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Lithogenic and biogenic particle fluxes on the Lomonosov Ridge (central Arctic Ocean) and their relevance for sediment accumulation: Vertical vs. lateral transport

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Abstract

Investigations of lithogenic and biogenic particle fluxes using long-term sediment traps are still very rare in the northern high latitudes and are restricted to the arctic marginal seas and sub-arctic regions. Here data on the variability of fluxes of lithogenic matter, $CaCO_3$, opal, and organic carbon and biomarker composition from the central Arctic Ocean are presented for a 1-year period. The study was carried out on material obtained from a long-term mooring system equipped with two multi-sampling traps, at 150 and 1550 m depth, and deployed on the southern Lomonosov Ridge close to the Laptev Sea continental margin from September 1995 to August 1996. In addition, data from surface sediments were included in the study. Annual fluxes of lithogenic matter, $CaCO_3$, opal, and particulate organic carbon were 3.9, 0.8, 2.6, and 1.5 g m^{-2} y^{-1}, respectively, in the shallow trap and 11.3, 0.5, 2.9, and 1.05 g m^{-2} y^{-1}, respectively, in the deep trap.

Both the shallow and the deep trap showed significant variations in vertical flux over the year. Higher values were found from mid-July to the end of October (total mass flux of 75–130 mg m^{-2} d^{-1} in the shallow trap and 40–225 mg m^{-2} d^{-1} in the deep trap). During all other months, fluxes were fairly low in both traps (most total mass flux values <10 mg m^{-2} d^{-1}). The interval of increased fluxes can be separated into (1) a mid-July/August maximum caused by increased primary production as documented in high abundances of marine biomarkers and diatoms and (2) a September/October maximum caused by increased influence of Lena River discharge indicated by maximum lithogenic flux and large amounts of terrigenous/fluvial biomarkers in both traps. During September/October, total mass fluxes in the deep trap were significantly higher than in the shallow trap, suggesting a lateral sediment flux at greater depth. The lithogenic flux data also support the importance of sediment input from the Laptev Sea for the sediment accumulation on the Lomonosov Ridge on geological time scales, as indicated in sedimentary records from this region.

Keywords: Central Arctic Ocean; Organic carbon flux; Biomarker; Sea ice; River discharge; Lateral transport

1. Introduction

The composition and quantity of lithogenic and biogenic matter and its vertical and lateral fluxes are poorly known in the Arctic Ocean. Data on total

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mass, lithogenic matter, carbonate ($CaCO_3$), opal, and particulate organic carbon (POC) fluxes can be obtained by means of sediment trap deployments. In the Arctic Ocean proper, however, sediment-trap data have not been available until now but have been restricted to marginal seas and subarctic areas (Hebbeln and Wefer, 1991; Hebbeln, 2000; Wassmann et al., 2004). In this context, the open Arctic Ocean area close to the Laptev Sea is especially important for Arctic oceanography.

The Laptev Sea (Fig. 1) is characterized by high export rates of sea ice and high input of suspended and dissolved material by Siberian rivers, both having a great influence on the sedimentary and chemical budgets of the entire Arctic Ocean (Eicken et al., 1997, 2000; Holmes et al., 2002; Stein and Fahl, 2004). A major contributor is the Lena River (discharge = 523 km^3/yr), transporting large amounts of dissolved and particulate material, i.e., chemical elements, lithogenic and terrestrial/fluvial organic matter, and nutrients. The annual discharge of total suspended sediments by the Lena River is 20.7×10^6 tons (Holmes et al., 2002; Rachold et al., 2004); particulate organic carbon supply is estimated to reach about 1.2×10^6 tons per year. The Lena River is an important freshwater source characterized by a seasonally pulsed inflow in June/July and moderate inflow during May and August/September (Fig. 1). During this short season of strong freshwater discharge, water masses on the Laptev Sea shelf are characterized by low salinities of 4–28 (Dmitrenko et al., 1999), which can be encountered far off the shelf, causing stratification of the surface waters.

Here, we present the first record of the annual variability and composition of particle fluxes in the Lomonosov Ridge area close to the Laptev Sea continental margin. The characterization of

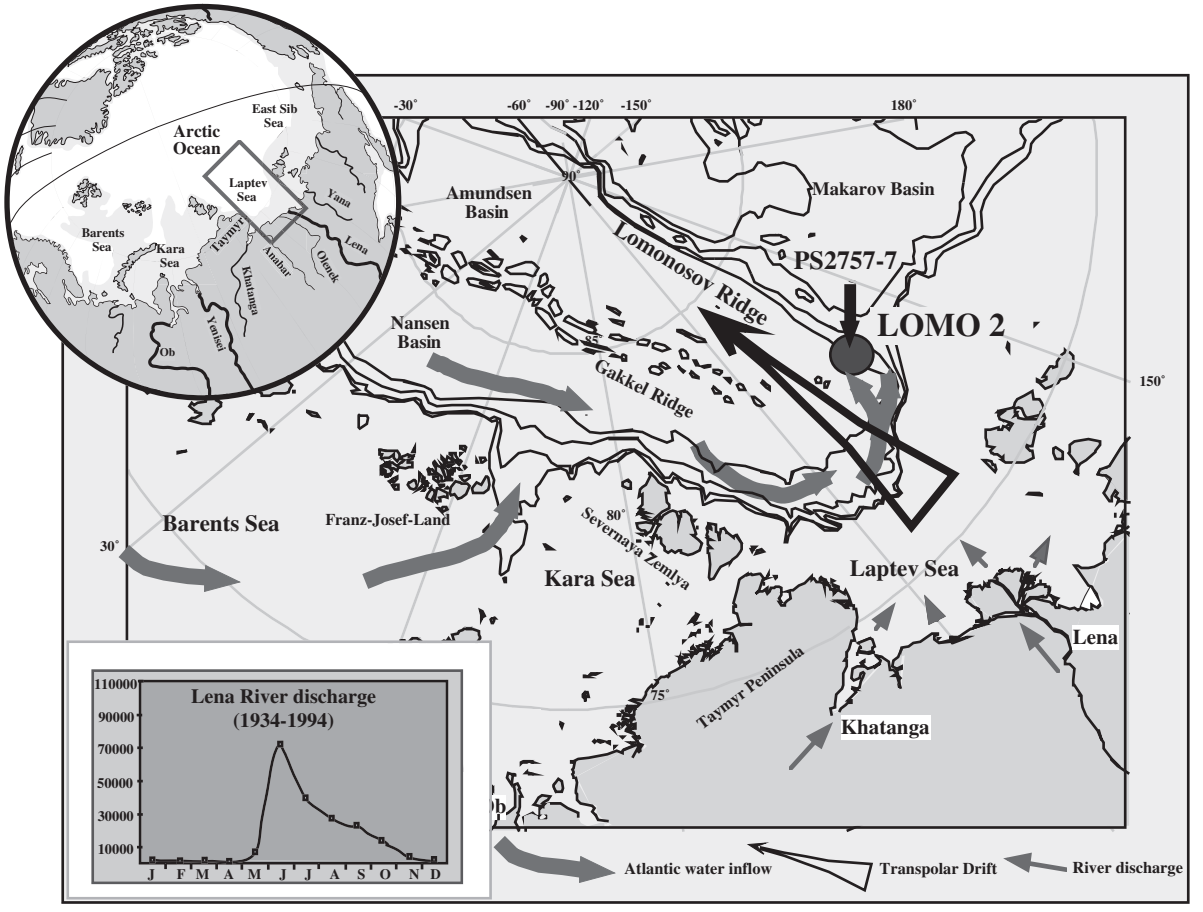

Fig. 1. Geographic map of the Eurasian part of the Arctic Ocean with the location of the moored sediment trap Lomo2. In the lower left corner, the annual variability of Lena river discharge is shown (http://www.R-ArcticNET.sr.unh.edu).

the organic matter (here by biogeochemical bulk parameters and biomarkers) will give information about processes controlling export, degradation, and accumulation of the organic substances.

2. Material and methods

During the "Polarstern" Expedition ARK-XI/1 in 1995 (Rachor, 1997) a long-term mooring system with two cone-shaped multi-sampling traps (SMT 230 K.U.M.; sampling area 0.5 m^2) was deployed at the almost permanently ice-covered western slope of the Lomonosov Ridge (Fig. 1, Table 1, Lomo2; 81°04.5′N, 138°54.0′E, 1712 m water depth; Daranall and Rudels, 1997). One trap was installed at 150 m below the sea surface and the other at 150 m above bottom at 1550 m depth. The total mass, POC, opal, and $CaCO_3$ fluxes (Figs. 2a–d and Table 3) and sterol and fatty acid fluxes (Fig. 3 and Table 4) were measured for the period from September 1995 to August 1996.

The 20 collecting cups were filled with sterile filtered North Sea water made up to a salinity of 40 with NaCl and poisoned with $HgCl_2$. After recovery the samples were stored at temperatures below 10°C before analysis (ca. 4 months). Samples were split wet into aliquots after Fischer and Wefer (1991).

Table 1
Sampling interval of the sediment trap Lomo2 (81°04.5′N, 138°54.0′E)

150–1550 m	Start	End	Duration (days)
Sept. 95/2	15.09.1995	30.09.1995	15
Oct. 95/1	30.09.1995	15.10.1995	15
Oct. 95/2	15.10.1995	30.10.1995	15
Nov. 95/1	30.10.1995	14.11.1995	15
Nov. 95/2	14.11.1995	29.11.1995	15
Dec. 95/1	29.11.1995	14.12.1995	15
Dec. 95/2	14.12.1996	01.01.1996	18
Jan. 96	01.01.1996	01.02.1996	31
Feb. 96	01.02.1996	01.03.1996	29
March 96/1	01.03.1996	16.03.1996	15
March 96/2	16.03.1996	01.04.1996	16
April 96/1	01.04.1996	16.04.1996	15
April 96/2	16.04.1996	01.05.1996	15
May 96/1	01.05.1996	15.05.1996	14
May 96/2	15.05.1996	01.06.1996	17
June 96/1	01.06.1996	16.06.1996	15
June 96/2	16.06.1996	01.07.1996	15
July 96/1	01.07.1996	16.07.1996	15
July 96/2	16.07.1996	01.08.1996	16
Aug. 96/1	01.08.1996	16.08.1996	15

Subsamples for total dry weight (DW), POC, $CaCO_3$, opal, and biomarker (lipid) analyses were taken from each cup and analyzed according to the methods listed in Table 2. We did not correct the fluxes for dissolution in the sampling cups after particle collection (Bauerfeind, 2004). Thus, these fluxes shown here are minimum values.

In order to get information on the proportion of marine organic carbon we use the diatom-specific fatty acids *cis*-9-hexadecenoic acid ($C_{16:1(n-7)}$), *cis*-11-hexadecenoic acid ($C_{16:1(n-5)}$), and all-*cis*-5,8,11,14,17-eicosapentaenoic acid ($C_{20:5(n-3)}$) for interpretation (Kates and Volcani, 1966; Ackman et al., 1968; Kattner et al., 1983; Fahl and Kattner, 1993; Graeve et al., 1994). All fatty acid components up to carbon chain length of 22 were determined in this study, however, and the data are available on doi:10.1594/PANGAEA.602289. The short-chain *n*-alkanes, which are also stated to be of marine origin (Blumer et al., 1971; Prahl and Muehlhausen 1989), and the corresponding long-chain components, indicating a terrigenous organic carbon source (Nichols et al. 1984; Prahl and Muehlhausen 1989; Yunker et al. 1995), occur only in trace amounts in the samples. In order to estimate the relevance of "terrestrial input" campesterol (24-methylcholest-5-en-β-ol) and β-sitosterol (24-ethylcholest-5-en-3β-ol), synthesized by higher plants (e.g. Huang and Meinschein 1976; Volkman 1986), were used.

All data are available in the data bank PANGAEA (doi:10.1594/PANGAEA.602289).

3. Results and discussion

The Lomonosov Ridge, crossing the Arctic Ocean from Greenland to the New Siberian Islands and separating the Eurasian and Amerasian basins, underlies an area with nearly permanent ice cover. Satellite passive microwave ice concentration data show that the southern Lomonosov Ridge, close to the Eurasian continental margin, is generally covered by more than 95% ice during most of the season, and even during summer ice concentration remains above 90% (Haas and Eicken, 2001). Sea-ice cover in the study area, however, shows a distinct interannual variability, and sometimes ice-free areas occur (Comiso, 2002; Comiso and Parkinson, 2004; Bareiss and Görgen, 2005). Because of the extensive sea-ice cover and light limitation, primary production is restricted to a period of about 3 months during summer (Sakshaug, 2004).

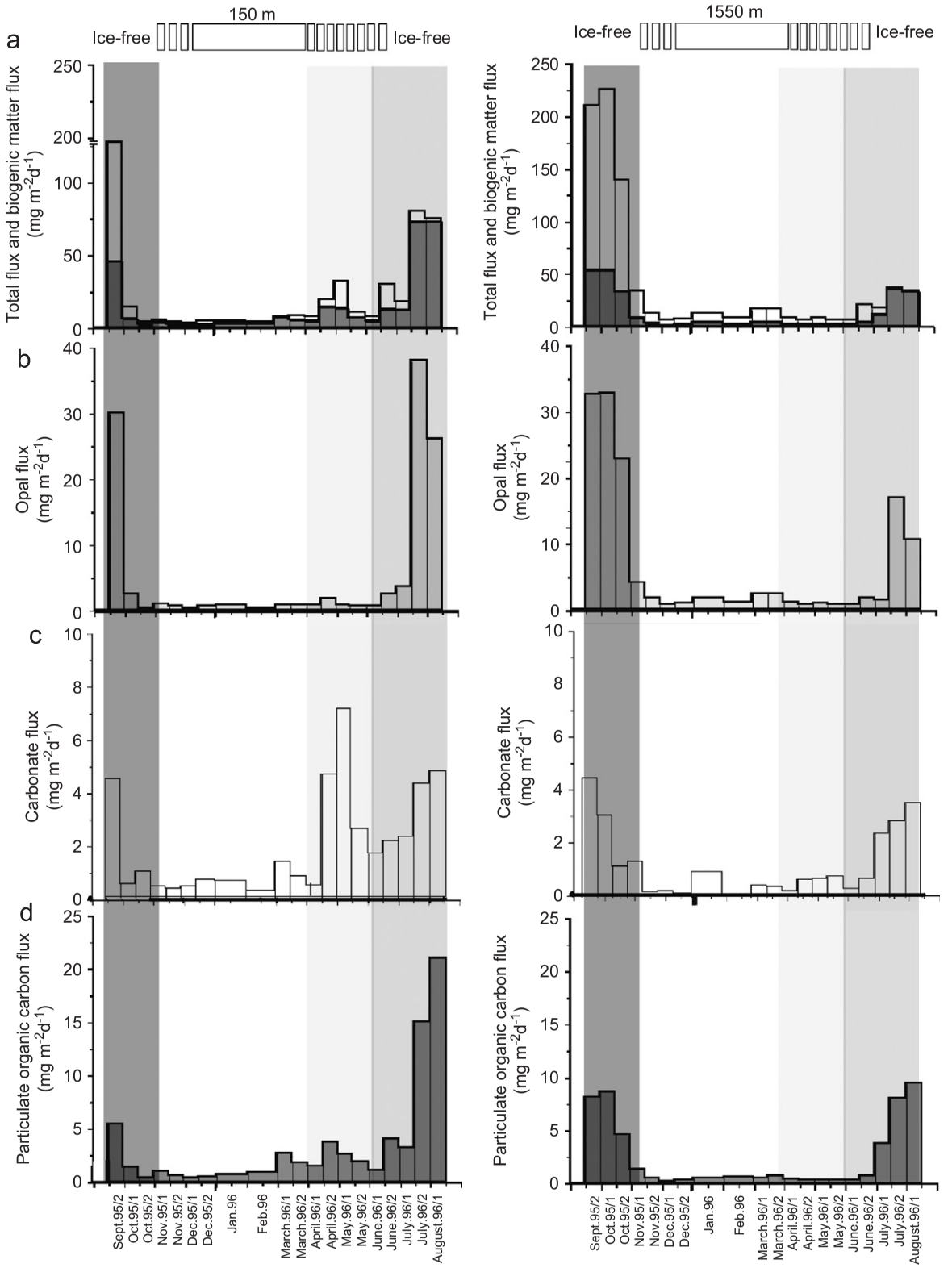

Fig. 2. Daily fluxes of total mass and biogenic matter (a), opal (b), $CaCO_3$ (c), and POC (d) from September 1995 to August 1996 (given in $mg\,m^{-2}\,d^{-1}$) at 150 m (left figure) and 1550 m (right figure) depth on the Lomonosov Ridge. The different seasonal periods are marked (dark-grey: *lithogenic phase*, light-grey: *biogenic phase*, white: *winter phase*).

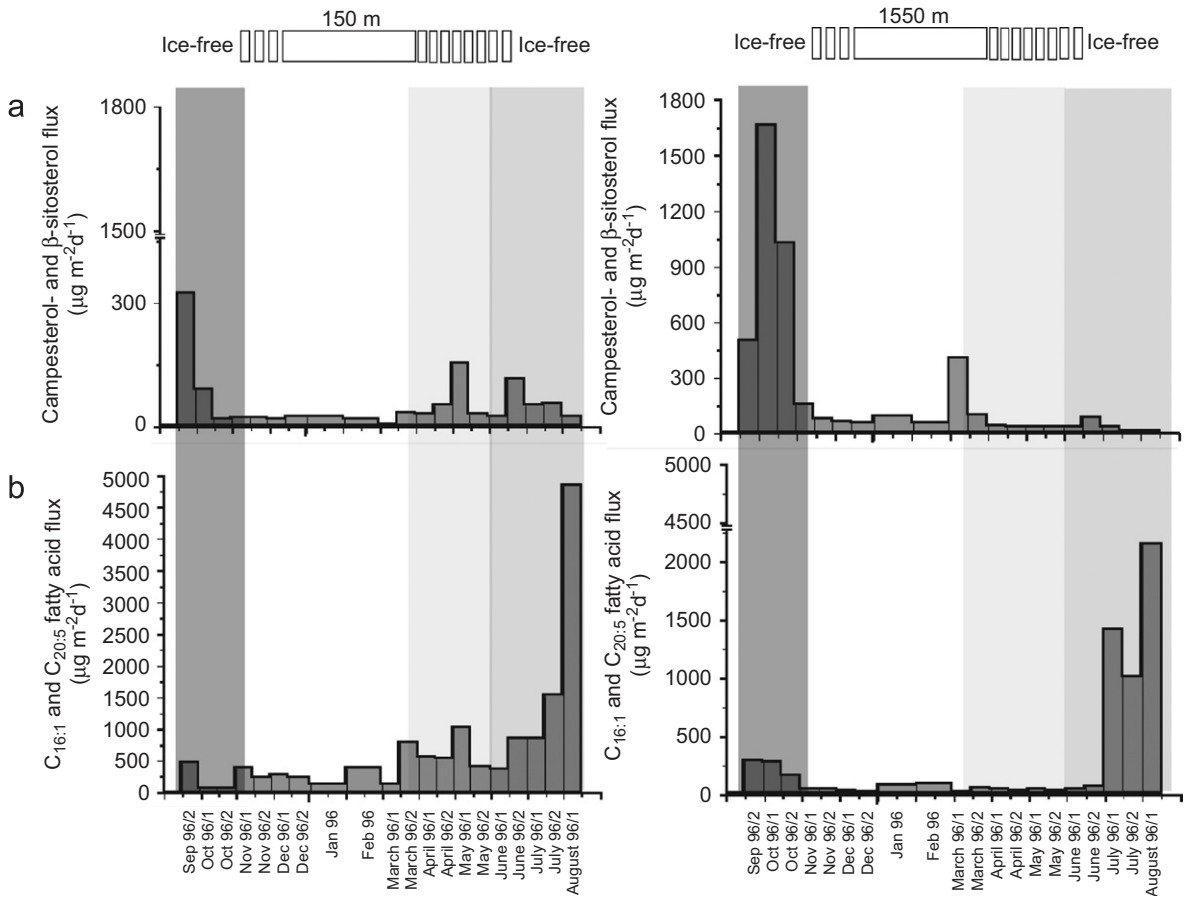

Fig. 3. Daily fluxes of the sum of campesterol and β-sitosterol (a) and the sum of $C_{16:1(n-7)}$, $C_{16:1(n-5)}$, and $C_{20:5(n-3)}$ (b) from September 1995 to August 1996 (given in $\mu g\,m^{-2}\,d^{-1}$) at 150 m (left figure) and 1550 m (right figure) depth on the Lomonosov Ridge. The different seasonal periods are marked (dark-grey: *lithogenic phase*, light-grey: *biogenic phase*, white: *winter phase*).

Table 2
Material and methods used to obtain the data (including references containing descriptions of the methods applied)

	Parameter	Technique	Reference
Biogeochemical bulk parameter	Total mass (total dry weight)	Weighing	von Bodungen et al. (1991)
	Biogenic matter	Calculation Biogenic matter = 2 × POC + $CaCO_3$ + Opal (Opal = 2.1 × bPSi)	von Bodungen et al. (1991)
	Lithogenic matter	Calculation (total matter-biogenic matter)	Modified after
	Opal	Wet-alkaline digestion	von Bodungen et al. (1991)
	$CaCO_3$	Mass loss by acidification and weighing	von Bodungen et al. (1991)
	POC	Heraeus CHN-analyzer	von Bodungen et al. (1991)
Phytoplankton	Taxa	Microscopy	Zernova et al. (2000)
	Abundances	Calculation	Zernova et al. (2000)
Biomarker	Sterols	Gas chromatography/mass spectrometry	Fahl et al. (2003)
	Fatty acids	Gas chromatography	Fahl et al. (2003)

Table 3
Daily fluxes of total mass, biogenic and lithogenic matter, opal, carbonate, and POC from September 1995 to August 1996 (given in mg $m^{-2} d^{-1}$) and corresponding annual fluxes (given in g $m^{-2} y^{-1}$) at 150 m depth from sediment trap Lomo2 (a), daily fluxes of total mass, biogenic and lithogenic matter, opal, carbonate, and POC (given in mg $m^{-2} d^{-1}$) and corresponding annual fluxes (given in g $m^{-2} y^{-1}$) at 1550 m depth (b), and percentages of the fluxes of total mass flux at 150 m and 1550 m depth, respectively (c)

	Total mass (mg $m^{-2} d^{-1}$)	Biogenic (mg $m^{-2} d^{-1}$)	Lithogenic (mg $m^{-2} d^{-1}$)	Opal (mg $m^{-2} d^{-1}$)	$CaCO_3$ (mg $m^{-2} d^{-1}$)	POC (mg $m^{-2} d^{-1}$)
(a) *150* m						
Sept. 95/2	127.70	45.45	82.24	30.03	4.49	5.47
Oct. 95/1	13.89	5.91	7.98	2.52	0.58	1.41
Oct. 95/2	3.59	2.16	1.42	0.42	1.01	0.37
Nov. 95/1	5.37	3.44	1.93	1.05	0.48	0.95
Nov. 95/2	3.55	2.06	1.49	0.63	0.38	0.52
Dec. 95/1	2.70	1.57	1.12	0.42	0.50	0.33
Dec. 95/2	4.41	2.32	2.09	0.63	0.73	0.48
Jan. 96	4.68	2.89	1.79	0.84	0.69	0.68
Feb. 96	3.97	2.52	1.45	0.42	0.31	0.89
March 96/1	7.63	7.56	0.08	0.84	1.43	2.64
March 96/2	8.36	5.28	3.08	0.84	0.84	1.80
April 96/1	7.60	4.24	3.36	0.84	0.51	1.45
April 96/2	19.61	13.87	5.74	1.89	4.64	3.67
May 96/1	32.09	13.12	18.98	0.84	7.11	2.58
May 96/2	10.27	7.03	3.24	0.63	2.65	1.87
June 96/1	7.51	4.56	2.95	0.63	1.69	1.12
June 96/2	29.42	12.75	16.67	2.52	2.18	4.03
July 96/1	18.10	12.21	5.89	3.57	2.35	3.14
July 96/2	80.34	72.41	7.93	38.01	4.33	15.03
Aug. 96/1	74.52	72.82	1.70	26.04	4.77	21.00
Annual flux (g $m^{-2} y^{-1}$)	10.3	6.4	3.9	2.6	0.8	1.5
(b) *1550* m						
Sept. 95/2	209.74	53.16	156.58	32.55	4.48	8.07
Oct. 95/1	225.87	52.96	172.91	32.76	3.04	8.58
Oct. 95/2	139.54	33.17	106.38	22.89	1.16	4.56
Nov. 95/1	33.47	8.24	25.23	4.20	1.34	1.35
Nov. 95/2	12.82	3.11	9.71	1.89	0.19	0.52
Dec. 95/1	5.72	1.54	4.18	0.84	0.21	0.25
Dec. 95/2	7.72	1.87	5.85	1.05	0.16	0.33
Jan. 96	12.90	3.92	8.98	1.89	0.94	0.55
Feb. 96	8.50	2.52	5.98	1.26	0.09	0.58
March 96/1	16.41	3.98	12.43	2.52	0.43	0.51
March 96/2	16.55	4.30	12.25	2.52	0.37	0.70

Table 3 (*continued*)

	Total mass ($mg\,m^{-2}\,d^{-1}$)	Biogenic ($mg\,m^{-2}\,d^{-1}$)	Lithogenic ($mg\,m^{-2}\,d^{-1}$)	Opal ($mg\,m^{-2}\,d^{-1}$)	$CaCO_3$ ($mg\,m^{-2}\,d^{-1}$)	POC ($mg\,m^{-2}\,d^{-1}$)
April 96/1	8.07	2.25	5.82	1.26	0.24	0.38
April 96/2	6.03	2.03	4.00	0.84	0.66	0.26
May 96/1	8.26	2.44	5.83	1.05	0.70	0.34
May 96/2	6.76	2.26	4.50	0.84	0.75	0.34
June 96/1	6.04	1.71	4.33	0.84	0.31	0.28
June 96/2	20.34	4.01	16.33	1.89	0.67	0.73
July 96/1	17.41	11.45	5.96	1.47	2.39	3.80
July 96/2	37.25	35.94	1.31	17.01	2.85	8.04
Aug. 96/1	33.62	33.06	0.56	10.71	3.53	9.41
Annual flux ($g\,m^{-2}\,y^{-1}$)	16.7	5.5	11.3	2.9	0.5	1.05

(c)	150 m				1550 m			
	Lithogenic flux (%)	Opal flux (%)	$CaCO_3$ flux (%)	POC flux (%)	Lithogenic flux (%)	Opal flux (%)	$CaCO_3$ flux (%)	POC flux (%)
Sept. 95/2	64.4	23.5	3.5	4.3	74.7	15.5	2.1	3.9
Oct. 95/1	57.5	18.1	4.2	10.1	76.6	14.5	1.3	3.8
Oct. 95/2	39.7	11.7	28.0	10.3	76.2	16.4	0.8	3.3
Nov. 95/1	36.0	19.6	8.9	17.8	75.4	12.6	4.0	4.0
Nov. 95/2	42.0	17.8	10.8	14.7	75.7	14.8	1.5	4.0
Dec. 95/1	41.7	15.6	18.4	12.2	73.2	14.7	3.6	4.3
Dec. 95/2	47.4	14.3	16.5	10.9	75.8	13.6	2.0	4.3
Jan. 96	38.3	18.0	14.7	14.5	69.6	14.7	7.3	4.2
Feb. 96	36.5	10.6	7.9	22.5	70.3	14.8	1.1	6.9
March 96/1	1.0	11.0	18.8	34.6	75.8	15.4	2.6	3.1
March 96/2	36.9	10.1	10.0	21.5	74.0	15.2	2.2	4.2
April 96/1	44.2	11.1	6.6	19.0	72.1	15.6	3.0	4.7
April 96/2	29.3	9.6	23.6	18.7	66.4	13.9	11.0	4.4
May 96/1	59.1	2.6	22.2	8.0	70.5	12.7	8.5	4.1
May 96/2	31.6	6.1	25.8	18.3	66.5	12.4	11.0	5.0
June 96/1	39.3	8.4	22.5	14.9	71.8	13.9	5.2	4.6
June 96/2	56.7	8.6	7.4	13.7	80.3	9.3	3.3	3.6
July 96/1	32.6	19.7	13.0	17.4	34.2	8.4	13.7	21.8
July 96/2	9.9	47.3	5.4	18.7	3.5	45.7	7.7	21.6
Aug. 96/1	2.3	34.9	6.4	28.2	1.7	31.9	10.5	28.0

Note: Biogenic matter $= 2 \times POC + CaCO_3 + Opal$, see Table 2.

3.1. Annual fluxes

Annual fluxes of lithogenic matter, $CaCO_3$, opal, and POC were 3.9, 0.8, 2.6 and 1.5 $g\,m^{-2}\,y^{-1}$, respectively, at 150 m and 11.3, 0.5 and 2.9, 1.05 $g\,m^{-2}\,y^{-1}$, respectively, at 1550 m (Table 3), indicating a clear dominance of lithogenic matter in both traps. The lithogenic character of the sedimentary material is pronounced in the entire central Arctic Ocean and is due to the high input of terrigenous matter by the Eurasian and Amerasian rivers and the relatively low primary production. Because of the restricted "growth period," the food web is highly developed; most of the carbon produced by the phytoplankton is effectively grazed down by zooplankton. Detritus and faeces are also effectively recycled in the upper water column (Grahl et al., 1999). Carbonate is of minor importance, as documented in the Laptev Sea and Lomonosov Ridge sediments, where carbonate contents are between 0 and 3 and $<10\%$, respectively (Stein et al., 1994; Stein, 1996). In summary, the central Arctic Ocean seems to be a "terrigenous, low-productivity ocean."

The flux of organic carbon on the Lomonosov Ridge is similar to the fluxes found in the seasonally ice-covered Greenland Sea (Noji et al., 2001; Peinert et al., 2001; Peinert and Noji, 2004) but up to nine times lower than fluxes determined in the southern Kara (Gaye et al., submitted) and Beaufort Seas (Moran, 2004; O'Brien et al., 2006). The latter fluxes are large because of the river discharge in these regions (Table 5). In the permanently ice-covered, very low-productivity region north of the Canadian Archipelago, the lowest vertical flux values ever measured in the ocean were found in sediment traps deployed from large ice floes ("Canadian Ice Islands") (Hargrave, 2004; Table 5). Flux values obtained from the western part of the Weddell Sea (Antarctic) are 10 times higher than those determined on the Lomonosov Ridge (Fischer et al., 2003; Table 5).

3.2. Seasonal variability

Our data from the long-term sediment traps representing the time interval from September 1995 to August 1996 reflect seasonality in all measured and calculated parameters. We can distinguish three different periods during the year: first, a period characterized by low productivity, low fluxes and extensive sea-ice cover (second half of November–March; *Winter phase*); second, a period characterized by ice-melting, ice-free conditions and high biogenic matter flux (April–August; *Biogenic phase*); and third, a period characterized by ice-free conditions and highest lithogenic matter flux (September–end of October; *Lithogenic phase*). These characteristics are obvious in both the shallow (150 m) and the deep (1550 m) trap, although flux values and particle composition are somewhat different in the two traps.

3.2.1. Winter phase (second half of November–March)

In general, the fluxes are fairly low at both 150 and 1550 m depth during the ice-covered winter months. The average total mass flux is less than 10 $mg\,m^{-2}\,d^{-1}$, with POC, opal and $CaCO_3$ fluxes $<2\,mg\,m^{-2}\,d^{-1}$ (averages calculated from Table 3). The average lithogenic proportion is much higher at 1550 m (8.5 $mg\,m^{-2}\,d^{-1}$; 74% of total mass flux) than at 150 m (1.6 $mg\,m^{-2}\,d^{-1}$; 31% of total mass flux) water depth, suggesting an additional, lateral input at 1550 m. The existence of the lateral input is also supported by the downward-increasing fluxes of the land-derived terrigenous biomarkers campesterol and β-sitosterol (Tables 4 and 5). The fluxes of POC and the relatively labile fatty acids, on the other hand, are lower in the deep trap because of degradation. The typical fast degradation of the lipid compounds, which are labile because their molecular structures include one or more double bonds (here the monounsaturated fatty acids $C_{16:1(n-7)}$ and $C_{16:1(n-5)}$, and the polyunsaturated $C_{20:5(n-3)}$ fatty acid), is also described by Wakeham et al. (1997) for sedimentary records from the Pacific.

Microscopic investigation of the trapped material shows mostly detritus agglomerates containing diatoms, debris and empty valves of the diatoms *Fragilariopsis oceanica*, *Melosira arctica, Nitzschia frigida*, and *Chaetoceros radiatus. C. radiatus* is frequently predominant in the shallow trap at 150 m depth (Zernova et al., 2000). *C. radiatus* and *Chaetoceros furcellatus* and *Chaetoceros* resting spores were probably entrained into the sea ice during its formation on the Laptev Sea shelf and transported with the Transpolar Drift to the Lomonosov Ridge. The other above-mentioned diatom species are thought to belong to the sub-ice communities or to be pelagic (Table 6, Zernova et al., 2000).

In general, we found a typical winter situation from the end of November to March due to the permanent sea-ice cover and light limitation. For

Table 4
Daily fluxes of the sum of campesterol and β-sitosterol and the sum of $C_{16:1(n-7)}$, $C_{16:1(n-5)}$, and $C_{20:5(n-3)}$ from September 1995 to August 1996 (given in $\mu g\,m^{-2}\,d^{-1}$) and corresponding annual fluxes (given in $mg\,m^{-2}\,y^{-1}$) in 150 m and 1550 m sediment traps at Lomo2

	150 m Campesterol + β-sitosterol ($\mu g\,m^{-2}\,d^{-1}$)	$C_{16:1}+C_{20:5}$ fatty acids ($\mu g\,m^{-2}\,d^{-1}$)	1550 m Campesterol + β-sitosterol ($\mu g\,m^{-2}\,d^{-1}$)	$C_{16:1}+C_{20:5}$ fatty acids ($\mu g\,m^{-2}\,d^{-1}$)
Sept. 95/2	321.75	466.42	499.54	281.62
Oct. 95/1	89.96	52.02	1662.35	271.02
Oct. 95/2	16.89	50.11	1021.71	160.49
Nov. 95/1	21.62	373.95	155.09	40.93
Nov. 95/2	19.18	222.42	75.04	37.98
Dec. 95/1	16.44	260.26	56.16	25.00
Dec. 95/2	23.12	232.57	54.22	21.73
Jan. 96	22.82	125.80	88.49	76.70
Feb. 96	17.40	376.69	55.52	85.05
March 96/1	4.22	126.92	400.67	15.85
March 96/2	30.99	785.90	96.77	55.33
April 96/1	30.22	541.79	36.96	37.31
April 96/2	49.88	524.67	32.10	24.28
May 96/1	152.08	1028.37	32.68	42.37
May 96/2	28.99	398.84	30.27	33.21
June 96/1	24.10	356.04	28.85	35.43
June 96/2	115.79	842.93	83.36	60.32
July 96/1	50.90	853.67	28.46	1420.67
July 96/2	53.31	1527.08	5.14	1006.97
Aug. 96/1	21.75	4835.51	5.82	2147.87
Annual flux ($mg\,m^{-2}\,y^{-1}$)	22.6	304.4	77.7	130.5

Table 5
Particulate organic carbon (POC) fluxes and primary production (both given in in $g\,m^{-2}\,y^{-1}$) at other Arctic regions and other ocean areas in comparison to out data from the Lomonosov Ridge, where (a) is normalized to 133 m depth (according to Schlitzer, 2002), (b) data from Sakshaug (2004), (c) calculated after Boetius and Damm (1998)

Site	Region	Position	Depth of trap (m)	Time (month)	Vertical POC flux ($g\,C\,m^{-2}\,y^{-1}$)	Primary production ($g\,C\,m^{-2}\,y^{-1}$)	Reference
WS1	Weddell Sea	62.4°S, 34.8°W	133[a]	12	14	84	Fischer et al. (2003)
WR1	SW Africa	20.1°S, 9.2°E	133[a]	12	68	328	Fischer et al. (2003)
NEW	Fram Strait	80°N, 11°W	130	11	1.0	20–50[b]	Bauerfeind (2004)
KS	Kara Sea	74°N, 80°W	36	12	9.8	30–5[b]	Gaye et al., 2007
SS-4	Beaufort Sea	69.9°N, 138.5°W	200	12	6	30–70[b]	O'Brien et al. (2006)
CII	Canadian Ice Island	81°N, 96°W	100	9	0.07	–	Hargrave (2004)
Lomo2	Lomonosov Ridge	81°N, 139°E	150	11	1.5	18[c]	This paper
Lomo2	Lomonosov Ridge	81°N, 139°E	1550	11	1.05	18[c]	This paper

other Arctic regions the winter season occurs approximately within the same time period (Bauerfeind, 2004). In the Fram Strait, for example, freshly produced material was present in trap material during March/April (Bauerfeind, 2004), whereas in the Kara Sea the fluxes increased some weeks later in April/May with the first break-up of the ice cover and polynya formation (Gaye et al., submitted). Focusing in detail on the time interval April/May, it becomes obvious that the pronounced growth period of phytoplankton starts some time later on the Lomonosov Ridge (see Section 3.2.2). That means that the ice edge and primary production fluctuate widely in the Arctic Ocean in response to seasonal and regional changes in wind, ice production, sea-surface temperature and insolation.

Table 6
Dominant diatom composition during different phases during the year (after Zernova et al., 2000 and Nöthig unpubl. data, 1996)

Growth phases	Cells containing chloroplasts	Sub-ice algal community; *Nitzschia frigida*, *N. promare*, *Gyrosigma* spec., *Melosira arctica*	Pelagic/ice more open ocean; *Fragilariopsis oceanica*	Pelagic more shelf-associated; *Chaetoceros* spp resting spores
Winter phase	<5%	+	+	++
Biogenic phase				
Early (April/May)	About 5%	Rare	+	+++
Late (June–Aug.)	> 70%	+++	+++	+
Lithogenic phase	< 10%	Rare	++	Rare

One cross (+) indicates common with many empty valves, two crosses (++) indicate abundant, and three crosses (+++) indicate abundant in high cell numbers with intact cells.

3.2.2. Biogenic phase (April–August)

From April to August the fluxes continuously increased. Average total mass fluxes were $31\,mg\,m^{-2}\,d^{-1}$ at 150 m and $16\,mg\,m^{-2}\,d^{-1}$ at 1550 m depth (Table 3). The composition of sedimenting particles shows a dominance of biogenic matter with 24 and $11\,mg\,m^{-2}\,d^{-1}$ (76% and 66% of total mass flux) for the shallow and deep traps, respectively. The lithogenic fluxes are very similar at both depths (7 and $6\,mg\,m^{-2}\,d^{-1}$). The low lithogenic proportion of the sedimentary material correlates with the very low fluxes of the land-derived biomarkers campesterol and β-sitosterol (Table 4). The average POC fluxes are 6 and $2.5\,mg\,m^{-2}\,d^{-1}$ at 150 and 1550 m water depth, respectively. Opal fluxes decrease downwards from 8.3 to $4\,mg\,m^{-2}\,d^{-1}$ (Table 3). These decreasing opal fluxes are probably caused by dissolution (see below).

The start of algal growth occurs at the end of April to the beginning of May, dominated by the ice-associated *Nitzschia* species although in low abundances (Zernova et al., 2000). This early start of algal growth under sea-ice cover was also noted for the Laptev Sea by Okolodkov (1992), who related it to the slightly increasing insolation. Increasing diatom fluxes occur from the beginning of June, dominated by pennate diatoms (*N. frigida*, *Nitzschia promarae*, *F. oceanica*, *Gyrosigma stuxbergii*), until the end of July, with centric and pennate species (*M. arctica*, *F. oceanica*) (Zernova et al., 2000). The highest summer peak in August is caused by the pennate diatoms *F. oceanica* and *N. frigida* (Table 6). The high abundances of diatoms at 150 m depth during July/August is supported by the high fluxes of the diatom-specific fatty acids and opal. The latter reaches values up to $40\,mg\,m^{-2}\,d^{-1}$, which is almost 50% of the total mass flux during these weeks (Tables 3 and 4).

In general, the time interval from April to August is characterized by a high biogenic proportion. Lithogenic material derived from melting sea ice is of minor importance. The marine organic matter (here POC and fatty acids) undergoes degradation from 150 to 1550 m depth. Opal is partly dissolved during its sinking to the sea floor. This is also supported by the comparison of our trap data with surface sediment data from Lomonosov Ridge close to the trap location. Based on an opal content of 2% (Nürnberg, 1996) and the accumulation rate of total sediment ($48\,g\,m^{-2}\,y^{-1}$; Stein et al., 2001), opal accumulation rate is $0.96\,g\,m^{-2}\,y^{-1}$. The annual opal flux determined at 1550 m depth, on the other hand, is $2.9\,g\,m^{-2}\,y^{-1}$ (Table 3). According to Heiskanen and Keck (1996) and Nürnberg (1996), opal contents in the surface sediment decrease from the Lena River in the direction of the Lomonosov Ridge, supporting our assumption that the downward decrease in opal fluxes is caused by dissolution.

3.2.3. Lithogenic phase (September–end of October)

From September to the end of October, the highest total mass fluxes were $130\,mg\,m^{-2}\,d^{-1}$ at 150 m and $230\,mg\,m^{-2}\,d^{-1}$ at 1550 m depth (Table 3). The composition shows a dominance of lithogenic matter, with 31 and $145\,mg\,m^{-2}\,d^{-1}$ (54% and 75% of total mass flux) for the shallow and the deep trap, respectively (Table 3). This is also supported by the terrigenous biomarkers campesterol and β-sitosterol. The highest fluxes of these land-derived components occur during

these months (up to 320 and 1600 mg $m^{-2} d^{-1}$ at 150 and 1550 m, respectively; Table 4). The good correlation between the biomarker and the lithogenic matter fluxes at both depths is shown in Figs. 4a and b. In general, the fluxes at 1550 m depth are distinctly higher than at 150 m depth. This is also true for most of the biogenic compounds (see Figs. 2b, d, 3, Table 3 and 4). Average daily fluxes of POC and opal are 6 mg $m^{-2} d^{-1}$ and 11 mg $m^{-2} d^{-1}$, respectively, at the shallow trap and 8 mg $m^{-2} d^{-1}$ and 30 mg $m^{-2} d^{-1}$, respectively, at the deep trap. The $CaCO_3$ fluxes at both depths, on the other hand, are similar (2 and 2.6 mg $m^{-2} d^{-1}$ for the shallow and deep trap, respectively; Table 3), suggesting no carbonate dissolution with depth. This is in agreement with results of investigations of carbonate dissolution on planktonic foraminifera tests from the eastern central Arctic Ocean (Pagels, 1991). Based on these results, the modern lysocline of this area is at about 4700 m water depth, and carbonate dissolution seems to be negligible in shallow depths.

In summary, the terrigenous character (see Figs. 2a and 3a) of the material transported downward to the sea floor during these ice-free months is clearly pronounced. The biological production is of only minor importance during this time as, also supported by the microscopic data, which show mostly empty diatom valves at both depths (Zernova et al., 2000; Nöthig unpubl. data, 1996). These valves cause the relatively high opal fluxes (Fig. 2b), especially at 150 m depth, where the cells without chloroplasts were dominated by *M. arctica* and with chloroplasts by *F. oceanica* (Zernova et al., 2000; Table 6).

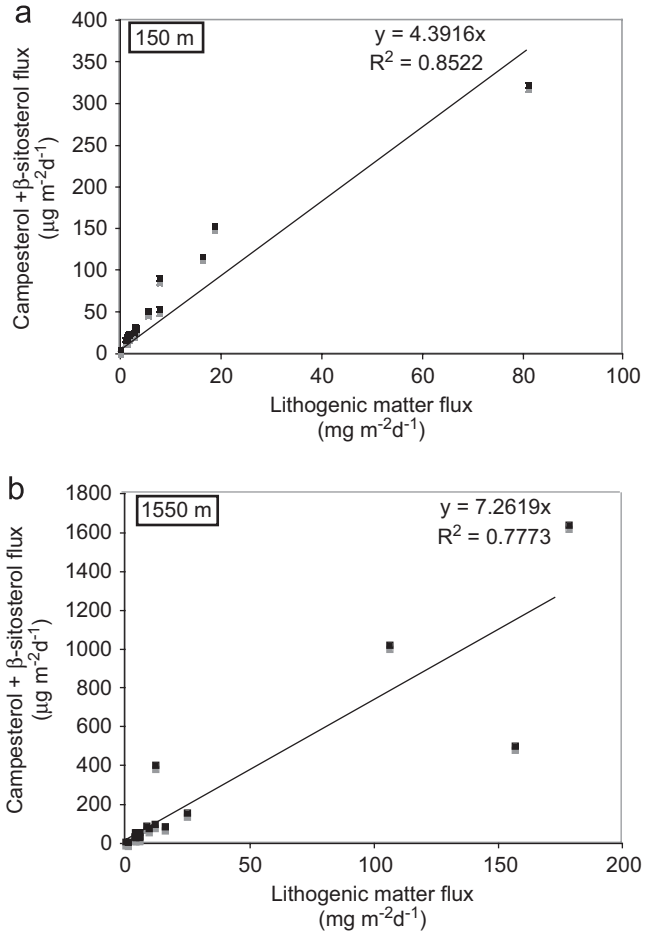

Fig. 4. Correlation between lithogenic matter flux (given in mg $m^{-2} d^{-1}$) and sum of campesterol and β-sitosterol (given in µg $m^{-2} d^{-1}$) from September 1995 to August 1996 at 150 m (a) and 1550 m (b) depth.

3.2.4. Source and transport of the lithogenic matter

A remaining question is the source the trapped terrigenous material. Focusing on 150 m depth we assume that the terrigenous particulate organic material derived from the Laptev Sea shelf (with the Lena River as a dominant source), was transported with sea ice by the Transpolar Drift to the Lomonosov Ridge. In general, the sea ice is an important transport mechanism for terrigenous organic carbon (see Section 3.1), but we have to consider that only 6% (0.18×10^6 t, Eicken, 2004) of the annual terrigenous POC input (2.74×10^6 t, where more than 70% is supplied by the Lena River; Rachold et al., 2004) is a sea-ice-associated transport from the Laptev Sea into the Arctic Ocean, whereas 30% of the input is supplied towards the interior ocean via currents, including turbidity currents (Stein and Fahl, 2004).

We now consider the possibility that the terrigenous material that is trapped at 150 m comes from ice melting in September/October can be related to the high Lena River discharge in June (Fig. 1). Because of the patchy ice conditions on the Laptev Sea shelf, greatly differing values for the ice velocity have been reported (Colony and Thorndike, 1984; Eicken et al., 1997; Rigor and Colony, 1997; Eicken et al., 2000; Martin and Augstein, 2000), but 0.1 m/s seems to be a reasonable estimate (Haas, pers. commun., 2006). Using this velocity and a distance to the Lomonosov Ridge of about 850 km, the sea-ice-associated sediments would reach the investigation area in about 3 months. This is only a rough estimate, but it seems to explain the correlation between the high terrigenous flux in the traps in September/October and the high Lena River discharge in June. Because sea ice is only one transport mechanism for the fluvial material, with only 6% of the annual terrigenous POC from the Laptev Sea being transported northward via sea ice (Eicken, 2004), we conclude that ocean currents are responsible for the transport as well. This is supported by several investigations in the Kara Sea showing that $>$ 50% fluvially derived organic carbon could be detected even in surface sediments from the central and northern Kara Sea, i.e., far away ($>$600 km) from the coast and river mouths (e.g., Krishnamurthy et al., 2001; Stein and Fahl, 2004). We have to consider, however, that no fluvially derived diatoms could be determined in the traps. This fact is supported by the Kara Sea investigation where fluvially derived diatom cells in the southern part off the Yenisey were empty or destroyed when entering the saline water (Gaye et al., submitted).

The major importance of terrigenous sediment input from the Laptev Sea for sediment accumulation on the Lomonosov Ridge is also supported on geological time scales (Stein et al, 1994, 2001, 2004; Darby et al., 1997; Nørgaard-Pedersen et al., 1998). Sedimentation rates from Late Quarternary sediments decrease from 5 cm ky^{-1} on the Lomonosov Ridge close to the Eurasian continental margin to 0.7 cm ky^{-1} near the North Pole (Stein et al, 1994, 2001), following the route of the Transpolar Drift as an important source of dirty sea ice. Based on geophysical data the thickness of the sediment cover decreases from the south to the north of the Lomonosov Ridge indicating the importance of terrigenous input even throughout the Tertiary (Jokat, 2005). In addition, mineralogical data support the transport of material from the Laptev Sea via sea ice to the Lomonosov Ridge. In this context heavy minerals seem to be a good tracer because they cannot be transported via ocean currents over such a long distance (Stein and Korolev, 1994; Behrends et al., 1999). High contents of the heavy mineral amphibole derived from the Lena River hinterland, and pyroxene originating from the Putoran Mountains, were found on the Lomonosov Ridge. Sediment transport by turbidity currents, which are important in the deep basins of the Arctic Ocean, is not thought to be important on the Lomonosov Ridge (Stein et al., 2004).

At 1550 m depth the source of the trapped material seems to be different. The order-of-magnitude higher total mass flux values (Figs. 2a and 3a), correlating with high lithogenic fluxes (Table 3) and land-derived sterol fluxes (Table 4), point to a strong influence of lateral transport at the deep trap. The most probable transport is related to the Atlantic and intermediate water layers, which may carry material from the Barents and Kara Seas along the Eurasian continental margins and recirculate northwards to the Amundsen Basin, passing the trap position (Rudels et al., 2000). Additional transport of material to the trap position within a benthic nepheloid layer (BNL), which may extend several hundred meters above the seafloor (Rutgers van der Loeff et al., 2002), and local resuspension cannot be excluded. The BNL is maintained by fine particles (e.g., clay minerals), which can be transported over very long distances (Rutgers van der Loeff et al., 2002). Unfortunately, no data on

Table 7
Basics and results from the calculation of the proportion of lateral terrigenous organic carbon flux and lateral lithogenic matter flux including data from (a) Stein et al. (2001), (b) Boucsein and Stein (2000), (c) calculated according to Betzer et al. (1984) with primary production of 18 $g C m^{-2} y^{-1}$ after Boetius and Damm (1998), and (e) Stein et al., 2004. Betzer et al. (1984) formula: Carbon flux $= 0.409 \times \text{depth}^{-0.63}$surface water productivity$^{1.41}$

Depth	Lithogenic flux	Lateral (based on lith. flux)	POC flux	Marine Maceral	Vertical Marine POCflux	Vertical terrigenous POC flux	Lateral terrigenous (based on OC)
(m)	($gC m^{-2} y^{-1}$)	($gC m^{-2} y^{-1}$)	($gC m^{-2} y^{-1}$)	(%)	($gC m^{-2} y^{-1}$)	($gC m^{-2} y^{-1}$)	($gC m^{-2} y^{-1}$)
150	3.9	?	1.5	–	1.03[c]	0.47[d]	?
1550	11.3	7.4 (65%)*	1.05	–	0.24[c]	0.47[d] (total: 0.81)	0.34 (42%)
	AR of total sediment	Additional lateral input (into the sediment)	Accumulation rate (AR)	Marine Maceral	Marine AR	Terrigenous AR	
	($gC m^{-2} y^{-1}$)	($gC m^{-2} y^{-1}$)	($gC m^{-2} y^{-1}$)	(%)	($gC m^{-2} y^{-1}$)	($gC m^{-2} y^{-1}$)	
1712	48[e]	30	0.3[a]	25[b]	0.07	0.23	

[d]Calculated with no degradation of terrigenous organic compounds.
*Under the assumption that 3.9 $gC m^{-2} y^{-1}$ is vertically transported.

the existence of a BNL at the trap location are available.

To estimate the importance of lateral transport we estimate the portion of the laterally transported lithogenic fraction and terrigenous organic carbon fraction (see Table 7). First we calculate the lateral proportion of flux based on the lithogenic flux data (Table 7). This results in a lateral transport of lithogenic material of 65%. Second, using the primary production according to Boetius and Damm (1998), the depth-dependent degradation of marine organic carbon after Betzer et al. (1984), and the measured POC flux in the trap (Table 7), we calculate the terrigenous organic carbon proportion. At the shallow trap, we do not know the exact amount of lateral transport. The relatively high proportion of terrigenous material (0.47 $g C m^{-2} y^{-1}$ or 30% of the total POC flux) cannot be explained just by melting of the sediment-laden sea ice at the trap position, because only 6% of the terrigenous POC from the Laptev Sea is from sea-ice-associated transport (Eicken, 2004). The quite high input of terrigenous matter at 150 m, however, could be caused by the release of ice-rafted sediments taking place in other regions and then lateral transport to the trap location by currents (Trimble et al., 2004; Baskaran, 2005).

At 1550 m depth we calculated the terrigenous carbon flux under the assumption that there is no degradation of the terrigenous organic carbon. This seems to be realistic because long-distance transport of material from the source (here the Laptev Sea shelf) has been found, suggesting that only the more stable terrigenous fraction reaches the Lomonosov Ridge (for discussion of degradation of terrigenous organic matter, see Ittekkot, 1988). This calculation gives a lateral transport of terrigenous organic carbon of 0.34 $g m^{-2} y^{-1}$ at 1550 m, which is 42% of the terrigenous POC flux (0.81 $g m^{-2} y^{-1}$) (Table 7). The order-of-magnitude correspondence with the laterally transported lithogenic matter supports our estimates. Considering all the assumptions used above, the calculated number should be considered a first-order estimate of lateral flux. Additionally, we show that the Betzer et al. (1984) formula for calculation of carbon flux seems to work also for the Arctic Ocean.

To show the complexity of the whole system we compared the trap data with results from near-surface sediments of Core PS2757-7 (giant box corer) taken close to the location of the sediment trap (Fig. 1; Stein et al., 2001, 2004). Based on the accumulation rates of total organic carbon, which includes the marine as well as the terrigenous proportion (Stein et al., 2001), and the microscopical investigations of the organic carbon composition (maceral data show that 25% of the carbon is marine; Boucsein and Stein, 2000), only 0.4% of the

marine organic carbon ($18\,g\,m^{-2}\,y^{-1}$, Boetius and Damm, 1998) is buried (Table 7). Focusing on the terrigenous portion of organic carbon in the sediments (75% based on maceral data) we found increasing values from the upper water column (trap data) to the sediment. Based on the assumption that the labile terrigenous organic compounds already have been degraded near the source of the material, we speculate that there must be a lateral transport of organic carbon away from the sediment surface, preventing burial of organic carbon. On the other hand, the comparison between the total sediment accumulation rate ($48\,g\,m^{-2}\,y^{-1}$; Stein et al., 2004) and the sum of lithogenic and opal fluxes at 1550 m ($14.2\,g\,m^{-2}\,y^{-1}$) shows that there must be up to $30\,g\,m^{-2}\,y^{-1}$ lateral input to the surface sediment (Table 7). This means that there must be different transport mechanisms for the accumulation of particulate organic carbon and the lithogenic fraction, even between 1550 m and the sediments surface (1712 m). One has to keep in mind, however, that the sedimentation rates are averages over long time scales while the vertical flux from the sediment traps are only 1-year measurements. Thus, the comparison carried out above, is only a rough estimate.

To solve the lateral transport issue and the problem of trapping efficiency, an additional multi-tracer approach using ^{230}Th, ^{10}Be, ^{210}Pb, and ^{231}Pa has to be used. These tracers have been widely used in marine environments to determine particle removal rates, settling velocity of particles, and export of particulate organic carbon, and they may allow to distinguish between vertical and lateral transport of particulate organic matter in more detail (e.g., Yu et al., 2001; Rutgers van der Loeff et al., 2002; Trimble et al., 2004; Baskaran, 2005). These data, however, are not yet available for the area of sediment trap Lomo2.

4. Conclusions

- We can distinguish three different periods during 1995/1996: first the low productivity, low fluxes and ice-covered winter months (second half of November–March; *Winter phase*), second the higher flux period with ice-melting and ice-free conditions and high biogenic matter flux (April–August; *Biogenic phase*), and third the highest flux period with ice-free conditions and highest lithogenic matter flux (September–end of October, *Lithogenic phase*).
- Most of the autochthonous carbon is recycled in the upper 150 m (except for the diatom event during July/August).
- The Betzer et al. (1984) formula for calculation of carbon flux seems to work also for the Arctic Ocean.
- At 1550 m depth we estimate a lateral input of 42% (based on terrigenous organic carbon) and 64% (based on lithogenic matter). In addition, sea-ice transport is of major importance.
- Accumulation on the southern Lomonosov Ridge is strongly influenced by the outflow of the Lena River, exhibiting relatively high vertical terrestrial POC export in September/October.

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