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Major flux of terrigenous dissolved organic matter through the Arctic Ocean

Abstract—High-latitude rivers supply the Arctic Ocean with a disproportionately large share of global riverine discharge and terrigenous dissolved organic matter (DOM). We used the abundance of lignin, a macromolecule unique to vascular plants, and stable carbon isotope ratios ($\delta^{13}\text{C}$) to trace the high molecular weight fraction of terrigenous DOM in major water masses of the Arctic Ocean. Lignin oxidation products in ultrafiltered DOM (UDOM; $>1,000$ Da) from Arctic rivers were depleted in syringyl relative to vanillyl phenols ($S/V = 0.3–0.5$) compared to UDOM in temperate and tropical rivers ($S/V = 0.5–1.2$), indicating that gymnosperm vegetation is a major source of terrigenous UDOM to the Arctic Ocean. High concentrations of lignin oxidation products ($83–320$ ng L^{-1}) and a depletion of ^{13}C ($\delta^{13}\text{C} = -23.0$ to -21.9) in UDOM throughout the surface Arctic Ocean indicate that terrigenous UDOM accounts for a much greater fraction of the UDOM in the surface Arctic (5–33%) than in the Pacific and Atlantic oceans (0.7–2.4%). In contrast, UDOM in deep water from the Arctic Ocean as well as waters from throughout the Greenland Gyre had relatively low concentrations of lignin oxidation products ($24–45$ ng L^{-1}) and was enriched in ^{13}C ($\delta^{13}\text{C} = -21.0$ to -20.8). Terrigenous UDOM has a relatively short

residence ($\sim 1–6$ yr) in surface polar waters prior to export to the north Atlantic Ocean. Assuming that the bulk of Arctic-derived DOM is compositionally similar to the UDOM fraction, we estimate that 12–41% of terrigenous DOM ($2.9–10.3$ Tg C yr^{-1}) discharged by rivers to the Arctic Ocean is exported to the North Atlantic via surface waters of the East Greenland Current. It appears very little terrigenous DOM from the Arctic is incorporated into North Atlantic Deep Water and distributed globally via deep thermohaline circulation.

The Arctic Ocean receives $\sim 10\%$ of the freshwater and dissolved organic matter (DOM) supplied globally by rivers (Aagaard and Carmack 1989; Gordeev et al. 1996; Macdonald et al. 1998; Anderson et al. 1998), yet it represents only 1% of the global ocean volume (Menard and Smith 1966). Thus, the flux of terrigenous DOM to the Arctic Ocean is much greater on a volume basis than corresponding fluxes to the Atlantic, Indian, and Pacific oceans. Furthermore, the supply of terrigenous DOM to the Arctic Ocean may be

increasing due to changes in global climate. Current estimates indicate that up to 60% of soil organic matter resides in taiga and tundra soils (Dixon et al. 1994) found in Arctic drainage basins, and the thawing of permafrost due to global warming could elevate the amount of terrigenous DOM discharged into the Arctic Ocean. As part of recent interdisciplinary studies of Arctic Ocean biogeochemistry, we investigated the sources of terrigenous DOM to the Arctic Ocean, the distribution of the terrigenous fraction among major Arctic Ocean water masses, and the export of terrigenous DOM from the Arctic Ocean.

Sampling and methods—Water samples were collected from throughout the Arctic Ocean and adjacent seas (Fig. 1) during expeditions aboard the nuclear submarines *USS Pogy* (1996) and *USS Archerfish* (1997), the *F. S. Polarstern* (1997), and the *Akademik Boris Petrov* (1997). Samples were prefiltered through 0.2- μm pore-size filters to remove particulates, and DOM was isolated from each water sample (30–194 liters) using Amicon DC10 and Proflux M30 tangential-flow ultrafiltration systems with polysulfone membranes (1,000 Da cutoff; Benner 1997). The recovery efficiency of dissolved organic carbon (DOC) was 50–70% from low-salinity waters of the Kara Sea and 17–40% from surface and deep marine waters. These recovery efficiencies are similar to those from other river and marine waters (Benner and Hedges 1993; Benner et al. 1997). Benner and Hedges (1993) reported high DOC recovery efficiencies (average of 78%) in the Amazon River and its tributaries with lower efficiencies being characteristic of sediment-laden (white water) rivers. Most of the large Arctic rivers (the Mackenzie is one notable exception) have characteristically high DOC concentrations and low sediment loads, which explains why the recovery efficiencies of DOC from Kara Sea waters were relatively high. The DOC concentrations of all water samples were measured using a high-temperature combustion method with a Shimadzu TOC 5000 (Benner and Strom 1993).

The terrigenous component of ultrafiltered DOM (UDOM) was characterized by its signature of lignin oxidation products produced during CuO oxidation (Hedges and Ertel 1982) and its stable carbon isotope composition ($\delta^{13}\text{C}$). Lignin oxidation products provide a sensitive tracer that is specific for terrigenous DOM because lignin is biosynthesized only by vascular plants. Lignin oxidation products also provide information about the source vegetation and diagenetic state of the terrigenous DOM (Ertel et al. 1986). Trimethylsilyl derivatives of lignin oxidation products produced during CuO oxidation were separated using a Hewlett Packard 5890 GC equipped with an HP-5MS capillary column (30 m, 0.25 mm inner diameter). A Hewlett Packard 5972 mass-selective detector provided positive identification of the lignin oxidation products based on comparison with commercially available standards. The mass selective detector was also used to quantify the lignin oxidation products using selected ion monitoring and ethylvanillin and cinnamic acid as internal standards (Opsahl and Benner 1997). Lignin phenol concentrations ranged over three orders of magnitude in this study and the response of individual phenols using selected ion monitoring is not linear over such a broad range. Therefore, separate standard curves were generated for each phe-

nol to ensure that appropriate response factors were used for quantification at different concentrations. The sum of six major CuO oxidation products of lignin (vanillin, acetovanillone, vanillic acid, syringaldehyde, acetosyringone, and syringic acid) was used to quantify lignin in UDOM (Opsahl and Benner 1997).

Stable carbon isotope ratios were measured using a Finnegan Delta Plus system with in-line combustion. Stable carbon isotope ratios were calculated using $\delta^{13}\text{C} (\text{‰}) = [(R_{\text{sample}}/R_{\text{standard}}) - 1] \times 1,000$ where R is the ratio of $^{13}\text{C}/^{12}\text{C}$ relative to the Pee Dee Belemnite standard. To our knowledge, these are the first $\delta^{13}\text{C}$ values to be reported for Arctic Ocean DOM.

$\delta^{13}\text{C}$, lignin, and DOC in the Kara Sea—Samples from the Kara Sea were collected at the discharge sites of the Ob and Yenisei rivers (Fig. 1) that collectively account for ~34% of total fluvial discharge to the Arctic Ocean (Aagaard and Carmack 1989). The stable carbon isotopic composition of Kara Sea UDOM ($\delta^{13}\text{C} = -27.6$ to -27.1) indicated that it was derived predominantly from terrestrial vegetation (Table 1). High DOC concentrations (460–540 μM) in Kara Sea waters were consistent with previous reports of elevated DOC concentrations in high-latitude rivers (Telang et al. 1991; Cauwet and Siderov 1996; Gordeev et al. 1996; Lara et al. 1998; Kattner et al. 1999). Concentrations of lignin oxidation products were slightly higher in the Kara Sea ($\sim 27.8 \mu\text{g L}^{-1}$) than in the Amazon and Mississippi rivers ($\sim 21.6 \mu\text{g L}^{-1}$; Ertel et al. 1986; Opsahl and Benner 1997). Carbon-normalized yields of lignin oxidation products (Λ_c) in Kara Sea UDOM (0.68–0.96) were somewhat lower than average values reported for Amazon and Mississippi river UDOM (~ 1.1 ; Opsahl and Benner 1997).

Sources and diagenetic state of Arctic Ocean UDOM—The molecular composition of lignin-derived phenols reflects both the sources and biogeochemical processing of terrigenous DOM. The ratios of vanillic acid to vanillin, (ad/al)v, in Kara Sea and Arctic Ocean (Polar Surface Water [PSW], East Greenland Current [EGC], and Fram Strait) UDOM fell within a range of 0.7–1.5 (Table 1) that is similar to previously published values for river and ocean UDOM (Opsahl and Benner 1997). These (ad/al)v values are elevated relative to fresh plant tissues and reflect an increase in oxidation state during decomposition and transport. The ratio of syringyl to vanillyl phenols (S/V) is typically used as an indicator of source vegetation. This appears to be valid for UDOM in the Arctic Ocean because S/V values were similar in the Kara Sea and Arctic Ocean samples, indicating minimal diagenetic alteration of S/V during mixing in the Arctic Ocean. Recent results have shown that UDOM in temperate and tropical rivers has high S/V values (0.5–1.2) relative to UDOM in the Atlantic and Pacific oceans (0.1–0.4; Opsahl and Benner 1997), suggesting that diagenetic alterations may lead to reductions in S/V in other oceanic environments. Photochemical degradation represents a mechanism that can selectively alter the S/V signature of terrigenous DOM (Opsahl and Benner 1998). A lack of change in S/V argues against substantial photochemical decomposition of terrigenous DOM in Arctic waters.

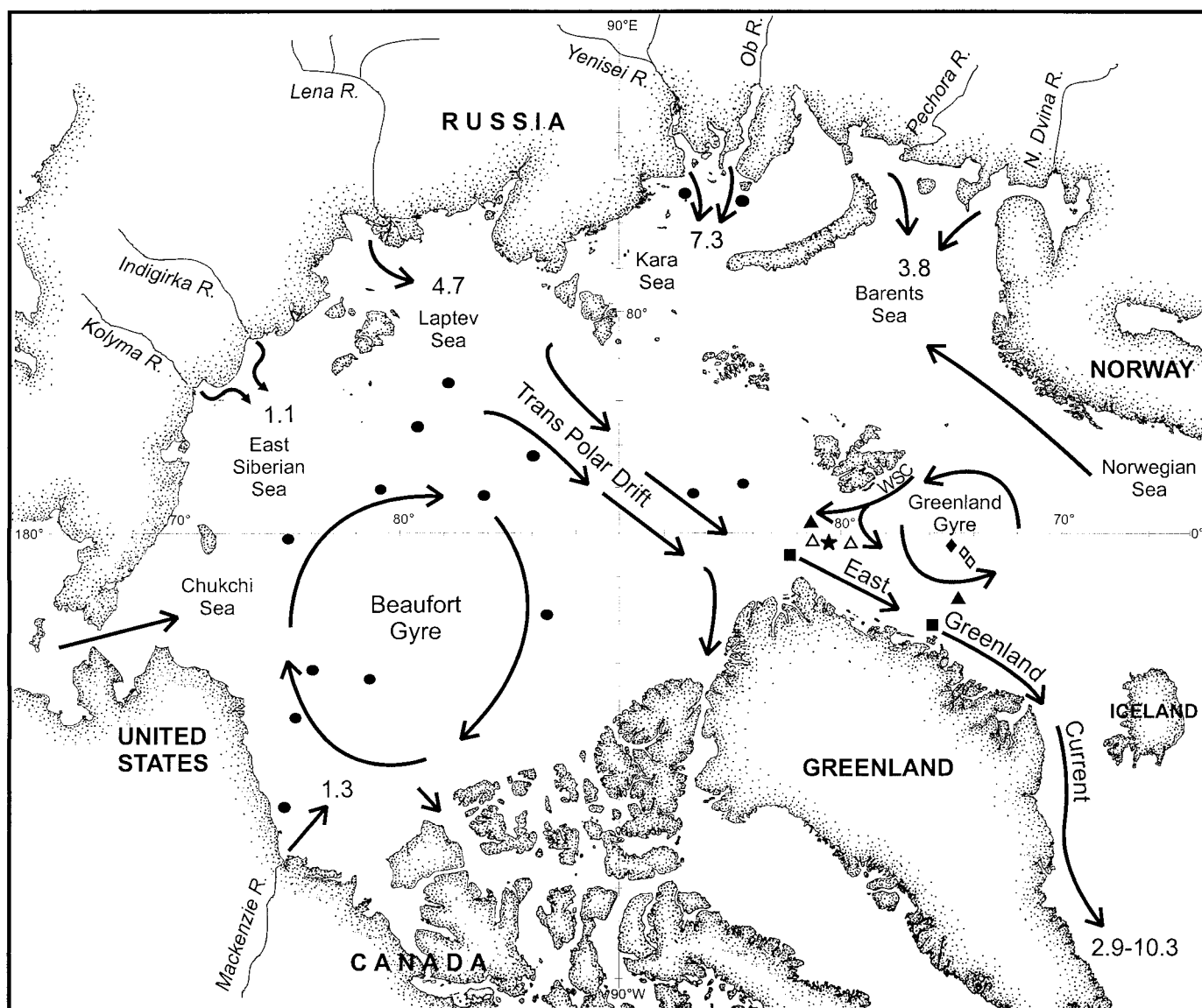


Fig. 1. Fluxes (Tg yr^{-1}) of dissolved organic carbon (DOC) from major Arctic rivers and estimated export of terrigenous DOC from the Arctic Ocean in the upper 200 m of the EGC. Smaller rivers account for 28% of the total river discharge and contribute an additional 6.9 Tg DOC annually (calculated from data in Aagaard and Carmack [1989], Gordeev et al. [1996], and Macdonald et al. [1998]). Generalized surface circulation features of the Arctic Ocean are depicted by arrows. Sampling locations included PSW and the Kara Sea (closed circles), the EGC (closed squares), Fram Strait surface (<250 m; closed triangles), and deep (>250 m; open triangles) waters, Greenland Gyre surface (200 m; closed diamond) and deep ($>1,800$ m; open diamonds) waters, and sea ice from the Fram Strait. WSC, West Spitzbergen Current.

As a source indicator, the ratio of syringyl to vanillyl phenols (S/V) in soils, sediments, and DOM reflects the relative contributions of gymnosperm and angiosperm vegetation. Gymnosperm lignins are comprised mostly of vanillyl phenols (Hedges and Ertel 1982), therefore relatively low ratios of syringyl to vanillyl phenols (S/V) are expected for organic matter derived from gymnosperm-dominated ecosystems. The S/V values for Kara Sea UDOM (0.3–0.5; $n = 9$) were similar to low values reported for particulate and sedimentary material collected from the Lena estuary (Lobbes and Kattner pers. comm.) and are consistently lower than those reported for UDOM from the Amazon and Mississippi rivers

(0.5–1.2; Opsahl and Benner 1997). The lower S/V values in Kara Sea UDOM likely reflect drainage of vast areas of taiga in which coniferous forests predominate (Raven et al. 1986). In contrast, the Mississippi and Amazon rivers drain forests and grasslands dominated by angiosperm vegetation, which appears to explain their elevated S/V ratios. The low S/V values in the Kara Sea were also consistent with the low S/V values (0.18–0.31) measured in all UDOM samples collected from surface waters of the Arctic Ocean (Table 1), indicating that contributions from other Arctic rivers not surveyed in this study also contribute DOM from gymnosperm-dominated ecosystems.

Table 1. Sampling locations and physical characteristics of the water masses sampled. Samples of ultrafiltered dissolved organic matter (UDOM) were analyzed for stable carbon isotope ratios and lignin oxidation products. The following parameters were calculated from lignin oxidation products: the carbon-normalized yield (mg lignin oxidation products/100 mg ultrafiltered dissolved organic carbon; Λ_6), the ratio of syringyl to vanillyl phenols (S/V), and the ratio of vanillic acid to vanillin (ad/al)v.

	Latitude	Longitude	Depth (m)	Salinity	Temperature (°C)	$\delta^{13}\text{C}^*$ (‰)
Kara Sea—Ob range ($n = 5$)	72°10'N to 73°57'N	73°10'E to 76°08'E	Surface	2.7–12.7	5.4–6.3	–27.6 to –27.1
Kara Sea—Yenisei range ($n = 4$)	72°05'N to 73°40'N	80°05'E to 80°30'E	Surface	1.5–10.0	6.6–7.8	–27.2 to –27.1
Polar Surface Water range ($n = 13$)	See Fig. 1		38–165	32.04–34.49	ND	–23.0 to –21.9
East Greenland Current	75°16'00N	15°30'00W	51	33.251	–1.666	–23.0
East Greenland Current	81°41'20N	04°33'20W	80	33.968	–1.690	–22.5
Fram Strait—Atlantic Inflow	81°01'50N	01°26'10E	250	34.926	1.900	–21.0
Fram Strait—Atlantic Return	74°59'40N	12°33'30W	149	34.905	2.406	–21.1
Fram Strait—Canada Basin	79°40'50N	03°56'40W	1,820	34.924	–0.541	–20.9
Fram Strait—Eurasian Basin	81°03'90N	03°29'60W	3,600	34.934	–0.699	–20.8
Greenland Gyre	75°04'80N	03°29'10W	200	34.855	–0.542	–21.0
Greenland Gyre	74°59'90N	03°30'90W	1,800	34.906	–0.878	–20.8
Greenland Gyre	74°58'90N	04°20'00W	3,200	34.902	–0.967	–20.9
Sea ice	80°53'53N	02°35'16W	Surface	2.510	ND‡	–22.1

* Expressed relative to the PDB standard.

† $n = 7$ for (ad/al)v ratios because data from the 1996 cruise are not included.

‡ ND, not determined.

UDOM from the Yenisei River had consistently lower S/V values (0.33 ± 0.01) than UDOM from the Ob (0.46 ± 0.12), providing an interesting difference that appears to result from variations in drainage basin vegetation. Both ecosystems drain extensive reaches of coniferous forests, but the Ob River drainage basin has two major geographic regions that probably contribute a substantial amount of DOM with an elevated S/V value due to an abundance of angiosperm vegetation. The region in Siberia from 60 to 65° N and 75 to 80° E includes the largest *Sphagnum* bog system in the world, in which angiosperms (shrubs, grasses, and sedges) are abundant (Walter and Breckle 1986). Further south, the area bounded by 50–55° N and 65–85° E consists of broadleaf deciduous forests, expansive grassy steppes, and agricultural land, all of which support angiosperm vegetation (Strasburger et al. 1971). Thus, drainage basin-specific distinctions of source waters to the Arctic Ocean may also be possible based on the molecular signature of lignin oxidation products.

$\delta^{13}\text{C}$ and lignin in PSW—River water discharged into the Arctic Ocean mixes with water from the Atlantic and Pacific oceans and contributes to the formation of an ice-covered, relatively low salinity (<34.4) water mass referred to as PSW (Aagaard and Carmack 1989; Jones et al. 1991). Concentrations of dissolved lignin in UDOM from PSW (83–320 ng L⁻¹; Table 1) were very high relative to lower latitude surface waters of the Pacific and Atlantic oceans (6–25 ng L⁻¹; Opsahl and Benner 1997). Corresponding stable carbon isotope ratios of UDOM from PSW ($\delta^{13}\text{C} = -23.0$ to -21.9) were depleted in ¹³C relative to values reported for Pacific and Atlantic ocean UDOM ($\delta^{13}\text{C} = -22.2$ to -21.3 ; Benner et al. 1997). Furthermore, Guay et al. (1999) report a strong fluorescence signal (320 nm excitation, 420 nm emission) in PSW that appears to be derived primarily from terrigenous DOM and is characteristic of surface Arctic wa-

ters. Collectively, these characteristics demonstrate an abundance of terrigenous organic matter in PSW and clearly distinguish the surface Arctic Ocean from the Pacific and Atlantic oceans.

Terrigenous component of PSW—The terrigenous fraction of UDOM in seawater can be estimated independently from lignin oxidation products and stable carbon isotope data. Carbon-normalized yields of lignin oxidation products (Λ_6 ; Table 1) are used for estimating the fraction of terrigenous UDOM in surface waters using the equation: % terrigenous UDOM = (Λ_6 PSW)/(Λ_6 Kara Sea) × 100 (Opsahl and Benner 1997). Using the lowest and highest Λ_6 for UDOM in the Kara Sea and PSW samples (Table 1) to calculate a range of values, we estimate 5–22% of the UDOM in PSW is of terrigenous origin. In comparison, using a simple two-end-member mixing model with a terrigenous UDOM $\delta^{13}\text{C}$ of -27.3 ‰ (average of Kara Sea samples) and a marine UDOM $\delta^{13}\text{C}$ of -20.9 ‰ (average of all Fram Strait and Greenland Gyre samples), we estimate that 16–33% of the UDOM in PSW is of terrigenous origin.

These independent estimates of terrigenous DOM vary by about twofold, but both indicate very high concentrations of terrigenous UDOM in PSW. The concentrations of lignin oxidation products and $\delta^{13}\text{C}$ values in UDOM were weakly correlated ($r^2 = 0.69$, $P < 0.05$), suggesting some variability among chemical and isotopic signatures of UDOM sources or removal processes. Further studies are needed to resolve these differences and refine estimates from these independent techniques. For example, several studies have shown that planktonic (particulate organic matter) stable carbon isotope ratios in Arctic waters are depleted in ¹³C relative to more temperate oceanic environments (Rau et al. 1982; Hobson et al. 1995). However, any effect that this may have on the $\delta^{13}\text{C}$ of the marine endmember for Arctic UDOM is currently unknown. A shift in the $\delta^{13}\text{C}$ of the marine endmem-

Table 1. Extended.

DOC (μM)	Lignin oxidation products (ng L^{-1})	Λ_6 (mg/100 mg OC)	S/V	(ad/al)v
423–528	20,908–24,512	0.683 to 0.843	0.33–0.55	1.12–1.50
503–537	30,920–34,935	0.694 to 0.960	0.31–0.34	1.14–1.47
66–80	84–320	0.0464 to 0.150	0.12–0.31	0.90–1.40†
85	599	0.169	0.32	1.24
75	306	0.090	0.26	1.26
61	35	0.0172	0.28	1.26
65	62	0.0295	0.34	1.06
53	27	0.0142	0.24	1.05
49	24	0.0104	0.29	1.16
58	45	0.0242	0.31	1.39
54	34	0.0205	0.29	1.31
50	44	0.0201	0.36	0.72
107	86	0.0473	0.51	3.36

ber to 0.8‰ more depleted $\delta^{13}\text{C}$ would reduce the estimate of terrigenous UDOM provided by the stable carbon isotope model by about half. Regardless, the high percentages of terrigenous UDOM in PSW indicated by both methods strongly contrasts the trace levels (0.7–2.4%) reported for surface waters of the Pacific and Atlantic oceans (Opsahl and Benner 1997).

The lignin oxidation product and stable carbon isotope data in this study come from measurements on the UDOM fraction of DOM. To address broader questions relating to bulk DOM cycling and budgets, we presently must rely on the assumption that the UDOM fraction is representative of bulk DOM. At present, we cannot say whether carbon-normalized yields of lignin oxidation products in UDOM are entirely representative of bulk DOM. Therefore, lignin-based estimates of the terrigenous fraction in UDOM may be the same, higher, or lower for bulk DOM depending on the concentration of lignin oxidation products in the low molecular weight fraction. There is growing evidence indicating that the $\delta^{13}\text{C}$ of UDOM is representative of bulk DOM. Hedges et al. (1994) found that the $\delta^{13}\text{C}$ of UDOM samples collected from the Amazon River and its major tributaries ranged from -28.0 to -29.5‰ , and were similar to $\delta^{13}\text{C}$ values (-28.0 to -30.0‰) for bulk DOM in samples from the same rivers (Quay et al. 1992). Additionally, Williams and Gorden (1970) measured an average of -28.5‰ for bulk DOM in the Amazon River. Benner et al. (1997) measured the $\delta^{13}\text{C}$ of marine UDOM in a suite of samples from the Pacific and Atlantic oceans and the Gulf of Mexico. All samples reflected a marine isotopic signature ($\delta^{13}\text{C} = -21.3$ to -22.2) and fell within the range of $\delta^{13}\text{C}$ values reported by Druffel et al. (1992) for oceanic DOM samples. Assuming the lignin and isotopic compositions of UDOM are representative of bulk DOM, we estimate that 5–33% of the DOM in PSW is terrigenous.

Residence time of terrigenous UDOM—The residence time of terrigenous UDOM in PSW was estimated using the

equation: residence time = (reservoir size of lignin oxidation products in PSW UDOM)/(river discharge of lignin oxidation products in UDOM). A range of reservoir sizes of lignin oxidation products was estimated using the high and low measurements of lignin oxidation products in PSW (84–320 ng L^{-1} ; Table 1). The volume of PSW (0–200 m) was estimated using the total surface area of the Arctic Ocean (Menard and Smith 1966) after excluding the shallow continental shelves that account for $\sim 35\%$ of the surface area (i.e., $[0.2 \text{ km} \times (9.485 \times 10^6 \text{ km}^2) \times 0.65] = 1.233 \times 10^6 \text{ km}^3$). For river discharge, we used the range of lignin oxidation product concentrations from the Kara Sea (20,908–34,935 ng L^{-1}) and the average Arctic river discharge of 3,300 $\text{km}^3 \text{ yr}^{-1}$ given by Aagaard and Carmack (1989). We estimate the residence time of terrigenous UDOM in PSW is about 1–6 yr, which is short relative to that of the Pacific and Atlantic oceans (21–132 yr; Opsahl and Benner 1997). The short residence time of terrigenous UDOM in PSW is within the range of residence times estimated for the freshwater discharge by Arctic rivers (1–14 yr; Östlund 1982; Schlosser et al. 1994). As with freshwater, entrainment above the halocline and rapid physical export are probably the predominant driving forces that lead to the short residence time of terrigenous DOM. Microbial and photochemical oxidation could also contribute to the removal of terrigenous DOM, but we suspect that physical processes predominate in the cold, ice-covered waters of the Arctic Ocean.

Export of terrigenous UDOM in Arctic Ocean surface waters—Most PSW exits the Arctic Ocean via the EGC in the Fram Strait and through the Canadian Archipelago. The EGC is about 60 km wide and 2,500 km long and is the single largest surface current that exports water from the Arctic Ocean (Burke et al. 1987; Foldvik et al. 1988). Based on lignin oxidation products (Λ_6) in UDOM, we estimate that 9–27% of the UDOM in the EGC is of terrigenous origin. Using the two-endmember mixing model described above, the $\delta^{13}\text{C}$ ratios from EGC UDOM indicate that 25–33% of the UDOM is of terrigenous origin. The sea-ice sample from Fram Strait contained about 5–7% terrigenous UDOM based on Λ_6 values (Table 1). An estimate based on $\delta^{13}\text{C}$ values for sea-ice will not be made for comparison because of probable contributions by ice-algae with an unusual $\delta^{13}\text{C}$ signature (see Table 1).

Using these estimates of the terrigenous fraction in UDOM samples and the assumption that UDOM is representative of bulk DOM, we can estimate export of terrigenous DOM in surface waters of the EGC as follows. Volume transport for the EGC is $\sim 1 \text{ Sv}$ for the upper 200 m (Burke et al. 1987; Foldvik et al. 1988), which we use to represent PSW export. An annual average of about 0.09 Sv of ice is exported through Fram Strait (Vinje et al. 1998). Using an average DOC value of 80 μM for the EGC and 107 μM for ice (similar to average values measured in Arctic sea-ice cores; Thomas et al. 1995), we estimate an annual export through the Fram Strait of 2.9–10.3 Tg terrigenous DOC in the upper 200 m of the EGC. This represents 12–41% of the annual Arctic river discharge of terrigenous DOC (25.1 Tg C; Fig. 1). Export of water through the Canadian Archipelago is similar in magnitude to the surface EGC (Rudels 1987; Fissel et al. 1988), thus total export of terrigenous

DOC from the surface Arctic Ocean to the Atlantic Ocean could be as high as the discharge of DOC from the Amazon River (19 Tg yr⁻¹) to the Atlantic (Degens et al. 1991). Furthermore, export by surface currents could account for the majority of the net export of DOC (terrigenous + marine) from the Arctic Ocean that has been estimated to be about 25 Tg C yr⁻¹ (Wheeler et al. 1997).

The West Spitzbergen Current (WSC) carries warm salty water from the Atlantic to the Arctic (Gascard et al. 1995). The concentration of lignin oxidation products in UDOM from Atlantic Inflow water (35 ng L⁻¹) was similar to that of the central Atlantic (Opsahl and Benner 1997), indicating little mixing with lignin-enriched shelf waters prior to entering the Arctic. Part of the WSC inflow loops southward below 80°N and returns to the Atlantic after a brief residence in the southern Arctic. The Atlantic Return water UDOM had a concentration of lignin oxidation products about 1.7-fold higher than Atlantic Inflow water (Table 1), indicating a contribution of terrigenous UDOM from Arctic rivers through shelf-exchange processes or mixing with PSW. Outflow of Atlantic Return water from the Arctic is difficult to quantify; however, the relatively low concentration of lignin oxidation products and predominantly marine stable isotopic composition ($\delta^{13}\text{C} = -21.1$) indicate that it carries relatively little terrigenous UDOM.

Contribution of terrigenous UDOM to deep Arctic basins—Deep water in the Canada and Eurasian basins has a much longer residence time (200–500 yr) than overlying PSW (1–14 yr; Östlund 1982; Schlosser et al. 1994). The specific sources of Arctic Ocean deep water remain unclear, but transport of dense water from continental shelves is a possible source of terrigenous DOM to the deep Arctic. However, low concentrations of lignin oxidation products (<27 ng L⁻¹) and the predominance of marine isotopic signatures ($\delta^{13}\text{C} < -21.0$) for UDOM in deep water from the Canada and Eurasian basins (Table 1) indicate that shelf waters make a minor contribution of terrigenous UDOM to deep water of the Arctic Ocean. Atlantic Inflow water spreads over the shelves of the Barents and Kara seas and it has a relatively minor terrigenous component (Table 1). Cooling and deep advection of Atlantic Inflow water is recognized as an important mechanism for transport of dense water to the Arctic interior (Aagaard et al. 1985), and it probably represents the primary source of DOM to the deep Arctic Ocean.

Contribution of terrigenous UDOM to North Atlantic Deep Water (NADW)—Freshwater and ice from the Arctic Ocean play an important role in the formation of NADW and maintenance of global thermohaline circulation (Broecker et al. 1985; Aagaard and Carmack 1989; Dickson et al. 1990). The Greenland Sea is an area of NADW formation (Aagaard and Carmack 1989; Dickson et al. 1990), and it is in close proximity to the lignin-enriched EGC. The Greenland Gyre, situated in the heart of the Greenland Sea between the EGC and WSC, was uniformly cold and saline throughout the water column at the time of sampling (Table 1). The relatively low concentrations of lignin oxidation products (35–45 ng L⁻¹) and ¹³C-enriched isotopic composition (-21.0 to -20.8 ‰) in UDOM from the Greenland

Gyre indicate little input of terrigenous DOM. Substantial contributions of terrigenous DOM at other sites of NADW formation, such as the Labrador Sea, also seem unlikely given the low concentration of lignin oxidation products (28 ng L⁻¹) in UDOM from NADW at Bermuda (Opsahl and Benner 1997). Thus, thermohaline circulation driven by deep-water renewal in polar regions currently plays a relatively minor role in the distribution of terrigenous DOM in the global ocean.

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