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Winter sediment resuspension in a submarine canyon drives the offshore export of toxigenic *Alexandrium catenella* cysts

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Abstract

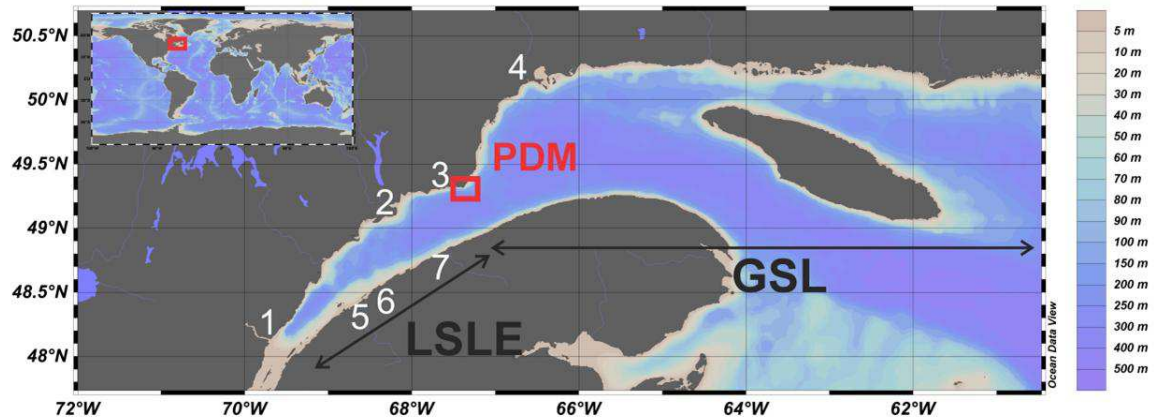
Harmful algal blooms (HABs) caused by the toxigenic dinoflagellate *Alexandrium catenella* recur regularly in the Lower St. Lawrence Estuary (LSLE, eastern Canada). Using quantitative polymerase chain reaction (qPCR) to detect *A. catenella* DNA as a proxy for cyst abundance in the Pointe-des-Monts canyon system, we show that resting cysts are concentrated in nearshore sediments and on the canyon fan, but are depleted along the canyon axis. Sediment traps reveal that major cyst resuspensions occur exclusively during winter storms under ice-free conditions, with peaks in *A. catenella* DNA fluxes coinciding with turbidity currents and high total particulate matter export. These events effectively flush coastal cysts offshore, creating a negative feedback loop that reduces subsequent local bloom potential. Conversely, climate change-driven increases in summer-to-autumn storm frequency and intensity could resuspend cysts under optimal proliferation conditions. Sedimentary ancient DNA in a ^{210}Pb -dated sediment core also demonstrates that qPCR reliably records known historical *A. catenella* bloom events. These results highlight the critical, yet underappreciated, role of submarine canyon systems and storm-driven sediment dynamics in modulating *A. catenella* bloom risks, and suggest that ongoing climate-driven shifts in sea-ice cover and storm seasonality are likely to influence future HABs in the LSLE and similar high-latitude systems.

Keywords: *Alexandrium catenella*, dinoflagellate cyst resuspension, Harmful Algal Blooms, qPCR, sedimentary ancient DNA, sediment dynamics, particulate matter export, sediment traps, submarine canyons

Introduction

Harmful algal blooms (HABs), caused by eukaryotic phytoplankton or cyanobacteria, represent a growing natural threat to wildlife and human health worldwide¹⁻⁵. Although the causes of their apparent rise are uncertain, it may reflect an expansion of monitoring efforts^{6,7} or potentially a combination of anthropogenic pressures and climate change⁸. In temperate to subpolar marine regions, the cyst-producing dinoflagellate *Alexandrium catenella* is a major concern, forming recurrent coastal blooms, sometimes associated with mass mortality across multiple trophic levels⁹⁻¹¹. Certain strains produce potent neurotoxins called saxitoxins, as well as derivative compounds (paralytic shellfish toxin group). These compounds can bioaccumulate to high levels in filter feeders and can subsequently cause paralytic shellfish poisoning in consumers¹²⁻¹⁴.

HABs of *A. catenella* have long been recognised in the Lower St. Lawrence Estuary (LSLE) and the Gulf of St. Lawrence (GSL; Fig. 1). Indigenous accounts of shellfish toxicity date back to the 1600s^{11,15,16}. Since the 1880s, recurrent paralytic shellfish poisonings have been documented in the LSLE and GSL almost every summer (¹⁶and references therein; ^{10,11,17}). They have been particularly well documented over the last four decades, largely thanks to monitoring programs^{16,18-20}. Toxic HABs trigger shellfish harvesting bans when saxitoxin concentrations exceed the regulatory threshold of 80 µg STXeq per 100 g of tissue¹⁹. Historically, this threshold was typically surpassed when *A. catenella* cell concentrations reached 1000 cells L⁻¹²⁰. The largest bloom on record reached concentrations up to 80 × 10³ cells L⁻¹ and caused mass mortalities of fish, seabirds, and marine mammals in August 2008^{10,14,21}.



1: Saguenay Fjord mouth and Tadoussac; 2: Baie-Comeau and Manicouagan River;
3: Godbout River; 4: Sept-Îles; 5: Rimouski; 6: Mont-Joli; 7: Saint-Ulric

Fig. 1: Location of the study area between the Lower St. Lawrence Estuary (LSLE) and the Gulf of St. Lawrence (GSL). PDM: Pointe-des-Monts. Adapted from Ocean Data View²².

Like all phytoplankton, *A. catenella* is sensitive to environmental conditions²³. Optimal growth occurs at sea-surface temperatures between approximately 9°C and 22°C, with maximum growth rates above 12°C, and low salinities between 20 and 26 psu^{24–27}. Heavy precipitations enhance stratification and runoff, both of which are linked to elevated cell concentrations^{12,24,28,29}. Humic substances can also stimulate growth of *Alexandrium* cells^{30,31}, even at low levels, as in the Manicouagan River plume³². Consequently, climate driven increases in runoff and earlier spring freshets are expected to promote an earlier onset of *A. catenella* blooms along Canada's east coasts throughout the 21st century²⁶. They are also expected to increase bloom frequency, broader spatial extent and longer seasonal duration. These changes would pose growing risks to ecosystems, fisheries, and human health.

Resting cysts (hereafter referred to simply as cysts) underpin bloom recurrence¹⁴ and can remain viable for decades in the nepheloid layer (i.e., the bottom water layer with high concentrations of suspended particles) or seabed sediments^{33,34}. Encystment typically follows bloom decline and is triggered by nutrient depletion and sexual reproduction^{35,36}. Transitions between quiescence (i.e., a non-dormant state in which germination occurs when environmental conditions are favorable) and dormancy are increasingly understood to be regulated by cumulative environmental exposure rather than an intrinsic circannual rhythm^{37,38}. Concurrently, dissolved oxygen, nutrient availability, temperature, and light further modulate dinoflagellate cyst germination³⁹⁻⁴¹. In addition to direct excystment from sediments, the resuspension of benthic cysts has been hypothesized to inoculate the water column and fuel the initiation of new blooms of various cyst-forming dinoflagellates through hydrodynamic processes⁴²⁻⁴⁶ or anthropogenic disturbances⁴⁷. These sedimentary cyst banks act both as seed reservoirs and as potential indicators of bloom magnitude in some regions^{23,36}. Moreover, cysts can contain higher toxin levels than vegetative cells⁴⁸. Despite their ecological importance, the natural factors regulating cyst bed formation and dynamics, including the effects of resuspension, remain understudied, with only a few studies addressing these processes^{46,49,50}.

The LSLE and GSL represent one of the largest and most productive estuarine/marine ecosystems in the world^{51,52}. High-density *A. catenella* seedbeds, containing between 250 and over 500 cysts cm⁻³, have been reported in shallow sediments extending from the Manicouagan and Aux-Outardes rivers to Pointe-des-Monts (PDM)^{21,28,29,53,54} (Fig. 1). This region is further influenced by a network of submarine canyons and channel systems that affects sediment transport and local hydrodynamics⁵⁵⁻⁵⁸.

For example, off PDM, seafloor morphology combined with hydrodynamics promote upwelling, internal waves, water mass inflows, and the formation of a salinity front^{59–62}.

More details on the regional settings are presented in Supplementary Note 1.

Here, we investigate how sediment resuspension events in a submarine canyon system affect *A. catenella* resting cyst distribution and dynamics, using the PDM canyon system as a case study (Fig. 2). Our approach integrates multiple spatial and temporal scale datasets. We first integrate meteorological and environmental datasets from the canyon and surrounding region. These include mooring-derived measurements from an Acoustic Doppler Current Profiler (ADCP), an Acoustic Wave and Current Profiler (AWAC) and Conductivity-Temperature-Depth (CTD) probes to characterize hydro-sedimentary dynamics. We then combined molecular analyses of cyst distribution in surface sediments with two annual cycles of sediment trap data collected from November 2020 to October 2022. This period encompassed contrasting sea-ice conditions and potential resuspension events, allowing us to assess how canyon dynamics influence *A. catenella* dispersal across benthic and pelagic compartments in the LSLE. Finally, we analyzed *A. catenella* DNA preserved in a ²¹⁰Pb-dated sediment core to assess whether historically documented HAB events in the study area are recorded in the sedimentary archive.

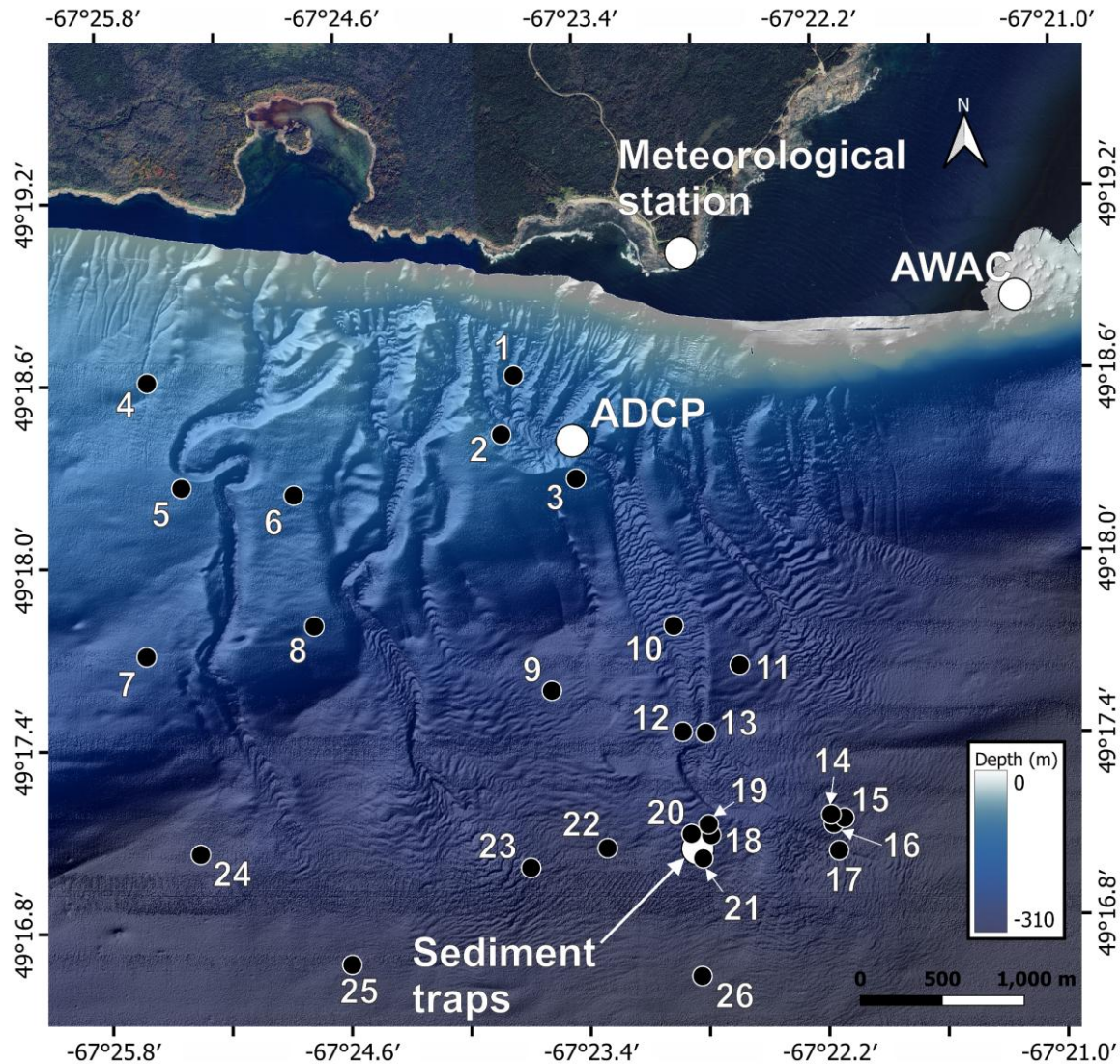


Fig. 2: Multibeam bathymetric map of the Pointe-des-Monts canyon system in 2021. White dots indicate the locations of the three moorings, equipped with an Acoustic Doppler Current Profiler (ADCP), an Acoustic Wave and Current Profiler (AWAC), and sediment traps, respectively, and the PDM meteorological station. Black dots indicate the locations of surface sediment samples. The sediment core COR2212-05BC was collected at station 20. Note that white arrows were used to avoid overlapping site labels.

Results

Resuspension events and meteorological data

The backscatter ADCP data allows identification of high suspended sediment concentration events on 23 December 2020 (R1, Fig. 3c), 3 February 2021 (T, Fig. 3a,b), 6 March 2021 (R2, Fig. 3d), and a smaller one on 19 April 2021 (Fig. 3e). Additional smaller-scale sediment remobilization events or sediment plumes occurred on 13–14 December 2020, 17 January 2021, 2–3 March 2021, 17 April 2021, and 04–07 November 2021. Some of them were directly associated with winter storms⁵⁸. Overall, backscatter intensity also increased during winter and August to September 2021, and throughout the water column in November 2021 and October 2022 (Fig. 4a,b). A moderate increase in backscatter was detected several times near the seabed from late April to late May 2022 (Fig. 4a,b).

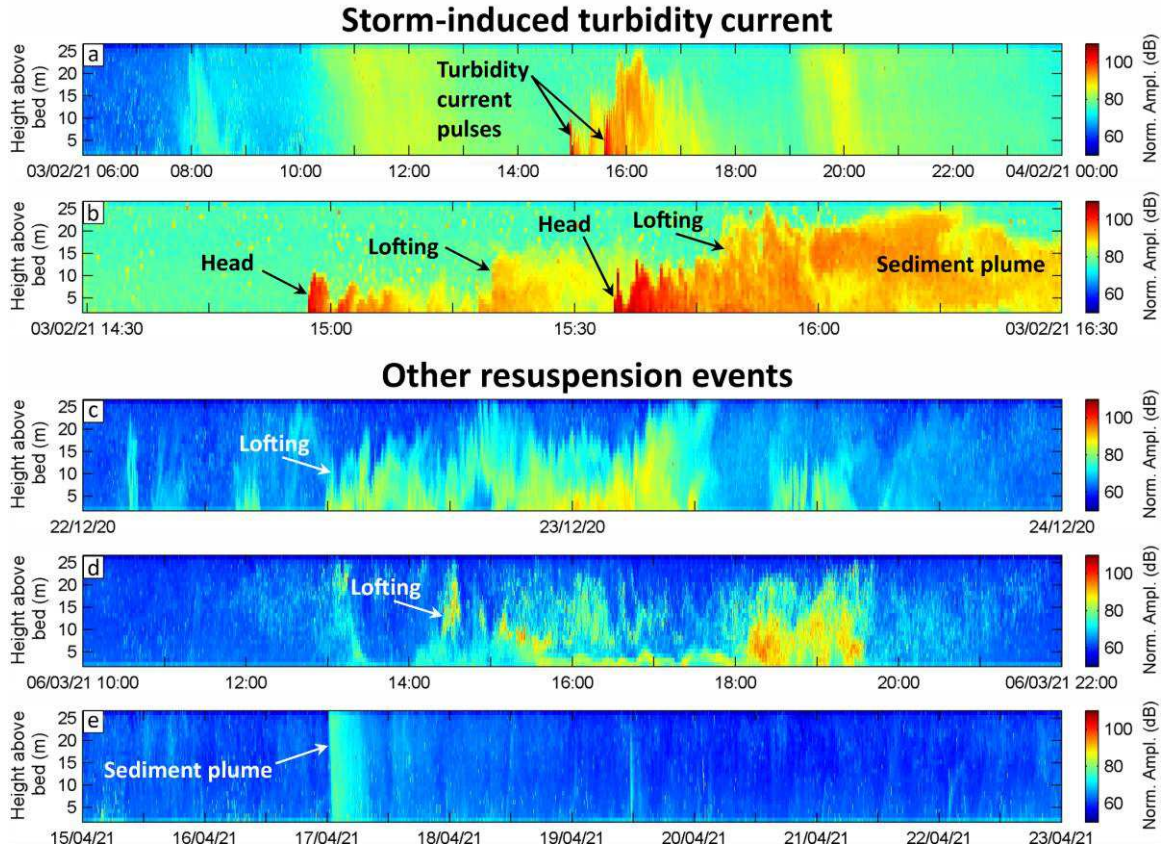


Fig. 3: Normalized backscatter amplitudes illustrating major resuspension events recorded by the ADCP-CTD 02M mooring. Panels (a) and (b) show the turbidity current of 3 February 2021 (T). Panels (c), (d) and (e) show remobilization events on 23 December 2020 (R1), 6 March 2021 (R2), and 19 April 2021, respectively. Adapted from Jacques et al.⁵⁸.

Sea-ice concentration was unusually low in 2020–2021, especially near PDM⁶³ (Fig. 4c). In contrast, the 2021–2022 season had sea-ice concentration and duration close to the regional climatological average for 1991–2021⁶⁴ (Fig. 4c).

Between October 2020 and October 2021, 19 storms produced wave heights larger than 2 m and were generally associated with strong wind speeds (when data are available, generally above 40 km h⁻¹ and up to more than 60 km h⁻¹), mostly in late autumn and winter (Fig. 4c–e). From November 2021 to October 2022, 20 storms with similar characteristics were observed, with most events occurring during late autumn, winter, and early spring (Fig. 4c–e).

The higher total precipitation values ($> 4 \text{ mm h}^{-1}$) were recorded episodically from mid-November to early December 2020, from mid-June to mid-July 2021, during the second half of August and the first half of September 2021, and from early June to mid-September 2022 (Fig. 4f).

Runoff from the Godbout River showed several peaks over the study period occurring in early December 2020, late December 2020–early January 2021, mid-April to the end of May 2021, from late September to late October 2021, and from early May to late June 2022 (Fig. 4g).

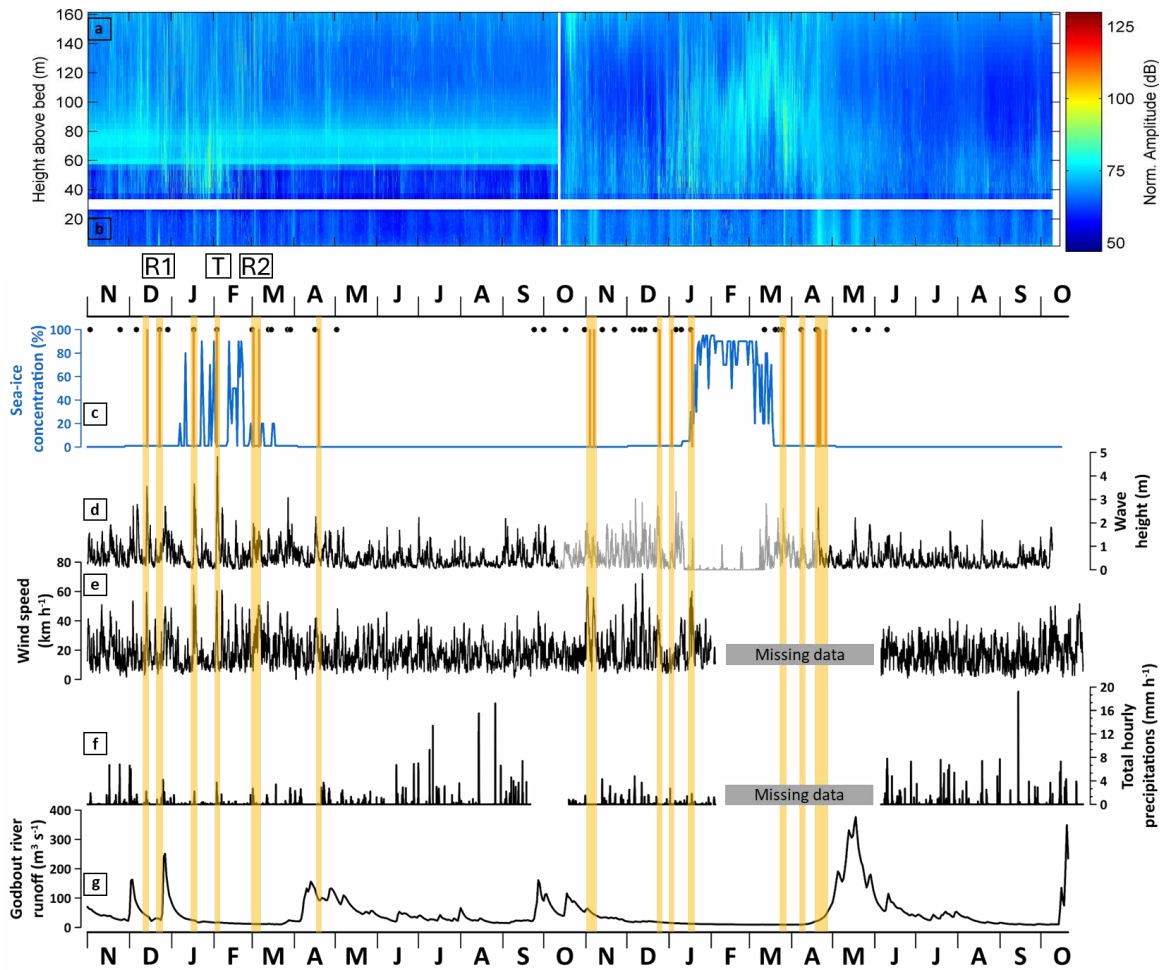


Fig. 4: Meteorological and oceanographic data collected from November 2020 to October 2022. (a) Upward-looking normalized backscatter ADCP (note a buoy-related artifact between 24 m and 60 m above the ADCP during the first deployment cycle). (b) Downward-looking normalized backscatter ADCP. (c) Sea-ice concentration derived from ice maps. Black dots indicate storms, and brown bars represent resuspension events. (d) Significant wave height measured by AWAC at PDM (black line) and at Saint-Ulric (grey line). (e) Hourly wind speed. (f) Total hourly precipitation recorded at the meteorological station of PDM. Total precipitation corresponds to the sum of the total rainfall and the water equivalent of the total snowfall in millimetres observed at the location per hour. Note

that total precipitation values were unavailable from 21 September to 19 October 2021 and from 4 February to 5 June 2022. (g) Godbout River runoff ($\text{m}^3 \text{s}^{-1}$). Yellow shading highlights resuspension events identified from the ADCP record. R1: resuspension event of 23 December 2020; T: turbidity currents of 3 February 2021; R2: resuspension event of 6 March 2021.

Export fluxes

Sinking fluxes collected at 154 m and 224 m from November 2020 to October 2021 were previously described in Sharpe et al.⁶⁵. TPM fluxes at both depths peaked in early February 2021, accompanied by two smaller peaks in late December 2020 and early March 2021 (Fig. 5a). Outside of these events, TPM fluxes remained low and relatively stable. During the second cycle of mooring deployment, TPM fluxes showed limited variation at both depths, with minor peaks observed in November 2021 and in late April 2022 (Fig. 5a).

Overall, during the first deployment cycle, particulate organic carbon (POC) fluxes were globally higher at both depths during autumn and winter, with notable peaks occurring in early November 2020, late December 2020, and early February 2021 (Fig. 5b). During the second cycle, POC fluxes followed patterns like TPM at both depths, with an initial peak in early November 2021 (Fig. 5a,b). Beyond that, their variations closely mirrored the chloropigment fluxes at their respective depth (Fig. 5a,b,e).

During the first deployment cycle, C:N mass ratio of the sinking particles ranged from 7.9 to 12.8 at 154 m and from 5.1 to 11.6 at 224 m (Fig. 5c). Major peaks in the C:N mass ratio at 154 m with values surpassing 11.2 occurred during early December 2020, late February, and late July 2021. In contrast, very low ratios were observed at 224 m from the last week of April to mid-May 2021. Peaks in the C:N ratio at 224 m were recorded from mid-February to the third week of April, mid-May to mid-June, and mid-July to mid-August 2021 (Fig. 5c). During the second cycle, C:N mass ratios of the sinking particles ranged from 4.1 to 8.3 at 154 m and from 5.3 to 9.1 at 224 m. Overall, C:N ratios were relatively stable and, on average, lower than during the first cycle. Slightly higher values were observed from late February to early March 2022 at both depths compared to the rest of the cycle. From April to October 2022, minor variations in the ratios closely followed trends in POC (Fig. 5b,c).

During the first cycle, $\delta^{13}\text{C}$ values at 154 m remained below -22.5‰ from early November through the third week of April, after which they increased, generally rising above -22.5‰ until the end of September. $\delta^{13}\text{C}$ values of the sinking particles at 154 and 224 m showed similar ranges starting from late April 2021 (Fig. 5d). During the second cycle, $\delta^{13}\text{C}$ values at 154 m (-24.3‰ to -21.9‰) and 224 m (-24.5‰ to -21.7‰) showed ranges and temporal patterns comparable to those observed during the first cycle (154 m -23.9‰ to -21.8‰; 224 m -24.3‰ to -21.8‰). From November 2021 to early April 2022, values were generally slightly lower than during the rest of the second cycle, with small peaks recorded in early January and between late February and early March 2022 (Fig. 5d). The highest $\delta^{13}\text{C}$ values of the second cycle were measured from mid-April to mid-June, coinciding with enhanced POC and chloropigment fluxes (Fig. 5d,e).

Chloropigment fluxes were generally higher at 224 m during spring 2021 and 2022 (Fig. 5e). In 2021, the spring bloom extended from early April to mid-May. In 2022, a major peak of chloropigment fluxes occurred at 154 m during late April and declined through the end of June, followed by a secondary peak in late August that decreased until early September. At 224 m, the 2022 chloropigment peak occurred slightly later, during early May (Fig. 5e). Slightly elevated chloropigment fluxes at 154 m were also observed throughout November 2021. Additionally, chloropigment peaks that aligned with the TPM and POC peaks were observed in early November 2020, in late December 2020, early February 2021, at both depths (Fig. 5a,e). A minor chloropigment peak was also detected in early July 2021.

05M 2020-2022

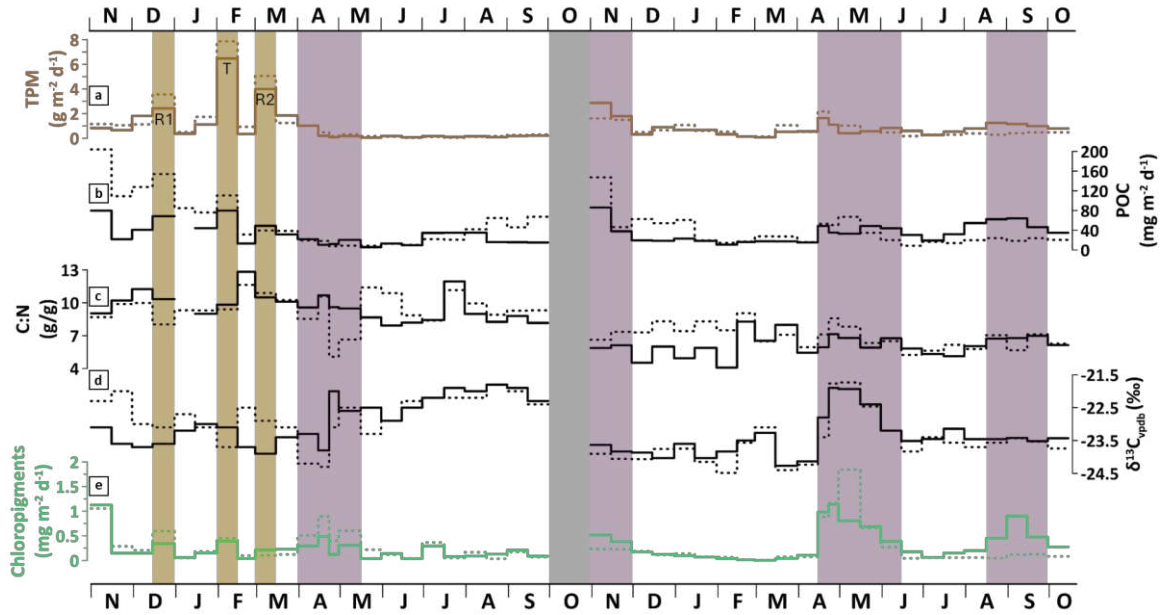


Fig. 5: Export fluxes at 154 m (solid lines) and 224 m (dotted lines) from November 2020 to October 2022. Data from November 2020 to October 2021 are from Sharpe et al. (2023). (a) Total particulate matter (TPM) flux. (b) Particulate organic carbon (POC) flux. (c) Particulate organic carbon:particulate nitrogen ratio of the sinking particles (C:N). (d) Carbon isotopic ratio ($\delta^{13}\text{C}$) of the sinking particles. (e) Chloropigment (i.e., chlorophyll *a* + phaeopigments) flux. Purple shading highlights bloom periods identified with chloropigments peaks, and yellow shading highlights resuspension events (R1, T and R2) recorded by the sediment traps and mainly identified by TPM peaks. Grey shading indicates periods without data.

Estimation of cysts of *A. catenella* presence

Surface sediments

Lower Cycle threshold (Ct) values indicate a higher abundance of *Alexandrium catenella* target gene, and thus a greater presence of cysts in the sediment. Accordingly, Ct values and their temporal variations are used as proxies for relative variations in *A. catenella* cyst abundance. This approach provides a relative, rather than absolute, estimate.

DNA of *A. catenella* was amplified at all sites (Fig. 6, locations shown in Fig. 2). Only site 6 showed a mean Ct value above 22 (≈ 29.7), indicating that this sample contained few target genes of *A. catenella*. qPCR-derived Ct values are lower near the coast and within the canyon fans, while samples from the main canyon axis (sites 10 and 13) showed relatively higher Ct values. No large nor recurrent differences were measured between samples collected in July 2020 and those from October 2022, particularly at nearby sites (Fig. 6).

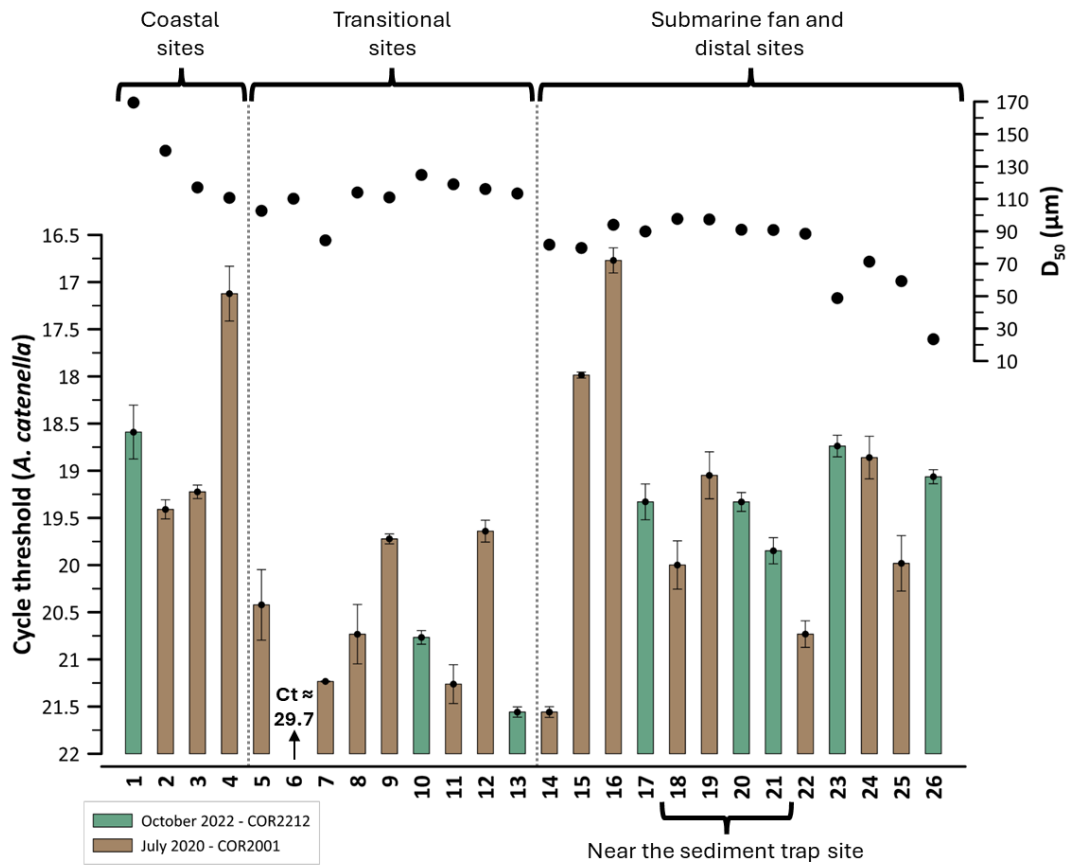


Fig. 6: Mean Cycle threshold (Ct) values (inverted axis) for each sediment surface sample collected in the PDM canyon system and in the area surrounding it. Smaller Ct values are indicative of higher relative abundance of *A. catenella* cysts. Mean Ct value of site 6 is not represented as it is the only site where mean Ct value is above 22 (i.e., 29.67). The median grain size (D₅₀) in the top 1 cm of each sediment sample (black dots) is also shown for each sample. Note that the relationship between Ct and target gene abundance is non-linear with one Ct difference representing a two-fold difference in target gene abundance.

Sediment trap 05M-B 2020–2021

A. catenella DNA was extracted from the 05M-B 2020–2021 sediment trap samples moored at 224 m. DNA amplification was successful for 16 of the 23 samples (Fig. 7a). Mean Ct values for successful amplifications ranged from 27.0 to 34.8 (Fig. 7a), with the lowest Ct values occurring in winter, during the first half of February and March. These low Ct values coincide with high TPM fluxes (Fig. 7a,c,f). Moderate to low Ct values were observed in late December, and a small peak appeared in the third week of April (Fig. 7a). During summer, low Ct values were recorded from mid-June to late July, with another short interval of low value in early September. Samples with unsuccessful amplifications are interpreted as containing no or extremely low amounts of targeted DNA. In particular, samples from trap bottles 13, 14, 16, 20, and 21, processed using 50 mL to obtain 250 mg of particulate matter, generally showed very high Ct values or failed to amplify (see Data and Methods section for sample identification). High Ct values were commonly associated with increased variability among replicates or occasional amplification failures (Fig. 7g).

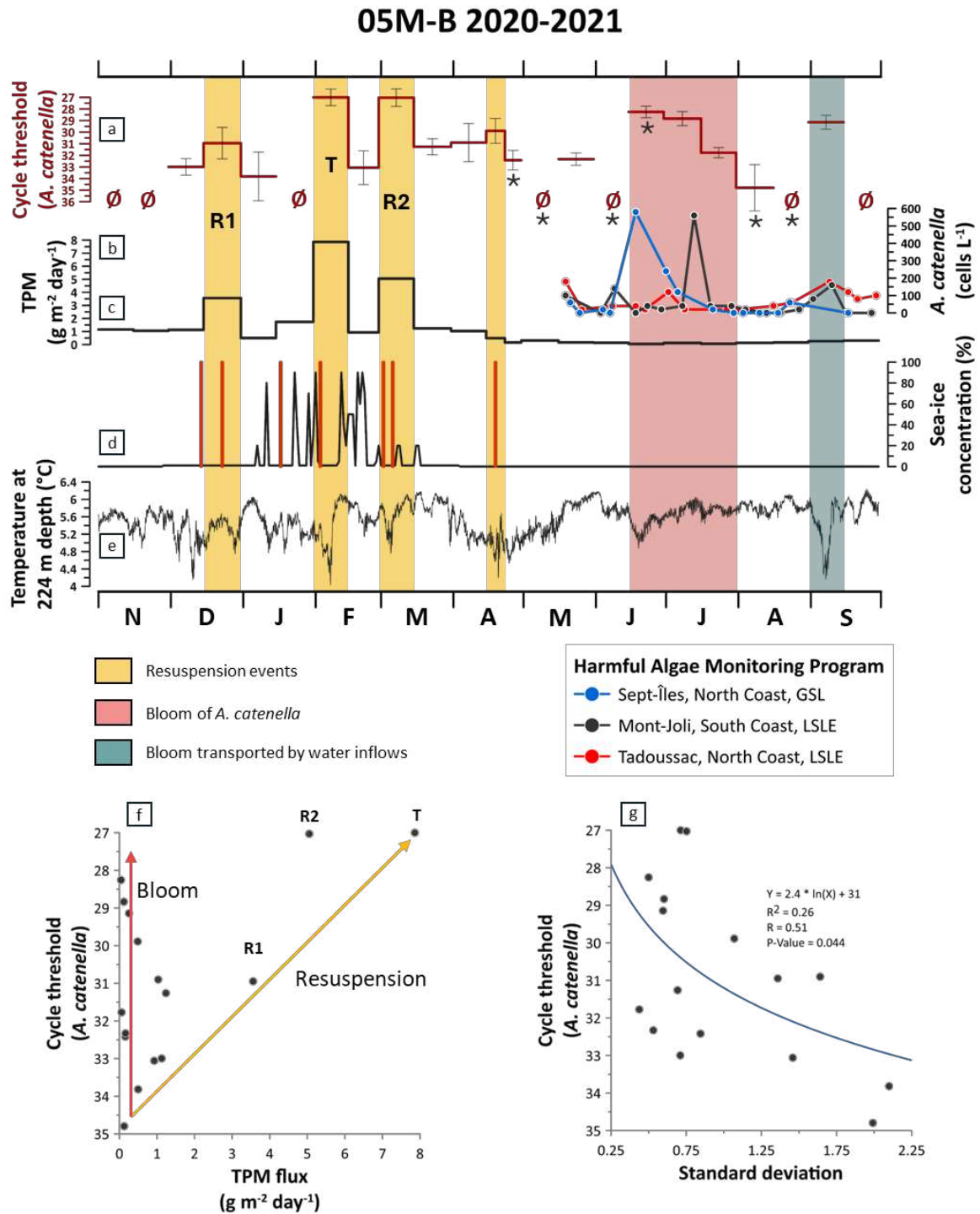


Fig. 7: (a) Cycle threshold (Ct) values of sinking particles (mean $\pm$ SD) from the 05M-B 2020-2021 sediment trap targeting *A. catenella* DNA. The red circle with a diagonal slash indicates samples with no amplification. The asterisks indicate samples collected from trap

bottles 13, 14, 16, 17, 20, 21, for which 50 mL was used to obtain enough particulate matter for the qPCR. (b) *A. catenella* cell counts from coastal water samples collected during May to mid-October 2021 at Sept-Îles, Mont-Joli, and Tadoussac stations within the framework of the Harmful Algal Monitoring Program (Fisheries and Ocean Canada - DFO). (c) Total particulate matter (TPM) sinking flux in sediment trap 05M-B 2020-2021. (d) Sea-ice concentration derived from ice maps (black curve). The thin orange-red bars on the (d) curve represent all major and minor resuspension events⁵⁸. (e) Temperature at 224 m at the 05M mooring site. (f) Relationship between mean Ct and TPM sinking flux. The lowest Ct values correspond to the highest TPM flux. (g) Relationship between mean Ct and its standard deviation, where higher variability generally coincides with higher mean Ct (i.e., lower initial targeted gene levels). R1: resuspension event of 23 December 2020; T: turbidity currents of 3 February 2021; R2: resuspension event of 6 March 2021.

Sediment core profile

A. catenella DNA was successfully amplified in several intervals of core COR2212-05BC (Fig. 8a,b), with the lowest Ct values observed at 2–3 cm, 4–5 cm, 6–8 cm, 12–15 cm, and 18–19 cm. Ct values above 30 were considered negative or indicative of trace DNA. Three other intervals in which DNA was successfully amplified with moderate Ct values (i.e., 21–22 cm, 24–25 cm, and 37–38 cm) are within the remobilized deposits (Fig. 8a,b,d). DNA amplification was unsuccessful from 33 to 35 cm.

COR2212-05BC

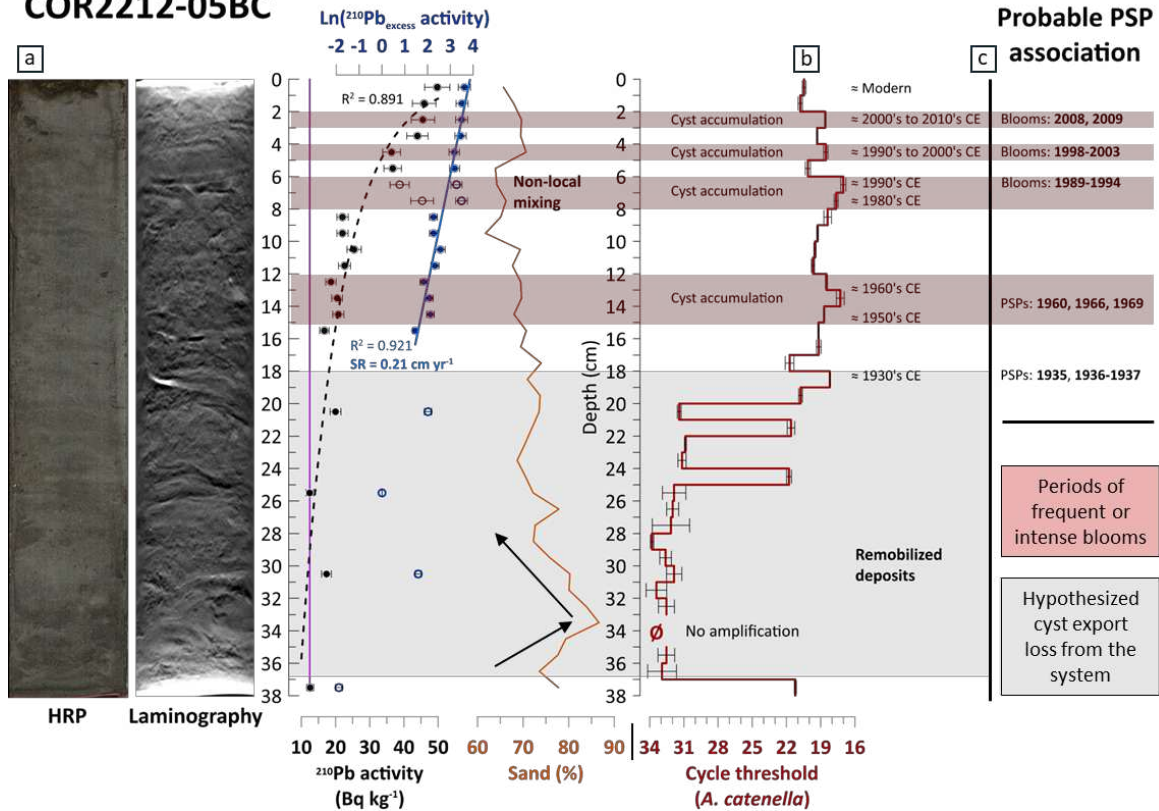


Fig. 8: Vertical profile of core COR2212-05BC, modified from Jacques et al.⁵⁸. (a) High-resolution photography (HRP), laminography, ²¹⁰Pb activity, Ln(²¹⁰Pb_{excess}), and percentage of sand. The sedimentation rate (SR) is calculated from the slope of Ln(²¹⁰Pb_{excess}). Non-local mixing and remobilized deposits along the core are identified. Biological mixing and remobilization intervals were excluded from the sedimentation rate calculation. Violet vertical line: ²¹⁰Pb_{unsupported} level. Blue line: sedimentation rate (SR). (b) Cycle threshold (Ct) values and their standard deviation as a function of depth. The red circle with a diagonal slash indicates samples with no amplification. (c) Periods of frequent or intense documented blooms most likely associated with the Ct data. References and locations of reported blooms are provided in Supplementary Table 4 (Supplementary Note 2).

Discussion

Sedimentary dynamics, particulate matter export, and resuspension events

Two-years of monitoring increased the likelihood of capturing resuspension events in the canyon system and encompassed contrasting sea-ice conditions. Among minor resuspension events, only one turbidity current and three resuspension events strong enough to be clearly identified by the ADCP and by particulate matter export in the sediment traps were observed (R1: 23 December 2020, T: 3 February 2021, and R2: 6 March 2021), all during the first year (Figs. 3 and 5a). These events were characterized by sharp increases in ADCP backscatter, indicating sediment transport lasting tens of minutes to hours. These three events were primarily linked to winter storms that occurred when the LSLE was ice-free in the PDM canyon region. This was particularly evident for wave heights exceeding four meters and wind speeds surpassing 60 kilometers per hour before the turbidity current (Fig. 4c–e). In sediment trap samples, they correspond to distinct peaks in TPM sinking fluxes, concurrent with the sedimentary events. Slight increases in chloropigment and POC fluxes were also observed, suggesting the potential transport of organic material (Fig. 5a,b,e).

Sediment resuspensions and storm-induced turbidity current events were of limited magnitude and quickly dispersed within the water column, producing a small and dilute sediment plume⁵⁸. The ADCP that captured these events is situated in a canyon axis near the coast suggesting that the resuspended material most likely originated from the coastal zone, canyon head, or upper canyon axis rather than from the fan or distal canyon areas.

C:N values of sinking particles from 2021–2022 were consistently lower than those from 2020–2021, showing no clear seasonal trend (Fig. 5c). Consistent with Sharpe et al.⁶⁵, these values suggest that the particulate organic matter is predominantly of marine origin (for the two cycles, $\delta^{13}\text{C} = -24.5\text{‰}$ to -21.7‰ and C:N = 4.1 to 12.8 g/g), with limited degradation and minimal contribution from degraded terrestrial material or resuspended sediments. However, our data suggest a greater proportion of degraded organic material in 2020–2021 compared to 2021–2022, potentially linked to enhanced resuspension from the seafloor. The highest C:N value was measured at 154 m between 15 and 28 February 2021, possibly reflecting the turbidity current of 3 February 2021⁶⁵. Alternatively, it may represent degraded organic matter remobilized near the coast by high waves during the storm that initiated the turbidity current and subsequently transported offshore. Similarly, slightly higher TPM fluxes collected at 154 and 255 m before the turbidity current of 3 February 2021 may be associated with the storm of 17 January 2021, which likely resuspended a small amount of sediment near the mooring.

Spatial distribution of *A. catenella* in surface sediments

DNA detected in surface sediment samples across the PDM canyon system demonstrates a widespread presence of *A. catenella* on the seafloor (Fig. 6). Sedimentary DNA can originate from intracellular DNA contained within the cysts or extracellular DNA released from lysed vegetative cells or fragmented cysts⁶⁶. In agreement with Sharpe⁶⁷, resting cysts of *A. catenella* containing cellular material were observed in surface sediments. Because our standard curves for surface sediment and core were generated using *A. catenella* cells rather than cysts, and because sediment trap samples were preserved in formalin, we chose not to perform quantification to avoid introducing additional sources of error. Therefore, Ct values are interpreted as a proxy for relative cyst abundance, while acknowledging that some contribution from extracellular DNA cannot be excluded. We note that qPCR assays have been widely used to quantify *Alexandrium* cyst inventories in sediments worldwide^{68–73}. In regions near our study area, *Alexandrium* cysts have been reported at abundances of 100–250 cysts cm⁻³⁵⁴, 150–300 cysts cm⁻³ at the mouth of Godbout River, and between 0 and > 400 cysts cm⁻³ within the PDM canyon system⁶⁷, further supporting their widespread occurrence.

Ct values were generally lower near the coast (Fig. 6). Low Ct values were also measured in the fan of the main canyon, corresponding to the most dynamic area of the system^{55,57,58}. This distribution suggests that canyon processes, including resuspension events and turbidity currents, may facilitate the transport and redistribution of *A. catenella* cysts along the canyon axis. In contrast, higher Ct values at transitional sites may reflect coarser grain sizes (Fig. 6), where strong bottom currents and sediment winnowing may limit the deposition of finer particles, including cysts, instead transporting them downslope

toward the fan⁵⁸. This is coherent with the well-established view that dinoflagellate cysts typically behave like fine silt particles in sedimentary environments⁷⁴.

Evidence of *A. catenella* bloom, resuspension, and transport

In the LSLE and GSL, *A. catenella* usually blooms during summer, especially in July, when a stable water column and warmer water temperatures favour its growth^{20,21,25,75} (Supplementary Table 4). Consistent with this seasonal pattern, relatively low Ct values, compared to our overall records, were measured in the bottom sediment trap from mid-June and decreasing until the end of July of 2021 (Fig. 7a). This likely reflects the species presence in the upper water column shortly before their detection, as cells and cysts sank to the trap over time. During this period, relatively low wind velocities and wave heights (Fig. 4d,e) would have diminished surface mixing, while previous high runoff during April and May 2021 (Fig. 4g) may have lowered surface salinity and increased humic substance input from terrestrial sources. These environmental conditions likely promoted the growth of *A. catenella* populations present at that time^{24,28,32}. The timing of the bloom is further supported by *A. catenella* cell counts from the Harmful Algal Monitoring Program (DFO, unpublished data), which recorded elevated cell abundances in coastal waters near Sept-Îles and Mont-Joli in June and July 2021 (Fig. 7b).

The most striking feature of the dataset is the strong association between TPM peaks and the *A. catenella* DNA peaks in late December, early February, and early March (Fig. 7a,c,f). These TPM peaks correspond to turbidity currents and major resuspension events identified with the 02M-ADCP mooring^{58,65} (Figs. 3, 5 and 7). This pattern strongly

suggests that the winter DNA peaks result from resuspended material rather than active cell growth, which is unlikely during that season (Fig. 7f). Therefore, the DNA signal likely reflects resuspended cysts, potentially mixed with extracellular DNA, mobilized from the seafloor. These observations also align with those of Fachon et al.⁷⁶, who showed that cyst resuspension on the Chukchi shelf, Alaska, occurs most often during storms.

An additional Ct peak in early September 2021 (Fig. 7a) is harder to interpret because it is not associated with resuspension events. Consequently, it may reflect newly encysted *A. catenella* cells produced towards the end of the growing season locally, or cyst advection (Fig. 7a,b). Cysts advection is supported by a shift of about 2°C in water temperature at 224 m depth between 1 and 10 September 2021, with the lowest temperatures recorded on 6–8 September 2021 (Fig. 7e). This period also coincided with an extratropical storm, for example, Hurricane Ida became an extratropical storm and remained over the southern Gulf of St. Lawrence on 3–4 September, causing strong wind and heavy rainfall⁷⁷. Such events can strongly influence zooplankton transport via regional currents and wind-forced water advection from the GSL to the LSLE at PDM, typically with a four-day lag in the upper water column and extending to depths of at least 180 m⁶¹. Therefore, water advection may have also transported *Alexandrium* cells and cysts to the study area. Although our data cannot confirm this, we hypothesize that such transport may have played a role in generating this Ct peak. Notably, a small increase in *A. catenella* cell counts was also observed at Mont-Joli and Tadoussac during this period (Fig. 7b).

441 **Implication for HABs and *A. catenella* dynamics in the LSLE**

442
443 Previous studies in other systems suggest that cyst resuspension can promote bloom
444 development (e.g., ^{43–45}). The presence of *A. catenella* cysts in surface sediments indicates
445 that the PDM canyon system is susceptible to harmful blooms, and that sedimentary
446 processes influence their local distribution. Moreover, export fluxes and DNA data show
447 that storm-induced resuspension and turbidity currents can remobilize and transport *A.*
448 *catenella* within the canyon system. A key question is how these processes might contribute
449 to HAB dynamics in the LSLE.

450 Timing of resuspension events. Over 2020–2022, turbidity currents and resuspension
451 events mainly occurred following winter storms during the ice-free period. We observed
452 no evidence of large increases in *A. catenella* during winter, except in samples associated
453 with high chloropigments and POC that corresponded to the resuspension or turbidity
454 current events. These signals are extremely unlikely to originate from vegetative cells as
455 the winter temperatures inhibit quiescent cysts from germinating, preventing excystment
456 during seasonally inappropriate periods^{36,37,78}. Indeed, *A. catenella* and associated PSP
457 intoxications are essentially absent during winter in the LSLE⁷⁹ (Supplementary Note 2).
458 The temperature range also precludes vegetative growth in winter, even without sea ice
459 (e.g., ^{24–26}), consistent with observations from the Pacific Arctic region⁷⁶. Consequently,
460 resuspension events in winter are generally unlikely to directly trigger new excystments or
461 bloom initiation, although the probability increases for events occurring closer to spring
462 warming.

Offshore transport and hypoxic conditions. Resuspension and turbidity currents primarily transport cysts offshore, into deeper and less favorable environments for germination and growth after redeposition, while simultaneously depleting the coastal cyst bank where inoculation is more likely to occur. In the LSLE in 2021, including the PDM canyon system, hypoxia was observed at ≈ 200 m depth, with severe hypoxic conditions below 250 m^{80–82}. Because the seafloor deepens rapidly offshore, cysts redeposited in these areas are exposed to cold, dark, hypoxic conditions, which can slow or inhibit *A. catenella* germination, especially under anoxia and in the absence of light⁸³. Many surface sediments and sinking particles collected in the sediment trap at 224 m likely fall within this hypoxic zone, where cyst banks are unlikely to effectively contribute to inoculation of future blooms. Consequently, unlike observations in other coastal systems, our results suggest that cyst resuspension generally does not promote HABs at PDM.

Zonneveld et al.⁸⁴ documented the resuspension of empty cysts inside a bottom sediment trap but not in the upper trap, as well as the offshore transport of viable cysts. These findings suggest that redeposition below the photic zone may still be part of their life strategy. Our observations, however, reveal a different dynamic in which sedimentary and hydrodynamic processes may limit, rather than trigger, local bloom development. This contrasts with findings from other systems, where upwelling, alongshore currents, advection (e.g., ^{85–88}), tidal-current driven resuspension⁸⁹, or tsunami-induced cyst redeposition⁹⁰ can trigger bloom events. While resuspension of dinoflagellate cysts is enhanced in coastal submarine canyons, it is not restricted to these environments and may occur in other coastal regions, potentially resulting in different ecological consequences.

However, ongoing climate change, particularly reduced sea-ice cover, warmer waters, and more frequent storms⁹¹, could shift this balance by enhancing cyst inoculation during spring and summer, when conditions favor vegetative growth. Observations from 2020–2022, covering contrasting sea-ice conditions and storm regimes, indicate that sea-ice persistence may strongly influence coastal sedimentary processes, mediating downstream effects on primary production and particle fluxes, with implications for *A. catenella* ecology. These findings demonstrate the value of combining conventional monitoring with molecular techniques to study HABs in dynamic systems^{92–94}, while noting that the presence of *Alexandrium* species does not necessarily indicate toxin production or predict the level and profile of toxins produced (e.g., ^{95–97}). Therefore, species identification⁹⁸ or quantification⁷² via molecular assays, and direct measurements of paralytic shellfish toxins using chemical or bioassay approaches remain essential for assessing poisoning risks^{17,99}.

Historical perspectives from sedimentary DNA

The successful amplification of *A. catenella* DNA in core COR2212-05BC (Fig. 8) shows the potential of sedimentary ancient DNA (*seda*DNA) for reconstructing past bloom history and species dynamics, as previously shown for other taxa (e.g., *Gymnodinium catenatum* in Bolch et al.¹⁰⁰; *A. minutum* in Klouch et al.¹⁰¹; *Polarella glacialis* in Harðardóttir et al.¹⁰²).

Despite moderate remobilization by bioturbation and bottom currents, Jacques et al.⁵⁸ estimated an average sedimentation rate of 0.21 cm per year using lead-210 (Fig. 8a). The sedimentary structures (e.g., remobilized flaser bedding, climbing ripples, and mud

offshoots) and granulometry (coarsening then finning upward fine sand) within the 18–38 cm interval of core COR2212-05BC was identified as a reworked turbidite⁵⁸. Although remobilization limits temporal precision, each sample integrates several years of deposition, allowing approximate dating of peaks of Ct values. The chronology indicates DNA maxima around 1930's, late 1950's to 1960's, 1980's to 1990's, and 2000's CE (Fig. 8), aligning with some documented blooms or paralytic shellfish poisoning (¹⁶ and references therein; ^{14,20,24,25}; Supplementary Note 2). For example, the Ct peak at 12–14 cm aligns with the 1966–1969 PSPs that occurred around Godbout and along the north coast of the LSLE (Supplementary Table 4). Also, the Ct peak at 18–19 cm seems to align with the 1935–1937 PSPs that occurred east of Godbout¹⁰³, although it lies atop remobilized deposits that may include redistributed cysts that resettled together after the remobilization event. Other peaks at 21–22 cm, 24–25 cm, and 37–38 cm likely reflect cyst redistribution within disturbed layers. Given the potential for moderate remobilization in other deposited intervals, the lack of systematic correspondence with PSP events or HABs, and incomplete documentation, these associations should be interpreted with caution.

Despite these constraints, our results support using *seda*DNA from well-preserved cores to study the temporal evolution of *A. catenella*, an otherwise inaccessible record for a species whose cysts are not fossilizable^{104,105}. Integrating *seda*DNA with palaeoceanographic proxies in well-dated cores offers a powerful approach for reconstructing the long-term history and identifying climatic and anthropogenic drivers of HABs caused by diverse harmful species. When combined with high-resolution environmental reconstructions, *seda*DNA can provide a unique and valuable context for

informing HAB prevention, control, and mitigation, potentially guiding progress in those areas in the near future.

Conclusion

A. catenella is widespread in sediments of the PDM canyon, especially along the coast, where resuspension events mobilize shallow cysts into the canyon system and redistribute them in the submarine fan. Sediment trap-derived export fluxes confirm that these events effectively resuspend cysts. However, contrary to previous observations in other environmental settings, our results suggest that these particular resuspension events in the LSLE are unlikely to promote HABs in the region. This is because resuspension usually occurs during winter storms, when environmental conditions, such as low water temperatures are generally not favorable for excystment and bloom initiation. Moreover, these resuspension events transport cysts offshore, into deep, dark, hypoxic waters further depleting coastal cyst banks. However, future climate conditions, including warmer winters or summer resuspension events, could provide conditions favourable for inoculation into the water column. Water inflow events associated with extratropical storms may contribute to cyst transport. DNA peaks aligning with some documented regional bloom or paralytic shellfish poisoning underscore the potential of *seda*DNA for reconstructing past bloom history, especially in well-dated cores.

These results highlight the value of molecular tools like qPCR for studying HABs, providing proxies that reveal environmental processes where conventional methods may

fall short. Our integrated, multi-level approach shows how sedimentary and hydrodynamic processes in a submarine canyon influence *A. catenella* dispersal and bloom potential at both local and regional scales in the LSLE. Although cyst resuspension is primarily considered to be a mechanism favoring excystment and bloom initiation, our findings indicate that its influence is highly system-dependent, with hydrodynamic and sedimentary context determining whether these processes enhance or suppress bloom development, and underscore the underappreciated influence of bathymetry on ecosystem functioning.

Data and Methods

Meteorological and environmental data

Meteorological data, including total precipitation, wind speed, and wind direction, were measured at the PDM meteorological station and obtained from historical climate data website¹⁰⁶. Wind speed and precipitation data from PDM and nearby meteorological stations were unavailable between 4 February and 5 June 2022. Godbout River runoff was obtained from the Environment and Climate Change Canada website¹⁰⁷. In addition, sea ice concentrations off PDM for the years with ADCP monitoring were compiled from daily ice charts made by the Canadian Ice Service¹⁰⁸ from which the sea-ice symbol total concentration was reported for the specific to the PDM area.

Samples and oceanographic data

Samples and oceanographic data (Fig. 2) were collected during four expeditions aboard the R/V Coriolis II in July 2020 (COR2001), October 2020 (COR2007), October 2021 (COR2110), and October 2022 (COR2212).

Surface sediments and sediment core

A total of 26 surface sediment samples (0–1 cm) were collected using a Van Veen grab sampler or a box corer (Fig. 2; Supplementary Table 1). A 38 cm push core (COR2212-05BC) was also collected using a box corer. Samples for sedimentary ancient DNA (*sedaDNA*) were stored at 4°C until subsequent analyses. Sedimentological data (including, high-resolution photography, X-ray computed tomography and grain size) and lead-210 (^{210}Pb) data for core COR2212-05BC used in this study were obtained from⁵⁸. Briefly, the core was scanned with a GEOTEK X-ray computed tomography (X-CT) system at the Geological Survey of Canada (Atlantic), allowing the acquisition of laminography length-wise slices. Grain-size analysis of surface and core sediment samples was performed using a Malvern Panalytical Mastersizer 3000 laser diffraction system, following the instrumental protocol from¹⁰⁹. Before analysis, samples were treated with H_2O_2 (30% v/v) and HCl (1 M), dispersed in 20% (v/v) sodium hexametaphosphate, wet-sieved to <2 mm, and agitated on an in-house rotator for 12 h to promote sediment dispersion. Grain size parameters were obtained using GRADISTAT software version 9.1¹¹⁰.

Lead-210 (^{210}Pb) measurements were performed on the core using alpha spectrometry¹¹¹ at the Radiochronology Laboratory of the Geotop Research Center in

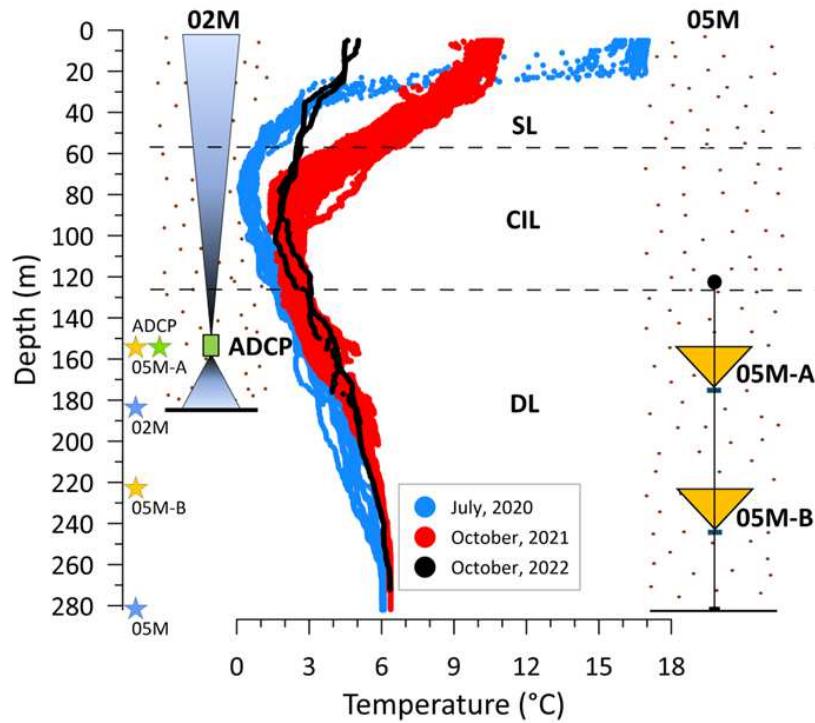
Montréal, Canada. The age-depth model and sedimentation rates were derived from the Constant Flux Constant Sedimentation model^{112,113}.

Moorings

Time-series sediment traps (Technicap PPS 6/2; diameter 0.5 m²) were deployed in the main submarine canyon of PDM at depths of 154 m (05M-A) and 224 m (05M-B) during the first cycle, and at depths of 160 m (05M-A) and 230 m (05M-B) during the second deployment cycle (Fig. 9, Supplementary Fig. 2; Supplementary Table 2). For simplicity, trap depths are referred throughout the text as 154 m (05M-A) and 224 m (05M-B) as the depth differences between deployment cycles are negligible. The traps collected sinking particles over two annual cycles, from October 2020 to October 2021 and from October 2021 to October 2022. Each trap was fitted with 24 bottles that rotated at intervals ranging from 7 to 16 days. The samples are numbered from 1 to 24 in chronological order, with number 1 corresponding to the first half of November 2020. To preserve biological material, bottles were pre-filled with a formalin solution neutralized with sodium borate to preserve the samples during deployment. Upon recovery, samples were stored in the dark at 4°C until analysis. A Seabird Electronics SBE 16 plus V2 SeaCAT CTD probe attached to both traps recorded temperature and salinity averaged over 4 min.

A mooring (02M) equipped with both an upward-looking RDI Workhorse 300 kHz ADCP (a vertical bin size of 4 m, one ping per 40 seconds), and a downward-looking RDI Workhorse 600 kHz ADCP (vertical bin size of 1 m, one ping per 20 seconds) was deployed upstream of the main PDM canyon for the same two years. This mooring was

positioned 30 m above the seafloor at a water depth of 183 m the first cycle and 195 m for the second deployment cycle (Fig. 9; Supplementary Fig. 2; Supplementary Table 2). The four acoustic beams of each ADCP were oriented at 20° relative to the vertical and recorded acoustic backscatter, water velocity, and pressure. The ADCP backscatter data were corrected for attenuation of sound waves in water and spherical spreading¹¹⁴ with Matlab (version R2012A) to obtain normalized amplitudes. Due to the difference in frequency between the upward and downward backscatter intensity (300 kHz and 600 kHz, respectively), the overall upward backscatter was largely superior to the downward. Therefore, the upward data scale was reduced by 15 units so that the upper part of the downward intensity profiles correspond to the bottom of the upward intensity profiles. The magnitude of this 15-unit adjustment was determined by time averaging all upward and downward backscatter profiles and calculating the difference between the means of the upward and the downward profiles. Only the backscatter intensity of beam 1 of each ADCP is presented in dB (arbitrary scale) as all four beams recorded very similar backscatter data. An AWAC (Acoustic Wave and Current Profiler) mooring was deployed near the shore in 40 m water depth during the same period as the ADCP and sediment trap moorings (Supplementary Table 2). It allowed retrieval of wave heights (see Jacques et al.⁵⁸). Due to technical issues, no AWAC data were available from 11 October 2021 to 20 April 2022. Because storm-related wave energy can propagate long distances with minimal attenuation, this gap was supplemented with wave-height records from AWAC moorings at Saint-Ulric presented in Neumeier and Joly¹¹⁵ (location on Fig. 1).



637

638 Fig. 9: Water temperature profiles collected in July 2020, October 2021, and October 2022.

639 Schematic position of the ADCP (02M) and sediment trap (05M) moorings in the water

640 column. The triangles emanating from the ADCP illustrate their range of data acquisition

641 depths. Blue stars indicate water column depth at each mooring site, the green star indicates

642 the depth of the ADCP, and yellow stars indicate the depths of the sediment traps. SL:

643 Surface Layer; CIL: Cold Intermediate Layer; DL: Deep Layer.

Laboratory analyses of sinking particulate matter

Chloropigment and total particulate matter (TPM) analyses were performed in triplicate following Sharpe et al.⁶⁵. All samples were gently homogenized for 100 s prior to subsampling. For chloropigment measurements, aliquots of 0.25–1.25 mL were filtered onto 25 mm Whatman GF/F filters (nominal pore size: 0.7 μ m). Chloropigments were extracted in 10 mL of 90% acetone in the dark at 4 °C for 18–24 h. Extracts were transferred to borosilicate tubes and analyzed fluorometrically using a Turner Designs 10-AU fluorometer. For TPM measurements, aliquots of 0.25–1.5 mL were filtered onto pre-combusted (450 °C, 5 h) 21 mm Whatman GF/F filters. Prior to filtration, filters were weighed with an MX5 microbalance (Mettler Toledo). After filtration, the filters were rinsed with at least 5 mL of Nanopure water. Then, they were oven-dried at 60 °C for 24 h and reweighed to calculate TPM as the difference between the final and initial filter mass. Subsequently, filters were placed in a desiccator saturated with HCl fumes for 24 h to remove inorganic carbon. After acidification, filters from the second annual cycle were analyzed for particulate organic carbon (POC; Elemental analyser Vario EL Cube, Elementar, Germany), particulate nitrogen (PN; Interface Conflo IV, Thermo, Germany), and isotopic ratios of carbon ($\delta^{13}\text{C}$; Isotope Ratio Mass Spectrometer Delta Advantage, Thermo, Germany) at the Ján Veizer Stable Isotope Laboratory (University of Ottawa, Ottawa, ON, Canada). C-51 Nicotiamide and C-54 caffeine were used as calibration standards for POC and PN. $\delta^{13}\text{C}$ is reported as ‰ vs. Vienna Pee Dee Belemnite (VPDB) and normalized to internal standards calibrated to international standards IAEA-CH-6, NBS-22, USGS-40, and USGS-41. Analytical precision based on the blind standard C-55,

a L-glutamic acid, is presented in Supplementary Table 3. The analytical instruments used for the first annual cycle are described in Sharpe et al.⁶⁵.

Molecular estimation of *A. catenella* presence

Quantitative Polymerase Chain Reaction (qPCR) was used to detect deoxyribonucleic acid (DNA) of *A. catenella* in the surface sediment and core COR2212-05BC samples, and in material collected by sediment traps from the PDM submarine canyon system. The assay primarily targeted intracellular DNA, enabling the detection of DNA from both cysts and vegetative cells. However, since DNA was extracted from unprocessed sediment samples, extracellular DNA may also have been measured. Analyses of surface sediment samples and core samples were performed at Ifremer (Concarneau, France), whereas sediment trap samples were analyzed at ISMER, UQAR (Rimouski, QC, Canada). Among the sediment traps samples, we focused on those from trap 05M-B-2020-2021, which is considered the most reliable for assessing cyst resuspension due to its bottom position and the occurrence of major resuspension events during the first year of deployment.

For DNA extraction, 240 - 250 mg of wet sediment was weighed directly into a crystal bead tube containing corundum grains (type C tube, Macherey-Nagel). DNA was extracted using the DNeasy PowerLyser PowerSoil kit (Qiagen), and amplification was performed using the primers of Vandersea et al.¹¹⁶ on a QuantStudio 5 thermocycler (Applied Biosystems), following the protocol description in the Supplementary Method 1.

The qPCR results are reported as cycle threshold (Ct) values, which are inversely related to the quantity of target DNA present in the qPCR reactions, and are also therefore related to the quantity of target DNA template in the respective DNA extracts^{92,117}. Specifically, the Ct values corresponds to the number of qPCR cycles required for the fluorescence signal to exceed a defined threshold above background noise¹¹⁸. As amplification proceeds, signals will double each PCR cycle, and consequently a change in 1 Ct value represents a two-fold difference in target DNA.

Data availability

Analytical data presented are partly available electronically in the Observatoire global du Saint-Laurent at <https://doi.org/10.26071/7bb5f2d7-b91e-46ce> and at <https://doi.org/10.26071/ogsl-9b07076f-e47b>. Other analytical data presented will be available electronically in the Observatoire global du Saint-Laurent (<https://catalogue.ogsl.ca/en/>).

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Competing interests

The authors declare no competing interests.

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