U.S. GEOTRACES Arctic Workshop
29 September - 1 October 2010
U.S. National Science Foundation, Washington DC

Workshop Report

Contents

INTRODUCTION

GEOTRACES is an international research program focused on understanding the cycling of trace elements and isotopes (TEIs) in the oceans (Henderson et al., 2007). Details of the program as well as various planning documents can be found at: http://www.geotraces.org. The GEOTRACES mission is:

> **To identify processes and quantify fluxes that control the distributions of key trace elements and isotopes in the ocean, and to establish the sensitivity of these distributions to changing environmental conditions.**

This is extremely relevant to the Arctic, where *rapid climate change* and *accompanying biogeochemical responses* are occurring**.** For this reason there has been strong interest in carrying out studies in the Arctic Ocean since the inception of GEOTRACES. The Arctic Ocean is at the epicenter of climate change, and warming climate will likely have profound impact on the carbon budget, geochemical cycles, and ecosystem of the Arctic. Furthermore, these changes will ultimately be felt globally, through feedbacks related, for example, to melting ice and release of carbon from permafrost.

This interest has led to several discussions, including a planning meeting held in Germany in June 2009 (http://www.ldeo.columbia.edu/res/pi/geotraces/documents/ArcticWorkshopReportNov09B.pdf). That workshop outlined important scientific issues and constructed a map of proposed GEOTRACES Arctic Ocean sections, but did not formulate plans for implementation. Because of the logistical requirements and costs of working in the Arctic, participants recognized the need for international collaboration to make future GEOTRACES efforts viable in this region.

To focus these discussions and to generate an action plan for future GEOTRACES activities, a group of approximately 40 U.S. investigators, key international partners, and students met to discuss future Arctic collaborative undertakings. Although the meeting (funded by The U.S. National Science Foundation) was centered on a U.S. perspective, discussions were developed in an international framework to facilitate planning and sharing of infrastructure. During the first day, invited speakers presented an overview of existing relevant U.S. and international programs and activities with an eye toward constructing large scale, international geochemical surveys of the Arctic. The complexity of such an undertaking suggested that a timeframe for implementation would be on the order of 3–5 years and would ideally encompass an international, multi-icebreaker approach. It was agreed that planning discussions would be ongoing and possible future international meetings were discussed.

This overview was followed by short advocacy talks by meeting participants suggesting TEI measurements suitable for application to Arctic geochemical processes. These presentations led in the following 2 days to discussion of scientific issues that could be addressed within GEOTRACES. It was demonstrated that TEIs are tools that can provide insight into the current processes and interconnectivity of the Arctic system, as well as the future trajectory of Arctic change. TEI's further provide important data to test model predictions.

This report presents the opinions of participants at the workshop regarding the important processes for trace-element cycling in the Arctic, and suggestions for appropriate ocean sections to sample this region in an efficient manner. The role of international collaboration to achieve these goals is considered paramount. We anticipate that this report will provide useful ideas and justification to those seeking funding for the planned research in the coming years.

David Kadko
Robert Anderson
Greg Cutter
William Landing
Chris Measures
Peter Schlosser
William Smethie

Presentations

Introductory presentations

29 Sept - Day 1

Overview of GEOTRACES -- Bob Anderson

Background and Goals for Arctic GEOTRACES -- Dave Kadko

Henrietta Edmonds -- NSF/OPP

Morning - The Arctic Ocean and GEOTRACES: key processes and sites, existing relevant US and international programs and activities (plenary session)

Convener: Peter Schlosser

International programs:

Roger Francois (Canada)

Per Andersson (Sweden)

Michiel Rutgers van der Loeff (Germany)

US programs

James Swift- Arctic repeat hydrography and GEOTRACES

Richard Coffin - Geochemical and geophysical investigation of deep sediment and permafrost hydrate deposits in the Beaufort Sea.

Brad Moran - Overview of BEST and SBI

Peter Schlosser - Overview of AON and other US programs-- ties to GEOTRACES

Afternoon: Tracers in the Arctic: key parameters, advocacy talks (plenary session
Convener: Bill Smethie

Mike Steele - the future of arctic sea ice and ocean temperature

Lou Codispoti - Nutrients and primary production in the Arctic

Advocacy talks

Dennis Hansell: Dissolved Organic Carbon (DOC)

Brad Moran: Water column and sedimentary ^{231}Pa and ^{230}Th

Ken Buesseler: Short lived ^{234}Th and ^{228}Th measurements

Gillian Stewart: ^{210}Pb and ^{210}Po

Mark Baskaran: Role of Ice-rafted Sediments in the Biogeochemical Cycling of Key TEIs in Surface Waters Using a Suite of Short-lived Radionuclides

Jim Bishop: Particulate TEIs

Nicolas Cassar: O_2/Ar NCP measurements

Jingfeng Wu: Seawater Pb isotope as a novel tracer for the Atlantic water flow path in the Arctic

Dave Kadko: ^{7}Be as a tracer of atmospheric inputs into the Arctic Surface Ocean

Bill Landing/Greg Cutter: Atmospheric deposition of contaminant and bioactive elements, Asian pollution

Laodong.Guo: Arctic Land-Ocean Interaction

(Henrietta Edmonds for) Kelly Falkner**:** R/V Sikuliaq: Alaska Region Research Vessel

Breakout Groups:

Days 2-3

Rationale for a US Arctic GEOTRACES Program

Although the Arctic constitutes less than 3 % of the World Ocean area and only about 1% of the volume, 10% of the global river run-off is delivered to the Arctic Ocean and about 30% of the world's soil carbon is estimated to be stored in within the Arctic catchment area. Effects due to a warming climate may have profound impact on the Arctic resulting in increased export of organic carbon and sediments to the Arctic Ocean (e.g., Moran et al., 2005; Bates et al., 2006; Jorgenson et al., 2006; Rachold et al., 2000; Schuur, et al., 2008; Mars and Houseknecht, 2007). Arctic shelves constitute about 25% of the World Ocean shelf area and are among the shallowest in the world, acting as an important regulator of the river export of organic carbon and trace element and isotopes (TEIs) to the central Arctic Ocean. In addition, as sea-ice conditions evolve over the coming decades the partitioning of chemical species such as micronutrients (e.g. iron) and anthropogenic contaminants (e.g. mercury, lead) between the ice and ocean will change, affecting the structure of the Arctic ecosystem and its relationship to surrounding human communities (e.g. Measures, 1999; Outridge et al., 2008; Cota et al., 2006; Baskaran, 2005; Meese et al., 1997)

The breakout sessions centered on developing TEIs for understanding the environmental changes that are currently taking place in the Arctic and those anticipated to occur in the coming years. While it was felt that there currently exist numerous TEI "tools" for studying Arctic change, other TEIs have great potential for such application but more development is required. This assessment stems largely from the dearth of previous measurements for these chemical species in the Arctic; such studies in the Arctic are in their infancy when compared to other ocean basins.

Two breakout groups were constructed, one a "Sea ice and freshwater budget change" group and another, a "Margins/shelf-processes" group. The main foci of these groups were:

1) Utilize TEIs

- to understand the changing Arctic and the trajectory of change.
- to understand the current state of the Arctic, elements of its interconnectivity, and its processes: "the present as indicator of the future"

2) Explore the potential of novel tracers and approaches to study processes and change

3) Establish

- a data set to allow validation of current and predictive models of Arctic circulation
- a data set with which to establish a reference point to judge change.

The application of TEIs to study of Arctic change centered around four main themes initially formulated at the June 2009 Arctic GEOTRACES meeting in Delmenhorst, Germany.

1. Sea ice

Sea ice serves as a platform for retaining and transporting TEIs incorporated from various sources, including ice rafted sediment (IRS), wet and dry atmospheric deposition, as well as dissolved and suspended particulate constituents incorporated into brine channels during ice formation. The distribution of TEIs in the Arctic is affected by sea ice movement and processes (e.g., Darby, 2008; Pfirman *et al.*, 1997). For example, entrained sediment in sea ice is commonly observed in the Arctic and this material likely provides a dominant source of TEIs to sea water. This process has been traced by high concentrations of dissolved Al, Fe and ^{232}Th coinciding with the presence of high concentrations of ice-rafted sediments (Measures, 1999; Trimble *et al.*, 2004). Coastal sediments are derived from different source rocks bordering the coastal areas and therefore the isotopic composition of key tracers (such as ^{143}Nd/^{144}Nd and ^{87}Sr/^{86}Sr) of the weathered detrital material are likely different. Measurements of these nuclides in the coastal sediments and sea ice sediments may yield insight on the sediment source and transport (Tütken *et al.*, 2002).

The sea ice transport of key TEIs has not been constrained. To accomplish this, the residence times of TEIs in sea ice and the transport time scales must also be constrained. The use of radiotracers such as ^{7}Be and ^{210}Pb in the accompanying ice-rafted sediments might offer tools for elucidating time scales (Baskaran, 2005). Further, inputs due to ice melting must be distinguished from other fresh water inputs. Stable oxygen isotope composition, nutrients and dissolved Ba concentrations of surface waters have been used as tracers to differentiate freshwater inputs in Arctic waters (e.g., Macdonald et al, 1989; Guay and Falkner, 1997; Taylor et al, 2003). A high priority for GEOTRACES will be the development of other TEIs as tracers of freshwater sources (see also next section).

Increased flux of particulate material to the water column could be expected as a result of increased ice melt (e.g. Hebbel and Wefer, 1991). A change in quantity and quality of sedimentation flux has the potential to affect TEI scavenging towards the seafloor. There exist several radioisotopic tracers, such as ^{234}Th-^{228}U and ^{210}Po-^{210}Pb, that have proved valuable in assessing particle scavenging and the corresponding flux of carbon from the surface water to depth (e.g., Buesseler et al., 2006; Rama et al., 1961; Turekian et al., 1974; Cochran and Masqué, 2003). Measures of water column particles (by sampling and optically) in the Arctic, especially now - prior to loss of permanent sea ice, may prove valuable. Additionally, release of biologically required TEIs (such as Fe and Zn) during the melting of sea ice in seasonally ice-covered areas could potentially influence the spring bloom. Assessing this input can reveal possible ecosystem changes in the following decades.

ANTICIPATED BENEFITS

- understanding the effect of diminished sea-ice on the timing and nature of ocean productivity
- understanding how the transport of shelf sediments (and accompanying carbon, nutrients and trace metals) will be altered under a changing sea-ice regime.
- understanding how the transport of anthropogenic contaminants is partitioned between ice and ocean and the fate of these contaminants.

• understanding how the supply of freshwater will evolve in coming decades.

2. Rivers and shelves

The largely landlocked Arctic Ocean receives input from the Pacific and Atlantic Oceans, and from rivers draining the surrounding continents. These inflows are important sources of salt, freshwater, heat, nutrients, sediment and organisms to the central basin. With the exception of a portion of the Atlantic contribution, these inputs must cross continental shelves where they are significantly modified by benthic, water column, air/sea and sea/ice interactions (Fig 1). A number of processes occur that control TEI addition, removal, and bioavailability; interaction with suspended sediments, porewater reactions, interactions with suspended biological material, association with colloids, and changes in speciation. In addition, changing sea ice cover affects the supply of freshwater, interactions with the atmosphere, biological activity, and wind-driven mixing. There are therefore significant biogeochemical exchanges between the shelves and basins. Owing to their conservative chemistry, strong source in near-shore sediments, and built-in "clocks", radium isotopes (^{223}Ra, ^{224}Ra, ^{228}Ra) are useful tracers of terrestrial fluxes and cross-shelf dispersion and transport. The isotope ^{228}Ra has been used for decades to quantify lateral mixing processes between shelf waters and the open ocean (Moore et al., 1980; Key et al., 1985; Moore et al., 1995) including the Arctic (e.g., Rutgers van der Loeff 1995; 2003; Smith et al., 2003). Excess ^{224}Ra was measured over 200 km from any shelf source during the ICEX project in the Beaufort Sea in April 2003, requiring a NE offshore flow of 40 cm s^{-1}, assuming that the source water derives from the mouth of Barrow Canyon (Kadko and Muench, 2005).

2.1. River inputs: A dominant input of dissolved and particulate TEIs onto the shelves is from river flow, which is strongly modified by estuarine processes. The resulting TEI concentrations and isotopic compositions then provide fingerprints of waters moving into the ocean basin. The water fluxes, as well as concentrations and isotopic compositions of TEIs, vary within rivers seasonally, and between rivers (e.g. DOC-rich rivers vs. suspended particle-rich rivers), and so studies focused on rivers are also required. Other efforts to accumulate discharge and major element data include the Pan-Arctic River Transport of Nutrients, Organic Matter and Suspended Sediments (PARTNERS) Program (http://ecosystems.mbl.edu/partners/), although there is little data available on TEIs. This program is now continuing as the Arctic Great Rivers Observatory (Arctic-GRO).

There is recent evidence that the flow of freshwater from Arctic rivers into the Arctic Ocean has increased significantly over recent decades (Peterson et al, 2002). This increase, coupled with associated effects such as increased coastal erosion and permafrost thaw, suggests that the riverine input of carbon, nutrients and metals will be significantly altered in coming years. As shown in Fig. 2, the majority of the river runoff to the Arctic in fact comes from Russian rivers, and it will be essential to develop strong collaborations with Russian colleagues studying river input to the Arctic Ocean.

Specific objectives for river/shelf studies include:

• Seasonal collection and characterization of river waters to obtain the fluxes during different shelf conditions and to obtain annual average fluxes. This would include development of tracers of river input (e.g., Guay and Falkner 1997; Andersen et al., 2007)

• Collection and analysis of waters, suspended particles, and colloids across the salinity gradients and to the shelf edge for analysis of TEI concentrations and speciation, as well as nutrients, organic compounds that serve as ligands for TEIs, and markers of biological activity that affects TEI cycling.

• Collection and characterization of underlying sediments using short cores to determine chemical processes occurring near the sediment-water interface.

2.2. Submarine groundwater discharge (SGD) inputs: SGD to coastal regions have been found to be important in various areas of the world. While groundwater discharge can be a major source of water and TEIs onto the shelf environment, the flux of submarine groundwater in the Arctic has not been quantified. Groundwater flow to the Arctic Ocean is complicated by permafrost, which can restrict recharge on shore and discharge offshore where submerged permafrost is present. Nevertheless, pressure gradients across sedimentary structures produced by tides, waves and currents may still introduce substantial fluxes of carbon, nutrients and TEIs from sediment pore waters, and these are also included among the globally significant SGD fluxes. Discharges may occur throughout the shelves, where components can interact in the shelf environment, as well as from the continental slope into the open ocean. Short-lived Ra isotopes, ^{222}Rn, and Ba are indicators of groundwater discharge; in addition, areas of high methane fluxes in regions of underlying permafrost might serve as indicators of high flow through the underlying drowned permafrost on the shelves. Increased methane release from shallow shelf regions might now be occurring and could represent a significant climate feedback mechanism (Shakova et al, 2010).

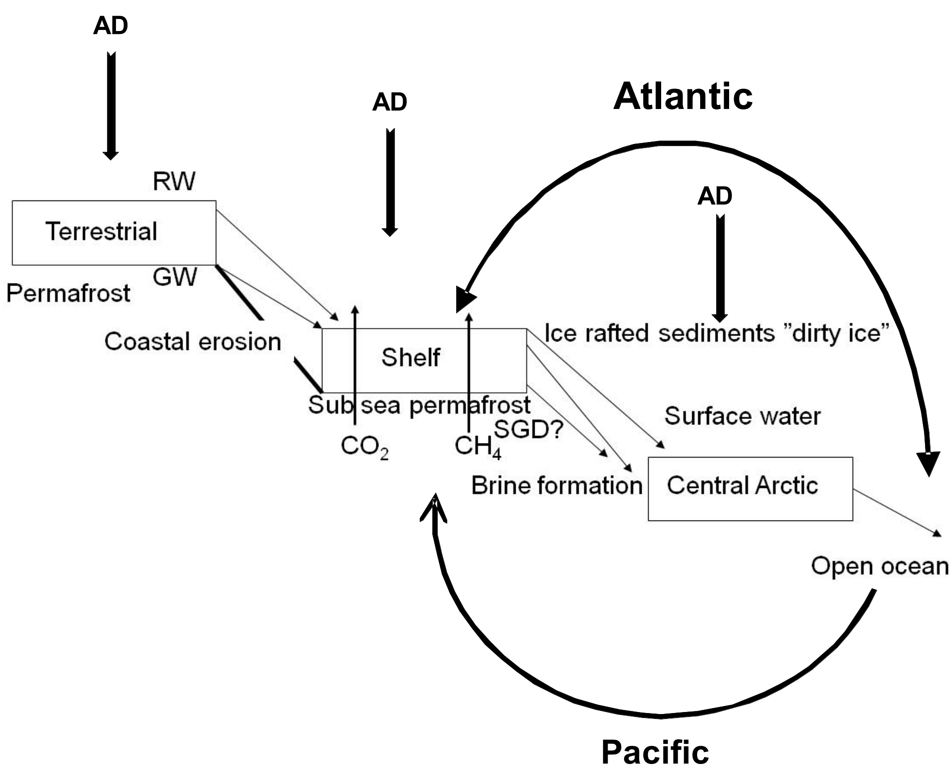


Figure 1. Schematic representation of the transport and chemical exchanges within the Arctic and bordering oceans. AD= atmospheric deposition; RW= river water; GW = groundwater; SGD= submarine groundwater discharge.

With the thawing of permafrost, it is expected that groundwater discharge will change considerably in the coming years.

• Sampling of waters across the shelves and onto the shelf slope, in particular submarine canyons associated with paleo-river channels will allow an assessment of the current magnitude of discharge. Particularly, sampling under winter conditions when river discharges are minimized will allow groundwater inputs to be more clearly perceived in river plume areas.

2.3 Boundary Scavenging: Due to the extensive continental shelf areas surrounding the Arctic Ocean, boundary scavenging of particle reactive TEIs (e.g. Pa/Th, ^{210}Pb, contaminant metals and organic compounds, etc.) is expected to significantly influence the cross-shelf transport of TEIs delivered to shallow waters from river and SGD flow. In fact, the processes that affect carbon, nutrient and TEI cycling on continental shelf and slope environments on a global scale (particle scavenging, biogeochemical cycling, redox and photochemical transformations, retention and burial, offshore plume transport and settling, etc.) should be accentuated in the Arctic Ocean. This suggests that the Arctic Ocean can serve as a "natural laboratory" in which to study the rates and mechanisms of these important processes occurring at ocean margins around the world (e.g., Smith et al., 2003; Moran et al, 2005).

ANTICIPATED BENEFITS

- development of tracers of river input to understand the Arctic freshwater, carbon and nutrient budgets.
- characterization of submarine groundwater discharge and how this might change as permafrost and the associated hydrologic regime evolves in coming years.
- improved knowledge on the rates and mechanisms for carbon, nutrient, and TEI cycling and exchange across ocean margins.

3. Aerosols and atmospheric deposition

The atmospheric input of numerous chemical species into the global ocean equals or exceeds that from river sources and thus constitutes an important budgetary component for these elements (Duce et al., 1991). In addition, the atmospheric input of trace elements plays a key role in ocean biogeochemical processes (e.g., Martin *et al*., 1990, Falkowski, 1997; Coale *et al*., 1996, Morel *et al*., 2003; Morel and Price, 2003; Paytan, et al. 2009). Existing data show that atmospheric deposition of "volatile" contaminant elements like Hg, Pb, and perhaps Se may be a major source of these elements to the Arctic, with likely sources being anthropogenic – industrial or power plant emissions associated with fossil fuel combustion in Europe, Russia, and Asia. This input has strong implications for the ecosystem, and even human health.

Assessment of this input is difficult however because measurements of deposition rates to the ocean—particularly the Arctic-- are rare and susceptible to problems of temporal and spatial variability. Furthermore the Arctic is complicated by different catchments (ice and water) that partition the atmospheric input such that elements will have circuitous paths through the ecosystem.

Key questions regarding atmospheric deposition that arise for the Arctic include:

1. What is the seasonality and what are trends of atmospheric deposition?
2. What are the seasonal changes of the partitioning between the different compartments (i.e. atmosphere, surface water, snow, ice and biota) and also the subsequent effect on ocean chemistry and the ecosystem? Understanding the seasonal change in the partitioning will provide insight into how the partitioning of TEIs (and the ecological consequences) will change as the Arctic ice-cover evolves over the coming years.
3. What are the geographical regions and sources (anthropogenic or natural) of atmospheric particles?
4. What is the effect of atmospheric deposition on the water column?

As sea-ice conditions evolve over the coming decades the partitioning of chemical species such as micronutrients (e.g. Fe) and anthropogenic contaminants (e.g. Hg, Pb) between the ice and ocean will change, affecting the structure of the Arctic ecosystem and its relationship to surrounding human communities. Radionuclides deposited from the atmosphere (e.g. ^{7}Be and ^{210}Pb) can trace the pathways of atmospherically delivered species (Kadko, 2000; Kadko and Swart, 2004) and particle reactive TEIs (e.g.^{234}Th, ^{210}Pb, ^{210}Po) can be used to assess changes in the biological pump (e.g., Moran et al., 2005; Buesseler et al., 2006; Cochran and Masqué, 2003). Assessment of the release of biologically required TEIs (such as Fe and Zn) during the melting of sea ice in seasonally ice-covered areas can reveal the trajectory of possible ecosystem changes in the following decades. The atmospheric deposition of biologically required TEIs onto sea ice not formed over shallow shelves could become an important input of these elements into the water column during melting.

ANTICIPATED BENEFITS

• provide insight into the seasonality and trends of atmospheric deposition and its effect on ocean chemistry and ecology

• provide an assessment of the geographical regions and sources (anthropogenic or natural) of atmospheric particles.

• understanding the seasonal change in the partitioning of atmospheric inputs will provide insight into how the partitioning of TEIs (and the ecological consequences) will change as the Arctic ice-cover evolves over the coming years.

4. Exchange with Atlantic and Pacific

The Arctic Ocean is unique in having only narrow connections (i.e., "choke points") with its neighboring ocean basins (Fig. 2). Shallow Pacific waters enter the Arctic Ocean through the

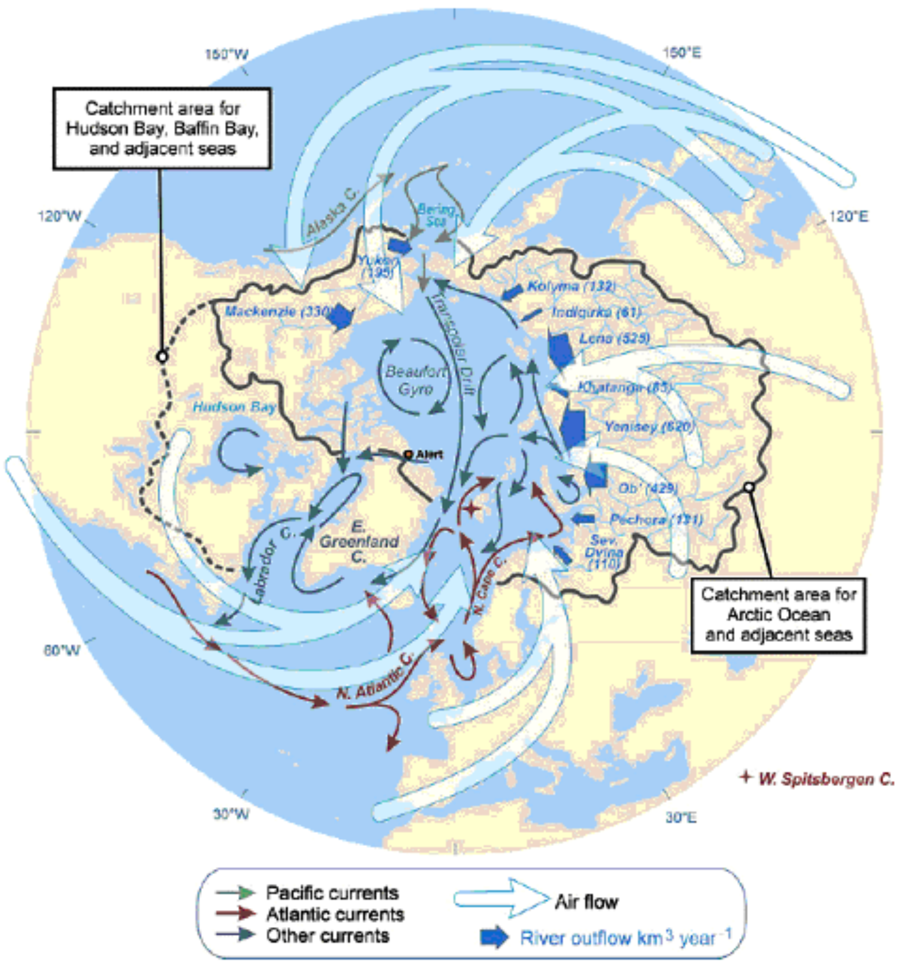


Figure 2. Major physical transport pathways (wind, rivers and ocean currents) bringing contaminants into the Arctic Ocean (Macdonald *et al.*, 2005; Outridge *et al.*, 2008).

Bering Strait while deeper Atlantic waters enter through Fram Strait and the Barents Sea shelf. Likewise, seawater exits the Arctic Ocean and enters the North Atlantic through Fram Strait and Davis Strait (e.g., Smith et al., 2005). It may therefore be relatively easy to establish a partial budget in the Arctic Ocean for many TEIs (i.e. input from the Pacific + input from the Atlantic – output to the Atlantic), which could inform us on the less easily quantifiable but potentially important terms of the Arctic's TEI budgets, such as aeolian, river and groundwater input, shelf exchanges, and sinks such as biological removal.

Constraining the TEI's budget for the Arctic Ocean will not only elucidate processes affecting their cycling in the Arctic Ocean, but could also have important implications for understanding the biogeochemical cycling of TEI's in the North Pacific and, especially, in the North Atlantic. For this reason, it will be important to connect and coordinate Arctic GEOTRACES sections with those already planned for the Atlantic and Pacific Ocean. For instance, it has been estimated that addition of nitrogen depleted water from the Pacific to the Atlantic through the Canadian Archipelago may sustain a significant fraction of the relatively high rates of nitrogen fixation in the North Atlantic. River input and/or shelf interactions in the Arctic Ocean could likewise affect the input of important micronutrients from the Arctic and therefore influence ecosystem structure and productivity in the North Atlantic.

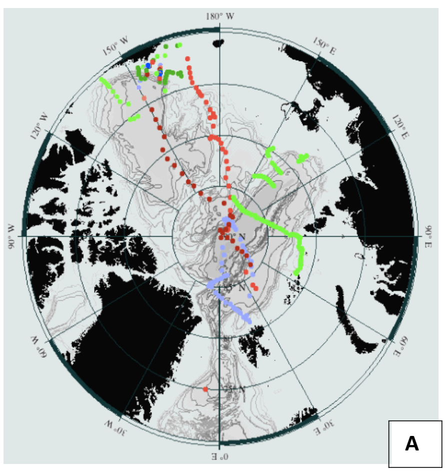
Processes in the Arctic Ocean may also influence the distribution of geochemical tracers that have been used to reconstruct past changes in Atlantic Meridional Overturning Circulation (AMOC). The ratio $^{231}Pa/^{230}Th$ measured in Atlantic sediments has been used to evaluate past changes in the rate of the AMOC (e.g., Yu et al., 1996; McManus et al., 2004; Gherardi et al., 2005; Hall et al., 2006). Input of these two nuclides from the Arctic modulated by sea ice extent could potentially affect the interpretation of this paleoceanographic tracer. For example, we might also expect little scavenging of particle reactive elements, such as ^{230}Th and ^{231}Pa, under permanent ice cover, which could result in a net export of these TEI's from the Arctic to the North Atlantic (Edmonds et al., 1998, 2004; Moran et al., 2005). Authigenic neodymium isotopes (expressed as εNd) have also been exploited to infer past changes in AMOC (Piotrowski et al., 2004; Piotrowski et al., 2008; Roberts et al., 2010). The Arctic through-flow connects water masses with extreme endmember values of εNd. The εNd of North Pacific water is very radiogenic (positive εNd), reflecting Nd input from young volcanic rocks, while seawater in the North Atlantic have very negative values, reflecting input from old cratons (Andersson *et al.*, 2008; Porcelli *et al.*, 2009). The resulting systematic variations in the Nd isotopic ratio of seawater potentially provide a water mass tracer that is recorded in the authigenic phase of marine sediments for the reconstruction of paleocirculation. The mechanisms that impart different Nd isotopic signatures to seawater are not well understood, but seem to mainly involve river discharge and isotopic exchange with shelf sediments, two processes that can profoundly impact the chemistry of seawater in the Arctic Ocean. Continental erosion by ice sheets may also be an important factor in determining the εNd of continental runoff (von Blanckenburg and Nagler, 2001). By following the evolution of the Nd isotopic composition of Pacific water from its point of origin, through the Arctic Ocean and to the Labrador and Nordic seas, we will be able to better document the role of these processes in imparting the isotopic signature of seawater and to better assess the limit to which εNd can be considered a conservative tracer, a key assumption for its use as a water mass tracers in paleoceanography. These questions, among others, could be addressed by monitoring the flow of TEIs at the Arctic choke points and by following the evolution of the chemical and isotopic composition of the different water masses of the Arctic Ocean (Polar mixed layers, Pacific waters, Atlantic water, Polar Deep Water) as they enter in, transit through, and exit from the Arctic ocean.

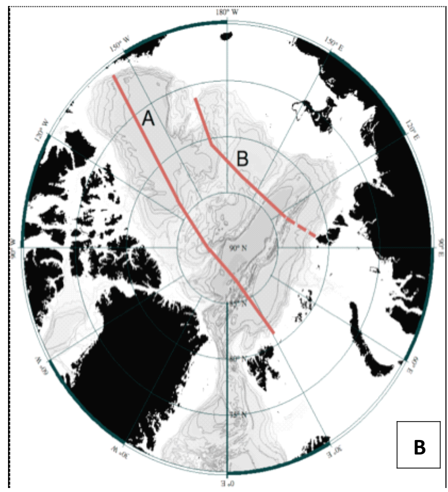
ANTICIPATED BENEFITS

- improve our understanding of the elemental and isotopic budgets of the Arctic Ocean by quantifying fluxes through the choke points.
- improve interpretation of paleoceanographic tracer techniques applied to past climate and ocean circulation.

Day 3-Timelines, international opportunities, potential ocean sections

The availability timeline of both US and international icebreakers was discussed to formulate the extended planning needed for a large scale GEOTRACES expedition in the Arctic involving sampling from multiple icebreakers in different regions of the Arctic Ocean during the same year to acquire a quasi-synoptic data set. The motivation behind this approach is the rapid pace of change occurring now in the Arctic Ocean. Schedules, as currently understood, suggest that the year 2015 would be a reasonable target for launching a major initiative. Prior to that, likely opportunities exist on ships of opportunity such as the German vessel *Polarstern*, the Canadian icebreakers *Louis St Laurent* and *Amundsen*, and the new University of Alaska R/V *Sikuliaq*. A number of potential sampling sections were discussed; these were based on discussions at the Delmenhorst meeting and on plans under development from international partners. In addition, suggestions based on potential compatibility with an Arctic repeat hydrography program were considered.





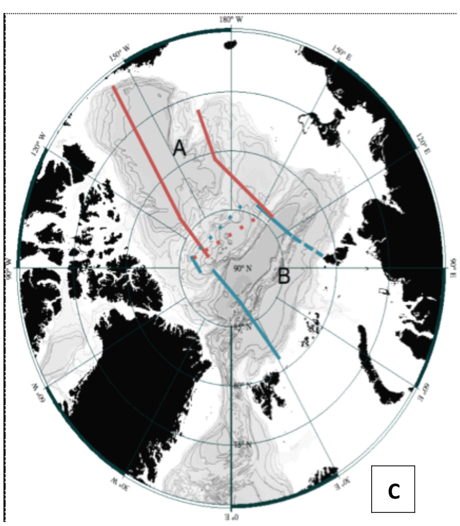


Figure 3. A) Arctic Ocean hydro cruises through 2005 which have ocean carbon and research-quality dissolved oxygen data. **B)** Schematic concept of a pair of one-way, trans-Arctic sections in support of global ocean change research. (The dashed line on "B" schematically shows sampling in the Russian EEZ. **C)** Schematic concept of two trans-Arctic sections as paired roundtrips. Both A and B should occur in the same year to reduce inter-cruise data uncertainties. Such pairings may permit icebreakers to return to their home ports, and also may help with international coordination.

Arctic Ocean hydrography cruises through 2005, which have ocean carbon and research-quality dissolved oxygen data (the rarest of the traditional parameters in this domain), are shown in Fig

3a. [This does not address ADCP and some tracer data.] Some areas of the Arctic Ocean have not yet been measured once to WOCE standards, let alone with repeat measurements to WOCE standards. There has not yet been a *complete* boundary-to-boundary trans-Arctic section. Figure 3b,c shows possible sampling approaches to allow broad, pan-Arctic coverage consistent with a repeat hydrography approach.

Several international plans were also discussed. Figure 4 shows the anticipated cruise track of the German icebreaker *Polarstern* in 2011; it is anticipated that ^{234}Th, Ra isotopes, ^{7}Be, and Hg will be measured on this expedition. Possible Canadian plans are shown schematically in Figure 5. These are under consideration and likely will involve coordination with other national programs; discussions are ongoing. Finally, in Figure 6, elements of a possible Swedish Arctic GEOTRACES program are shown.

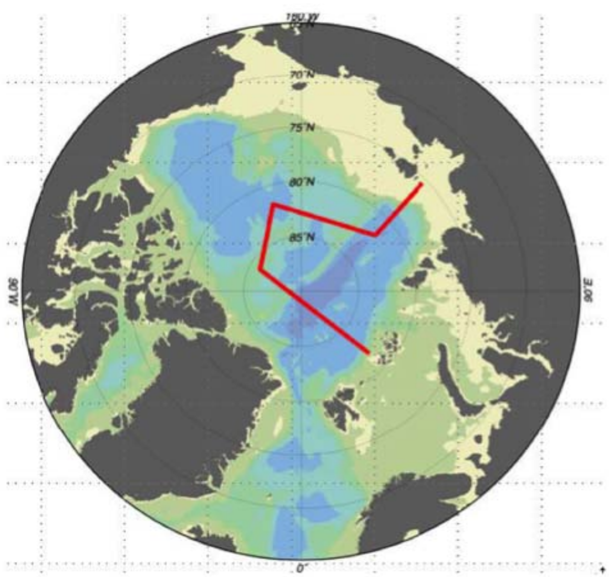


Figure 4. R/V Polarstern Transarc Aug-Sept 2011

<u>Trans-Arctic survey of the Arctic Ocean in transition.</u>
Study the large-scale changes of Arctic Ocean sea ice and ocean circulation and ecosystem in the context of sea ice retreat and ocean warming.

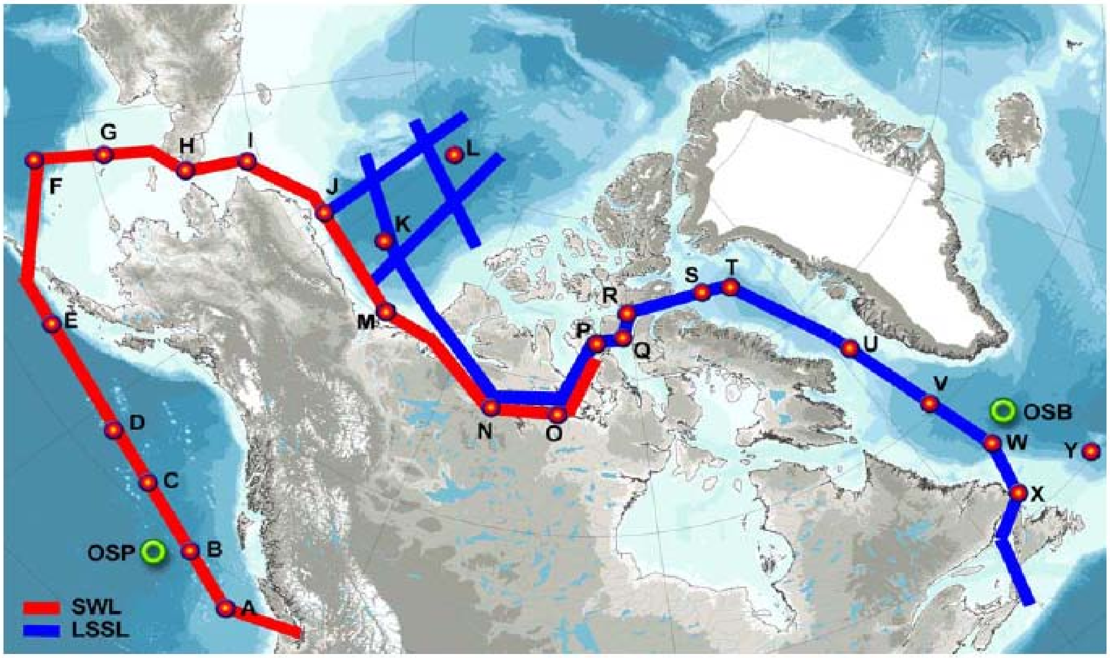


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Figure 5. Possible Canadian transects for a GEOTRACES program. SWL = Sir Wilfrid Laurier; LSSL = Louis St. Laurent.

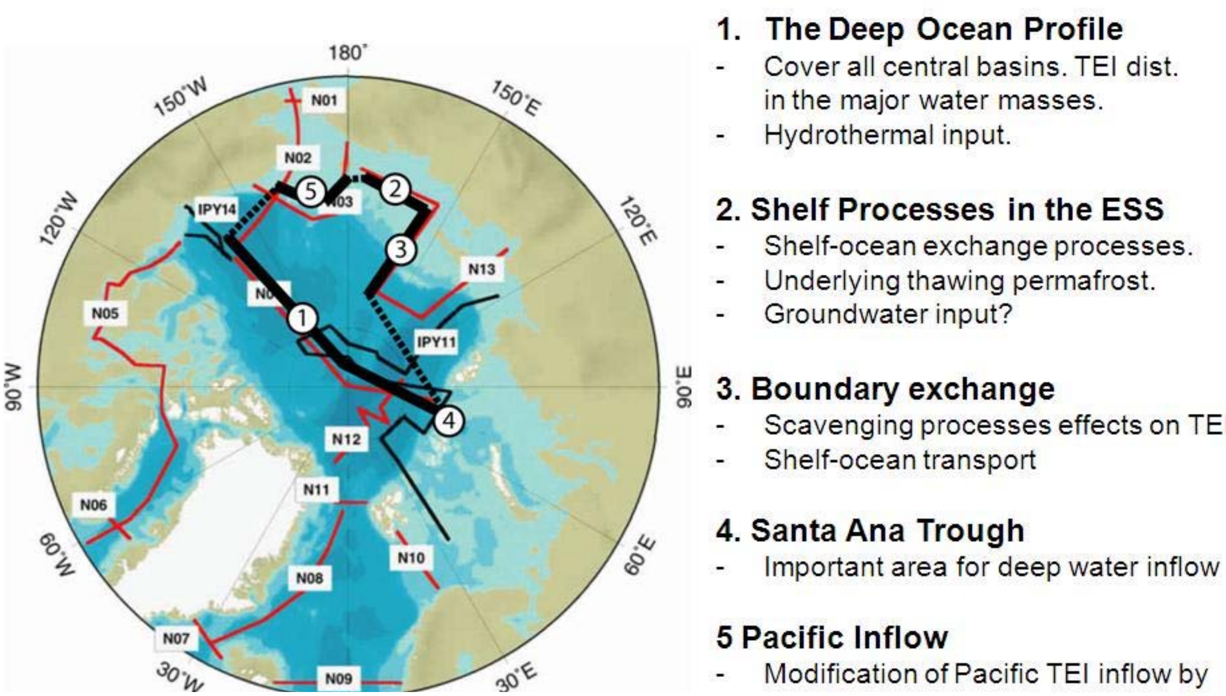

Figure 6. Elements of a possible Swedish Arctic GEOTRACES program

Summary and recommendations

The consensus of scientific thought holds that Arctic change is beyond natural variability and represents a harbinger of changes that will be felt world-wide. To understand the current state of Arctic processes and the trajectory of change, new approaches, such as those discussed in this workshop, are required. The GEOTRACES program offers many elemental and isotopic tools that have great potential as novel tracers to study processes and change. Participants recognized that in the Arctic there is a dearth of previous measurements for some of these chemical species; development of these tools would benefit from implementation of flexible funding mechanisms to take advantage of sampling opportunities that might arise in the short-term. Icebreaker opportunities are more difficult to come by than standard vessels in other ocean basins and agencies should be poised to take advantage of them when circumstances arise.

There are unusual logistical requirements and costs of working in the Arctic. During the meeting it was recognized the need for new partnerships within funding agencies as well as improved interagency coordination and collaboration to enable complex projects such as that envisioned here. Furthermore a major conclusion of the workshop was the need for international collaboration to make future GEOTRACES efforts viable in this region. Forward planning for icebreaker availability over the next five years is crucial to organizing any international effort. With the aid of funding agencies, establishment of an international collaborative framework would be highly beneficial. The ultimate goal would be a multi-national, multi-icebreaker project spanning several sections across the Arctic in a time frame of 3-5 years.

Despite numerous technological advances, ship-based sampling remains the only method for obtaining high-quality, high spatial and vertical resolution measurements of a suite of physical, chemical, and biological parameters over the full water column. Ship-based hydrography is essential for documenting ocean changes throughout the water column, and is the principal technique used for the deep ocean below 2 km (52% of global ocean volume not sampled by profiling floats). Arctic GEOTRACES observational sections will serve as an essential complement to long-term observing systems of moored measurements and drifters in effect now and anticipated to arise in the future.

Completion of a GEOTRACES Arctic initiative will provide the following benefits to the broader Arctic research community and to society at large:

- increase our understanding the effect of diminished sea-ice on the timing and nature of ocean productivity
- develop projections of how the transport of shelf sediments (and accompanying carbon, nutrients and trace metals) will be altered under a changing sea-ice regime.
- determine how the transport of anthropogenic contaminants is partitioned between ice and ocean and the fate of these contaminants.
- forecasting how the supply of freshwater will evolve in coming decades.
- provide tracers of river input to understand the Arctic freshwater, carbon and nutrient budgets.
- provide characterization of submarine groundwater discharge and how this might change as permafrost and the associated hydrologic regime evolves in coming years.
- provide insight into the seasonality and trends of atmospheric deposition and its effects on ocean chemistry and ecology.
- provide an assessment of the geographical regions and sources (anthropogenic or natural) of atmospheric particles.
- increase our understanding of the seasonal change in the partitioning of atmospheric inputs to provide insight into how the partitioning of TEIs (and the ecological consequences) will change as the Arctic ice-cover evolves over the coming years.
- improve our understanding of the budget of numerous chemical species by quantifying fluxes through the Arctic choke points
- improve interpretation of paleoceanographic tracer techniques applied to past climate and ocean circulation.

The final recommendation from the workshop is to establish a small ad hoc group (6 to 10 members) to develop an Implementation Plan for U.S. participation in GEOTRACES Arctic research. In addition to formulating a strategy to achieve the research objectives and related anticipated benefits identified above, this group must work closely with NSF program officers in OPP and in OCE, as well as with international partners, to design a viable and realistic plan that will serve as a basis for proposals to NSF and, possibly, to other agencies with interests in the changing Arctic environment.

Acknowledgements
We thank Moanna St. Clair, GEOTRACES Project Office Coordinator, and Dr. Henrietta Edmonds, Program manager (NSF/OPP) for handling the logistical requirements of the meeting. The meeting was supported by the Office of polar Programs, National Science Foundation and by the US-GEOTRACES office.

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APPENDICES

A1: Workshop Announcement

FIRST ANNOUNCEMENT

US Arctic GEOTRACES Planning Workshop

29 September - 1 October 2010

Washington DC, USA

Please send initial expressions of interest to:
dkadko (at) rsmas.miami.edu

Since the inception of the international GEOTRACES Program, a strong interest has developed in carrying out GEOTRACES-related activities in the Arctic Ocean. The Arctic Ocean is at the epi-center of climate change, and changes there will ultimately be felt globally. It constitutes less than 3 % of the World Ocean area and about 1% of the volume, but it is unique in several ways. About 10% of the global river run-off is delivered to the Arctic Ocean and about 30% of the world's soil carbon is estimated to be stored in northern ecosystems within the Arctic catchment area. Effects due to a warming climate may have profound impact on the Arctic resulting in increased export of organic carbon and sediments to the Arctic Ocean. Arctic shelves constitute about 25% of the World Ocean shelf area and are among the shallowest in the world acting as an important regulator of the river export of organic carbon and TEIs to the central Arctic Ocean.

This interest has already led to several discussions and deliberations, including a GEOTRACES planning meeting held in Delmenhorst Germany in June 2009 which recognized the need for international collaboration to make future GEOTRACES efforts viable in this region.

In order to focus these discussions and to generate an action plan for future GEOTRACES activities between US investigators and international collaborators, a US Arctic GEOTRACES workshop is planned.

We invite:
- **Initial expressions of interest in participating in this workshop,**
- **Comments on the program structure,**
- **Suggestions for potential topics for talks and break-out sessions, as well as for speakers, and**
- **Suggestions about additional sources of funding.**

The Organizing Committee:
- **David Kadko, Chair, RSMAS**
- **Peter Schlosser, LDEO**
- **William Smethie, LDEO**
- **Gregory Cutter, ODU**
- **William Landing, FSU**
- **Chris Measures. UH**

Funding and Travel Support
NSF will provide partial funding for this meeting.It is anticipated that limited travel support will be available and that this support will be distributed as a fixed subsidy, the amount of which will depend on pending requests.

A2: Attendees

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A3: Agenda

29 Sept - Day 1

Stafford I, Room 1235

Continental breakfast at Comfort Inn Ballston
Walk to NSF
8:30 Welcome and logistics -- Bob Anderson
8:40 Overview of GEOTRACES -- Bob Anderson
9:00 Background and Goals for Arctic GEOTRACES -- Dave Kadko
9:25 Henrietta Edmonds -- NSF/OPP

Morning - The Arctic Ocean and GEOTRACES: key processes and sites, existing relevant US and international programs and activities (plenary session)
Convener: Peter Schlosser

International programs:
9:35 Roger Francois (Canada)
10:00 Per Andersson (Sweden)
10:25 BREAK
10:40 Michiel Rutgers van der Loeff (Germany)

US programs
11:00 James Swift- Arctic repeat hydrography and GEOTRACES
11:20 Richard Coffin - Geochemical and geophysical investigation of deep sediment and permafrost
hydrate deposits in the Beaufort Sea.
11:35 Brad Moran - Overview of BEST and SBI
11:55 Peter Schlosser - Overview of AON and other US programs-- ties to GEOTRACES
12:15 LUNCH

Afternoon: I. Tracers in the Arctic: key parameters, advocacy talks (plenary session
Convener: Bill Smethie
13:30 Mike Steele - the future of arctic sea ice and ocean temperature
13:55 Lou Codispoti - Nutrients and primary production in the Arctic
14:10 Advocacy talks (~5 min each)
Dennis Hansell: Dissolved Organic Carbon (DOC)
Brad Moran: Water column and sedimentary ^{231}Pa and ^{230}Th
Ken Buesseler: Short lived ^{234}Th and ^{228}Th measurements
Gillian Stewart: ^{210}Pb and ^{210}Po
Mark Baskaran: Role of Ice-rafted Sediments in the Biogeochemical Cycling of Key TEIs in Surface Waters Using a Suite of Short-lived Radionuclides
Jim Bishop: Particulate TEIs
Nicolas Cassar: O_2/Ar NCP measurements
Jingfeng Wu: Seawater Pb isotope as a novel tracer for the Atlantic water flow path in the Arctic
Dave Kadko: ^{7}Be as a tracer of atmospheric inputs into the Arctic Surface Ocean
Bill Landing/Greg Cutter: Atmospheric deposition of contaminant and bioactive elements, Asian

pollution (10-15 m)

Laodong.Guo: Arctic Land-Ocean Interaction

15:00 Break
15:20 **Afternoon: II. Plenary Discussion on topics, organization for breakout sessions**
Convener: David Kadko
(Henrietta Edmonds for) Kelly Falkner**:** R/V Sikuliaq: Alaska Region Research Vessel (10 m)

Breakout sessions: Discussion on topics, organization -- leaders from organizing committee
17:30 Adjourn / Dinner on own

30 Sept - Day 2

Stafford II, Room 515

Continental breakfast at Comfort Inn Ballston
Walk to NSF
8:30 Morning - Plenary: review and plan for the day / Convener: David Kadko
Breakout sessions: Discussion on topics, organization
10:30 Break
Breakout sessions: Discussion on topics, organization
12:15 LUNCH
13:30 **Afternoon I - Breakout sessions: meetings and plenary discussion**
15:00 Break
Afternoon II - Breakout sessions: meetings and plenary discussion
17:30 Adjourn / Dinner on own

1 Oct – Day 3

Stafford I, Room 1235

Continental breakfast at Comfort Inn Ballston
Walk to NSF
8:30 Morning - Plenary: review and plan for the day / Convener: David Kadko
Breakout sessions: meetings and report drafting
10:30 Break
Breakout sessions: meetings and report drafting
12:15 LUNCH
13:30 **Afternoon - Synthesis and planning for future action (plenary discussion)**
Breakout sessions: meetings and report drafting
17:30 - Meeting adjourn