effects of climate change and permafrost thawing on the sediment transport rate in the Mackenzie River.

These processes of SPM release into the Arctic Ocean should be studied next on a pan-Arctic scale: can we expect a similar behavior based on the regional variations of river discharges reported by ArcticGRO? A recent study of Zolkos et al. 2022 used only in situ data, and further analysis of SPM distribution into the Arctic Ocean with satellite data will be beneficial. Studying the seasonal variability for specific years (e.g., 2006-2008, 2012) is also required using higher resolution data, including satellite imagery, to better understand changing river regimes in Arctic regions.

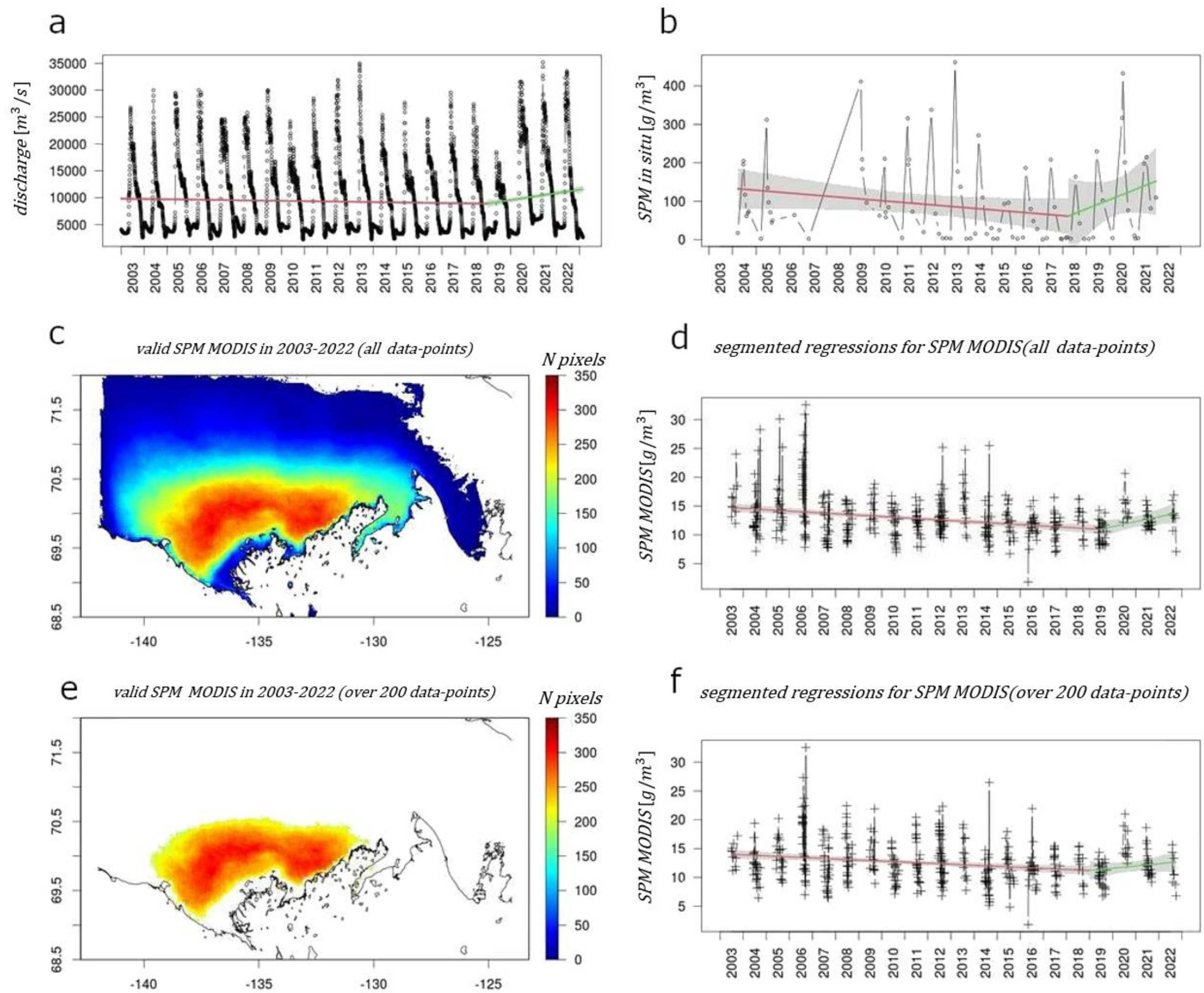


Figure 2: Interannual variations of in situ and satellite data (river discharge and SPM) with their segmented linear regression slopes (red and green colors show negative and positive regressions, respectively): (a) river discharge Q_{insitu}, (b) SPM_{insitu} time series; (c) maximum number of valid SPM_{sat} pixels in 2003-2022 (d) satellite SPM_{sat} time series;

(e-f) similar to (c-d), but for the area with at least 200 valid pixels

5. Data availability

In situ measurements described in section 1 (river water discharge and TSS) are provided at https://arcticgreatrivers.org/data/. MODIS data is accessible from the NASA website https://oceancolor.gsfc.nasa.gov. Sea ice concentrations are available at ~~https://seaice.uni-bremen.de/data-archive/.~~https://seaice.uni-bremen.de/data-archive/. ERA5 LAND reanalysis data can be found at https://doi.org/10.24381/cds.68d2bb30 with a detailed description at https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation, and ERA5 wind data is available at https://doi.org/10.24381/cds.adbb2d47 with a detailed description at

~~ERA5 LAND reanalysis data can be found at https://doi.org/10.24381/cds.68d2bb30.~~

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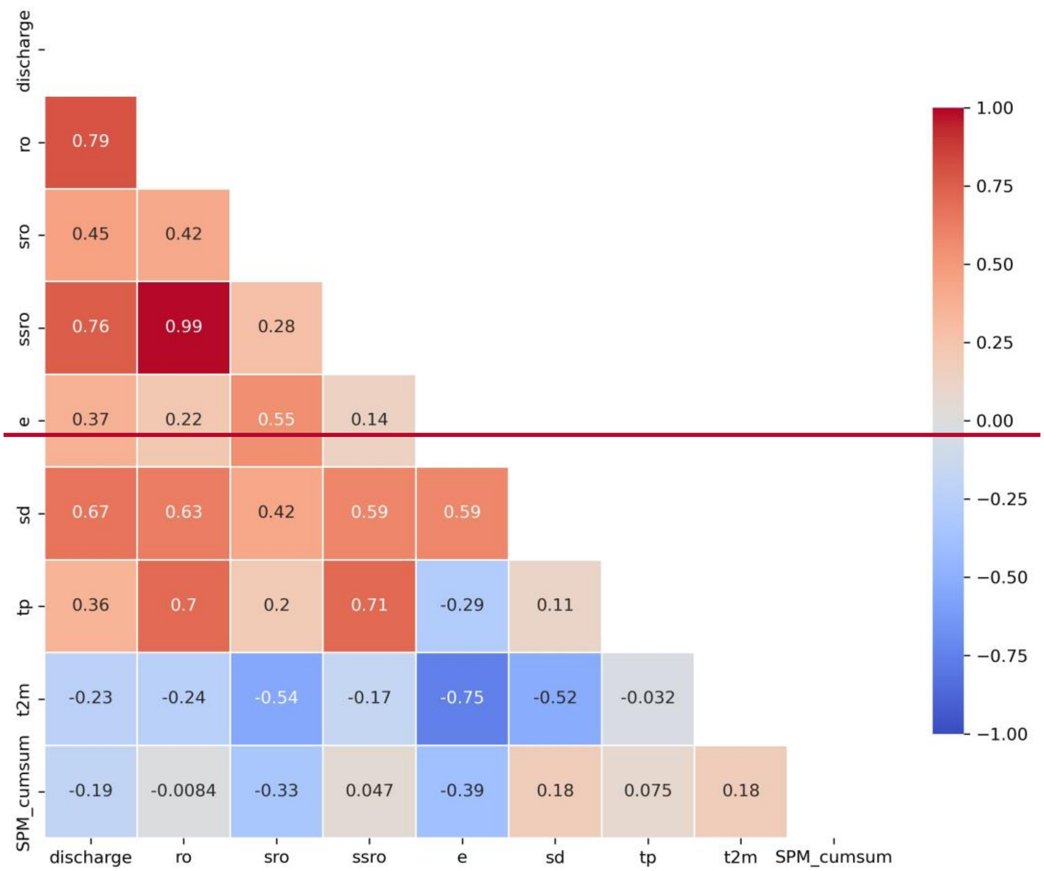
No conflict of interest is stated.

Appendix A. ERA5-Land

The appendix contains Fig.A.3 illustrating correlation between ERA5 parameter, the Mackenzie discharge from the Arctic GRO dataset, and in situ and satellite SPM concentrations.


discharge
ro
sro
ssro
e
sd
tp
t2m
SPM_cumsum
0.79
0.45 0.42
0.76 0.99 0.28
0.37 0.22 0.55 0.14
0.67 0.63 0.42 0.59 0.59
0.36 0.7 0.2 0.71 -0.29 0.11
-0.23 -0.24 -0.54 -0.17 -0.75 -0.52 -0.032
-0.19 -0.0084 -0.33 0.047 -0.39 0.18 0.075 0.18
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00

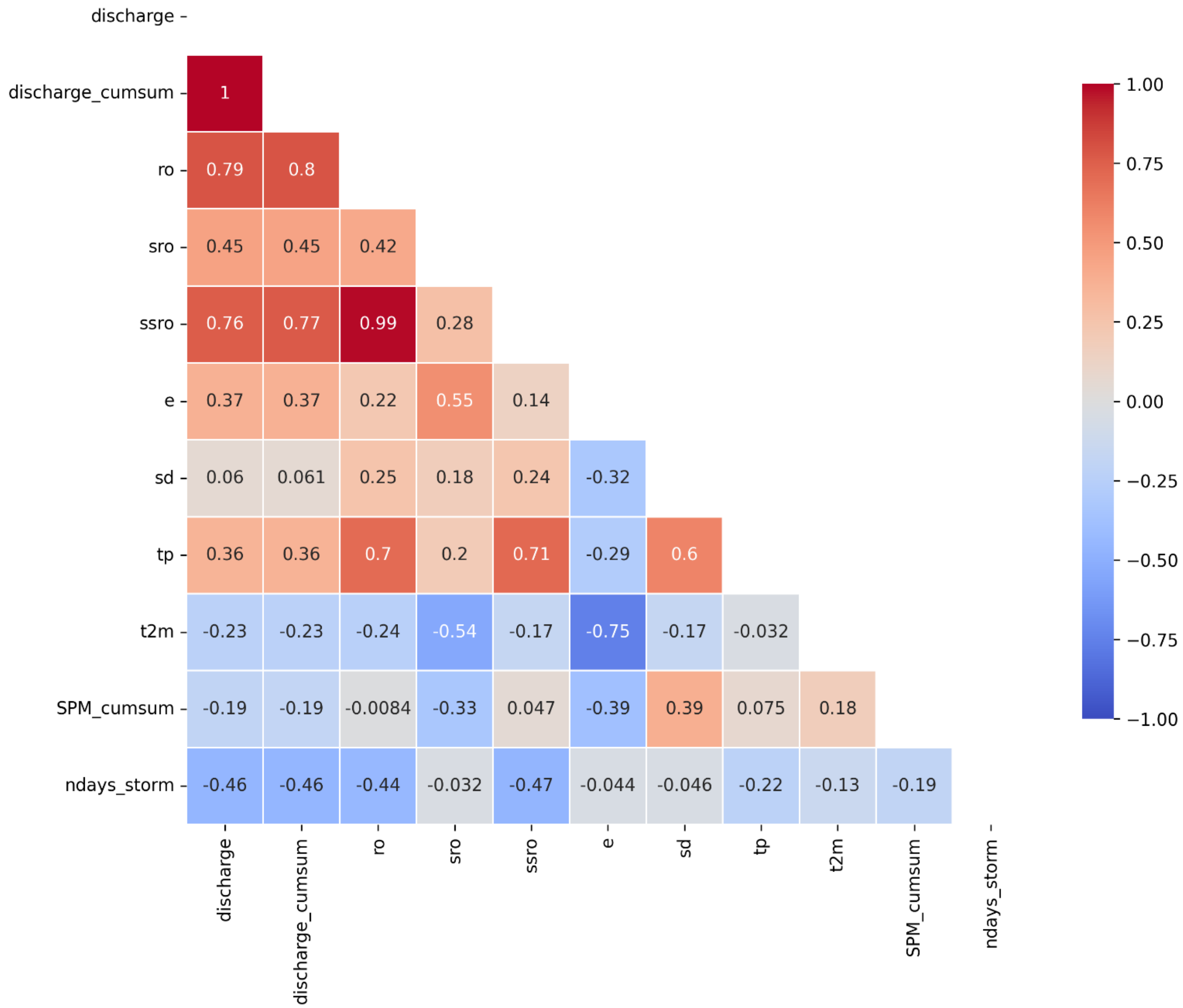


Figure A.3: Correlation matrix of all mean yearly reanalysis (ERA5 LAND) parameters over the Mackenzie basin and in situ (Arctic GRO) discharge for Mackenzie (Arctic Red station). ERA5 Land parameters are described in main text (ro - total runoff, sro surface runoff, ssro - subsurface runoff (ssro = ro-sro), e - evaporation, sd - snow depth, tp - total precipitation, t2m - air temperature at 2 m, SPM_{cumsum} - annual cumulated SPM concentrations, discharge - Arctic GRO in situ discharge).

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Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Credit Author Statement

AT has written the original and revised manuscript, participated in the investigation, visualization and data analysis. DD did the conceptualization, project administration, supervision and manuscript revision and editing. BG did the data curation, formal analysis, visualization and manuscript editing.