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Key Points:

- Satellite observations of chromophoric dissolved organic matter and salinity effectively trace coastal river water (RW) and offshore sea ice melt (SIM) in Hudson and James Bays (HJB)
- Satellite data show increasing surface RW in HJB over the summer despite declining river discharge
- Satellite data suggest rising RW fraction and declining SIM fraction in HJB surface waters from 2011 to 2019

Supporting Information:

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

Correspondence to:

J. K. Ehn,
Jens.Ehn@umanitoba.ca

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Author Contributions:

Conceptualization: Atreya Basu, Simon Bélanger, Zou Zou A. Kuzyk, Jens K. Ehn

Data curation: Atreya Basu, Alessia C. Guzzi, Emma L. Ausen

Formal analysis: Atreya Basu, Rakesh K. Singh, Soham Mukherjee, Alessia C. Guzzi, Emma L. Ausen

Funding acquisition: Zou Zou A. Kuzyk, Jens K. Ehn

Investigation: Atreya Basu

Methodology: Atreya Basu

Project administration: Alessia C. Guzzi, Emma L. Ausen

Resources: Zou Zou A. Kuzyk, Rakesh K. Singh, Pierre Larouche, Alessia C. Guzzi, Emma L. Ausen, Greg McCullough, Jens K. Ehn

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Satellite Data Trace Seasonal Freshwater Dispersion in Hudson and James Bays

Atreya Basu¹ , Simon Bélanger², Zou Zou A. Kuzyk¹ , Rakesh K. Singh³, Soham Mukherjee² , Pierre Larouche^{4,5} , Alessia C. Guzzi¹, Emma L. Ausen¹ , Greg McCullough^{1,5}, and Jens K. Ehn¹ 

¹Center for Earth Observation Science, University of Manitoba, Winnipeg, MB, Canada, ²Département de Biologie, Chimie et Géographie, Université du Québec à Rimouski, Rimouski, QC, Canada, ³Pixxel Space, Bengaluru, India, ⁴Maurice Lamontagne Institute, Mont-Joli, QC, Canada, ⁵Retired

Abstract Freshwater dispersal controls stratification, circulation, and biogeochemical processes in Hudson and James Bay (HJB); however, limited field observations hinder understanding of how different freshwater types drive change. This study uses Aqua-Moderate Resolution Imaging Spectroradiometer and Soil Moisture and Ocean Salinity-Microwave Imaging Radiometer using Aperture Synthesis data to distinguish and map river water (RW) and sea ice melt (SIM), the main freshwater types in HJB. Satellite-derived RW and SIM agree with in situ tracers, filling field data gaps that support future freshwater research. Higher RW fractions up to 0.40 in southern HJB and a seasonal SIM decline from 0.35 to 0.00 in central HJB match observed patterns. RW spreads offshore in July, contracts in August, and forms a coastal band in September, sustained by cyclonic winds despite reduced discharge. From 2011 to 2019, RW fractions increased (0.0048 yr^{-1}) while SIM fractions declined (-0.003 yr^{-1}) across HJB.

Plain Language Summary To address the scarcity of field observations in remote polar waters, this study explores whether satellite-derived chromophoric dissolved organic matter (CDOM) (Aqua-Moderate Resolution Imaging Spectroradiometer) and sea surface salinity (Soil Moisture and Ocean Salinity-Microwave Imaging Radiometer using Aperture Synthesis) can effectively trace freshwater dispersion in Hudson and James Bay (HJB) over space and time. In HJB, the two main types of freshwaters, river water (RW) and sea ice melt (SIM), cannot be distinguished by the sea surface salinity tracer alone, as both have low salinity. CDOM was added as a tracer since RW is rich in CDOM, while SIM has almost none, enabling their distinction. The results show that satellite-derived RW and SIM estimates match those from field-measured salinity and oxygen isotopes. The satellite data capture the main spatial patterns of freshwater distribution in HJB, including more RW in southern HJB than in the north, concentration of RW into a coastal corridor because of wind-driven circulation, and seasonal decline of SIM throughout summer in central HJB. From 2011 to 2019, satellite data showed that RW presence increased while SIM decreased in the surface waters of HJB. This satellite approach fills in the gaps from field studies and supports future freshwater research as sea ice cover declines and river discharge evolves in HJB.

1. Introduction

River water (RW) and sea ice melt (SIM) are the primary freshwater sources in the coastal Arctic, including Hudson and James Bays (HJB, Figure 1a), where they influence circulation, stratification, and biogeochemical processes (Deschepper et al., 2023; Prinsenberg, 1986a, 1986b; Ridenour, Hu, Jafarikhazragh, et al., 2019; Ridenour, Hu, Sydor, et al., 2019). While salinity quantifies total freshwater, distinguishing RW and SIM contributions requires additional tracers. In the Arctic Ocean and HJB, oxygen isotope ratio ($\delta^{18}\text{O}$) combined with salinity distinguishes isotopically light RW from heavy SIM (Ahmed et al., 2020; Granskog et al., 2011; Kuzyk et al., 2008; Östlund & Hut, 1984). Other tracers, including alkalinity, salinity, and temperature, were used to trace freshwater in HJB (Jones & Anderson, 1994). Several other studies have incorporated, alongside salinity and $\delta^{18}\text{O}$, in situ measurements of chromophoric dissolved organic matter (CDOM), as this is an effective tracer of freshwater derived from the CDOM-rich HJB watershed (Évrard et al., 2023; Granskog, 2012; Granskog et al., 2007, 2009; Guéguen et al., 2011, 2016). However, these approaches rely on sparse, late summer ship-based observations, which limit the spatiotemporal assessment of freshwater variability in HJB, despite documentation

Supervision: Simon Bélanger, Zou Zou A. Kuzyk, Jens K. Ehn
Validation: Atreya Basu, Soham Mukherjee
Visualization: Atreya Basu, Emma L. Aussen
Writing – original draft: Atreya Basu
Writing – review & editing: Atreya Basu, Simon Bélanger, Zou Zou A. Kuzyk, Rakesh K. Singh, Soham Mukherjee, Pierre Larouche, Alessia C. Guzzi, Emma L. Aussen, Greg McCullough, Jens K. Ehn

of opposing trends in river discharge (increasing) and sea ice extent (decreasing) in HJB (Crawford et al., 2021; Feng et al., 2021; McCullough et al., 2019; Tivy et al., 2011).

In contrast to field data, satellite remote sensing offers synoptic and temporal tracing of surface water properties. Satellite-derived sea surface salinity (S^{sat}) supports freshwater monitoring in high latitude seas but cannot distinguish RW from SIM (Supply et al., 2020). In HJB, S^{sat} and altimetry have been used to quantify freshwater stored in sea ice in April (Landy et al., 2017). Here, we combine ocean color observations with S^{sat} to separate CDOM-rich RW from CDOM-poor SIM during summer, similar to an approach applied in the Beaufort Sea (Matsuoka et al., 2016). However, HJB is particularly well suited for satellite-based freshwater tracing due to its large river inflows, high CDOM export, seasonal ice cover, shallow bathymetry (<350 m), isolation from other oceans, and large spatial extent (>800,000 km²) (Martini, 1986; Pelletier, 1986; Figure 1a, Text S1 in Supporting Information S1).

The objectives of the study are the following:

1. Determine RW and SIM fractions in the surface water of HJB during summer using satellite-derived CDOM and S^{sat} , referenced to fractions calculated using in situ (salinity- $\delta^{18}\text{O}$) methods.
2. Evaluate satellite-based RW and SIM tracing in HJB by assessing spatial and temporal patterns relative to established trends.
3. Assess seasonal and inter-annual variations of satellite-derived RW and SIM fractions in the surface water of HJB from 2011 to 2019 as a basis for establishing a robust baseline, which could be used to assess change in future decades.

2. Data and Methods

2.1. Field Data

Surface waters collected from HJB between 2005 and 2021 ($n = 110$, Figure 1a) were analyzed in the laboratory for CDOM absorption coefficient at 412 nm ($a_{\text{CDOM}}^{\text{lab}}$ (412), m⁻¹; Bricaud et al., 1981), salinity (S^{lab} , Practical salinity unit), and $\delta^{18}\text{O}^{\text{lab}}$ (‰) (Text S2 in Supporting Information S1).

Linear relationship between $\delta^{18}\text{O}^{\text{lab}}$ and S^{lab} (Figure 1b, $R^2 = 0.91$, $p < 0.001$, $\delta^{18}\text{O}^{\text{lab}} = 0.32 S^{\text{lab}} - 12.66$) was used to estimate $\delta^{18}\text{O}^{\text{lab}}$ sea water (SW) endmember. Mass balance Equations 1–3 were solved for in situ RW, SIM, and SW fractions within each sample, using appropriate S^{lab} and $\delta^{18}\text{O}^{\text{lab}}$ endmembers (Östlund & Hut, 1984) (Text S3 in Supporting Information S1).

$$\text{RW} + \text{SIM} + \text{SW} = 1 \quad (1)$$

$$\text{RW } S_{\text{RW}} + \text{SIM } S_{\text{SIM}} + \text{SW } S_{\text{SW}} = S^{\text{lab}} \quad (2)$$

$$\text{RW } \delta^{18}\text{O}_{\text{RW}} + \text{SIM } \delta^{18}\text{O}_{\text{SIM}} + \text{SW } \delta^{18}\text{O}_{\text{SW}} = \delta^{18}\text{O}^{\text{lab}} \quad (3)$$

A Type I regression linked $a_{\text{CDOM}}^{\text{lab}}$ (412) with $\delta^{18}\text{O}^{\text{lab}}$ -estimated RW fractions in Hudson Bay (HB) (i.e., for stations north of 55°N latitude as shown by Equation 4 and Figure 1d), and a power law fit described the relationship for James Bay (JB) (i.e., for stations south of 55°N latitude as shown by Equation 5 and Figure 1e).

$$\text{RW} = 0.32 a_{\text{CDOM}}^{\text{lab}} + 0.02, \text{ when latitude} > 55^\circ\text{N} \quad (4)$$

$$\text{RW} = 0.26 (a_{\text{CDOM}}^{\text{lab}})^{0.37}, \text{ when latitude} \leq 55^\circ\text{N} \quad (5)$$

2.2. Satellite Remote Sensing

2.2.1. CDOM and River Water Fraction

Satellite-derived CDOM absorption coefficients ($a_{\text{CDOM}}^{\text{sat}}$, m⁻¹) at 412 nm were obtained using an empirical blue (488 nm) to red (667 nm) remote sensing reflectance (R_{rs} , sr⁻¹) band ratio (BR) (Basu et al., 2023; Doxaran et al., 2005). The red band (667 nm) in BR compensates for suspended solids contamination in the blue band (488 nm), enabling CDOM retrieval (Basu et al., 2023). BR was applied on the NASA Aqua satellite's Moderate

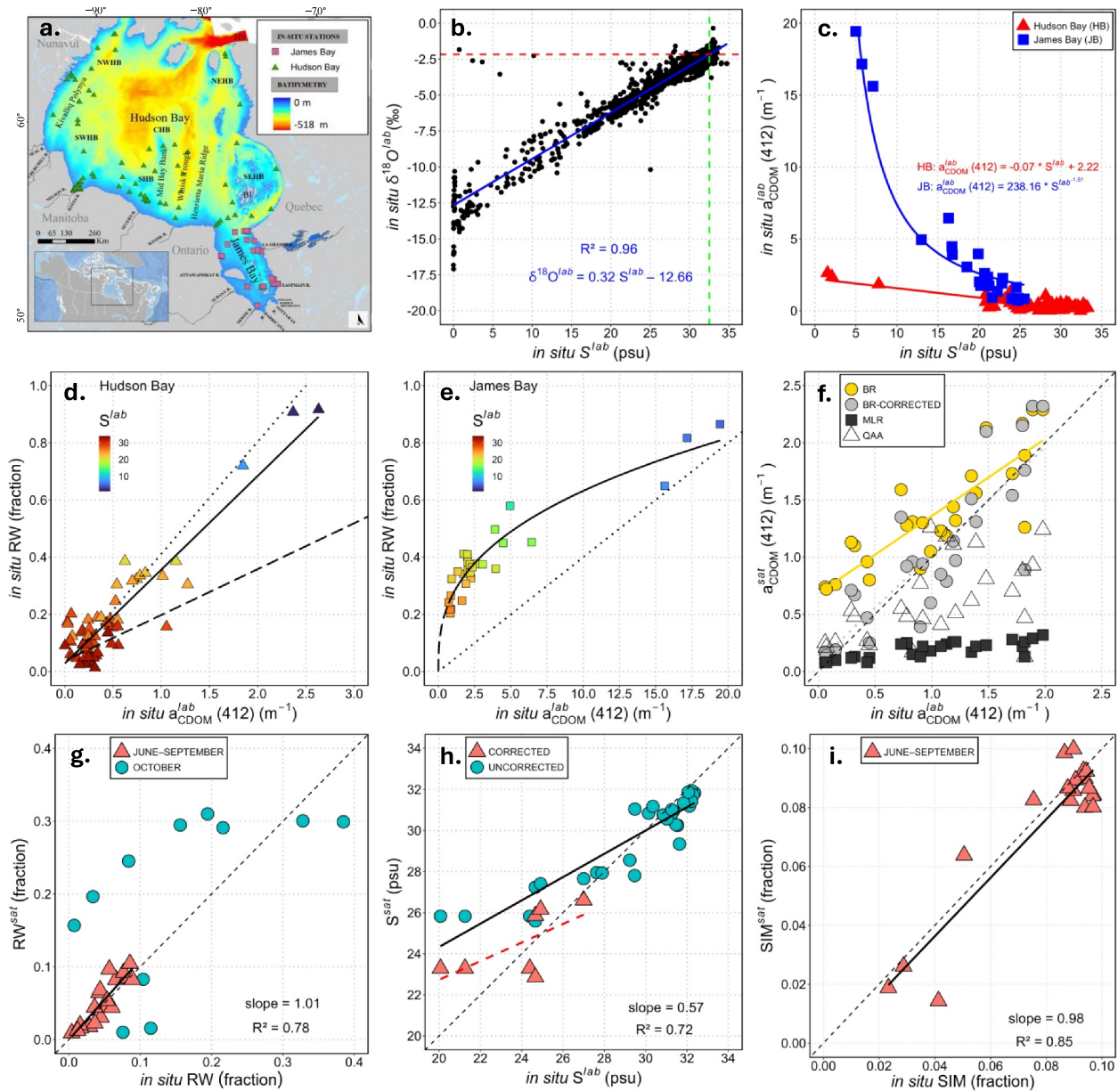


Figure 1. (a) Hudson and James Bay (HJB) study area showing bathymetry, sampling stations, major rivers, key regions, and features: NWHB, SWHB, SHB, SEHB, and CHB (northwestern, southwestern, southern, southeastern, and central Hudson Bay [HB]), Belcher Islands (BI), Hudson Strait (HS), Kivalliq Polynya, Mid Bay Bank, Winisk Trough, and Henrietta Maria Ridge. The inset map shows the location of HJB (black square) within Canada. (b) Relationship between in situ salinity (S^{lab}) and in situ oxygen isotope ratio ($\delta^{18}O^{lab}$) in HJB. Dashed green and red lines show salinity (32.5 psu) and $\delta^{18}O^{lab}$ (-2.16‰) seawater endmembers, respectively. (c) Relationships between in situ colored dissolved organic matter concentration measured at 412 nm, $a_{CDOM}^{lab}(412)$, and in situ S^{lab} in HJB. (d) Linear relationship between in situ river water fraction (RW) and in situ $a_{CDOM}^{lab}(412)$ in HB (solid black line). Dotted and dashed black lines show mixing using in situ $a_{CDOM}^{lab}(412)$ of 2.5 m^{-1} (this study) and 6.4 m^{-1} (Granskog et al., 2007, 2009) at RW = 1, respectively. (e) Non-linear relationship between in situ RW and in situ $a_{CDOM}^{lab}(412)$ in James Bay (solid black and long-dashed curved line extrapolated to zero intercept). Dotted linear line shows mixing using in situ $a_{CDOM}^{lab}(412) = 25 \text{ m}^{-1}$ at RW = 1. (f) Matchup between in situ $a_{CDOM}^{lab}(412)$, and satellite-derived $a_{CDOM}^{sat}(412)$, employing red to blue band ratio, Multiple Linear Regression, and Quasi Analytical Algorithm, v.6 (QAA). The gold line shows fit for $a_{CDOM}^{BR}(412)$ and the gray dotted line shows fit for corrected $a_{CDOM}^{BR}(412)$. (g) Matchup between in situ RW fraction and satellite-derived RW^{sat} fraction, with the solid black line showing the fit. (h) Matchup between in situ S^{lab} and satellite-derived S^{sat} in HB, with the solid black line showing the fit and the red dashed line showing the corrected S^{sat} fit for $S^{lab} \leq 27$ psu. (i) Matchup between in situ sea ice melt fraction (SIM) and satellite-derived SIM^{sat} fraction, with fit shown by the solid black line. The black diagonal dashed lines in panels (f–i) indicate the 1:1 fit.

Resolution Imaging Spectroradiometer (MODIS) imagery ($n = 1,377$ days, 1 km resolution, June–October, 2011–2019). R_{rs} was computed from MODIS Level 1A radiance data and atmospherically corrected using a spectral shape parameter-based algorithm for coastal waters implemented in SeaDAS (Singh & Shanmugam, 2014; Singh et al., 2019).

A match-up analysis between $a_{CDOM}^{sat}(412)$ and $a_{CDOM}^{lab}(412)$ was conducted for 26 stations with a <2-hr difference between satellite overpass and field sampling. The match-up analysis revealed a positive bias in comparison with in situ CDOM, necessitating bias correction using Equation 6 (Text S4 and Table S1 in Supporting Information S1, Figure 1f).

$$a_{CDOM}^{sat}(412) = 1.39 a_{CDOM}^{BR}(412) - 0.86 \quad (6)$$

Within HJB, the corrected $a_{CDOM}^{BR}(412)$ (Equation 6) was used to retrieve satellite-based RW fraction (RW^{sat}), applying Equation 7 for pixels $>55^\circ N$ and Equation 8 for pixels $\leq 55^\circ N$ at 1 km resolution. This regional approach of RW^{sat} retrieval was based on the in situ relationships between $a_{CDOM}^{lab}(412)$ and RW (Equations 4 and 5, Figures 1d and 1e).

$$RW^{sat} = 0.32 a_{CDOM}^{sat}(412) + 0.02 \text{ when latitude } > 55^\circ N \quad (7)$$

$$RW^{sat} = 0.26 (a_{CDOM}^{sat}(412))^{0.37}, \text{ when latitude } \leq 55^\circ N \quad (8)$$

Three-day composites of RW^{sat} (to compensate for missing pixels due to cloud and sea ice cover) were validated against concurrent in situ RW fractions from June ($n = 11$), August ($n = 6$), September ($n = 2$), and October ($n = 10$). The results showed agreement with in situ RW fractions, except for October (Text S5 and Table S1 in Supporting Information S1, Figure 1g).

2.2.2. Sea Surface Salinity, Freshwater, and Sea Ice Melt Fraction

The Soil Moisture and Ocean Salinity (SMOS) satellite's Microwave Imaging Radiometer using Aperture Synthesis sensor maps sea surface salinity (S^{sat}) using L-band interferometry (1.4 GHz, 21 cm). This study used 3-day averaged S^{sat} at 25 km resolution from the Barcelona Expert Centre (BEC) Arctic-SMOS v3 product (2011–2019, Martínez et al., 2022) for estimating surface freshwater content in HJB. S^{sat}_{BEC} was validated against S^{lab} from 32 stations (2016, 2018, and 2019) in HB, showing good agreement for $S^{lab} > 27$ psu (Figure 1h, Equation 9). For $S^{lab} \leq 27$ psu, overestimations in southern and southeastern HB required correction using Equation 10 obtained from the slope and intercept of the match-up (Figure 1h and Table S1 in Supporting Information S1).

$$S^{sat} = S^{sat}_{BEC}, \text{ when } S^{sat}_{BEC} > 27 \text{ psu}, \quad (9)$$

$$S^{sat} = 1.82 S^{sat}_{BEC} - 23.7, \text{ when } S^{sat}_{BEC} \leq 27 \text{ psu}. \quad (10)$$

Satellite-derived surface freshwater fraction (FW^{sat}) of each pixel was estimated from corrected S^{sat}_{BEC} at 25 km resolution:

$$FW^{sat} = 1 - S^{sat}/32.5, \quad (11)$$

which is based on the linear relationship between in situ FW ($RW + SIM$) and S^{lab} (i.e., $FW = 1 - S^{lab}/32.5$). Resampled RW^{sat} was subtracted from FW^{sat} to deduce the SIM fraction (SIM^{sat}) at 25 km resolution:

$$SIM^{sat} = FW^{sat} - RW^{sat}. \quad (12)$$

Pixels with unrealistic RW^{sat} , indicated by $-SIM^{sat}$, were excluded, assuming errors were due to retrieval uncertainties, autochthonous CDOM, and brine from sea ice formation. Three-day composites of SIM^{sat} agreed well against concurrent in situ SIM fractions from June, August, and September (Table S1 in Supporting Information S1, Figure 1i).

3. Results

3.1. In Situ CDOM and Salinity Variability

The surface waters of JB had higher $a_{\text{CDOM}}^{\text{lab}}$ (412) and lower S^{lab} than HB, consistent with previous studies (Évrard et al., 2023; Granskog, 2012; Granskog et al., 2007, 2011; Guéguen et al., 2011, 2016) (Table S2 in Supporting Information S1). Furthermore, regional variability of $a_{\text{CDOM}}^{\text{lab}}$ (412) and S^{lab} (Text S6 and Table S2 in Supporting Information S1), underscores the role of river discharge and circulation in distributing CDOM across HJB, leading to distinct $a_{\text{CDOM}}^{\text{lab}}$ (412) to S^{lab} relationships in HB and JB (Figure 1c). Consequently, separate RW^{sat} retrieval models were applied for each basin (Equations 7 and 8).

3.2. Satellite-Derived Freshwater Fractions

Surface water in HJB exhibited satellite-derived freshwater fractions (FW^{sat}) ranging from 0.04 to 0.71 (Figure 2a) and salinities (S^{sat}) ranging between 10 and 32 psu from June to September. The mean FW^{sat} across HJB was 0.15 ± 0.09 , corresponding to a mean S^{sat} of 27.7 ± 2.6 psu. Per pixel mean FW^{sat} ($\overline{FW}^{\text{sat}}$) was lowest in northwestern HB and highest in southeastern HB and JB, consistent with field salinity data and past studies (Figures 2b–2e, Table S2 in Supporting Information S1, Eastwood et al., 2020; Jones & Anderson, 1994). Satellite observations generally showed higher $\overline{FW}^{\text{sat}}$ in eastern HB compared to the west, except in June and July 2017, when this pattern reversed (Figure 3a, Figures S1a and S1b in Supporting Information S1).

The satellite-based approach enabled the detection of seasonal and interannual FW^{sat} patterns not captured by ship-based observations. $\overline{FW}^{\text{sat}}$ in HJB decreased from 0.21 ± 0.10 in June to 0.15 ± 0.07 in September, indicating a typical seasonal decline (Figure 2a). In western HB (i.e., west of -83° longitude), $\overline{FW}^{\text{sat}}$ was generally higher in July than in June, except in 2017 (Figure S3a in Supporting Information S1), while eastern HB (i.e., east of -83° longitude) showed a July decline, with exceptions in 2011 and 2019 (Figure S3b in Supporting Information S1). $\overline{FW}^{\text{sat}}$ decreased through August and September in both regions, though minor September increases occurred in eastern HB in 2011, 2016, and 2017 (Figures S3a and S3b in Supporting Information S1). From 2011 to 2019, $\overline{FW}^{\text{sat}}$ increased in July but declined in other months (Figures S1a–S1d in Supporting Information S1), yielding an overall non-significant trend of -0.0003 yr^{-1} ($p > 0.05$) in HJB for June–September (Figure 3a).

3.3. Satellite-Derived River Water Fractions

Surface water in HJB exhibited satellite-based RW fractions (RW^{sat}) ranging from 0.03 to 0.40 (Figure 2a), with a mean RW^{sat} of 0.11 ± 0.05 from June to September. Per pixel mean RW^{sat} ($\overline{RW}^{\text{sat}}$) were higher in the southern and southeastern HB and JB, with lower values in central and northwestern HB, aligning with $\overline{FW}^{\text{sat}}$ patterns (Figures 2f–2i). Coefficient of variation of $\overline{RW}^{\text{sat}}$ ($CV_{RW^{\text{sat}}}$, 2011 – 2019) was lower in southern and southeastern regions, but higher in other regions (Figure 1a, Figures S2e–S2h in Supporting Information S1), mirroring $CV_{FW^{\text{sat}}}$ patterns (Figures S2a–S2d in Supporting Information S1).

Across HJB, $\overline{RW}^{\text{sat}}$ declined from 0.13 ± 0.03 in June to 0.10 ± 0.02 in July–August, then increased to 0.13 ± 0.02 in September (Figure 2a). Eastern HB consistently showed higher $\overline{RW}^{\text{sat}}$ than western HB (Figure 3b), with peaks in 2015 and 2018 coinciding with $\overline{FW}^{\text{sat}}$. However, unlike $\overline{FW}^{\text{sat}}$, $\overline{RW}^{\text{sat}}$ generally decreased from June to July in western HB, except in 2012, 2014, and 2016. From July to August, $\overline{RW}^{\text{sat}}$ declined in western HB in most years, while eastern HB showed variability, increasing in some years (e.g., 2012, 2014, 2017, and 2019) and decreasing in others. Between August and September, $\overline{RW}^{\text{sat}}$ increased in both regions (Figures S3c and S3d in Supporting Information S1).

The correlation between $\overline{RW}^{\text{sat}}$ and $\overline{FW}^{\text{sat}}$ progressively weakened through summer, reaching its lowest in September (Figures S4a–S4d in Supporting Information S1). Satellite observations further revealed seasonal RW dispersion. In July, $\overline{RW}^{\text{sat}}$ indicated offshore spread from southwestern and southern HB (Figure 2g), which was not observed in August (Figure 2h). By September, a distinct band of $\overline{RW}^{\text{sat}}$ was visible within the saltier surface waters of these regions (Figure 2i). In southeastern HB, $\overline{RW}^{\text{sat}}$ increased west of the Belcher Islands from June to

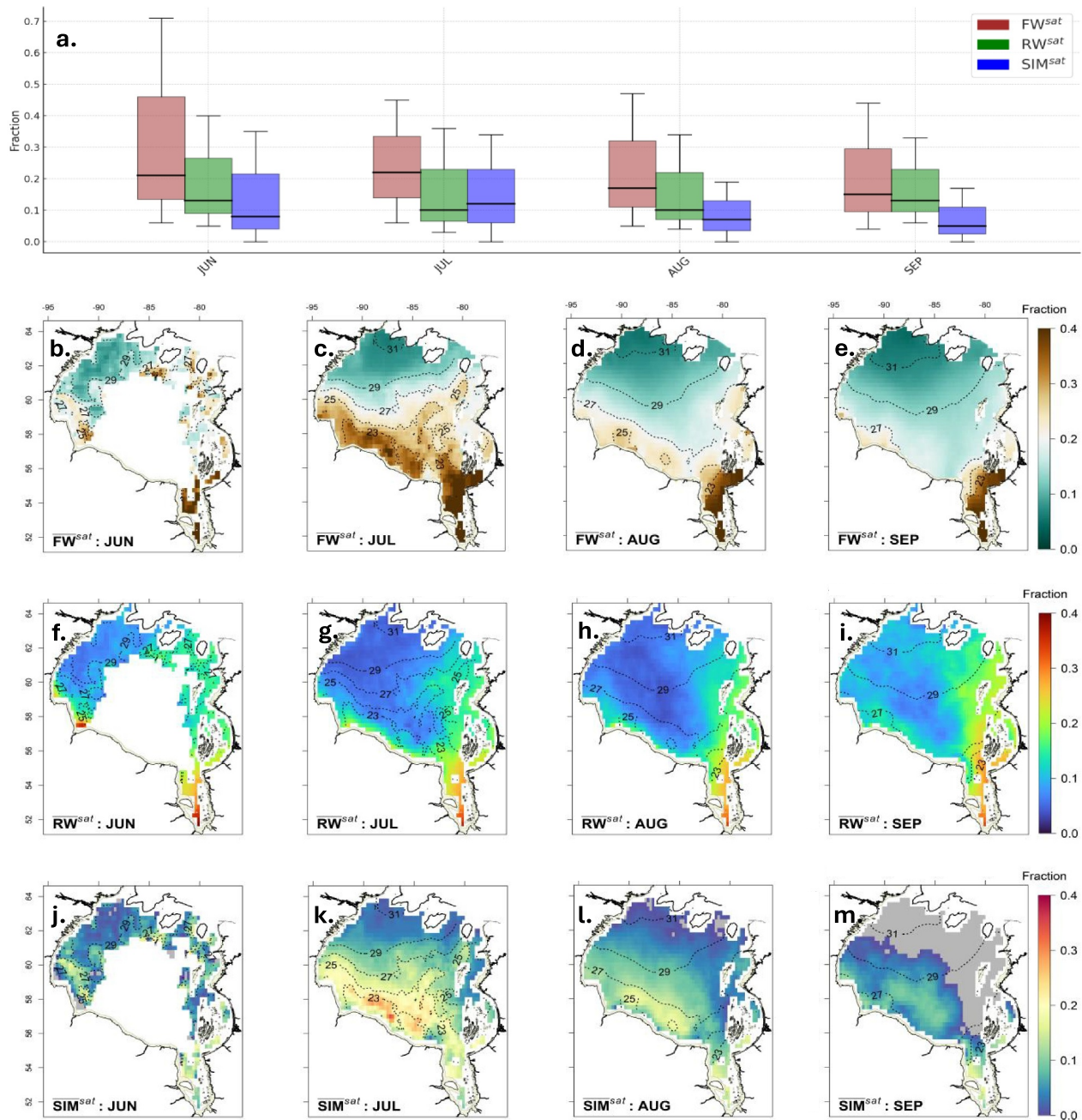


Figure 2. (a) Box plots showing monthly distribution FW^{sat} , RW^{sat} , and SIM^{sat} across Hudson and James Bay (HJB) for June (JUN), July (JUL), August (AUG), and September (SEP). Per-pixel monthly mean (2011–2019) of satellite-derived fractions of (b–e) freshwater (FW^{sat}), (f–i) river water (RW^{sat}), and (j–m) sea ice melt (SIM^{sat}) in HJB. For panels (b–m), dotted contours show satellite-derived salinity (S^{sat} , psu), white and gray areas indicate missing data and $-SIM^{sat}$, respectively, and pixels ≤ 10 m depth are masked (beige).

September and persisted along the southeastern coast throughout the season (Figures 2f–2i), consistent with CDOM field observations and reflecting freshwater input from JB, which contributes more than half of HJB's river discharge (cf. Déry et al., 2011). From 2011 to 2019, $\overline{RW^{sat}}$ increased in all months (Figures S1e–S1h in Supporting Information S1), yielding a significant overall trend of 0.0048 yr^{-1} ($p < 0.05$) in HJB for June–September (Figure 3b).

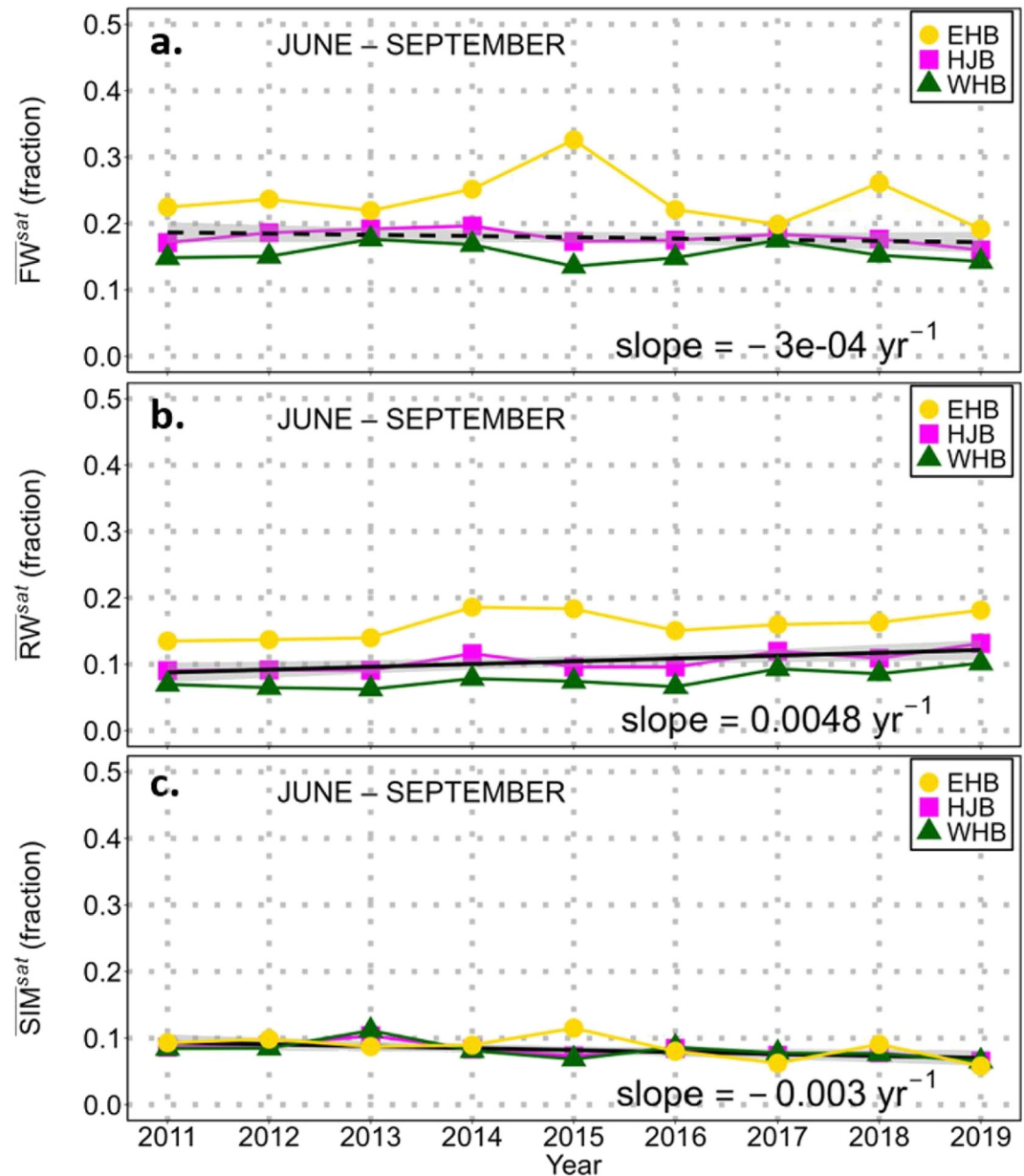


Figure 3. Mean (June–September) satellite-derived fractions of (a) freshwater ($\overline{FW}^{sat}$), (b) river water ($\overline{RW}^{sat}$), and (c) sea ice melt ($\overline{SIM}^{sat}$) across Hudson and James Bay (HJB), western Hudson Bay (WHB), and eastern HB (EHB) from 2011 to 2019. Solid and dashed black lines indicate significant ($p < 0.05$) and non-significant ($p > 0.05$) trends for HJB, respectively.

3.4. Satellite-Derived Sea Ice Melt Fractions

Surface water in HJB showed satellite-derived SIM fractions ($\overline{SIM}^{sat}$) ranging from 0.00 to 0.35 (Figure 2a) with a mean $\overline{SIM}^{sat}$ of 0.08 ± 0.03 between June and September. Per pixel mean $\overline{SIM}^{sat}$ ($\overline{SIM}^{sat}$) peaked in July, particularly around central and southeastern HB, the Winisk Trough, and JB, accompanied by low $CV_{\overline{SIM}^{sat}}$ (Figure 2k, Figure S2j in Supporting Information S1). By late summer, only traces remained in southern HB, JB and southeast of the Belcher Islands (Figures 2l and 2m). Anomalous $\overline{SIM}^{sat}$ distributions appeared in both western and eastern HB, with slightly higher values in the west, except in June 2015 (Figure 3c, Figures S1i–S1l in Supporting Information S1).

Seasonal $\overline{\text{SIM}}^{\text{sat}}$ in HJB increased from 0.08 ± 0.06 in June to 0.12 ± 0.07 in July, then decreased to 0.07 ± 0.05 in August and 0.05 ± 0.03 in September (Figure 2a). From June to July, $\overline{\text{SIM}}^{\text{sat}}$ increased in western HB but declined in the east, except in 2011 (Figures S3e and S3f in Supporting Information S1). A July to August decrease of $\overline{\text{SIM}}^{\text{sat}}$ followed in both regions, with exceptions in 2015 (western HB) and 2015, 2019 (eastern HB) (Figures S3e and S3f in Supporting Information S1). Between August and September, $\overline{\text{SIM}}^{\text{sat}}$ declined in western HB, while minor increases were observed in eastern HB during 2014, 2016, 2018, and 2019 (Figures S3e and S3f in Supporting Information S1). $\overline{\text{SIM}}^{\text{sat}}$ showed the strongest positive correlation with mean $\overline{\text{FW}}^{\text{sat}}$ in July, weakening in later months (Figures S4f–S4h in Supporting Information S1). From 2011 to 2019, $\overline{\text{SIM}}^{\text{sat}}$ decreased in all months (Figures S1i–S1l in Supporting Information S1), yielding a significant overall trend of -0.003 yr^{-1} ($p < 0.05$) for June–September (Figure 3c).

4. Discussion

4.1. Relationship Between In Situ $a_{\text{CDOM}}^{\text{lab}}$ (412) and In Situ River Water Fraction

The conservative relationship between in situ $a_{\text{CDOM}}^{\text{lab}}$ (412) and in situ RW fractions in HB (Figure 1d) contrasts with the non-conservative CDOM behavior observed by Granskog et al. (2009) in southwestern HB, which suggested a potential underestimation of RW fractions by 50%–80%. However, the Granskog et al. (2009) study was limited to the anomalous 2005 flood year and focused only on the southwestern HB, dominated by Nelson and Churchill River inputs. The present study benefits from several years of observations and broad geographic coverage, rendering the observed in situ CDOM–RW relationship more representative of typical conditions, consistent with findings from Granskog et al. (2007) and Meilleur et al. (2023).

However, the JB-wide field observations indicate very high surface $a_{\text{CDOM}}^{\text{lab}}$ (412) and a nonlinear relationship with in situ RW fraction (Figure 1e). This nonlinearity may reflect the contribution of CDOM-poor river inputs, SIM dilution, or CDOM degradation by light and microbes. Despite this nonlinearity, CDOM remains a robust RW tracer in HJB due to its conservative mixing behavior in several HB estuaries (e.g., Basu et al., 2023) and relatively small area of JB ($< 70,000 \text{ km}^2$) within the HJB complex.

4.2. Satellite-Derived River Water Dispersion

HJB experiences high river discharge during spring freshet, which peaks in May and June (McCullough et al., 2019), is evident from elevated mean $\overline{\text{RW}}^{\text{sat}}$ and $\overline{\text{FW}}^{\text{sat}}$ in June and July (Figure 2a). The uneven distribution of RW^{sat} and FW^{sat} , with higher values in southern waters, is due to major rivers draining into southern and southwestern HB and JB. In contrast, northern HB lacks significant river sources (Déry et al., 2011) and is influenced by saline inflows from the Arctic and Atlantic Oceans (Figures 2b–2i). Low variability and strong correlation between $\overline{\text{RW}}^{\text{sat}}$ and $\overline{\text{FW}}^{\text{sat}}$ confirm the dominance of RW in the southern coastal waters (Meilleur et al., 2023, Figures S2a–S2h and S4a–S4d in Supporting Information S1). Overestimated S^{sat} in southeastern HB indicates higher RW in this region (Figure 1h); however, general alignment of RW^{sat} with FW^{sat} in eastern HB supports the use of satellite-derived CDOM for RW retrieval in HJB (Figures S4a–S4d in Supporting Information S1).

Although 9 years of data is insufficient to assess long-term trends, HJB is known to exhibit seasonal and inter-annual trends in river discharge (cf., Déry et al., 2011), which we expect to translate into trends and spatial patterns in RW^{sat} . RW^{sat} generally declined month-to-month from June to September across HJB, mirroring the decreasing river discharge, with occasional increases corresponding to discharge peaks (Figures S3c, S3d, S5a, and S5b in Supporting Information S1). At regional scales, RW^{sat} showed a marginal yet significant inter-annual increase over the study period (2011–2019), particularly in the eastern HB (Figure 3b). Despite declining river discharge in the western HB, a post-2016 rise in RW^{sat} aligned with the 2017 discharge peak (Figure 3b; Figure S5c and Table S3 in Supporting Information S1). These observations demonstrate that satellite data effectively capture both seasonal and inter-annual RW^{sat} variability linked to river discharge patterns across HJB.

However, regional trends in RW^{sat} over 2011–2019 cannot entirely be explained by river discharge alone. For example, in eastern HB, positive RW^{sat} changes from July to August during some years contrast with declining discharge trends (Figures S3d and S5d in Supporting Information S1). This may be due to the increased influence

of CDOM-rich outflow from JB, even when August discharge is lower than July, as observed in some unregulated rivers draining into JB (see Table 2 of Évrard et al. (2023)). Furthermore, while RW^{sat} showed a year-to-year increase in June through September from 2011 to 2019 in eastern HB (Figures S1e–S1h in Supporting Information S1), river discharge increased in June and July but declined during August and September (Figure S5d and Table S3 in Supporting Information S1). This suggests a shift in the timing and redistribution of RW^{sat} within the system. These insights further emphasize the importance of using satellite-based methods to trace RW redistribution in HJB.

Circulation driven by winds and sea surface height gradients redistribute RW^{sat} across HJB (Dmitrenko et al., 2021). In July, RW^{sat} get transported offshore from southwestern and southern HB (Figure 2g), but this weakens in August (Figure 2h, Basu et al., 2023; St-Laurent et al., 2011). Cyclonic vorticity in late summer, drive northward RW^{sat} transport from JB to east of the Belcher Islands, sustaining high RW^{sat} in southeastern HB despite reduced discharge (Figures 2h and 2i). This wind-driven transport forms a “riverine corridor” in the saltier waters of southern HB, visible in September imagery (Figure 2i) and marked by low RW^{sat} and FW^{sat} variability (Figures S2d and S2h in Supporting Information S1). In contrast, the high variability near the Winisk Trough in August suggests circulation changes linked to wind vorticity reversal (Figures S2c and S2g in Supporting Information S1). Additionally, variability in RW^{sat} and FW^{sat} in southwestern and northwestern HB (Figures S2b and S2f in Supporting Information S1) suggests that redistribution of RW^{sat} , consistent with Ridenour, Hu, Jafarikhazragh, et al. (2019) and Ridenour, Hu, Sydor, et al. (2019). Therefore, RW^{sat} dispersion in HJB aligns with modeled and observed August and September circulation, which transport RW along the eastern coast of HB and subsequently along the southern shore of Hudson Strait, into the Labrador Sea in the North Atlantic Ocean (Dmitrenko et al., 2020; Granskog et al., 2011; Ridenour, Hu, Jafarikhazragh, et al., 2019; Ridenour, Hu, Sydor, et al., 2019; Straneo & Saucier, 2008).

4.3. Satellite-Derived Sea Ice Melt Dispersion

Following the peak sea ice volume in late April (Landy et al., 2017), melting likely begins in May and pools in southern HB by June, unseen in satellite data due to ice cover. This meltwater spreads into central HB, as indicated by SIM^{sat} during July and August (Figures 2k and 2l), when RW^{sat} in this region remains minimal (Figures 2g and 2h). The low variability and the strong correlation between $\overline{SIM}^{\text{sat}}$ and $\overline{FW}^{\text{sat}}$ in July confirm SIM as the main freshwater source in central HB at that time, resulting in higher $\overline{FW}^{\text{sat}}$ (Figures S2j and S4f in Supporting Information S1, Figure 2a).

In western HB, SIM^{sat} peaks in July, exceeding June values, and typically declines through August and September, except in August 2015, when delayed SIM led to a rise (Figure S3e in Supporting Information S1, cf. Tang et al., 2020). Generally, northwesterly winds push sea ice away from the Kivalliq polynya (Figure 1a) in western HB to central and southeastern HB (Figure 1a), leading to thicker spring sea ice in the east (Bruneau et al., 2021; Kirillov et al., 2020; Landy et al., 2017) and consequently higher SIM additions to its surface waters (Granskog et al., 2011). However, this study showed that eastern HB exhibits slightly lower SIM^{sat} than western HB (Figure 3c), potentially due to the overestimation of S^{sat} (even after correction) in southeastern HB (Figure 1h), a region with substantial RW and SIM input from JB (Figures 2g–2i, Eastwood et al., 2020). Additionally, some studies have also reported, contrary to the expected eastward displacement, sea ice tends to persist longer in southwestern and southern HB (Barber et al., 2021; Galbraith & Larouche, 2011), likely contributing to higher SIM^{sat} in western HB.

Nevertheless, SIM^{sat} in eastern HB declined from June through September (Figure 3c, Figure S1i–S1l in Supporting Information S1), following the expected seasonal pattern. However, in 2015, late SIM led to high SIM^{sat} in eastern HB during August (Figures S1k and S3f in Supporting Information S1, cf. Tang et al., 2020). The elevated SIM^{sat} could be observed in FW^{sat} during June–August 2015 in eastern HB (Figures S3a–S3c in Supporting Information S1). Corresponding with the eastward ice displacement, SIM^{sat} was traced in southeastern HB later in the season, during August and September (Figures 2l and 2m). Additionally, the deeper bathymetry (>100 m) southeast of the Belcher Islands (Figure 1a) may also contribute to late-season SIM^{sat} in certain years, as longer sea ice persistence in this region can lead to elevated SIM^{sat} . Cyclonic circulation and tidal and wind-driven mixing disperse SIM^{sat} in HJB, leading to its gradual decline in the surface water during summer, and subsequent transport together with RW into the Labrador Sea (Granskog et al., 2011; Saucier et al., 2004) (Figures 2k–2m). Both SIM and RW accounts for 50% of the freshwater transported by the Labrador current in the

North Atlantic Ocean (Straneo & Saucier, 2008). The marginal decline detected in SIM^{sat} between 2011 and 2019 (Figure 3c) may be due to anomalous sea ice distribution in western and eastern HB.

5. Conclusion

Freshwater in HJB sources from river discharge and SIM. Since river input is enriched in CDOM and suspended solids, a blue-to-red BR is applied to reduce effects of suspended solids on satellite-based CDOM retrieval, enabling CDOM to serve as a conservative tracer of RW in HJB (Basu et al., 2023). Satellite observations capture seasonal and interannual freshwater variability across HJB. High RW fractions were observed during the early summer and are redistributed by wind-driven circulations in late summer. SIM declined through summer. From 2011 to 2019, surface RW increased and SIM decreased, consistent with rising river discharge and declining sea-ice cover (Crawford et al., 2021; Feng et al., 2021; McCullough et al., 2019; Tivy et al., 2011). Uncertainty in satellite-based RW estimates arises due to autochthonous CDOM production from phytoplankton degradation in northwestern HB (Barbedo et al., 2022; Kitching et al., 2025; Matthes et al., 2021). Other factors, including CDOM photo- and microbial degradation, sea ice cover, cloudiness, air–sea freshwater fluxes, low sea surface temperature, sun angle, and algorithmic limitations (Bélanger et al., 2007; Guéguen et al., 2016; Kazmiruk et al., 2021; Loisel et al., 2013; Martínez et al., 2022; Tang et al., 2020), add to the uncertainty of satellite-based freshwater tracing. Despite these limitations, satellite remote sensing remains essential for monitoring freshwater variability in HJB and its impacts on regional oceanography, primary productivity, and ecology, as well as on North Atlantic circulation and climate (Ausen et al., 2023; Barbedo et al., 2022; Basu et al., 2023; Wu et al., 2023).

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The Aqua-MODIS Level 1A radiance data at 1 km resolution were obtained from MCST (2017). The BEC Arctic-SMOS V3 sea surface salinity 3-day average product at 25 km resolution are available from [sftp://eodata-bec.icm.csic.es](http://ftpuser.eodata-bec.icm.csic.es) (Username: ftpuser, Password: .x8UP(ar.YZ2R), and Port: 22758). In situ data for salinity, oxygen isotope ratio, CDOM absorption at 412 nm, along with data on river water, sea ice melt, and sea water fractions for Hudson and James Bays were obtained from Basu and Guzzi (2025).

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