

Lateral organic carbon supply to the deep Canada Basin

Jeomshik Hwang,¹ Timothy I. Eglinton,¹ Richard A. Krishfield,¹ Steven J. Manganini,¹ and Susumu Honjo¹

Received 8 April 2008; revised 12 May 2008; accepted 19 May 2008; published 12 June 2008.

[1] Understanding the processes driving the carbon cycle in the Arctic Ocean is important for assessing the impacts of the predicted rapid and amplified climate change in this region. We analyzed settling particle samples intercepted by a time-series sediment trap deployed in the abyssal Canada Basin (at 3067 m) in order to examine carbon export to the deep Arctic Ocean. Strikingly old radiocarbon ages (apparent mean ^{14}C age = ~ 1900 years) of the organic carbon, abundant lithogenic material ($\sim 80\%$), and mass flux variations temporally decoupled from the cycle of primary productivity in overlying surface waters together suggest that, unlike other ocean basins, the majority of the particulate organic carbon entering the deep Canada Basin is supplied from the surrounding margins. **Citation:** Hwang, J., T. I. Eglinton, R. A. Krishfield, S. J. Manganini, and S. Honjo (2008), Lateral organic carbon supply to the deep Canada Basin, *Geophys. Res. Lett.*, *35*, L11607, doi:10.1029/2008GL034271.

1. Introduction

[2] It has been predicted that anthropogenically-driven climate change will occur far more rapidly and be amplified in the Arctic, both on the surrounding continents and in the ocean [Dowdeswell *et al.*, 1997; Intergovernmental Panel on Climate Change (IPCC), 2007]. Destabilization of permafrost soils [IPCC, 2007] and attendant shifts in the hydrologic cycle [Peterson *et al.*, 2002, 2006] may release vast quantities of reduced carbon and associated nutrients stored in these soils to the Arctic marginal seas. Together with longer open-water seasons over larger expanses of the Arctic Ocean due to a reduction in sea-ice cover, carbon export to the interior basins seems likely to increase markedly. However, the fate of this carbon, as well as the extent to which the deep basin waters and underlying sediments will sequester carbon in the face of rapidly changing hydrographic and biogeochemical conditions, remains uncertain. Existing knowledge on organic carbon dynamics including primary production, export production, and burial in sediments is largely restricted to the shallow flanks of the Arctic Ocean [Wassmann *et al.*, 2004], whereas we have only rudimentary understanding of processes operating in the seasonally or permanently ice-covered interior ocean.

2. Methods

[3] Settling particles were intercepted by a bottom-tethered time-series sediment trap from August 2004 to

July 2005 in the marginal ice zone of the Canada Basin (75°N , 150°W ; total water depth 3824 m, trap depth 3067 m; Figure 1). Samples collected in mercuric chloride-poisoned cups, each representing a 16.81 day sampling period were freeze-dried and fumigated with concentrated HCl to remove inorganic carbon, and further processed following standard techniques for carbon isotope measurements in the National Ocean Sciences AMS facility at Woods Hole Oceanographic Institution [McNichol *et al.*, 1994]. Settling particles intercepted at 120m depth by a time-series sediment trap tethered to the overlying sea-ice during the SHEBA (Surface Heat Budget of the Arctic Ocean) project in 1997/8 [Krishfield *et al.*, 1999] were also analyzed for carbon isotope ratios. Although these samples were poisoned with formalin, robust ^{14}C data can be obtained after rinsing with Milli-Q water and freeze-drying (S. Wakeham, personal communication, 2006; J. Hwang, unpublished data, 2007). Radiocarbon results are reported in $\Delta^{14}\text{C}$ notation, which is the per mil deviation of $^{14}\text{C}/^{12}\text{C}$ ratio from a 19th century wood standard, normalized to a stable carbon isotopic ($\delta^{13}\text{C}$) value of -25‰ to correct for fractionation [Stuiver and Polach, 1977]. Empirical uncertainties (standard deviations of duplicate analyses of samples of a similar type) are smaller than $\pm 10\text{‰}$. Biogenic and lithogenic particle fluxes were estimated from total mass flux, total carbon, inorganic carbon (coulometry), silicon, calcium, and aluminum concentrations and the representative ratios of each metal to aluminum in the continental crusts [Taylor and McLennan, 1985; Honjo *et al.*, 2008].

3. Results and Discussion

[4] The $\Delta^{14}\text{C}$ values of settling POC (particulate organic carbon) were extremely low, ranging between -97 and -257‰ with an average of -217‰ . The latter is equivalent to 1900 ^{14}C years (all ^{14}C ages reported in this paper are apparent ages and are not reservoir-corrected) (Figure 2a). With the exception of settling POC intercepted in the exceptionally deep Japan Trench (8789 m) [Nakatsuka *et al.*, 1997], the average $\Delta^{14}\text{C}$ value observed in the deep Canada Basin is more than 100‰ lower than the lowest published values for settling POC in all other environments [Anderson *et al.*, 1994] (data compiled by Hwang and Eglinton). Due to particle settling velocities of a few hundred meters per day [Honjo *et al.*, 2008], $\Delta^{14}\text{C}$ values should reflect that of dissolved inorganic carbon in the surface water ($\sim +25\text{‰}$) [Jones *et al.*, 1994] if primary production were the only source of settling POC. However, the much lower observed $\Delta^{14}\text{C}$ values imply that recently produced POC in the overlying water column was mixed with a significant proportion of aged (^{14}C -depleted) POC transported from elsewhere. The $\Delta^{14}\text{C}$ values were higher in late summer (maximum $\Delta^{14}\text{C} = -97\text{‰}$ in August and

¹Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA.

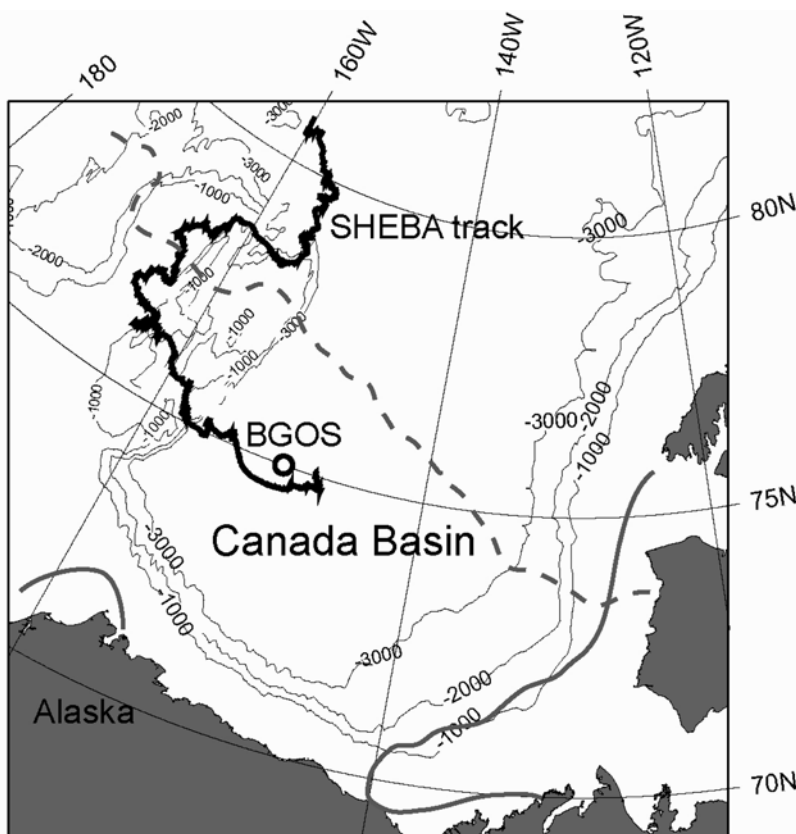


Figure 1. Map of the Canada Basin showing the location of Beaufort Gyre Observation System (BGOS) sediment trap mooring (3067 m) and the drift track of the ice-tethered sediment trap (120 m) during the Surface Heat Budget of the Arctic Ocean (SHEBA) study. It also shows 90% ice-concentration lines in September 2004 (dashed line) and May 2005 (solid lines).

September), when sea ice concentration was low (Figure 2b). While these results imply that autochthonous POC accounts for higher proportion of settling POC in summer, the carbon flux during this interval was low (Figure 2b). In contrast, POC fluxes were highest between March and early May when shortwave radiation was at its minimum and overlying waters were completely ice-covered (Figure 2b). Settling POC intercepted during this period yielded amongst the lowest $\Delta^{14}\text{C}$ values (average = -242‰ , 2170 ^{14}C years).

[5] Since the sediment trap was deployed well above the sea floor (approximately 760 meters above the bottom, mab) and bottom currents are considered low [Hunkins *et al.*, 1969], we exclude local sediment resuspension as a potential source of the aged POC. Similarly, although transport of sediment-laden ice may supply POC to the interior basins [Rachold *et al.*, 2004], the higher $\Delta^{14}\text{C}$ values during the ice melt period, when this input would be greatest (June), imply that ice-rafted debris was not the dominant source of aged POC. We suggest therefore that tangential supply from the surrounding margins constitutes the most plausible source of aged POC to the deep Canada Basin. High abundances of lithogenic material ($\sim 80\%$) and low abundances of biogenic minerals in the sediment trap samples also indicate that primary production is not the major source of settling particles. The lithogenic particles, which must have derived from the margins, may serve as vehicles for POC delivery to the deep Canada Basin. The observed average POC flux ($0.5 \pm 0.4 \text{ mgC m}^{-2} \text{ d}^{-1}$ or $15 \pm 13 \text{ mmolC m}^{-2} \text{ yr}^{-1}$; the uncertainty

represents the standard deviation) is extremely low compared to the values observed in other pelagic environments [Honjo *et al.*, 2008]. In addition, the observed mass flux variation (Figure 2b) is distinct from the results at other locations on the margins (at various sediment trap deployment depths between surface and 1550 m) of this ocean basin where high fluxes were supported by river discharge and/or primary production in spring/summer [Wassmann *et al.*, 2004; O'Brien *et al.*, 2006; Fahl and Nöthig, 2007].

[6] Settling particles intercepted at 120 m depth by a time-series sediment trap tethered to the overlying sea-ice during the SHEBA project in 1997/8 [Krishfield *et al.*, 1999] provide a useful comparison to particles collected from the deep Canada Basin. During the deployment, the trap drifted from the southern Canada Basin to the Mendeleev Abyssal Plain, passing over the Northwind Ridge and the Chukchi Plateau (Figure 1). The settling particles therefore reflect both seasonal and spatial variations in upper ocean conditions during the deployment (see also Macdonald *et al.* [2002, Figure 2] for the variation in total water depth along the drift track). The $\Delta^{14}\text{C}$ values of POC intercepted by the trap during this deployment, which ranged between -154‰ and $+18\text{‰}$, were lower when the water depth was shallower, implying a contribution of aged POC from sediment resuspension to the settling POC. Together with the data from the deep basin trap (3067 m) trap, $\Delta^{14}\text{C}$ values of settling POC and aluminum concentrations of settling particles show a distinct inverse relationship ($R^2 =$

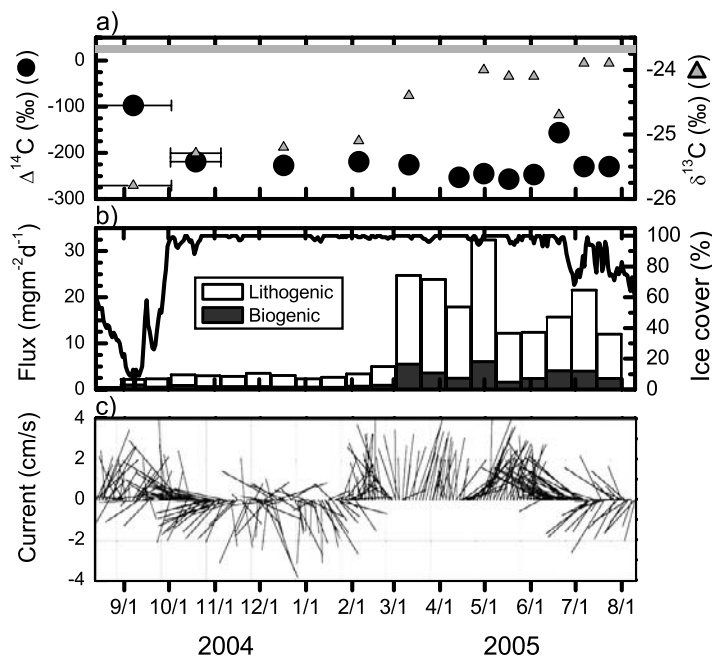


Figure 2. (a) $\Delta^{14}\text{C}$ (circles) and $\delta^{13}\text{C}$ (triangles) values of the organic matter (gray bar indicates approximate range of $\Delta^{14}\text{C}$ of surface water dissolved inorganic carbon; the error bars for the first two isotope data points indicate that respectively three and two samples were combined for these measurements), (b) fluxes of biogenic and lithogenic particles intercepted by a sediment trap moored at 3067 m (757 m above the bottom) from August 2004 to July 2005, and ice concentration at the surface calculated from NSIDC (National Snow and Ice Data Center) data using Bootstrap method (right y-axis), and (c) current speed and direction measured at 2000 m on the same mooring. The x-axis is time in month/date.

0.86; Figure 3), suggesting that POC represents a mixture between recently produced organic matter and aged organic carbon associated with lithogenic minerals.

[7] The $\Delta^{14}\text{C}$ values of settling POC and aluminum concentrations of settling particles intercepted at 3067 m during the late winter period may be used to define an end member for constraining the proportions of these two sources of POC supplied to the deep basin throughout the year. The $\Delta^{14}\text{C}$ end member for aged, lithogenic particle-associated POC estimated from this correlation ($\Delta^{14}\text{C} = 4 - 32.07 \times \text{Al}$) and an average crustal aluminum concentration [Taylor and McLennan, 1985] (8.23%), is -260‰ , similar to the observed values in April and May. Using this value and the observed $\Delta^{14}\text{C}$ values for dissolved inorganic carbon in the surface water in the Canada Basin ($+20$ – 30‰ at 100m depth [Jones *et al.*, 1994]) as the end members, the flux-weighted $\Delta^{14}\text{C}$ value of POC over the full deployment (-226‰) implies that freshly produced POC accounts for less than 15% of annual POC flux to the deep Canada Basin.

[8] An intriguing feature of the time-series data is that the particle flux increased abruptly in March when overlying waters were completely ice covered, and there were no obvious mechanisms (e.g., rapid ice melting) to cause this increase. In this context, the study period can be divided into low flux and high flux intervals that also display distinct biogeochemical properties. Organic carbon contents, $4.7 \pm 0.8\%$ in the low flux period (excluding the first three sampling periods when $>50\%$ of POC was estimated to have originated from primary production), were slightly higher than in the high flux period ($3.8 \pm 0.2\%$). Stable carbon isotopic ($\delta^{13}\text{C}$) values were considerably higher in

the high flux period than in the low flux period (Figure 2a). These biogeochemical characteristics appear to be correlated with current directions measured at 2000 m on the same mooring (Figure 2c). Although the current speeds measured at 2000 m were low (<4 cm/sec) and generally insufficient to support long-range particle transport, the current direction might be one manifestation of the process(es) responsible for particle transport. The low flux period is associated with mainly southward flow and the high flux period with northward flow, with the shift in current direction approximately coincident with the onset of the high flux period, implying that the particles in the two periods might have different provenances.

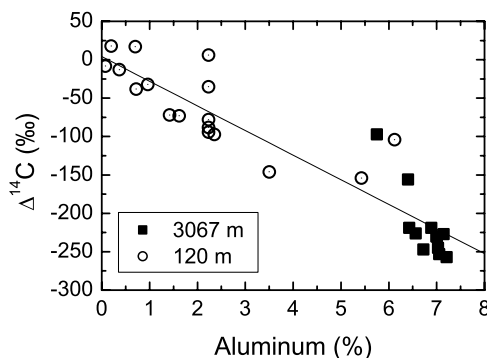


Figure 3. Correlation between $\Delta^{14}\text{C}$ of settling POC and aluminum concentration of settling particles at 120 m (circles) and 3067 m (squares) showing an inverse relationship.

[9] Potential sources of laterally transported POC include particles entrained by anticyclonic eddies produced from the eastward-flowing boundary current on the Beaufort margin [Aagaard *et al.*, 1985; Plueddemann *et al.*, 1998; Pickart *et al.*, 2005]. To the east, the Beaufort shelf receives substantial contributions of extensively aged terrestrial POC including fossil POC (e.g., kerogen) from the Mackenzie River [Yunker *et al.*, 1993; Goni *et al.*, 2005; Drenzek *et al.*, 2007], the largest riverine source of POC to the Arctic Ocean [Macdonald *et al.*, 1998; Holmes *et al.*, 2002]. Lipid biomarkers (fatty acids, *n*-alkanes and *n*-alkanols) also indicate that continentally-derived organic matter accounts for a significant fraction of the POC (up to 60–70%) preserved in southwest Canada Basin sediments [Belicka *et al.*, 2004; Drenzek *et al.*, 2007]. Isopycnal intrusion of the benthic nepheloid layer formed by thermohaline convection, windstorms, and current surges on the Beaufort Shelf [Forest *et al.*, 2007] may initiate transport of resuspended particles further into the interior ocean. Alternatively, POC could originate from Northwind Ridge, northwest of the sample site. Entrainment of particles in deep eddies propagating from the western margin of the basin (A. Proshutinsky and R. Krishfield, unpublished data, 2007) could transport associated POC to the interior ocean.

[10] The contrasting $\delta^{13}\text{C}$ values between the samples in the low and high flux periods may point to differing organic matter sources. Terrestrial POC typically has lower $\delta^{13}\text{C}$ values ($-27 \sim -28\%$ [Naidu *et al.*, 2000; Goni *et al.*, 2005]) and the $\delta^{13}\text{C}$ value of the marine POC end member was suggested to be -24% on the Beaufort shelf [Naidu *et al.*, 2000]. Based on these values, isotopic mass balance would imply that POC in the low flux period reflects a mixture of both terrestrial POC and marine POC, whereas marine organic matter dominates POC in the high flux period. POC transported by entrainment in the ice is likely to originate from the inner shelf where terrestrial POC is predominant [Cooper *et al.*, 1998], and hence is not likely a major source of POC in the high flux period. Reconciliation of the stable and radiocarbon isotopic data, together with current trajectories during the high flux period would therefore imply supply of pre-aged marine POC emanating from the Beaufort margin. However, detailed geochemical characterization of specific organic components and mineralogy of particulate matter [Schoster *et al.*, 2000] supplied to and settling in the interior of the Canada Basin are needed to unequivocally establish the provenance of this POC.

[11] Overall, our results show that the Arctic Ocean is unique in the extent to which organic carbon cycling is dominated by advective processes. This distinctive behavior implies that models developed to describe carbon cycling in other oceanic settings are not applicable. For example, estimates of primary production based on POC fluxes at depth would be subject to substantial errors [Macdonald and Carmack, 1991]. The biological reactivity of laterally transported organic matter closely associated with lithogenic particles may also differ, influencing benthic faunal density and diversity [Clough *et al.*, 1997]. Moreover, carbon cycling in this system is likely to change markedly in the face of a warming climate. The extent and manner in which the system will undergo change will only become apparent through concerted efforts to characterize high Arctic Ocean ecology and biogeochemistry.

[12] **Acknowledgments.** We thank Daniel Montluçon for guidance in laboratory work and staff at the National Ocean Sciences AMS facility for carbon isotope measurements. Sampling was possible through the Beaufort Gyre Observation System (A. Proshutinsky, lead-PI; <http://www.whoi.edu/beaufortgyre/>) and SHEBA programs. We acknowledge help from the captain and crew on the icebreaker *Louis S. St-Laurent*. This research was funded by the NSF Ocean Sciences Division (Chemical Oceanography program) and NSF Office of Polar Programs, Office of Naval Research, as well as the Ocean and Climate Change Institute and Arctic Research Initiative at the Woods Hole Oceanographic Institution.

References

- Aagaard, K., *et al.* (1985), Thermohaline circulation in the Arctic Mediterranean seas, *J. Geophys. Res.*, *90*, 4833–4846.
- Anderson, R. F., *et al.* (1994), Carbon budget for the mid-slope depocenter of the Middle Atlantic Bight, *Deep Sea Res., Part II*, *41*, 669–703.
- Belicka, L. L., *et al.* (2004), The role of depositional regime on carbon transport and preservation in Arctic Ocean sediments, *Mar. Chem.*, *86*, 65–88.
- Clough, L. M., *et al.* (1997), Infaunal density, biomass and bioturbation in the sediments of the Arctic Ocean, *Deep Sea Res., Part II*, *44*, 1683–1704.
- Cooper, L. W., *et al.* (1998), The distribution of radiocesium and plutonium in sea ice-entrained Arctic sediments in relation to potential sources and sinks, *J. Environ. Radioactivity*, *39*, 279–303.
- Dowdeswell, J. A., *et al.* (1997), The mass balance of Circum-Arctic glaciers and recent climate change, *Quat. Res.*, *48*, 1–14.
- Drenzek, N. J., *et al.* (2007), Constraints on the origin of sedimentary organic carbon in the Beaufort Sea from coupled molecular ^{13}C and ^{14}C measurements, *Mar. Chem.*, *103*, 146–162.
- Fahl, K., and E.-M. Nöthig (2007), Lithogenic and biogenic particle fluxes on the Lomonosov Ridge (central Arctic Ocean) and their relevance for sediment accumulation: Vertical vs. lateral transport, *Deep Sea Res., Part I*, *54*, 1256–1272.
- Forest, A., *et al.* (2007), Particulate organic carbon fluxes on the slope of the Mackenzie Shelf (Beaufort Sea): Physical and biological forcing of shelf-basin exchanges, *J. Mar. Syst.*, *68*, 39–54.
- Goni, M. A., *et al.* (2005), The supply and preservation of ancient and modern components of organic carbon in the Canadian Beaufort Shelf of the Arctic Ocean, *Mar. Chem.*, *93*, 53–73.
- Holmes, R. M., J. W. McClelland, B. J. Peterson, I. A. Shiklomanov, A. I. Shiklomanov, A. V. Zhulidov, V. V. Gordeev, and N. N. Bobrovitskaya (2002), A circumpolar perspective on fluvial sediment flux to the Arctic Ocean, *Global Biogeochem. Cycles*, *16*(14), 1098, doi:10.1029/2001GB001849.
- Honjo, S., *et al.* (2008), Particulate organic carbon fluxes to the ocean interior and factors controlling the biological pump: A synthesis of global sediment trap programs since 1983, *Prog. Oceanogr.*, *76*, 217–285.
- Hunkins, K., E. Thorndike, and G. Mathieu (1969), Nepheloid layers and bottom currents in the Arctic Ocean, *J. Geophys. Res.*, *74*, 6995–7008.
- Intergovernmental Panel on Climate Change (IPCC) (2007), IPCC, 2007: Summary for Policymakers, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon *et al.*, Cambridge Univ. Press, Cambridge, U.K.
- Jones, G. A., *et al.* (1994), High-precision AMS radiocarbon measurements of central Arctic Ocean sea waters, *Nucl. Instrum. Methods, Sect. B*, *92*, 426–430.
- Krishfield, R., *et al.* (1999), Ice-Ocean Environmental Buoy Program: Archived data processing and graphical results from April 1992 through November 1998, technical report, pp. 75–83, Woods Hole Oceanogr. Inst., Woods Hole, Mass.
- Macdonald, R. W., and E. C. Carmack (1991), Age of Canada Basin deep waters: A way to estimate primary production for the Arctic Ocean, *Science*, *254*, 1348–1350.
- Macdonald, R. W., *et al.* (1998), A sediment and organic carbon budget for the Canadian Beaufort Shelf, *Mar. Geol.*, *144*, 255–273.
- Macdonald, R. W., *et al.* (2002), Fresh water and its sources during the SHEBA drift in the Canada Basin of the Arctic Ocean, *Deep Sea Res., Part I*, *49*, 1769–1785.
- McNichol, A. P., *et al.* (1994), TIC, TOC, DIC, DOC, PIC, POC-unique aspects in the preparation of oceanographic samples for ^{14}C -AMS, *Nucl. Instrum. Methods, Sect. B*, *92*, 162–165.
- Naidu, A. S., *et al.* (2000), Organic carbon isotope ratios ($\delta^{13}\text{C}$) of Arctic Amerasian continental shelf sediments, *Int. J. Earth Sci.*, *89*, 522–532.
- Nakatsuka, T., *et al.* (1997), Origin and decomposition of sinking particulate organic matter in the deep water column inferred from the vertical distribution of its $\delta^{14}\text{N}$, $\delta^{13}\text{C}$ and $\delta^{14}\text{C}$, *Deep Sea Res., Part I*, *44*, 1957–1979.

- O'Brien, M. C., et al. (2006), Particle fluxes and geochemistry on the Canadian Beaufort Shelf: Implications for sediment transport and deposition, *Cont. Shelf Res.*, *26*, 41–81.
- Peterson, B. J., et al. (2002), Increasing river discharge to the Arctic Ocean, *Science*, *298*, 2171–2173.
- Peterson, B. J., et al. (2006), Trajectory shifts in the Arctic and Subarctic freshwater cycle, *Science*, *313*, 1061–1065.
- Pickart, R. S., et al. (2005), Flow of winter-transformed Pacific water into the western Arctic, *Deep Sea Res., Part II*, *52*, 3175–3198.
- Plueddemann, A. J., R. Krishfield, T. Takizawa, K. Hatakeyama, and S. Honjo (1998), Upper Ocean Velocities in the Beaufort Gyre, *Geophys. Res. Lett.*, *25*, 183–186.
- Rachold, V., et al. (2004), Modern terrigenous organic carbon input to the Arctic Ocean, in *The Organic Carbon Cycle in the Arctic Ocean*, edited by R. Stein and R. W. Macdonald, pp. 33–55, Springer, New York.
- Schoster, F., et al. (2000), Modern river discharge and pathways of supplied material in the Eurasian Arctic Ocean: Evidence from mineral assemblages and major and minor element distribution, *Int. J. Earth Sci.*, *89*, 486–495.
- Stuiver, M., and H. A. Polach (1977), Reporting of ^{14}C data, *Radiocarbon*, *19*, 355–363.
- Taylor, S. R., and S. M. McLennan (1985), *The Continental Crusts: Its Composition and Evolution*, Blackwell Sci., Oxford, U. K.
- Wassmann, P., et al. (2004), Particulate organic carbon flux to the Arctic Ocean sea floor, in *The Organic Carbon Cycle in the Arctic Ocean*, edited by R. Stein and R. W. Macdonald, pp. 101–138, Springer, New York.
- Yunker, M. B., et al. (1993), Alkane, terpene, and polycyclic aromatic hydrocarbon geochemistry of the Mackenzie River and Mackenzie shelf: Riverine contributions to Beaufort Sea coastal sediment, *Geochim. Cosmochim. Acta*, *57*, 3041–3061.
-
- T. I. Eglinton, S. Honjo, J. Hwang, R. A. Krishfield, and S. J. Manganini, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA. (jhwang@whoi.edu)