The Canadian Arctic GEOTRACES Program:

*Biogeochemical and tracer study of a rapidly changing Arctic Ocean*

27 co-PIs from:

9 Canadian Universities
- University of Victoria
- University of British Columbia
- University of Alberta
- University of Saskatchewan
- University of Manitoba
- Trent University
- University of Toronto
- McGill University
- Dalhousie University

2 DFO research institutions
- Institute of Ocean Sciences
- Bedford Institute of Oceanography
First leg
Quebec City - Kugluktuk
July 10 – August 20, 2015

13 Stations
• 67 hydrocasts with AN CTD-rosette
• 31 hydrocasts with TM CTD-rosette
• 24 LVP casts
• 1 trace metal clean deck pump deployment for large volume incubation experiments

278 incubations
• 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
+ ArcticNet’s 156 12h $^{14}$C incubations

Underway trace gas analysis

Two $CO_2 / light$ manipulation experiments

Sampling at 15 Arctic rivers draining in the CAA

Aerosol sampling
**Chemical and biological parameters measured or sampled in the water column**

<table>
<thead>
<tr>
<th>Hydrography/CTD sensors</th>
<th>Trace gases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>Biogenic gases</td>
</tr>
<tr>
<td>Temperature</td>
<td>CH4, N2O</td>
</tr>
<tr>
<td>Salinity</td>
<td>O2/Ar, N2/Ar (K1; LS2; BB1, 2, 3; CAA1, 3, 4, 5, 6, 7)</td>
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<tr>
<td>Oxygen</td>
<td>Triple oxygen isotopes (K1; LS2; BB1, 2, 3; CAA1, 3, 4, 5, 6, 7)</td>
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<tr>
<td>Fluorescence</td>
<td>Noble gases (K1 and BB2)</td>
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<td>Light transmission</td>
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<table>
<thead>
<tr>
<th>Nutrients</th>
<th>Trace elements and isotopes</th>
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<tbody>
<tr>
<td>Phosphate</td>
<td>Dissolved and particulate trace metals</td>
</tr>
<tr>
<td>Nitrate/Nitrite</td>
<td>Al, Mn, Fe, Cd, Zn, Cu, Pb, Ga, Ba, REE, Hg, MeHg</td>
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<tr>
<td>Ammonia</td>
<td>Dissolved and particulate radioisotopes</td>
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<tr>
<td>Silicate</td>
<td>230Th, 231Pa, 234Th, 226Ra, 228Ra, 223Ra</td>
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<table>
<thead>
<tr>
<th>Chemical parameters</th>
<th>Dissolved and particulate radiogenic isotopes</th>
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<tr>
<td>Total alkalinity</td>
<td>Nd, Pb</td>
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<tr>
<td>pH</td>
<td>Dissolved and particulate stable isotopes</td>
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<tr>
<td>Dissolved organic carbon</td>
<td>18O in water</td>
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<tr>
<td>Fluorescent dissolved organic matter</td>
<td>13C in DIC</td>
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<tr>
<td>Coloured dissolved organic matter</td>
<td>15N and 18O in nitrate</td>
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<td>Thiols</td>
<td>30Si</td>
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<td>Organic ligands</td>
<td>53Cr</td>
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<tr>
<td>Organic ligands</td>
<td>56Fe</td>
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<table>
<thead>
<tr>
<th>Biological parameters</th>
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<tr>
<td>Particulate organic carbon</td>
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<tr>
<td>Particulate nitrogen</td>
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<tr>
<td>Size fractionated chlorophyll a</td>
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<tr>
<td>Pigments</td>
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<tr>
<td>Particulate biogenic silica</td>
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<td>Flow cytometry</td>
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<td>Genomics</td>
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<tr>
<td>Proteomics</td>
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<tr>
<td>Incubations</td>
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</tbody>
</table>

- 14C uptake (K1; LS2; BB1, 2, 3; CAA1, 2, 3, 4, 5, 6, 7; VS)
- 13C uptake (K1; LS2; BB1, 2, 3; CAA1, 3, 5, 6, 7)
- 15NO3 uptake (K1; LS2; BB1, 2, 3; CAA1, 3, 5, 6, 7)
- 15NH4 uptake (LS2; BB1, 2, 3; CAA1, 3, 5, 6, 7)
- 32Si uptake (LS2; BB1, 2, 3; CAA1, 3, 5, 6, 7)
- H218O uptake (K1; LS2; BB1, 2, 3; CAA1, 3, 5, 6, 7)
- 55Fe uptake (CAA3, 7)

**Underway sampling/analysis:**

- Aerosols
- Atmospheric Hg concentration (Gaseous Elementary Mercury [GEM], Reactive Gaseous Mercury [RGM] and Particulate Hg [PHg])
- Surface gas measurements
  - gas chromatography (DMS/P/O)
  - membrane inlet mass spectrometry (CO2, ΔO2/Ar, and DMS)
- Photo-physiological measurements (FRRF)
Second leg  
September 4 – October 1, 2015  
Sachs Harbour – Resolute

6 Stations
• 22 hydrocasts with AN CTD-rosette
• 21 hydrocasts with TM CTD-rosette
• 12 LVP casts

Aerosol sampling

MVP survey

Glider survey (Leg 3a)
Source-water mass fractions in the water column of the western Canadian Arctic using an optimum multiparameter algorithm (S, δ¹⁸O, TA, DIC, θ).

Northern Atlantic Water (from Fram Strait)

Mucci et al.
Source-water mass fractions in the water column of the eastern Canadian Arctic:

Baffin Bay Arctic Water

Southern Atlantic Water (from Lab Sea)
Computed pCO$_2$ and saturation state with respect to aragonite in the water column of the western Canadian Arctic: from the Canada Basin to Barrow Strait.

Alexis Beaupré-Laperrière, Mucci, Thomas
Geographical location of the oceanographic stations covered by the dataset, color-coded according to the year of sampling, with the approximate boundaries of the main areas mentioned in the text.
Comparison of primary production and carbon export methods

In vitro
- Primary production
  - $^{13}$C
  - $^{14}$C
- Gross oxygen production
  - $^{18}$O
- Carbon export
  - $^{15}$N
- Recycled production
- Integration: 24 hours

In situ
- Diffusive gas exchange
- Bubble-mediated gas exchange
- Diapycnal mixing
- Horizontal advection/mixing
- Residence time of $O_2$ in mixed layer

Equation: $CO_2 + H_2O \rightleftharpoons CH_2O + O_2$
Generally near 1:1 except several outliers

- Episodic events
- Recently shoaled mixed layer
- Mixing at the base of the mixed layer
- Methodological issues
Key Findings:
• river geochemical characteristics reflect gradients in geology and hydrology across the CAA
• rivers can be local sources of inorganic ions and organic material, potentially important for CAA flow-through

Canadian Arctic GEOTRACES River Sampling
• collected samples from 15 rivers along the cruise track, Leg 2
• rivers sampled for: inorganic ions, water isotopes, carbon (organic, inorganic), sediments, trace metals (M. Colombo), isotope tracers ($^{13}$C, $^{15}$N, $^{14}$C, $^{87/86}$Sr), Pb-isotopes (J. De Vera), Si-isotopes (K. Giesbrecht)
• combined w Canadian Arctic Archipelago Rivers Study data

Small CAA rivers

Cullen (w/ Sarah Jackson and Dave Janssen)

Collected filtered seawater samples for dissolved TM at all stations using TMR

- Analysis complete for Mn, Fe, Co, Ni, Cu, Zn, Cd and Pb
  - Data sets merged with Orians (UBC) for Mn and Fe
  - Data will be submitted for IDP2021
- Intercompared “cross over” for Mn, Fe (Fitzsimmons/Jensen) want to talk to others here
- Al intercalibration samples from Measures/Hatta

Publications (Jackson MSc 2018)

- Fe and Mn (Orians Colombo) in revision, 2020 GCA
- Cd (in prep)
dissolved Cd vs Phosphate GN02 & GNO3
Arctic dissolved Cd Section
Kristin Orians (w/ Manuel Colombo)

Collected filtered seawater samples for dissolved TM at all stations using TMR
- Analysis complete for Pb, Mn, Fe, & Ga
  - Data sets merged with J. Cullen (U Vic) for Mn and Fe
  - Intercalibrated with US colleagues
  - To be submitted to GEOTRACES data base soon
- Set of samples provided to A. Shiller for V analysis
- Analyzed TMs (diss. and part. Al, Fe, Mn, Ba, Ni, Cu, Zn, Cd, Pb, Ga) in small CAA rivers (collected by K. Brown).

- Rivers (w/ K. Brown, B. Bergquist and others) 2019 Chemical Geology, 525, 479-491.
- Fe and Mn (w/ J. Cullen and others) in revision, 2020 GCA
- Ga (in prep)
Dissolved Pb

- West Greenland Intermediate Water
- Alaskan Coastal Water
- Atlantic Layer (FSB and BSB)

Lowest in the Canada Basin

Higher in Baffin Bay / Labrador Sea
Joan De Vera & Bridget Bergquist, University of Toronto

Collaborators: Dr. P. Chandan, Dr. A. Steffen, G. Stupple, Dr. W. Landing, S. Jackson, Dr. J. Cullen, Dr. P. Pinedo-Gonzales and Dr. S. John

Overall Goal: Tracing the Distribution of Pb and Trace Elements (TEs) in the Canadian Arctic from the Atmosphere to the Ocean

Projects:
1. Pb isotopes and TEs in aerosols including dissolution experiments
   - complete and near submission (by March 2020)
2. Tracing Pb in Canadian Arctic waters using Pb isotope measurements in seawater
   - complete and near submission (by March 2020)
3. Fe isotopes in Canadian Arctic waters
   - samples prepped, but technical difficulties in measurement

1. Pb isotopes and TEs in aerosols

Europe and Russia (Eurasia) are the likely source of the anthropogenic Pb in aerosols during Arctic Haze

- **Spring aerosols**
  - Clustered together indicating a dominant source
  - Likely sources are Europe and Russia consistent with Arctic Haze pattern

- **Summer aerosols**
  - Scattered indicating mix of different sources
  - Lithogenic and North American sources
Arctic aerosols have high fraction of dissolvable Fe

Trend: Low dissolution (<10%) in aerosols with high Fe concentrations

This trend is not observed in the Arctic where the average maximum dissolution is 65 ± 18%
2. Tracing Pb in Canadian Arctic waters using Pb isotope measurements in seawater

Sources:

**Low** $^{206}\text{Pb}/^{207}\text{Pb}$
1. Historic Europe + Russian (Eurasian) Pb

**High** $^{206}\text{Pb}/^{207}\text{Pb}$
2. Natural Pb
3. US aerosols
4. Pre-20th century anthropogenic Pb

**Intermediate** $^{206}\text{Pb}/^{207}\text{Pb}$
5. Modern Arctic aerosols
Historic Eurasian Pb (low $^{206}\text{Pb}/^{207}\text{Pb}$) is an important source of dissolved Pb in the Arctic waters.

Low $^{206}\text{Pb}/^{207}\text{Pb}$ ratios (<1.15) are associated with elevated Pb concentrations (as high as 17 pM).
Cu ligands are concentrated near the chlorophyll maximum and where markers of terrestrial DOM are most abundant.

Ligands vs. Chlorophyll and dCu

- Cu ligand concentration is correlated with chlorophyll and dCu, suggesting that phytoplankton are a source of ligands and may produce some of them in response to Cu exposure.

**Main Results & Conclusion**

- Total Hg and MeHg distributions in seawater are de-coupled.
- MeHg shows a distinct enrichment in the shallow subsurface (100-300 m), and the peak concentrations are much higher in the western Canadian Arctic than in the east.
- The subsurface MeHg enrichment explains very well the spatial trend of Hg in marine animals in the Canadian Arctic.

**Potential for integration in pan-Arctic synthesis?**

- Yes
- Carl Lamborg / Cahd Hammerschmidt (US)
- Lars-Eric Heimburger-Boadvida (France)
Measurement of $\varepsilon$Nd, $^{230}$Th – $^{231}$Pa and REE concentration
M. Grenier, I. Bacroissais, C. Holmden, R. François, M. Soon, C. Jeandel

2015 ArcticNet – Canadian Arctic Geotraces (transects GN02-GN03)
20 seawater stations sampled, 13 river samples available
Measurement of $\varepsilon$Nd, $^{230}$Th – $^{231}$Pa and REE concentration
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20 seawater stations sampled, 13 river samples available

<table>
<thead>
<tr>
<th></th>
<th>LABRADOR SEA</th>
<th>BAFFIN BAY</th>
<th>CAA</th>
<th>CANADA BASIN</th>
<th>RIVERS</th>
<th>TOTAL</th>
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</thead>
<tbody>
<tr>
<td>$\varepsilon$Nd</td>
<td>28 data available</td>
<td>31 data available</td>
<td>79 data available</td>
<td>36 data available Published</td>
<td>13 data available</td>
<td>187 data to be submitted to GDAC</td>
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<tr>
<td>$^{230}$Th – $^{231}$Pa</td>
<td>26 data available</td>
<td>23 data available</td>
<td>9 data available</td>
<td>36 data available Published</td>
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<tr>
<td>REE concentration</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
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</tbody>
</table>

TBP = To Be Published
NA = Not Available (not measured yet)
KEY RESULTS:

• Only the surface layer [0-100 m] clearly circulates between Canada Basin to the Labrador Sea.

• Strong influence of margin processes from the Canada Basin to Baffin Bay through particle resuspension and lateral transport. Using $\varepsilon$Nd, they can be traced back to the source.

• Strong vertical processes seen in Baffin Bay are dominant in Labrador Sea: the discrimination between particle scavenging, particle composition and deep convection is in progress.

PAPERS IN PREPARATION:
Changes in Circulation and Particle Scavenging in the Amerasian Basin of the Arctic Ocean over the Last Three Decades Inferred from the Water Column Distribution of Geochemical Tracers

Melanie Grenier, Roger François, Maureen Soon, Michiel Rutgers van der Loeff, Xiaoxin Yu, Ole Valk, Christelle Not, S. Bradley Moran, R. Lawrence Edwards, Yanbin Lu, Kate Lepore, and Susan E. Allen

JGR Oceans
RESEARCH ARTICLE
10.1029/2019JC015265
Dissolved $^{230}$Th concentration at 500m depth

Arctic Northern Hemisphere Atlantic (ANHA4) configuration of the Nucleus for European Modeling of the Ocean (NEMO) model

Modeling dissolved and particulate $^{230}$Th in the Canada Basin: Implications for recent changes in particle flux and intermediate circulation

Xiaoxin Yu$^1$, Susan E. Allen$^1$, Roger François$^1$, Mélanie Grenier$^1$, Paul G. Myers$^2$ and Xianmin Hu$^{2*}$
Natural variations in $\delta^{30}\text{Si(OH)}_4$ across Arctic and Subarctic seas

July 2015

Sept 2015

Jul-Aug 2015
Variations in dissolved silica and Si(OH)$_4$ isotopes

Si isotopes track modification of nutrient-rich Pacific-origin waters on their transit from west to east through the Arctic.
Silicon isotopes reflect water mass composition

δ³⁰Si(OH)₄ (‰) vs. [Si(OH)₄] (µmol L⁻¹) vs. Depth (m)

- Surface waters
- Modified Pacific waters
- Modified Atlantic waters
- Canada Basin Deep Water

Water mass δ³⁰Si(OH)₄ signals agree with previous measurements
Data collected:

1. Nitrate $\delta^{15}N$ and $\delta^{18}O$
2. $N_2O$ $\delta^{15}N$ and $\delta^{18}O$, isotopomer abundance, site preference
## Data Collected

<table>
<thead>
<tr>
<th>NITRATE $\delta^{15}N$ and $\delta^{18}O$</th>
<th>N2O $\delta^{15}N$ and $\delta^{18}O$</th>
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<tbody>
<tr>
<td>Leg 2 Station</td>
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<tr>
<td>Leg 2 K1</td>
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<td>Leg 3 CB3</td>
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**BACKGROUND**

- **Canada Basin**: Distinct isotopic signatures for Pacific- and Atlantic-derived nutrients

\[ N^* = [\text{DIN}] - 16[\text{PO}_4^{3-}] + 2.9 \]

- **Pacific Winter Water (PWW)**:
  1. Elevated $\delta^{15}N_{\text{NO}_3}$ as a result of benthic coupled nitrification-denitrification on the Bering and Chukchi shelves
  2. Low $\delta^{18}O_{\text{NO}_3}$ indicative of substantial remineralization in transit (Chukchi shelf)

Granger et al., 2011, 2018; Brown et al., 2015
KEY FINDINGS

- Elevated $\delta^{15}$N$_{NO3}$ indicative of Pacific-derived nutrients traceable at subsurface (50-150m) throughout Archipelago and Baffin Bay.
**KEY FINDINGS**

- **Baffin Bay**: $^{15}$N-enrichment and N* minima in upper halocline and bottom waters

- Elevated $\delta^{15}$N$_{\text{NO}_3}$ and concurrently low $\delta^{18}$O$_{\text{NO}_3}$ in deep/bottom water indicate:
  1. Substantial remineralization of $^{15}$N-enriched organic matter in deep and bottom water
  2. Export production largely fueled by Pacific-derived nutrients
**KEY FINDINGS**

- **Baffin Bay**: Distinct supersaturation of N$_2$O in Baffin Bay Deep Water

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**Concurrent enrichment in N$_2$O $\delta^{15}$N and $\delta^{18}$O suggests:**

1. Predominant sedimentary source of N$_2$O in well oxygenated water column

2. Sedimentary denitrification acts as potential source of N-deficiency in deep Baffin Bay
Our group has been working to quantify ocean mixing rates and mechanisms first in Canadian Arctic shelf and shelf slope waters, and later Arctic-wide.

**Methods**

1. glider-based CTD & turbulence measurements collected during the Canadian program in Amundsen Gulf in Aug 2015 [Scheifele et al 2018; Scheifele et al in review]

2. indirect methods applied to historical data to infer turbulence and mixing rates that span space & time more broadly [Chanona et al 2018, Chanona et al submitted, Dosser et al. in prep]
Our group has been working to quantify ocean mixing rates and mechanisms first in Canadian Arctic shelf and shelf slope waters, and later Arctic-wide.

**Data Products**

1. highly-resolved sections of T, S & derived products (stratification etc.) + direct turbulent dissipation rate & inferred mixing rate estimates in Amundsen Gulf in August 2015
2. spatial maps + multi-year timeseries of stratification + indirect estimates of turbulent dissipation & mixing rate

![Glider Data in Amundsen Gulf in 2015](image)
Our group has been working to quantify ocean mixing rates and mechanisms first in Canadian Arctic shelf and shelf slope waters, and later Arctic-wide.

**Take Home Messages:**
- ocean mixing rates are exceptionally variable in space & time, but do show large-scale patterns in mixing regimes and mixing rates
- these large-scale patterns could be useful for providing a "mixing map" and/or representative seasonal cycle for upper ocean mixing rates to be applied in budget studies of GEOTRACES researchers