

Canadian Arctic GEOTRACES project

Two consecutive cruises covering stations from the southern Labrador Sea to the western Beaufort Sea have been successfully completed during Summer 2015. This was achieved despite a 2-week hiatus in our research program that resulted from the diversion of our ice breaker to open shipping lanes through the ice in eastern Hudson Bay.

1. Cruises synopsis

Our 2015 field program consisted of 2 separate legs. The first leg (**Fig. 1**) covered the Labrador Sea, Baffin Bay and the eastern and central Canadian Arctic Archipelago (CAA). The second leg crossed Canada Basin and covered the western CAA (**Fig. 2**). Note that the first leg of the Arctic GEOTRACES cruise corresponds to Leg2 of the CCGS Amundsen summer expedition, while our second leg corresponds to Leg 3b for the Amundsen.

2015 CCGS Amundsen expedition LEG 2 GEOTRACES/ARCTICNET

July 10 – August 20, 2015

Quebec City – Kugluktuk

Chief Scientists: Roger Francois, Philippe Tortell

This leg was shared between the Canadian Arctic GEOTRACES project and ArcticNet. As part of the international GEOTRACES program, the principal mandate of our project was to study the input, removal and cycling of trace elements and isotopes in the water column, and to use this information to document, monitor, and predict the evolution of physical and biogeochemical processes in the Arctic Ocean. Our project was also complemented by very extensive biological and trace gas measurements, which not only met the broader requirements of our funding agency (NSERC) but also were of direct relevance to the long-term goals of ArcticNet, facilitating coordination of sampling between the two programs.

Sampling operations for GEOTRACES during this leg consisted of:

- seawater sampling with ArcticNet's 24 x 12 L rosette – CTD (Niskin-type bottles)
- seawater sampling under trace metal clean conditions with a 12 x 12 L rosette – CTD (Go-Flo bottles)
- particle sampling with 6 McLane large volume in-situ pumps
- aerosol sampling with a volumetric flow controlled high volume sampler
- underway trace gas analysis with a Membrane Inlet Mass Spectrometer (MIMS) and a Gas Chromatograph (GC)

Additional GEOTRACES activities included:

- incubations for productivity measurements with different isotopic tracers (^{13}C , ^{15}N , ^{32}Si , ^{18}O , 2h ^{14}C and FRRF) complementing incubations conducted by ArcticNet (24h ^{14}C) and productivity estimates from water column measurements (O_2/Ar , triple O isotopes, ^{234}Th deficit)
- Ship-board manipulation experiments to examine the impacts of ocean acidification and enhanced mixed layer stratification on phytoplankton productivity and physiological ecology.

- river sampling to assess continental input into the CAA (15 rivers draining into the Canadian Arctic Archipelago; **Fig. 1**)

2015 CCGS Amundsen Expedition LEG 3b GEOTRACES/ARCTICNET

September 4 – October 1, 2015

Sachs Harbour – Resolute

Chief Scientists: Roger Francois, Kristin Orians

The second leg was also shared between the Canadian Arctic GEOTRACES project and ArcticNet. As during our first leg, the main GEOTRACES sampling operations consisted of seawater sampling with ArcticNet's 24 x 12 L rosette – CTD, GEOTRACES' trace metal clean 12 x 12 L rosette – CTD, and particle sampling with 6 McLane large volume in-situ pumps. The biogeochemical study conducted during this leg was complemented by a 4-day process study during which mesoscale mixing was measured by conducting a Moving Vessel Profiler and CTD mesoscale and mixing survey in Wellington, Maury and Perry Channels (**Fig. 2**). The goal of this work was to assess the impact of physical processes on the supply of micronutrients to surface waters. Toward the same goal, a glider was deployed in Canada Basin during Leg 3a (August 21 – September 3), which preceded leg 3b. The glider data provided high resolution 2d observations of water column hydrography and micro-structure that will provide new insight into mixing and turbulence across the Arctic continental shelf.

2. Cruise Tracks and discrete sampling summary

2.1 2015 CCGS Amundsen Expedition LEG 2

The initial plan for Leg 2 was to occupy 15 stations (2 stations in the Labrador Sea, 4 in Baffin Bay, and 9 in the Canadian Arctic Archipelago). Additional stations were to be occupied for ArcticNet on a section between Greenland and Devon Island, and in Kane Basin, Kennedy Channel and Petermann Fjord. Time was also allocated for additional stations in Queen Maud Gulf as part of The W. Garfield Weston Foundation - Parks Canada - ArcticNet collaborative project.

The work in the Labrador Sea was completed on schedule, but on July 19th the ship was unexpectedly diverted to Hudson Bay for ice-breaking duties. The resulting 2-week hiatus (from July 19th to August 3rd) demanded a dramatic re-organization of the cruise plan. To the benefit of the GEOTRACES program, ArcticNet cancelled nearly all its stations and the remaining science plan was reduced to occupying 3 of the 4 GEOTRACES Baffin Bay stations and 7 of the 9 archipelago (CAA) stations (Fig. 1). GEOTRACES sampling strategy in the CAA was also adjusted to existing ice conditions and to optimize scientific return within the remaining time. By the end of leg 2, GEOTRACES only lost 3 of its 15 stations (one station in eastern Baffin Bay and 2 stations in the CAA). The latter two of this skipped stations were sampled during the following leg 3B, so that our program only lost one station, which was deemed less important for the program (the CAA through flow into Baffin Bay, which was our main target, occupies the eastern side of the bay). Overall, the change in ship-operations had a large negative impact on proposed ArcticNet work, but almost no detrimental effect on the GEOTRACES program. We are extremely grateful to our collaborators at ArcticNet who went out of their way to ensure that our field campaign was successful. The scheduling and logistical issues we encountered highlight the larger problems associated with oceanographic ship-time allocations in Canada. Our situation garnered

national and international attention, and was the subject of several news pieces on the CBC and Globe and Mail. Three of the GEOTRACES PIs wrote an Op-Ed on this topic:

<http://www.theglobeandmail.com/globe-debate/canadas-ocean-science-capacity-is-limited-with-resource-constraints/article25729123/>.

By the end of leg 2, the GEOTRACES project completed:

- 67 hydrocasts with ArcticNet's CTD-rosette
- 31 hydrocasts with GEOTRACES' trace metal clean CTD- rosette
- 24 casts with GEOTRACES' six large volume pumps
- 22 deployments of XCTDs
- 1 GEOTRACES trace metal clean deck pump deployment (to sample clean water for large volume incubation experiments).

This resulted in 1,545 seawater or marine particle samples for multi-element and isotopic analysis (Table 1), which will amount to >6,000 individual measurements.

We also conducted 278 incubations for carbon fixation and nutrient uptake measurements (88 two-hour ^{14}C incubations/FRRF, 60 ^{13}C and ^{15}N incubations, 60 ^{32}Si incubations, 60 ^{18}O incubations, 10 ^{55}Fe incubations), which were complemented by ArcticNet's 156 twelve-hour ^{14}C incubations.

Two CO_2 / light manipulation experiments and sampling at 15 Arctic rivers draining in the CAA (Fig. 1) were also successfully completed.

2.2 2015 CCGS Amundsen Expedition LEG 3b

The CCGS *Amundsen* left Sachs Harbour on September 4th for our first station (CB1) in McClure Strait (Fig. 2) before crossing Canada Basin to occupy our next three stations (CB2 - CB4). The latter station was the location chosen for a cross-over station for inter-calibration with the US Arctic GEOTRACES program. Two stations were occupied in the archipelago (CAA8 and CAA9) to make up for the two stations lost during Leg 2.

During leg 3b, the GEOTRACES project completed:

- 22 hydrocasts with ArcticNet's CTD-rosette
- 21 hydrocasts with GEOTRACES' trace metal clean CTD- rosette
- 12 casts with GEOTRACES' six large volume pumps

This resulted in 709 seawater or marine particle samples for multi-element and isotopic analysis.

3. Parameters measured or sampled in the water column

3.1 2015 CCGS Amundsen Expedition LEG 2

Seventy-six chemical and biological parameters (**Table 1**) were measured on board or sampled for later analysis for vertical water profiles

In addition, several parameters were continuously measured or sampled along the cruise track:

- Atmospheric Hg concentration (Gaseous Elementary Mercury [GEM], Reactive Gaseous Mercury [RGM] and Particulate Hg [PHg]) with an automated Tekran atmospheric mercury speciation system. Discrete GEM measurements were obtained every 5 minutes. Analysis of PHg and RGM samples occurred after 2-hour collection periods.
- Surface gas measurements were conducted using automated purge and trap gas chromatography (PT-GC; for DMS/P/O), and membrane inlet mass spectrometry (MIMS; for CO₂, ΔO₂/Ar, and DMS) from the ship's seawater intake (**Figs. 3 and 4**).
- Photo-physiological measurements (e.g. variable Chl_a fluorescence, F_v/F_m, and cross sectional absorption area, σ) were measured from the ship's seawater intake using an FRRF equipped with a flow-through measurement cuvette (**Fig. 5**).

Using the MIMS ΔO₂/Ar data, and a steady-state mixed layer O₂ model, we were able to derive quantitative estimates of Net Community Production along the cruise track (**Fig. 6**).

3.2 2015 CCGS Amundsen Expedition LEG 3b

Fifty-seven chemical and biological parameters (**Table 2**) were measured on board or sampled for later analysis for vertical water profiles

4. Cruise participants

The GEOTRACES group on board the CCGS *Amundsen* during LEG 2 consisted of:

- 4 Principal Investigators (Francois, Tortell, Cullen, Thomas)
- 2 Research Technicians
- 4 Postdoctoral Fellows
- 9 PhD students
- 3 MSc students
- 1 BSc student

from 7 Canadian universities (University of Victoria, University of British Columbia, University of Manitoba, Trent University, University of Toronto, McGill University, Dalhousie University) and 2 partner foreign institutions (Alfred Wegener Institute, Woods Hole Oceanographic Institution)

The GEOTRACES group on board the CCGS *Amundsen* during LEG 3b consisted of:

- 3 Principal Investigators (Francois, Oriens, Klymak)
- 3 Research Technicians
- 9 PhD students
- 3 MSc students
- 1 BSc student

from 8 Canadian universities (University of Victoria, University of British Columbia, University of Saskatchewan, University of Manitoba, University of Toronto, University of Ottawa, McGill University, Dalhousie University)

5. Anticipated research direction for the remaining of the NSERC grant

Some analyses were performed on board (e.g. underway trace gases, ^{14}C primary productivity measurements, FRRF, incubation experiments) and these data are now being processed for interpretation and publication (e.g. **Fig. 3 – 6**). Indeed, a number of PIs and students already presented their results at the ArcticNet meeting held in Vancouver, December 7-11, 2015. Core parameters of the international GEOTRACES program will be completed in 2016-2017.

We have organized a first PI meeting in Vancouver on December 7, which coincides with the annual ArcticNet meeting. The purpose of this meeting was to take stock of the data and samples in hand, coordinate analysis, and start discussing publication of results. We have set up a linked computer server to more freely exchange core and ancillary data among the different research groups prior to submission to the GEOTRACES data product.

Coordination will carry on during year 4 at several levels:

- Collaborations within the PIs of the Canadian GEOTRACES program
- Collaborations at the national level with the Network of Centres of Excellence ArcticNet, with the CCAR project VITALS, and with JOIS and C3O programs of the Department of Fisheries and Ocean.
- Collaborations at the international level with our US, German and French partners to produce a quasi-synoptic database over most of the Arctic Ocean

6. Student training

As indicated above, 26 students (19 PhD, 6 MSc, 2 BSc), 2 postdocs, and 5 research staff were responsible for most of the analysis and sampling during the 2015 field season. Additional HQP were also involved in the project, but did not need to participate to field work (e.g. modelers) or could not be accommodated because of berth limitation.

The total number involved in the project to date is 57 students (16 BSc, 17 MSc, 24 PhD), 6 postdocs, and 13 research assistants, for a total of 76.

Students and postdocs have been involved in all important aspects of the research, including the development of research questions and methodologies, data collection and interpretation. They will also play a leading role in the presentation and publication of the results.

7. Data management

We have set up a local electronic platform for sharing raw and processed data between PIs to facilitate interaction and synergy between the sub-projects. Ultimately, the Canadian GEOTRACES data will be integrated into the international GEOTRACES database. The metadata for the two Canadian GEOTRACES cruises have been sent to GDAC.

8. Communication

In summer 2015, we developed a program with the Vancouver Aquarium summer camps. PI Tortell worked closely with a number of UBC graduate students who spend several hours per week over the summer working with children (ages 8 - 14). Specifically, we designed a number of interactive, hands-on modules dealing with Ocean Acidification and Remote Sensing, with a particular focus on the Arctic. The modules included field-sampling at the beach next to the Aquarium, wet-chemistry work with pH buffers etc., computer-based analysis of ocean color imagery, and drone-based imaging of the Vancouver coastline. Our activities were highly successful, and plans have been made to continue and expand this work for summer 2016. We also arranged for a live skype-call from the research vessel, with several scientists and Captain of the Amundsen spending about 30 minutes answering questions from the Aquarium gallery.

9. Intercalibration

Intercalibration is being conducted with PIs from the French GEOVIDE program (Labrador Sea) and the US Arctic GEOTRACES program (Canada Basin). GEOVIDE occupied stations in the southern Labrador Sea in summer 2014. US GEOTRACES was concurrent with the Canadian program but weather conditions prevented sampling for all core parameters at the pre-determined cross-over station. Therefore, intercalibration with the French program and the missing parameters from the cross over station with the US is being conducted following the protocols outlined by the International GEOTRACES Program Office for GEOTRACES cruises without crossover stations.

Appendix (Tables and Figures)

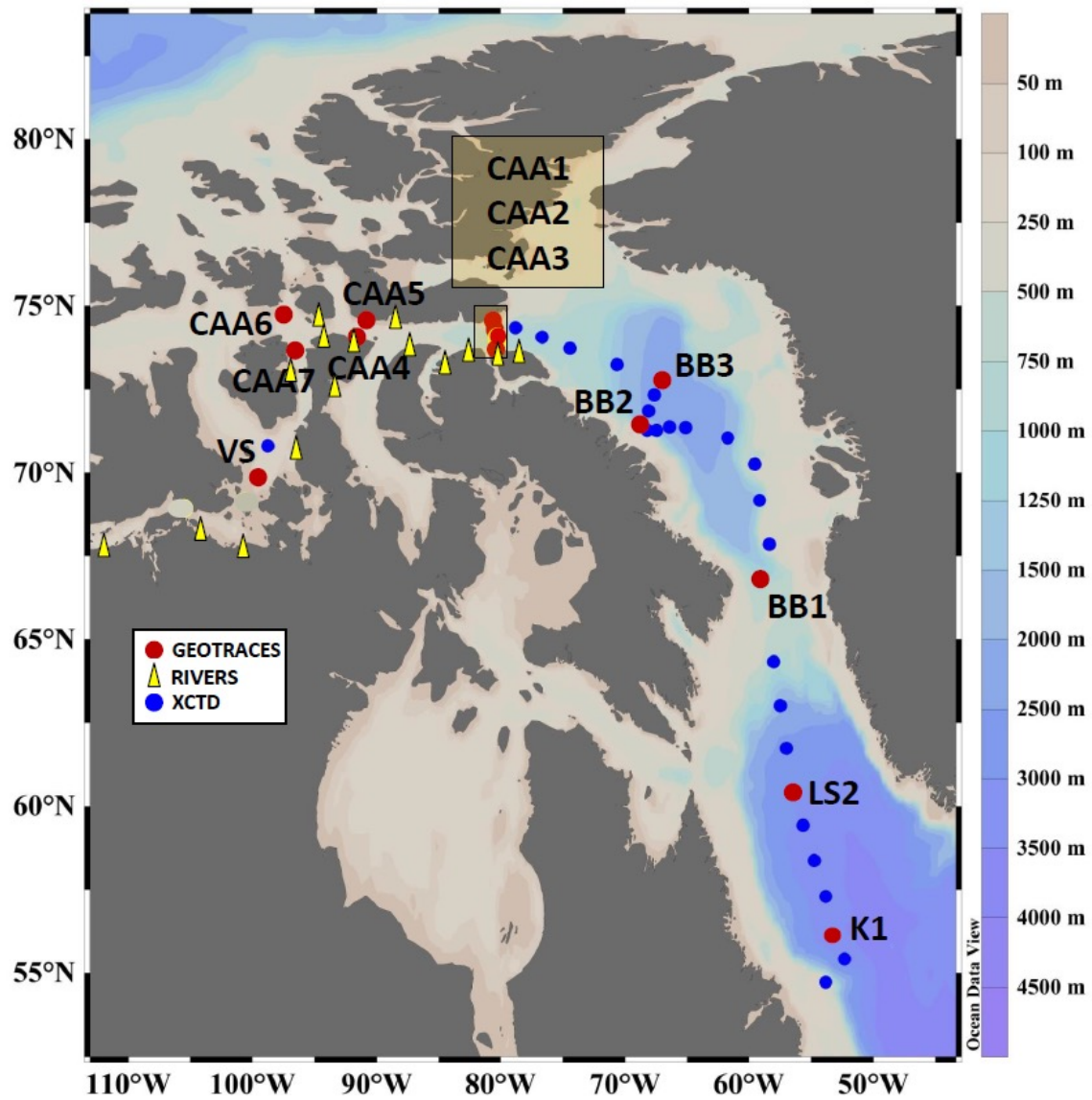


Figure 1: GEOTRACES station locations on the first sampling section (2015 CCGS *Amundsen* Expedition Leg 2)

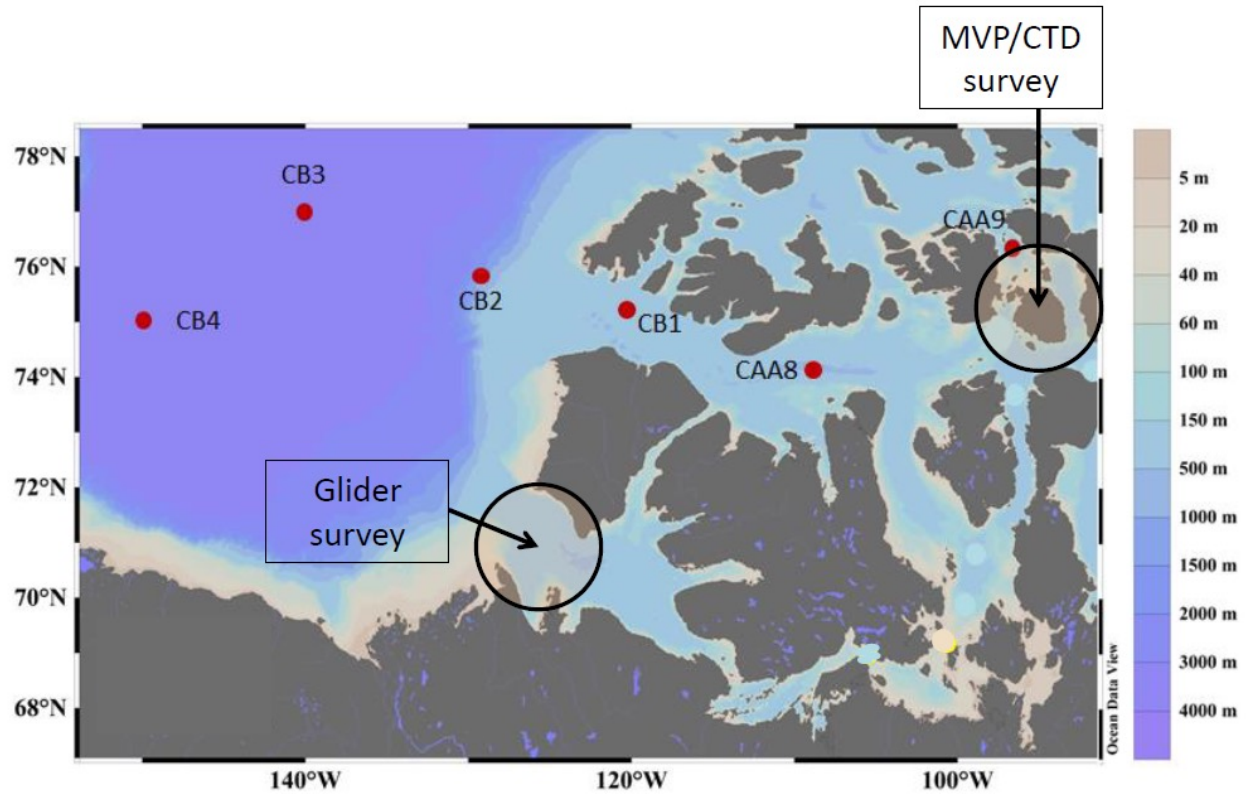


Figure 2. GEOTRACES station locations on the second sampling section (2015 CCGS *Amundsen* Expedition Leg 3b). The glider survey was conducted during 2015 CCGS *Amundsen* Expedition Leg 3a (August 21 – September 3).

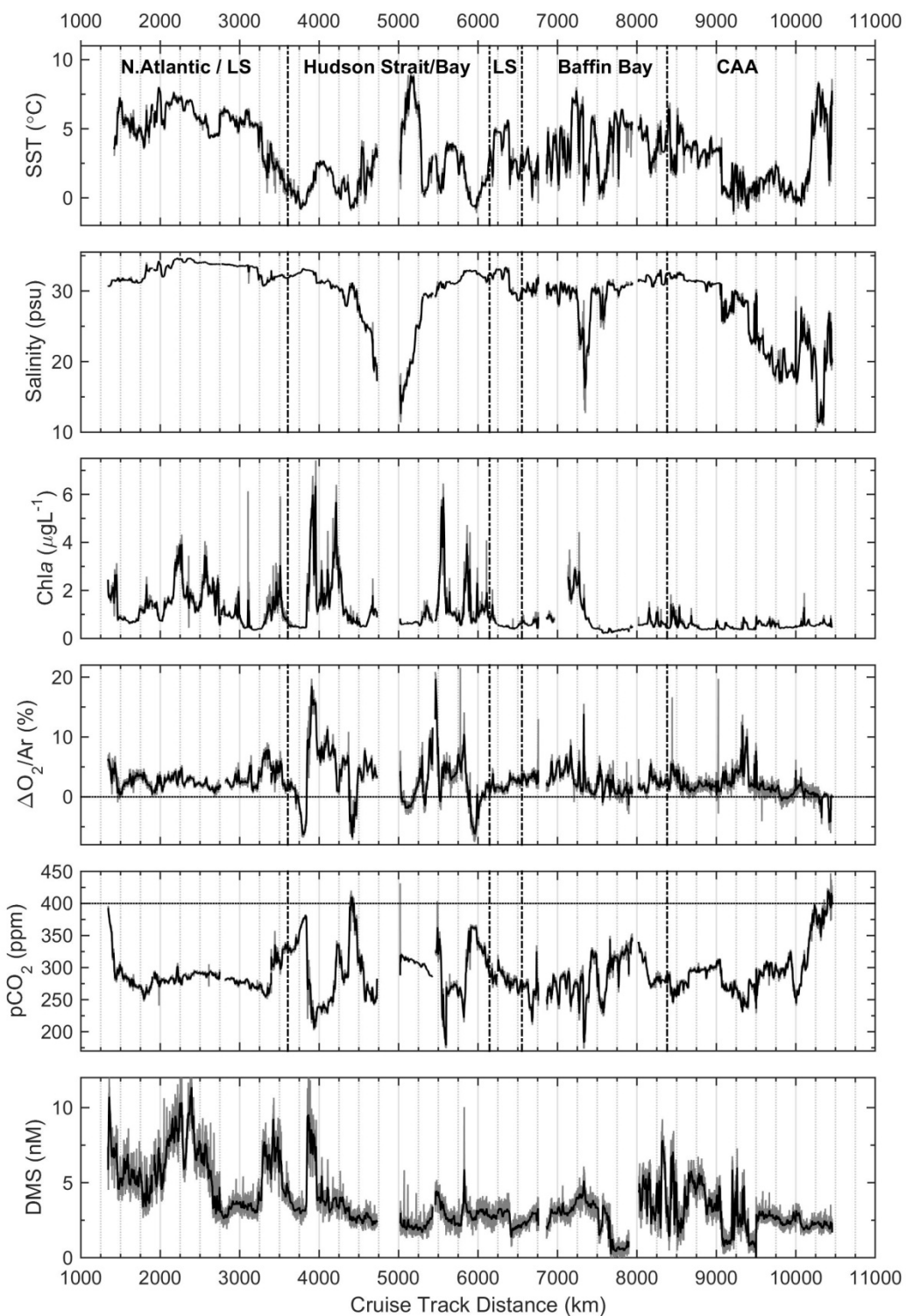


Figure 3. Underway measurements of surface water hydrography (temperature and salinity), phytoplankton biomass (inferred from Chlorophyll a levels) and bio-active gases ($\Delta\text{O}_2/\text{Ar}$, pCO_2 and DMS). Gases were measured using ship-board membrane inlet mass spectrometry.

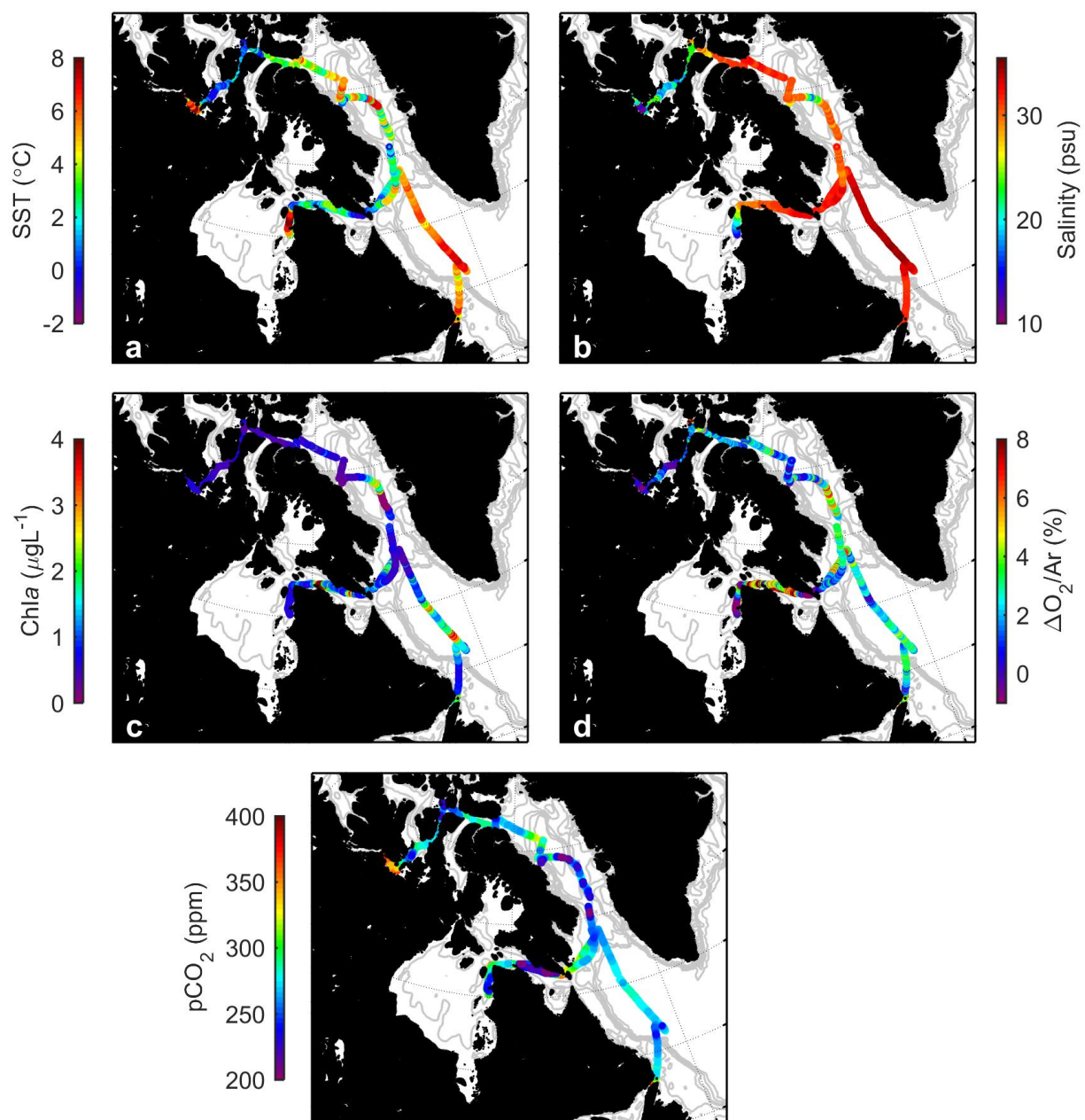


Figure 4. Underway hydrography and surface water gases (as in Fig. 3), but showing the spatial distribution along the cruise track. Note the areas of high apparent biological productivity indicated by elevated $\Delta\text{O}_2/\text{Ar}$ and low surface water pCO_2 .

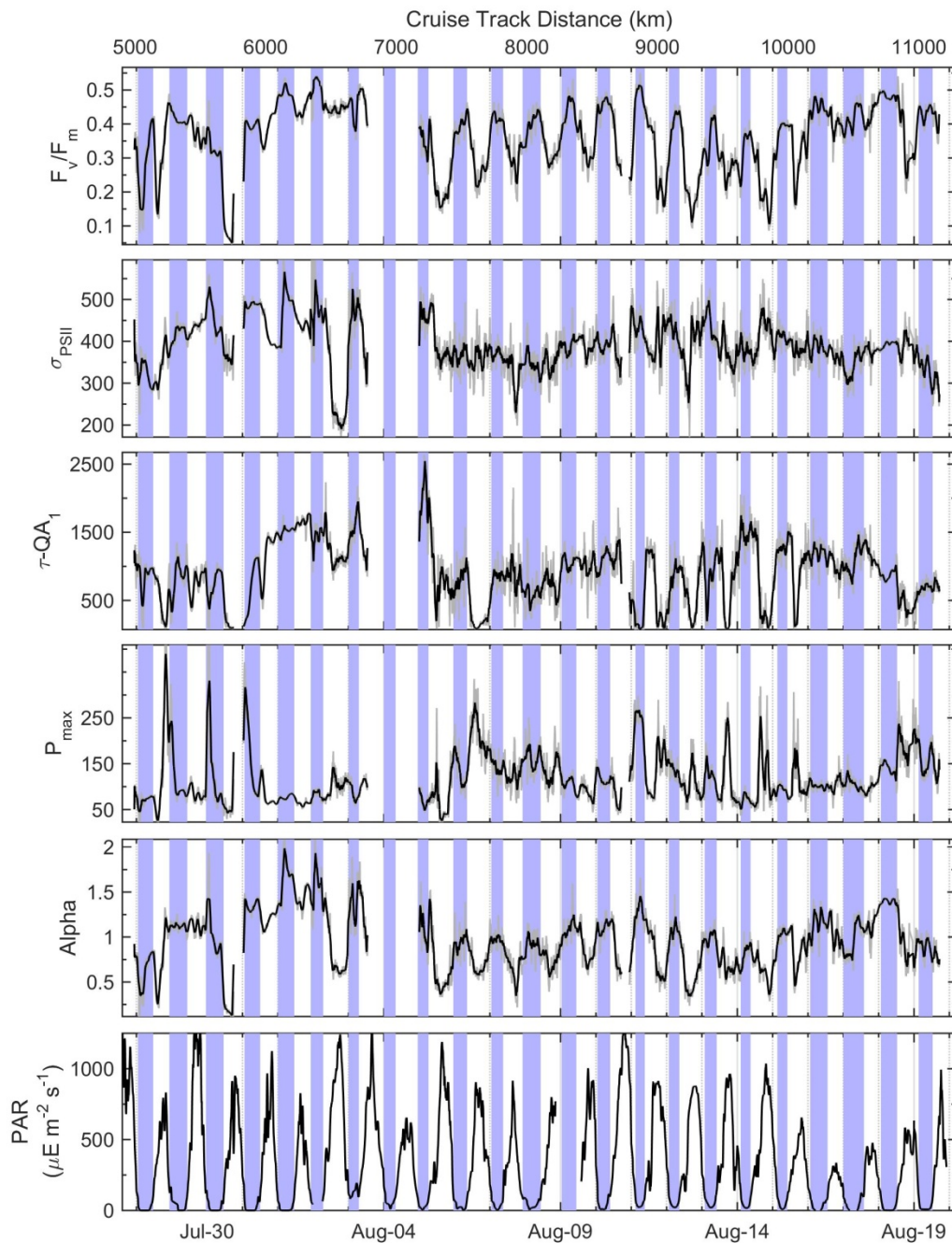


Figure 5. Continuous underway measurements of phytoplankton photo-physiological properties measured using Fast Repetition Rate Fluorometry (FRRF). Bottom panel shows the daily cycles in photosynthetically active radiation (PAR), while upper panels show derived values of photosynthetic efficiency (F_v/F_m), cross-sectional area of photosystem-II (σ), time constant for reoxidation of primary electron acceptor Qa (τ) and the maximum and light-dependent slope of photosynthetic electron transport in short-term P vs. I curves (P_{max} and α , respectively).

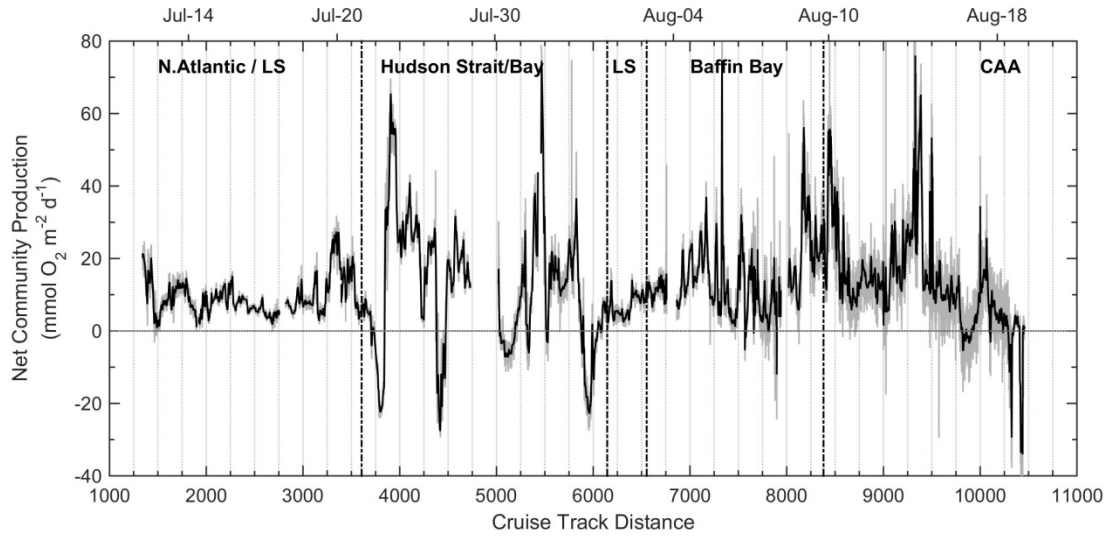


Figure 6. Derived Net Community Production (NCP = photosynthesis minus mixed layer respiration) obtained from MIMS $\Delta\text{O}_2/\text{Ar}$ data and wind-speed dependent gas exchange parameterization. The calculations were conducted following the steady-state mixed layer mass balance model (Reuer et al. 2007) that has been used in a number of previous studies.

Table 1: List of parameters measured or sampled in the water column

Hydrography/CTD sensors				Trace gases			
Pressure				Biogenic gases			
Temperature				CH ₄ , N ₂ O			
Salinity				O ₂ /Ar, N ₂ /Ar (K1; LS2; BB1, 2, 3; CAA1, 3, 4, 5, 6, 7)			
Oxygen				Triple oxygen isotopes (K1; LS2; BB1, 2, 3; CAA1, 3, 4, 5, 6, 7)			
Fluorescence				Noble gases (K1 and BB2)			
Light transmission				Trace elements and isotopes			
Nutrients				Dissolved and particulate trace metals			
Phosphate				Al, Mn, Fe, Cd, Zn, Cu, Pb, Ga, Ba, REE, Hg, MeHg			
Nitrate/Nitrite				Dissolved and particulate radioisotopes			
Ammonia				²³⁰ Th, ²³¹ Pa, ²³⁴ Th, ²²⁸ Ra, ²²⁴ Ra, ²²³ Ra			
Silicate				Dissolved and particulate radiogenic isotopes			
Chemical parameters				Nd, Pb			
Dissolved inorganic carbon				Dissolved and particulate stable isotopes			
Total alkalinity				δ ¹⁸ O in water			
pH				δ ¹³ C in DIC			
Dissolved organic carbon				δ ¹⁵ N and δ ¹⁸ O in nitrate			
Fluorescent dissolved organic matter				δ ³⁰ Si			
Coloured dissolved organic matter				δ ⁵³ Cr			
Thiols				δ ⁵⁶ Fe			
Organic ligands				Anthropogenic isotopes			
Biological parameters				¹²⁹ I, ²³⁶ U, ¹³⁵ Cs			
Particulate organic carbon				Large volume in-situ pumps			
Particulate organic nitrogen				Particulate ²³⁰ Th, ²³¹ Pa, ²³⁴ Th			
Size fractionated chlorophyll a				Particulate Si, Nd and Cr isotopes			
Pigments							
Particulate biogenic silica							
Flow cytometry							
Genomics							
Proteomics							
Incubations							
	¹⁴ C uptake (K1; LS2; BB1, 2, 3; CAA1, 2, 3, 4, 5, 6, 7; VS)						
	¹³ C uptake (K1; LS2; BB1, 2, 3; CAA1, 3, 5, 6, 7)						
	¹⁵ NO ₃ uptake (K1; LS2; BB1, 2, 3; CAA1, 3, 5, 6, 7)						
	¹⁵ NH ₄ uptake (LS2; BB1, 2, 3; CAA1, 3, 5, 6, 7)						
	³² Si uptake (LS2; BB1, 2, 3; CAA1, 3, 5, 6, 7)						
	H ₂ ¹⁸ O uptake (K1; LS2; BB1, 2, 3; CAA1, 3, 5, 6, 7)						
	⁵⁵ Fe uptake (CAA3, 7)						

Table 2: List of parameters measured or sampled in the water column

Hydrography/CTD sensors				Trace elements and isotopes			
Pressure				Dissolved and particulate trace metals			
Temperature				Al, Mn, Fe, Cd, Zn, Cu, Pb, Ga, Ba, REE, Hg, MeHg			
Salinity				Dissolved and particulate radioisotopes			
Oxygen				^{230}Th , ^{231}Pa , ^{234}Th , ^{228}Ra , ^{224}Ra , ^{223}Ra			
Fluorescence				Dissolved and particulate radiogenic isotopes			
Light transmission				Nd, Pb			
Nutrients				Dissolved and particulate stable isotopes			
Phosphate				$\delta^{18}\text{O}$ in water			
Nitrate/Nitrite				$\delta^{13}\text{C}$ in DIC			
Silicate				$\delta^{15}\text{N}$ - nitrate			
Chemical parameters				$\delta^{30}\text{Si}$			
Dissolved inorganic carbon				$\delta^{53}\text{Cr}$			
Total alkalinity				$\delta^{56}\text{Fe}$			
pH				Anthropogenic isotopes			
Dissolved organic carbon				^{129}I , ^{236}U , ^{135}Cs			
Fluorescent dissolved organic matter				Large volume in-situ pumps			
Coloured dissolved organic matter				Particulate ^{230}Th , ^{231}Pa			
Thiols				Particulate Si, Nd and Cr isotopes			
Organic ligands							
Biological parameters							
Particulate organic carbon							
Particulate organic nitrogen							
Pigments							
Particulate biogenic silica							
Genomics							
Proteomics							