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## 2.4. The role of Arctic sea ice in transporting and cycling terrestrial organic matter

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*Introduction*

The role of sea ice in the Arctic Ocean's budget of terrestrial organic carbon (tOC) is presently not well understood. While it is obviously not a source of tOC as such, the ice cover can potentially be of great importance in providing the fastest, most effective means for basin-wide transport as well as export of tOC from the Arctic into the European Nordic (in particular Greenland and Barents) Seas. In contrast with other ocean basins, Arctic surface waters exhibit unusually high concentrations of terrestrial dissolved organic carbon (tDOC), such that the basin-scale transport of tOC is dominated by the dispersal of riverine tDOC (Opsahl et al. 1999; Lobbes et al. 2000). Whereas sea ice may have slightly elevated levels of tDOC (Thomas et al. 1995; Opsahl et al. 1999), and has been attributed with a significant fraction of the flux of tDOC out of the Arctic Basin through Fram Strait, it is of much greater importance for the transport of particulate organic matter.

Evidence has accumulated over the past two decades demonstrating that entrainment of sediments into sea ice (at particulate concentrations of tens to hundreds of mg $l^{-1}$) is a common phenomenon in the Arctic and particularly widespread over the broad, shallow Eurasian shelves (e.g., Reimnitz et al. 1994; Pfirman et al. 1997; Eicken et al. 2000). Terrestrial particulate organic matter (tPOM) deposited on the shelves may thus potentially be removed and transported over large distances with sea ice moving with the Transpolar Drift away from the Siberian Arctic across the Pole and into the Greenland Sea (Pfirman et al. 1997). Given that the flux of tPOM into the central Arctic and the Nordic Seas is greatly limited due to the inefficiency of transport in the water column and the bathymetric isolation of the central basins from shelf-slope transport, sea ice input could thus even come to dominate the total flux of tPOM in the inner Arctic and Greenland and Barents Seas. Studies of modern sediment transport (Pfirman et al. 1990; Hebbeln and Wefer 1991; Reimnitz et al. 1993b; Eicken et al. 2000) together with interpretation of the sediment record (Bischof and Darby 1997; Nørgaard-Pedersen et al. 1998), suggest that sediments released from sea ice account for a major fraction of the

Holocene sedimentation in the deep Arctic Ocean and the Greenland Sea. Hence, in the context of the (terrestrially-derived) carbon budget of the Arctic Ocean, sea ice has to be considered as a most efficient means of redistributing tPOM over large distances in short periods of time. For the regional budgets of tPOC in different sectors of the Arctic, the ice cover can hence serve as a potentially important, yet mostly overlooked, sink or source function. This problem is highlighted by a recent study of the carbon budget of the Mackenzie shelf by Macdonald et al. (1998), which identified the sea-ice associated carbon and particulate fluxes as one of the key unknowns in the system. In this contribution, we will briefly review the magnitude of sea-ice transport of dissolved and particulate terrestrial organic matter and attempt an assessment of its importance as a redistributor of tOC.

*Methods*

While measurements of organic carbon parameters reported below have generally been obtained using standard methods (for details, see Naidu et al. 2000, for stable-isotope measurements, Reimnitz et al. 1993a, for sedimentological analysis, Stein et al. 1999, and Lindemann 1999, for kerogen microscopy and pyrolysis, and Wheeler et al. 1997, for measurements of dissolved organic carbon), the sampling process differs substantially from standard oceanographic or sediment-core analysis. With the exception of surface aggregations of sediments, typically occurring as a result of melt (Nürnberg et al. 1994), sampling of the dissolved and particulate load of sea ice requires coring with specialized equipment (see Eicken et al. 1995, for detailed description of methodology and overview of standard ice-core parameters). Measurements of DOC on melted cores require special precautions to minimize contamination (Thomas et al. 1995). The particulate matter is typically concentrated through filtration, preferably in a laminar-flow, clean-bench (Reimnitz et al. 1993a; Lindemann 1999). Further sample processing can then proceed as with other standard sediment samples.

Assessments of transport of materials by ice also require estimates of the ice volume fluxes which are mostly determined through one or a combination of the following: drifting buoy data (Rigor and Colony 1997; Pfirman et al. 1997), satellite remote-sensing data (Thomas and Rothrock 1993; Alexandrov et al. 2000), and modelling (Alexandrov et al. 2000). Recently, progress has also been made in identifying and mapping the distribution of sediment-laden ice using satellite remote-sensing techniques (for details see, Reimnitz et al. 1993b; Kolatschek 1998; Eicken et al. 2000).

*Sea ice transport in the Arctic Ocean and entrainment of particulate matter*

Summarizing direct measurements, remote sensing and modelling, Figure 2.4.1

shows the net export of sea ice from the marginal seas into the Arctic Ocean and the export through Fram Strait into the Greenland Sea. With the wind-driven Beaufort Gyre dominating circulation in the North American Arctic as well as the Chukchi and eastern East Siberian Seas (Proshutinsky and Johnson 1997), the latter regions contribute on average only small amounts of exported first-year ice to the ice budget of the Arctic Ocean. In contrast, the other main wind-driven circulation feature of the Arctic Ocean, the Transpolar Drift, results in an average export of more than 1000 $km^3$ of first-year ice from the Laptev, western and central East Siberian and Kara Seas (Proshutinsky and Johnson 1997, Alexandrov et al. 2000).

A major fraction of this ice forms during fall and the early stages of winter over the broad Siberian shelves in comparatively shallow water of mean depths around 50 m in the Laptev and East Siberian Seas (Figure 2.4.2; Timokhov 1994). Tidal and wind mixing during fall freeze-up as well as thermohaline mixing associated with rapid ice growth and brine rejection promote the resuspension of sediments (Sherwood 2000) from the seafloor and furthermore enhance the rate of formation of frazil ice in the water column (Smith et al. 1990). The combination of these processes results in the entrainment of substantial amounts of resuspended particulate matter into the newly formed ice (Figure 2.4.2 and 2.4.3; Pfirman et al. 1990; Reimnitz et al. 1993b, Eicken et al. 2000). While other processes such as anchor ice formation, deposition of river sediments onto a flooded fast ice cover and aeolian deposition may also contribute to the particulate load, the process of suspension freezing, though not at all well understood, appears to be the most significant contributor to the phenomenon of sediment-laden sea ice in the North American and Siberian Arctic (Osterkamp and Gosink 1984; Reimnitz et al. 1993a; Dethleff et al. 1993; Eicken et al. 2000). Shipboard observations and satellite remote sensing have established in recent years that the entrainment of particulates into sea ice is a widespread phenomenon in the Arctic and that ice-rafting of particulates figures prominently in the overall sediment budget of the Arctic Ocean. While a detailed analysis of the processes controlling entrainment and export of particulates is beyond the scope of this contribution, we will examine in more detail how sea-ice transport contributes to the redistribution and regional supply of tOC, both, in dissolved and particulate form.

*Dissolved organic carbon in sea ice*

Most ionic species dissolved in seawater are too large to be incorporated into the crystal lattice of ice (Ih) as a solid solution (Weeks and Ackley 1986). Thus, as a result of solute segregation at the ice-water interface, only between 15 and 30 % of the salt contained in seawater is actually retained in the corresponding volume of newly grown ice, mostly in the form of sub-millimeter brine inclusions (Weeks and Ackley 1986). Further desalination during ice growth and melt can reduce the salinity of sea ice to

values well below 10 % of that of seawater. While one would expect the same to hold true for dissolved organic molecules which are subject to similar constraints with regards to size and charge balance, little work has been done on the segregation of DOM during ice growth. Studies of the partitioning of glucose between growing ice and the parent solution indicate that solute concentrations in the ice range between <1 and 20 % of that in the liquid (Miyawaki et al. 1998). Experiments by Amon (this volume) and Giannelli et al. (2001) indicate that the bulk of the DOM fraction is expulsed from the ice along with the salt. Thus, it appears reasonable to assume that sea ice is not a particularly effective transport medium for (t)DOC. If the entrained DOC fraction in sea ice were to scale with the inorganic ionic fraction (which is reduced to mean salinities of about 2, Eicken et al. 1995), the concentrations of entrained DOC in sea ice of the Arctic Basin should be lower by about a factor of 15 than those in the source areas. The few data available on concentrations of DOC in sea ice suggest that this holds true (Thomas et al. 1995; Opsahl et al. 1999), although sea-ice biota may accumulate and release DOC, thereby complicating the picture (Thomas et al. 1995). Nevertheless, this is likely to affect only the marine and not the terrestrially derived DOC pool in the ice (Amon et al. 2001, Lobbes et al. 2000).

With average concentrations of tDOC of approximately 60 to 70 $\mu$M in the Siberian shelf seas (Kattner et al. 1999), concentrations in first-year sea ice would be on the order of 12 $\mu$M, if the segregation and drainage of tDOC were to parallel that of salt (with first-year ice salinities of about 6, Weeks and Ackley 1986). With further desalination reducing salinities to on average 2 in the central Arctic (Eicken et al. 1995), concentrations would drop to 4 $\mu$M. This corresponds reasonably well with a measurement on multiyear ice sampled in Fram Strait which contained between 5.4 and 7.5 $\mu$M tDOC (Opsahl et al. 1999). Given that maximum tDOC concentrations of 550 $\mu$M are found near the estuaries and deltas (Lobbes et al. 2000), the fate of ice forming in waters affected by river plumes of, e.g., Lena, Ob, Yenissey or the Mackenzie is of particular importance. A major fraction of the coastal sea ice over the Siberian and Beaufort Sea shelves becomes landlocked in fall. After the ice breaks up in summer it melts in place in most years, rather than being exported into the interior Arctic (Dean et al. 1994, Rigor and Colony 1997). Hence, the ice with the highest concentrations of tDOC does not contribute substantially to export from the shelf.

Based on the ice volume fluxes summarized in Figure 2.4.1 and average tDOC concentrations of 12 and 4 $\mu$M in first- and multi-year sea ice, respectively, the sea-ice flux of tDOC has been estimated for the different sectors of the Arctic Ocean and summarized in Table 2.4.1. It is assumed that export through Fram Strait balances import from the shelves and that the reduction in tDOC concentrations in the ice is adequately described by the reduction in bulk ice salinity. In comparison with other terms in the Arctic Ocean's DOC budget, such as the total annual river input of 23 Tg $yr^{-1}$ (Wheeler et

al. 1997), sea-ice transport is of little to no significance.

While of little apparent quantitative importance, sea ice may still play an important role in the cycling of tDOC in the Arctic Ocean. Dissolved and particulate impurities entrained in first-year ice tend to be concentrated in the surface layers of the ice during subsequent years as a result of surface melt (Weeks and Ackley 1986; Nürnberg et al. 1994; Eicken et al. 2002; Figure 2.4.2). Hence, tDOC entrained into sea ice is subjected to much higher time-integrated levels of shortwave radiation (incl. UV) and potentially also photochemically produced oxidants than the same compounds transported in the water column. While little is known about photochemical degradation of DOM under such conditions in the ice cover (Sydnes 1991, Amon, this volume), sea-ice entrainment may thus provide a unique reactive pathway for the breakdown and modification of DOM in the marine system. Moreover, such photodegradation is also likely to affect the bioavailability of DOM to sea-ice organisms (Thomas et al. 1995, Bussmann 1999; see also discussion further below).

*Table 2.4.1. Sea-ice associated fluxes of terrigenous dissolved organic carbon (tDOC) into the Arctic Ocean region*

| Region | Ice volume flux, $km^3\ yr^{-1}$ | Flux of tDOC, $Tg\ yr^{-1}$ |
|---|---|---|
| *Export to interior Arctic Ocean by first-year ice from shelves* | | |
| Chukchi & Beaufort Sea | 20 | 0.003 |
| East Siberian Sea | 150 | 0.019 |
| Laptev Sea | 670 | 0.087 |
| Kara Sea | 240 | 0.031 |
| Barents Sea | 35 | 0.004 |
| *Export with multi-year ice through Fram Strait* | | |
| Arctic Ocean export | –2850 | –0.12 |
| *Net balance (input to Arctic Ocean)* | | |
| Arctic Ocean input | | 0.024 |

*Particulate organic carbon in sea ice*

As described above, ice growth in well-mixed shallow waters, in particular over the broad Siberian shelves, can result in the entrainment of high concentrations of suspended particulate matter (SPM) into the ice cover (Figure 2.4.2 and 2.4.3). Here, we will assess whether the transfer of organic carbon of terrestrial origin associated with these ice-entrained sediments represents a significant contribution to the tOC flux through the Arctic Ocean. While marine POC may also be present in sea ice in higher concentrations (both from ice biota as well as POC associated with marine sediments), we will exclusively focus on the tOC component associated with the particulate load.

Quantifying the sediment transport by sea ice presents a considerable challenge, not least due to the patchy distribution of sediments (Figure 2.4.3), our lack of understanding of entrainment processes and the overall difficulty in obtaining data on the areal distribution and SPM concentrations characteristic of sediment-laden ice (Pfirman et al. 1990; Reimnitz et al. 1993b; Eicken et al. 2000). Data on sediment concentrations in sea ice require direct sampling of the ice and have shown concentrations to range between <10 to >1000 mg $l^{-1}$. Heavily sediment-laden ice exhibiting a strong discoloration typically contains SPM at concentrations of several hundreds of mg $l^{-1}$. Studies in the Siberian Arctic indicate that even visually "clean" ice grown in shallower water (<30 m depth) exhibits SPM background concentrations of around 2 to 20 mg $l^{-1}$ (Dethleff et al. 1993; Eicken et al. 1997), at least half of which can be considered to represent lithogenic sediments rather than particulates of biogenic origin (Nürnberg et al. 1994). Average SPM concentrations in visibly discolored, sediment-laden ice sampled in different regions range between 40 mg $l^{-1}$ in the Beaufort Gyre region (Reimnitz et al. 1993a), 192 mg $l^{-1}$ in the coastal Beaufort Sea (Osterkamp and Gosink 1984), 212 mg $l^{-1}$ in ice grown from slush in the Beaufort Sea (Kempema et al. 1989), 70 mg $l^{-1}$ in first-year ice in the Laptev Sea and 381 mg $l^{-1}$ in ice from the eastern Laptev and Western East Siberian Sea (Eicken et al. 2000) to 662 mg $l^{-1}$ in the upper layers of multi-year ice in the central Arctic (Nürnberg et al. 1994).

Few data are available on organic carbon concentrations in ice-rafted sediments. Lindemann (1999) completed an extensive survey of samples collected in the Laptev Sea, with a median POC fraction of 2.3 % for 71 samples from the northern and 3.6 % for 40 samples from the southern Laptev Sea. POC fractions in sediments sampled in multi-year ice from the central Arctic amounted to 1.8 wt-% (8 samples, Reimnitz, unpublished). Wollenburg (1993) found between 0.6 and 6.8 wt-% POC (averaging 2.1 wt-%) in sediments sampled from sea ice in the Eurasian Arctic. These values correspond well with organic carbon contents of surface shelf sediments, typically ranging between 1 and 2 % in the Laptev Sea (Stein et al. 1999) and 1 and 1.5 % over the Canadian Beaufort Shelf (Macdonald et al. 1998). An enrichment of organic carbon in ice-entrained sediments is attributed to selective incorporation of the clay and silt fraction, exhibiting

higher concentrations of POC (Reimnitz et al. 1998, Lindemann 1999).

The fraction of organic carbon of terrestrial origin associated with sediments transported by sea ice is less well established. Based on kerogen microscopy and pyrolysis data, Lindemann (1999) estimated the median tPOC in sediments sampled in sea ice of the southern and northern Laptev Sea as 76 and 83 %, respectively. This corresponds reasonably well with surface sediment data (Stein et al. 1999). Isotopic analysis ($\delta^{13}C$) of a small set of ice-rafted sediments from the Beaufort Sea is less conclusive but most likely shifted by in-situ primary production (Naidu et al. 2000). Surface sediments in the Beaufort Sea exhibit terrigenous fractions between 50 and 85 %, while the Chukchi and East Siberian Seas range between 50 and <10 % (Naidu et al. 2000) based on isotopic evidence. Given potentially large variations among terrestrial and marine endmembers in $\delta^{13}C$, in particular when considering the overall comparatively narrow range of values, future studies of ice-entrained sediments may benefit greatly from determinations of more discriminating tracers or biomarkers such as the hydrocarbons singled out by Yunker et al. (1995).

To arrive at the total fluxes of tPOC in the Arctic Ocean, we have estimated average SPM concentrations in sediment-laden ice ($SPM_{ice}$) based on the data presented above (Table 2.4.2). With only very limited data available for the Chukchi and Barents Seas, SPM concentrations at the background level (10 mg $l^{-1}$) have been assumed here. However, recent evidence from the Shelf-Basin Interaction (SBI) study indicates that both in the Chukchi and Beaufort Seas higher sediment loads may be quite common (Eicken and Gradinger, unpubl. data, 2002). The volume fraction ($f_{vol}$) of sediment-laden ice is conservatively estimated based on the areal distribution of shallow-water entrainment regions (water depth <20 m, Sherwood 2000) and the likelihood and extent of past entrainment events observed in these regions. The total export and net input into the Arctic Ocean have been estimated assuming a loss of 15 % of the total sediment load due to melt-out every summer based on an average residence time of three years in the Arctic Ocean (Figure 2.4.2; Freitag 1999; Eicken et al. 2000). Given the substantial errors associated in particular with the estimation of $SPM_{ice}$ and $f_{vol}$, the total export from the different regions are at best order-of-magnitude estimates.

More detailed data sets available from individual entrainment and export events can help constrain these estimates. For example, an entrainment event in the eastern Laptev/western East Siberian Sea in 1994/95 has been studied in detail by combining ground measurements, remote sensing and modelling (Kolatschek 1998; Lindemann 1999; Eicken et al. 2000). It could be established that the roughly 100,000 $km^2$ of highly sediment-laden ice produced in the vicinity of the New Siberian Islands resulted in the export of 18.5 Tg of sediment by sea ice. Based on the extensive measurements of POC and tPOC employing kerogen microscopy and pyrolytic analysis on 70 of the samples collected from the area (Lindemann 1999), we can estimate the total export of terrigenous

carbon to be on the order of 0.35 Tg (0.83 x 2.3 % tPOC fraction of total SPM). Upon melting of the ice, most of which was exported into the Greenland Sea within less than three years (Eicken et al. 2000), the ensuing flux of released sediments can represent a significant contribution to the regional carbon budget (Figure 2.4.2), with as much as 0.7 g C $m^{-2}$ $d^{-1}$ in the seasonally ice-covered Greenland Sea. This compares with typical OC sedimentation fluxes of 0.1 g C $m^{-2}$ $d^{-1}$ in the Arctic Ocean and 1.5 g C $m^{-2}$ $d^{-1}$ in the Greenland Sea as based on the compilation of data by Hargrave et al. (1994).

Thus, despite the substantial uncertainties involved in these assessments, it is clear that sea-ice export of tPOC can play an important role in the carbon budget of the Arctic Ocean. This is also borne out by a comparison with the magnitude of other terms in the Arctic Ocean's carbon budget (see chapters 4, 5 and 8 of this book). For example, sea-ice export from the Laptev Sea accounts for between one fifth and one half of the annual riverine input of POC, based on different input estimates for the area (Gordeev et al. 1996; Romankevich et al. 2000). While the corresponding fraction of total ice export of POC drops to below 1% of the total riverine input for the entire Arctic Ocean (Gordeev et al. 1996), release of POC from melting sea ice still constitutes an important term in the carbon budget of deep basins and remote seas that receive little direct input. Nevertheless, given the large uncertainty in several of the terms listed in Table 2.4.2, more research is needed to establish better estimates of ice-associated transport and in particular how this flux varies regionally and temporally. Most important, it needs to be investigated whether the combination of high ice-production rates, high concentrations of SPM in newly-grown sea ice and overall high fractions of tOC in resuspended and entrained surface sediments do in fact single out the Laptev Sea as contributing an order of magnitude more tOC to the Arctic Ocean via the sea-ice conveyor than all other sources combined.

*Table 2.4.2. Fluxes of terrigenous particulate organic carbon (tPOC) associated with sediment-laden sea ice in the Arctic Ocean region*

| Region | Ice volume flux $km^3\ yr^{-1}$ | $POC_{SPM}$ % | $tPOC_{SPM}$ % | $SPM_{ice}$ $mg\ l^{-1}$ | $f_{vol}$ % | Flux of tPOC $Tg\ yr^{-1}$ | $SPM_{ice}$ flux $Tg\ yr^{-1}$ |
|---|---|---|---|---|---|---|---|
| *Import with first-year ice from shelves* | | | | | | | |
| Beaufort Sea | 10 | 1.3[a] | 60[b] | 150 | 5 | $0.5 \times 10^{-3}$ | 0.075 |
| Chukchi Sea | 10 | 1.5[b] | 10[b] | 10 | 5 | $0.007 \times 10^{-3}$ | 0.005 |
| East Siberian Sea | 150 | 1.5[c] | 30[b] | 100 | 10 | $6 \times 10^{-3}$ | 1.5 |
| Laptev Sea | 670 | 2.5[d] | 80[e] | 150 | 10 | $180 \times 10^{-3}$ | 10 |
| Kara Sea | 240 | 1.6[f] | 50[f] | 100 | 10 | $17 \times 10^{-3}$ | 2.4 |
| Barents Sea | 35 | 1.3[f] | 30[f,g] | 10 | 5 | $0.06 \times 10^{-3}$ | 0.018 |
| *Export with multi-year ice through Fram Strait* | | | | | | | |
| Arctic Ocean export | | | | | | $-125 \times 10^{-3}$ | –8.6 |
| *Net balance (input to Arctic Ocean)* | | | | | | | |
| Arctic Ocean input | | | | | | $55 \times 10^{-3}$ | 5.4 |

Data sources - a: Macdonald et al. 1998; b: Naidu et al. 2000; c: Romankevich et al. 2000; d: Stein et al. 1999; e: Lindemann 1999; f: Stein and Fahl, Chapter 7.6, this volume; g: Hulth et al. 1996; for other data see explanations in text

*Conclusions*

The major conclusions from this survey are that (1) transport of terrestrial dissolved organic carbon (tDOC) by sea ice constitutes a minor to negligible component of the Arctic Ocean's tDOC budget, (2) entrainment and export of terrigenous particulate organic carbon (tPOC) into sea ice from the shallow shelves to the deep basins and the European Nordic Seas represents an important term in the Arctic Ocean's carbon budget, (3) tPOC and tDOC entrained into sea ice are potentially important for ice-associated primary (and secondary) production, and (4) due to the rapidity and effectiveness of ice transport as well as the potential for substantial alterations in its composition, sea-ice transport provides for a unique pathway of terrestrial organic carbon through the Arctic system, with implications for the marine sediment record.

Quantitatively, sea-ice transport is of particular regional importance in the Laptev Sea, where the average export into the Arctic Ocean has been estimated as 0.18 Tg (of C) $yr^{-1}$ (note, however, that given the considerable uncertainties in some of the source terms, this is only an order-of-magnitude estimate) and accounts for between one fifth and one half of the total riverine input of tPOC. An individual entrainment event has been shown

to remove as much as 0.35 Tg (of C) of tPOC. Sea ice is furthermore of great significance as a source of tPOC released from melting ice (mostly during the summer months) in the central Arctic, where other modes of transport are not as efficient, and in the Greenland Sea, where high net melt rates (up to 10 m of ice $yr^{-1}$) result in significant ice-derived particulate fluxes. Sediment trap data (Hebbeln et al. 1991) and tracking of sediment-laden sea-ice fields (Eicken et al. 2000) indicate that in the Greenland Sea and parts of the Eurasian central Arctic, the bulk of the lithogenous particle flux to the seafloor can be derived from the ice cover. In comparison with source sediments, ice-entrained material is sorted towards the fine-grained (clay and silt) fractions (Reimnitz et al. 1998; Lindemann 1999), which in turn are associated with higher concentrations of organic carbon (Mayer 1994). Given the substantial errors associated with these first assessments, future work needs to focus on more widespread measurements of the tPOC fraction in ice-rafted sediments as well as on the temporal and spatial variability of entrainment and export by sea ice.

Apart from the present-day quantitative importance of sea-ice rafting of organic matter, two further issues can be of substantial importance for the Arctic's carbon budget and need to be investigated in more detail. First, suspended particulates in sea ice tend to aggregate near the surface of the ice as a result of surface melting and bottom ice accretion (Figure 2.4.2; Pfirman et al. 1990; Nürnberg et al. 1994; Freitag 1999) and are thus subjected to arguably the most extreme environmental conditions at the low-temperature end in the marine realm with temperatures below –20 ˚C, salinities above 150, pH below 5 and high concentrations of oxidants due to high UV fluxes. At the same time, particulates in sea ice are associated with high bacterial biomass (Junge et al. 2001), which can result in significant respiration and turnover of organic carbon. Incubation experiments by Bussmann (1999) and tracer studies by Schell (1983) indicate that tOC may in fact enter the marine food web. Hence, it needs to be investigated to what extent diagenetic modification and remineralisation of the tOC fraction of ice-rafted material can significantly affect the quantity and composition of organic matter delivered to the seafloor after release from the ice.

This aspect ties in with the second important question related to variability in time and space of ice-transport of organic carbon. As evident from Table 2.4.2 and Figure 2.4.1, both sea-ice and associated tPOC fluxes can vary regionally by several orders of magnitude. Similar variability can be expected for the same location on geological time scales, depending on sea level, riverine supply of particulates and freshwater and other factors. This has potentially important implications for the transfer of organic carbon from the shelves into the deeper Arctic Ocean and the European Nordic Seas. Currently, conditions in the Laptev Sea are such that it represents by far the single largest source term in the ice-transported flux of tOC. However, as conditions for entrainment and export (mostly driven by atmospheric and to a lesser extent oceanic parameters, see

Eicken et al. 2000) change, other source areas may come to dominate the ice-associated flux of tOC. Since the latter constitutes a dominant term in parts of the Arctic under present-day conditions, the close linkage between sea-ice and tOC fluxes in geological present and past warrants a closer look at paleoceanographic sediment records to separate genuine changes in regional carbon budgets from those associated with changes in sea-ice entrainment and export.

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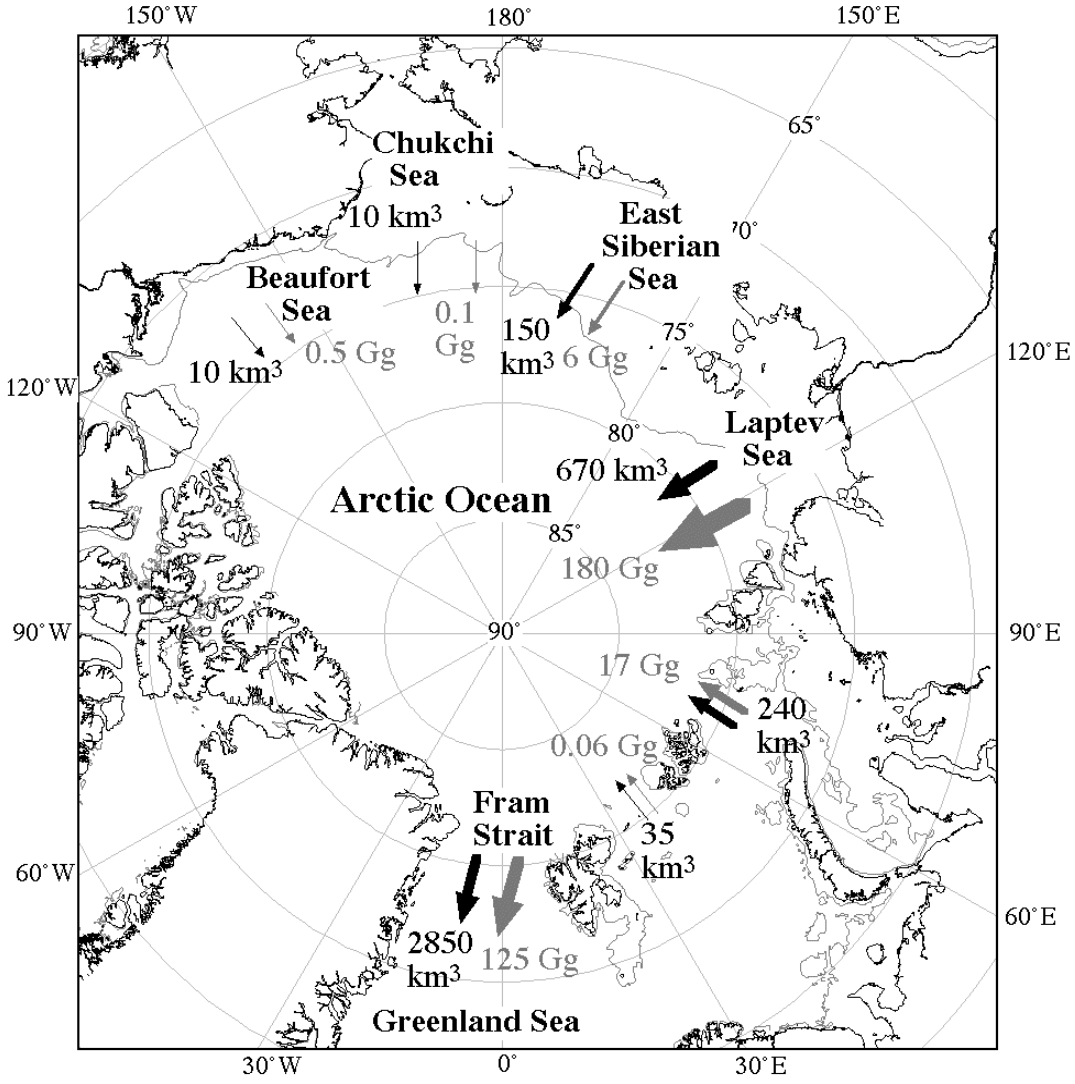


Figure 2.4.1: Net annual export of sea ice from the marginal seas into the Arctic Basin and through Fram Strait into the Greenland Sea (black) and associated transport of terrestrial organic carbon (tOC in Gg $yr^{-1}$). Ice-transport data compiled from Timokhov (1994) for the Chukchi, East Siberian and Kara Seas, Alexandrov et al. (2000) for the Laptev Sea (based on an average ice thickness of 1.5 m), and Vinje (1987) for the Barents Sea. Given the lack of data for the Beaufort Sea and Canadian Archipelago, the upper maximum limit for export to the Arctic has been assessed as 10 $km^3$, with a remote-sensing based ice-mass balance model suggesting no net import into the Arctic Ocean from this region (Thomas and Rothrock 1993). Also shown is the ice-associated transport of tPOC (grey), derived from data by Macdonald et al. (1998), Naidu et al. (2000), Romankevich et al. (2000), Stein et al. (1999), Lindemann (1999); Stein and Fahl (Chapter 7.6, this volume), Hulth et al. (1996) as outlined in Table 2.4.2. The 100-m isobath is shown in grey.

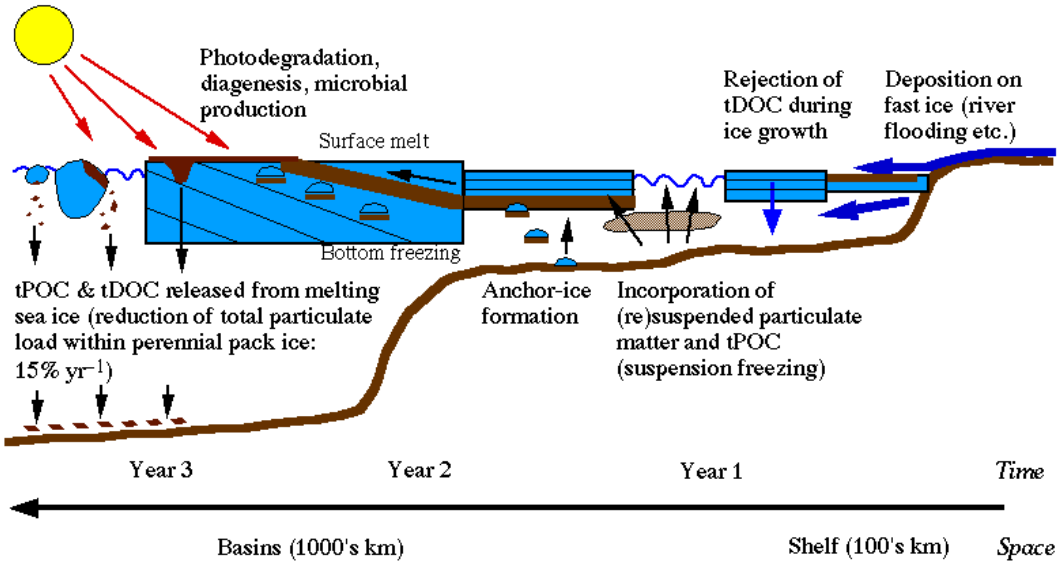


Figure 2.4.2: Schematic depiction of entrainment, transport and loss of terrestrial organic carbon (particulate and dissolved) by sea ice (processes and features depicted are not drawn to scale). Note that while anchor ice formation and direct deposition onto fast ice are responsible for entrainment of tPOC, they are not deemed as quantitatively important for basin-scale transport as suspension freezing.

Figure 2.4.3: Aerial (top, several hundred meters across) and ship-based photograph (bottom, several tens of meters across) of sediment-laden sea ice in the northeastern Laptev Sea (August 1995). Note the patchy distribution of darker, sediment-laden ice and the uniformly dark appearance of surface melt ponds due to sediment layers at the bottom. The white, linear features visible in the upper panel correspond to leads that opened and refroze after sediment concentrations in the water column had subsided, resulting in clean ice.