Chapter 6

Polar Margins

6.1 An Overview of Cross-Shelf Carbon Exchanges in Polar Margins

Walker O. Smith

The continental margins of polar oceans (those in the Arctic Ocean basin and around the continent of Antarctica) are extremely varied, and as such it is difficult to synthesize the processes that contribute to regional productivity, the vertical flux of carbon from the surface to the sediments, as well as any horizontal fluxes from the shelf to deeper waters. Indeed, it is easier to contrast their differences, which emphasize the factors that control the carbon cycle and fluxes of each region. Yet because of their polar nature, there also are similarities in physical forcing which can drive the chemical, biological and geological processes that influence the biogeochemical cycles of the regions.

The Arctic and Antarctic are strongly divergent with respect to physiography. For example, 30% of the surface area of the Arctic Ocean basin is encompassed by the continental shelf, whereas in the Antarctic only 2% of the Southern Ocean (defined as the area extending to 50°S) is covered by a shelf. Furthermore, the shelf break depth in the Arctic is ca. 150 m, whereas in the Antarctic it is approximately 800 m (Table 6.1.1) due to the depression of the continent by the substantial thickness (and weight) of the Antarctic ice sheet. Arctic continental shelves are broad and receive substantial input of terrestrial carbon from the continents surrounding it (Sect. 6.2); those of Antarctic waters are narrow, have essentially no terrigenous inputs (except some localized glacially transported rock debris), and no organic input from the continent. The Antarctic shelves are the sites of deep-water formation during winter (and hence have the potential for moving particulate carbon from the shelf to the slope and beyond; however, such transport has never been quantified), whereas Arctic shelves do not mediate the formation of extremely dense bottom water, but instead contribute to the formation of the permanent, relatively shallow pycnocline of the Arctic Ocean. Movement of waters into the halocline provides a mechanism of off-shelf transport.

Arctic shelves potentially have a significant role in organic carbon transport to off-shelf regions that is independent of deep-water formation. For example, Honjo and Doherty (1988) suggested that organic-rich material accumulates in the shallow waters of productive fjords and is transported to depth during event-scale bursts of dense water formation in winter. Such a mechanism has been verified for the Spitsbergen area (Quadfasel et al. 1988) and may also be operative in the Barents Sea. Walsh (1995) suggested that dissolved organic matter production on the shelves themselves also is a significant carbon export term and that this material may be incorporated during winter halocline-water formation. He further suggested that a key control of this DOC production was the incomplete oxidation of the DOC produced in a senescing phytoplankton bloom by bacteria. In some areas the terrigenous generation and Riverine input of DOC from peatlands onto the continental margins is significant (Frey and Smith 2005), and because this organic material is relatively refractory, it may be transported off the continental margin and over long distances.

W.O. Smith (✉)
Virginia Institute of Marine Science, College of William and Mary, Gloucester Pt., VA 23062, USA
e-mail: wos@vims.edu

K.-K. Liu et al. (eds.), *Carbon and Nutrient Fluxes in Continental Margins*, Global Change – The IGBP Series,
DOI 10.1007/978-3-540-92735-2_6, © Springer-Verlag Berlin Heidelberg 2010

Table 6.1.1 Various features of the continental margins of the Arctic Ocean basin, the Ross Sea, and the margins around Antarctica

Property	Arctic Ocean shelves	Ross Sea	Antarctic shelves
Shelf break depth (m)	150	800	800
Relative width	Broad	Narrow	Narrow
Spatial cover of entire ocean (%)	30	<1	2
Relative riverine discharge	Large	None	None
DOC concentrations in riverine water	High	–	–
Primary productivity (g C m^{-2} yr^{-1})	20 – > 400	150	20–150
Nutrient sources	Cross-shelf exchange, terrestrial	Deep ocean	Deep ocean
Forms of ice on shelves	Pack ice (annual)	Pack ice (annual), fast ice (multiyear), icebergs	Pack ice (annual), fast ice (multiyear), icebergs

The greatest quantitative term for shelf–slope exchanges in the Arctic is the input of organic matter from rivers (Sect. 6.2). Riverine discharge is a function of the location and surrounding terrestrial environment and is the largest source of organic matter (greater than aeolian input and similar to that of coastal erosion). Most of the organic matter is in the form of DOC (mean 77.8%, ranging from 48.8 to 93.0%) and is thus available for direct advection into halocline waters. The DOC of surface waters of the Arctic Ocean basin is quite high, with concentrations exceeding 100 μM near the North Pole (Wheeler et al. 1996); furthermore, the isotopic signature of the DOC suggests that it is largely of terrestrial origin. Therefore, while Arctic Ocean primary production (at least integrated over the entire basin) is substantially less than that of the Antarctic, the terrigenous inputs of rivers are a significant component of the cross-shelf exchanges of organic matter.

Measured vertical fluxes of organic carbon from the surface layer vary tremendously and appear to be a function of productivity, depth, time, and food web dynamics. In some regions the contribution of fecal material is substantial (e.g., Weddell Sea), whereas in others passively sinking phytoplankton (e.g., Bering Sea) or biogenic aggregates (e.g., Ross Sea) are the major determinant of flux. Polar systems appear to be characterized by a strong decoupling of the fluxes of organic carbon and biogenic silica (e.g., Tréguer et al. 1995; Nelson et al. 1996; DeMaster 2002; Ragueneau et al. 2002b, Chap. 10). The causes for this decoupling are the controls of the remineralization processes; that is, organic carbon is largely remineralized by biological processes (heterotrophic metabolism) and thus is relatively independent of temperature, whereas biogenic silica dissolution is in large part a chemical process and is thus largely temperature dependent. One result of this decoupling is to generate large silica deposits in polar regions that are not necessarily accompanied by large organic matter deposits. A quantitative comparison of both C and Si export relative to their production suggests that export efficiency is quite high in the Southern Ocean, allowing the absolute export rates to be among the largest observed anywhere (Buesseler et al. 2001). Laws et al. (2000) found a strong correlation between export and temperature, which suggests that decreased rates of heterotrophic processes relative to autotrophic ones may result in increased export efficiencies of carbon. Finally, the importance of diatoms in polar regions is well known; their "ballasting" by silica and enhanced sinking rates may also provide a means by which relatively enhanced carbon levels reach the sediments (Armstrong 2001). These unusual features of the polar systems result in systems that have enhanced carbon fluxes to depth and make them excellent areas to study the influence of various processes on local and regional biogeochemical processes.

Polar margins also appear to have enhanced coupling (relative to temperate and tropical waters) between the surface waters and benthos (Peterson 1984; Ambrose and Renaud 1995; Grebmeier and Barry 2006), which may be a result of the greater supply of oxidized nutrients (which favor larger phytoplankton species) and relatively reduced role of the microbial (regenerative) food web in polar regions. As such, phytoplankton growth is less grazed, and more material passively sinks to the relatively shallow benthos and enters the benthic food web. While most of the input is eventually remineralized in situ, the material may remain as high quality, labile POC for extended periods (Mincks et al. 2005), thus providing a food source for benthic fauna that is largely decoupled from surface processes. The generality of this result needs to be tested in different polar environments.

Based on the compilations of this volume (e.g., Sects. 6.2, 6.3 and 6.4), it is clear that polar margins have substantial spatial and temporal variability in vertical fluxes and carbon exchanges. Models of fluxes and exchanges not only need to account for production, advection, and temporal patterns, but also must include regional features such as riverine inputs, organic matter storage, remineralization and export, and the effects of ice. Determining the spatial and temporal patterns will greatly improve our understanding of the role of the continental margins in the carbon cycle of polar regions, and only by including these features will the biogeochemical structure and function of polar systems be adequately resolved.

6.2 The Arctic Ocean

Robie W. Macdonald, Leif G. Anderson, John P. Christensen, Lisa A. Miller, Igor P. Semiletov and Rudy Stein

6.2.1 Geographical Setting

The Arctic Ocean is a Mediterranean Sea with exceptionally large shelves that account for approximately 50% of the total area of the enclosed ocean (Fig. 6.2.1; Table 6.2.1). Accordingly, the inorganic and organic character of the sediments and water on the shelves and in the basins of the Arctic Ocean strongly reflect a pervasive influence from the surrounding land (Anderson et al. 2003; Bélanger et al. 2006; Belicka et al. 2002; Benner et al. 2004; Dittmar and Kattner 2003; Guo et al. 2004; Hernes and Benner 2005; Stein and Macdonald 2004; Yunker et al. 1995). During winter there is a complete ice cover on the ocean (greater than 9/10s) with a thick (3–7 m), permanent ice pack occupying the interior. The seasonal ice cover (up to about 2 m) on the shelves often clears out to the shelf edge and beyond during late summer (Parkinson 1992). The production and melting of ice, which occur with strongest annual amplitudes over the marginal seas, have a profound influence on the density structure of the surface waters and their interaction with the atmosphere, thereby strongly affecting exchange between shelves and basins. Despite the apparent continuity of the Arctic's annular shelf (Fig. 6.2.1), no two shelves are alike and each must be considered independently in the context of biogeochemical cycles, exchanges, and vulnerability to change (Carmack et al. 2006). Broadly speaking, the Arctic's shelves may be categorized as import shelves (Chukchi and Barents Seas), export shelves (north of the Canadian Archipelago), and interior shelves (East Siberian, Laptev, Kara and Beaufort Seas). The import shelves are capable of sustaining a relatively high new productivity by virtue of nutrients imported from the adjacent Pacific or the Atlantic Oceans (Grebmeier and Whitledge 1996; Hegseth 1998). In contrast, the interior shelves exhibit a lower productivity sustained partly by river inflow from land and partly by shelf-edge exchange. There are also important inter-shelf exchanges between the adjacent shelves extending from the Barents Sea all the way over to the Chukchi Sea. The export shelf north of the Canadian Archipelago is poorly sampled, but it is likely that it receives nutrients originating predominantly from the Pacific Ocean (see for example, Yamamoto-Kawai et al. 2006) and exports these together with primary and secondary production products to the Atlantic Ocean via outflow through the Archipelago to Baffin Bay or Hudson Bay (Jones and Coote 1980; Jones et al. 2003; Melling 2000; Tremblay et al. 2002).

Within the global ocean, the Arctic Ocean appears to be especially sensitive to global change simply

---

R.W. Macdonald (✉)
Department of Fisheries and Oceans, Institute of Ocean Sciences, 9860 West Saanich Road, Sidney, BC, Canada V8L 4B2
e-mail: Robie.Macdonald@dfo-mpo.gc.ca

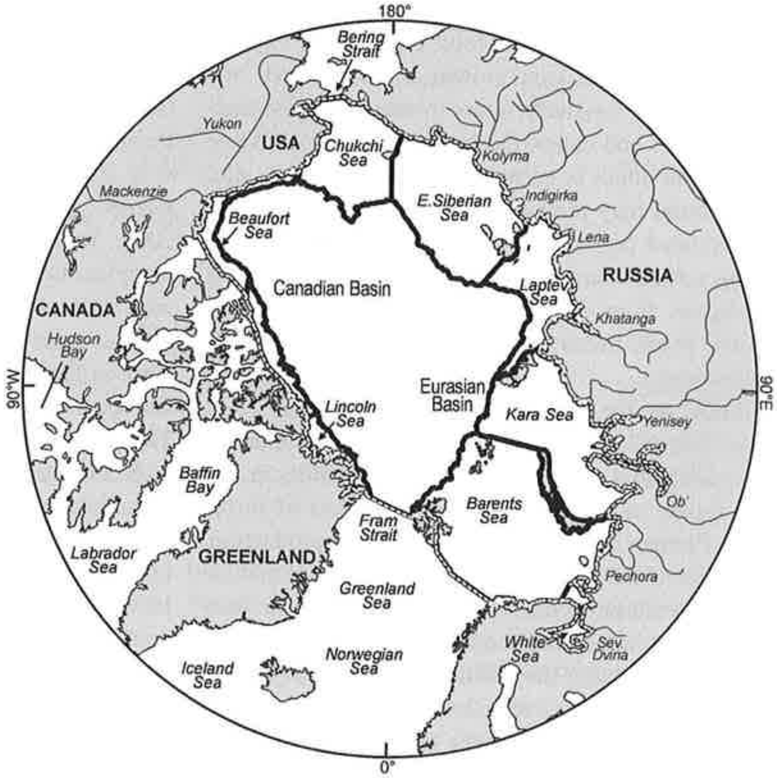

Fig. 6.2.1 Schematic of the Arctic Ocean showing the shelves (with demarcation lines) and connections to other oceans

because alterations of the cryogenic and hydrological cycles (Johannessen et al. 1995; Vörösmarty et al. 2001) could have, among other things, profound effects on the (1) river inflow (Déry and Wood 2005; Peterson et al. 2002); (2) shelf–edge exchange (Carmack and Chapman 2003); (3) air–sea exchange (Anderson and Kaltin 2001; Semiletov et al. 2004); (4) dispersal of winter inflow over shelves (Macdonald 2000); (5) ocean stratification (Lewis et al. 2000); (6) erosion of ice-bonded coastlines (Rachold et al. 2000); (7) stability of permafrost underlying large portions of continental shelf with risks of releasing ancient stored carbon including methane (Semiletov 1999a; Semiletov 1999b; Shakhova and Semiletov 2007); and (7) light climate in the upper ocean (Conover et al. 1990; Dickson 2005). Together, these sorts of

Table 6.2.1 Areas of the Arctic shelves and the freshwater inflows

Shelf sea	Area[a] $(10^3\ \mathrm{km}^2)$	Mean[a] depth (m)	Residence time (yr)	River inflow $(\mathrm{km}^3\ \mathrm{yr}^{-1})$	Shelf yield[c] $(\mathrm{m\ yr}^{-1})$	First-year ice export[d] $(\mathrm{km}^3\ \mathrm{yr}^{-1})$
Chukchi	620	80	0.2–1.2	78	0.12	10
East Siberian	987	58	3.5 ±2	213	0.21	150
Laptev	498	48	3.5 ±2	767	1.5	670
Kara	926	131	2.5	1133	1.2	240
Barents	1512	200	?	463	0.31	35
Shelf north of archipelago	240	290	~0.5	~ 60	0.25	?
Shelf within archipelago	~1250	250	~12	210[f]	0.17	−480[g]
Beaufort	178	124	0.5–1	330	1.9	10[h]
Central basin	4489	2748	2–30[b]	3044		−2850[e]

[a]Areas and mean depths after Jakobsson et al. (2004); [b]Basin surface water (0–200 m); [c]Total river inflow divided by shelf area; [d]Eicken (2004); [e]Ice export from Arctic Ocean through Fram Strait; [f]Vuglinsky (1997); [g]Ice export through Archipelago (Melling 2000); [h]This export term may be low (cf. Melling 1996; Melling and Moore 1995).

changes would have complex and as yet difficult to predict consequences for biogeochemical cycles (Macdonald et al. 2005; Macdonald et al. 2004; Walsh 1989). For example, projected and observed manifestations of climate change, such as alteration in general wind patterns, increase in open water due to extensive ice melt-back during summer and increased runoff (ACIA 2004; Dickson et al. 2000; Serreze et al. 2000), will impact the biogeochemical cycles of the shelves, including the supply and exchange of nutrients and the primary production these support.

The Arctic has likely already entered a time of change (Anderson and Kaltin 2001; Comiso and Parkinson 2004; Overland et al. 2004; Serreze et al. 2000; Stroeve et al. 2008; Walsh et al. 2004); regrettably a baseline-accounting of biogeochemical cycles from which such change might be assessed remains woefully incomplete. The Arctic Ocean has been suggested to be a net sink for atmospheric CO_2, favored by cold, relatively low salinity surface layers (Miller et al. 1999; Murata and Takizawa 2003; Takahashi et al. 1997). Unfortunately, estimates of annual CO_2 uptake from the atmosphere vary widely from 1700×10^9 mol (Anderson et al. 1998b) up to $11{,}000 \times 10^9$ mol (Lyakhin and Rusanov 1983), due to high spatial variability and a difficulty of establishing representative values.

6.2.2 Constructing Budgets for Arctic Shelves: The Special Influences of Sea Ice

Continental shelves are clearly important locations for storing and processing material that derives from the land (e.g., inorganic lithogenic particulates, old soil carbon, and newly produced organic carbon) and the sea (e.g., biogenic products including carbonate, silicate, and organic carbon), but shelves present a number of challenges to constructing budgets (Liu et al. 2000a). In addition to a disproportionate influence by rivers and coastal erosion, the Arctic Ocean has the added challenge of incorporating the influence of ice on material transport (Eicken et al. 2005; Stein and Macdonald 2004). Directly, ice can transport suspended sediments, salt, nutrients, contaminants, and organic material between shelves and basins with its drift. To estimate fluxes associated with ice transport, we need to know the composition of the ice, which can be very patchy (Eicken et al. 2005; Eicken et al. 2000; Eicken et al. 1997; Krembs et al. 2002; Thomas et al. 1995). Furthermore, there must be an accurate estimate of ice import to or export from each shelf, something that is difficult to measure.

Indirectly, ice formation is accompanied by salt rejection, which can produce dense brine that destabilizes the surface water to produce a polar mixed layer in winter. Where vigorous ice growth occurs, for example in divergent flaw leads over the mid to outer shelves, sufficient density can be attained through brine rejection that dense water plumes can be produced (Melling and Lewis 1982). This dense water then flows along the shelf bottom where it may entrain regeneration products, which it then transports into the halocline of the interior ocean below the surface mixed layer (Goldner 1999; Melling and Moore 1995). The process of halocline formation is of fundamental importance to the stratification of the Arctic Ocean and is widely recognized in the chemical composition of waters between 100 and 300 m water depth throughout the Arctic Ocean (Aagaard et al. 1981; Anderson et al. 1990; Jones and Anderson 1986; Macdonald et al. 1989). The nourishment of the halocline (Melling and Lewis 1982; Melling and Moore 1995) provides but one avenue of shelf–basin exchange. Like other continental margins, shelf–edge exchange occurs in response to winds, estuarine forcing and tides; these exchanges are poorly quantified and remain the topic of ongoing studies (e.g., Forest et al. 2007; Grebmeier and Harvey 2005; Kassens et al. 1999).

Ice also strongly affects air–sea exchange of gases by providing a variable cover over the ocean – a process that might enhance the ability of seasonally ice-covered seas to capture CO_2 (Yager et al. 1995). During spring and summer, melt ponds and open brine channels in sea ice contribute important air CO_2 sinks that have, hitherto, been neglected in Arctic regional CO_2 budgets (Semiletov et al. 2004). The direction and the amount of CO_2 transfer between air and sea may differ between freezing and thawing cycles and, during winter, CO_2 can accumulate beneath Arctic sea-ice (Semiletov et al. 2006).

6.2.3 Approach to Constructing Biogeochemical Budgets

We have attempted to constrain Arctic budgets by working from two directions. First, we have compiled material budgets for the shelves based on earlier work and references cited therein (e.g., Barrie et al. 1998; Chen et al. 2002; Stein and Macdonald 2004). These budgets include estimates of sediment and terrigenous organic carbon fluxes from land (Table 6.2.2), sediment capture by shelves (Table 6.2.2), nutrient supply from land (Table 6.2.3), shelf and basin primary production (Table 6.2.4), burial of marine organic carbon and nitrogen and loss of nitrogen by denitrification (Table 6.2.5), and the direct export of material from shelves by ice (Table 6.2.6).

Second, we have used the estimates of new production for each shelf (Table 6.2.4) to infer the input of nutrients required to support such export production.

Table 6.2.2 Sediment supply and burial in the Arctic Ocean[a]

	Terrigenous sediment supply (Mt yr^{-1})			Terrigenous POC supply (10^9 mol yr^{-1})			Sediment burial (Mt yr^{-1})	TerrigenousOC burial (10^9 mol yr^{-1})
Shelf sea	Eolian	Rivers	Coastal erosion	Eolian	Rivers	Coastal erosion		
Chukchi	0.37	0.7	70	9.1	>11	67	19	19
East Siberian	0.59	25	67	15	40	183	109	80
Laptev	0.30	29	58	7.5	108	150	67	81
Kara	0.55	41[d]	109[b]	14	75	83[b]	194	177
Barents	0.90	18	119	23	42	67	259	233
Shelf north of archipelago[c]	0.15	2.9	?	3.6	6.3	?	?	?
Shelf within archipelago[c]	0.76	10	?	19	22	?	?	?
Beaufort	0.11	124	7.9	2.5	175	8	123	126
Central basin	2.88						237	200
Total arctic	5.7	237	430	74	460	560	1008	917

[a]Based on the Stein and Macdonald (2004). [b]Recently, Vasiliev et al. (2005) propose a lower range for coastal erosion of 30–40 Mt yr^{-1} (total solids) and 0.3 Mt yr^{-1} organic carbon. We have continued to use the estimates by Vetrov and Romankevich (2004) but draw attention to uncertainty in this number. [c]Archipelago values have been estimated using average values for eolian (excepting Laptev) and rivers (excepting Mackenzie). [d]For the Yenisei, we have used a total suspended matter supply of 14.4 Mt yr^{-1} instead of the modern value of 4.7 M t yr^{-1} resulting in a total of about 41 Mt yr^{-1} for the Kara Sea. The higher Yenisei value was measured at a time preceding the 1967 construction of a dam near Krasnoyarsk (Holmes et al. 2002; Telang et al. 1991). For the terrigenous POC supply by the Yenisei river, we consequently also used a value three times higher than the modern (post-1967) one.

Table 6.2.3 Nutrient supply from rivers for Arctic shelves

Shelf sea	DIN[a] (10^9 mol yr^{-1})	DON[c] (10^9 mol yr^{-1})	DIP[a] (10^9 mol yr^{-1})	$Si(OH)_4^a$ (10^9 mol yr^{-1})
Chukchi	~0.8	2.2	~0.1	~8
East Siberian	1.4	2.5	0.05	13
Laptev	4.1	8.5	0.16	47
Kara	59	13.0	1.9	184
Barents	4.7	3.4	0.28	43
Shelf north of archipelago[b]	1.0	0.8	0.05	6
Shelf within archipelago[b]	3.4	2.9	0.16	20
Beaufort	1.0	4.6	0.03	15
Total	75	38	2.7	335

[a]Compiled from multiple sources including (Barrie et al. 1998; Chen et al. 2002; Dethleff 1995; Gordeev 2000; Gordeev et al. 1996; Hanzlick and Aagaard 1980; Holmes et al. 2000; Macdonald et al. 1998; Pavlov and Pfirman 1995; Rigor and Colony 1997; Sakshaug et al. 1994; Walsh 1989); [b]Archipelago numbers estimated from river inflow (Table 6.2.1) and average concentrations for the other rivers (excluding the Kara Sea); [c]Compiled from (Dittmar et al. 2001a; Guo et al. 2004; Köhler et al. 2003; Lara et al. 1998; Lobbes et al. 2000).

Table 6.2.4 Primary Production for Arctic shelves and implied imported nutrient supply

	Total primary production[a]		New primary production[a]		DIN[b]	DIP[b]	$Si(OH)_4$[b]
Shelf sea	g C m^{-2} yr^{-1}	10^9 mol yr^{-1}	g C m^{-2} yr^{-1}	10^9 mol yr^{-1}	10^9 mol yr^{-1}	10^9 mol yr^{-1}	10^9 mol yr^{-1}
Chukchi	20–>400 (95)[c]	4900	5–>160 (50)[c]	2600	390	24	829
Pacific Inflow					*520*	*65*	*690*
East Siberian	25–40 (30)	2500	6–10 (8)	660	100	6	212
Laptev	25–40 (30)	1250	6–10 (8)	330	50	3	106
Kara	30–50 (40)	3100	7–12 (10)	770	116	7	247
Barents	20–200 (90)	11,300	<9–100 (50)	6300	950	59	2020
Atlantic Inflow					*820*	*57*	*315*
Shelf north of archipelago	20–40 (30)	600	5–10 (8)	160	24	2	51
Shelf within archipelago	~60	~6000	40	4200	630	39	1340
Beaufort	30–70 (45)	670	7–17 (12)	180	27	2	58
Central basin	5–30 (20)	7500	<1	<370	<56	<3.5	120
Total[d]		31,800		11,300	1700	107	3640

[a]Hill and Cota (2005); McLaughlin et al. (2006); Sakshaug (2004); [b]Implied supply of new nutrients based on N:P:C:Si ratios of 16:1:106: 34±5 (see for example, Anderson and Dyrssen (1981); Carmack et al. (2004); Codispoti and Richards (1968); Harrison and Cota (1990); Jones et al. (1990); Koike et al. (2001); [c]Hill and Cota (2005); Walsh et al. (2005); [d]Total excludes production within the Archipelago.

We have adopted this procedure to constrain shelf budgets because the direct measurement of shelf exchanges in the context of biogeochemical cycles is exceptionally difficult and remains an elusive objective of large, multi-disciplinary research programs such as the Shelf–Basin Interaction (SBI) study of the Chukchi Sea (Grebmeier and Harvey 2005) and Canadian Arctic Shelf Exchange Study (CASES) (Forest et al. 2007; Sampei et al. 2003). Recently, Sakshaug (2004) has reviewed the state of knowledge of primary and secondary production for the Arctic Ocean on a shelf by shelf basis, and Vetrov and Romankevich (2004) have examined specifically the productivity of the Russian Arctic seas. New primary production, by definition, is supported by the exogenous supply of fixed nitrogen (Eppley and Peterson 1979) and this, therefore, can be used to set the limit for the amount of biologically fixed material that can be exported to the deep ocean. Accordingly, new production of organic carbon carries an implied flux for the major plant

Table 6.2.5 Sinks

	Marine organic carbon burial		Marine organic nitrogen burial[b]	Denitrification
Shelf sea	Mt yr^{-1}[a]	10^9 mol yr^{-1}	10^9 mol yr^{-1}	10^9 mol yr^{-1}
Chukchi	0.12	10	1.5	226[c]
East Siberian	0.29	24	3.6	11[d]
Laptev	0.08	7	1	5[d]
Kara	0.4	33	5	24[e]
Barents	1.96	163	25	55[f]
Archipelago	?	?	?	?
Beaufort	0.3	25	4	6[g]
Central basin	0.47	39	40	Negl?
Total Arctic	3.6	301	79	328

[a]See p 319 in Stein and Macdonald (2004); [b]Based on a C:N ratio of 6.6 which likely overestimates nitrogen burial. Denitrification rates based on [c]Devol et al. (1997), Chukchi Sea ~1 mmol m^{-2} d^{-1}; [d]Nitishinsky et al. (2005), Laptev Sea ~ 0.03 mmol m^{-2} d^{-1}; [e]Based on PP, assumed slightly higher than Laptev; [f]Assumed to be low and approximately the same as in the Beaufort Sea, [g]Chen et al. (2002), Beaufort Sea ~0.1 mmol m^{-2} d^{-1}.

Table 6.2.6 Transport by ice from shelf to basin

Shelf sea	Ice volume flux[a] ($km^3\ yr^{-1}$)	Total sediment[a] ($Mt\ yr^{-1}$)	Terrigenous DOC[a] ($10^9\ mol\ yr^{-1}$)	Terrigenous POC[a] ($10^9\ mol\ yr^{-1}$)	Total salt[b] ($10^9\ kg\ yr^{-1}$)	Total alkalinity[c] ($10^9\ mol\ yr^{-1}$)	DIN[d] ($10^9\ mol\ yr^{-1}$)	DIP[d] ($10^9\ mol\ yr^{-1}$)	$Si(OH)_4^d$ ($10^9\ mol\ yr^{-1}$)
Chukchi	10	6.5[e]	0.08	5.4	40	2.6	0.03	0.005	0.1
East Siberian	150	1.5	1.6	0.5	600	40	0.45	0.075	1.5
Laptev	670	10	7.3	15	2680	176	2.0	0.34	6.7
Kara	240	2.4	2.6	1.4	960	63	0.72	0.12	2.4
Barents	35	0.018	0.3	Negl	140	9.2	0.11	0.018	0.35
Archipelago throughflow	−480[f]	−3.6	−5.3	−1.6	−1920	−126	−1.4	−0.24	−4.8
Beaufort	10	0.075	0.2	Negl	40	2.6	0.03	0.005	0.1
Arctic Ocean export	−2850	−8.6	−10	−10	−11,400	−727	−8.6	−1.4	−28.5
Total shelf to basin export	1115	20	12	22	4460	293	3.3	0.56	11

[a] Eicken (2004); [b] Assuming average ice salinity of 4; [c] Assuming average ice alkalinity of 263 μmol kg^{-1} (Yamamoto-Kawai et al. 2005); [d] Ice concentration set ~ surface-water values for Arctic Ocean sections (Anderson et al. 1989; Swift et al. 1997) (Silicate = 10 ±10 mmol m^{-3}; Nitrate = 3 ±3 mmol m^{-3}; Phosphate = 0.5 ±0.5 mmol m^{-3}); [e] Eicken et al. (2005); [f] Melling (2000).

nutrients, nitrate, phosphate, and silicate, which traditionally have been estimated using the Redfield–Ketchum–Richards model wherein the N:P:C atomic ratios are assumed to be 16:1:106 (Jones et al. 1990). Silicate ratios are subject to greater variance in space and time but have also been estimated (Anderson and Dyrssen 1981; Harrison and Cota 1990; Koike et al. 2001; Codispoti and Richards 1968; Carmack et al. 2004) and based on these papers we have chosen a N:Si ratio of 16:34. These ratios have been used to infer the import/export of the inorganic macronutrients (N, P, Si) from estimates of new production (Table 6.2.4).

6.2.4 The Arctic Shelves

6.2.4.1 Chukchi Shelf

The Chukchi Sea is a broad, shallow shelf that receives relatively small amounts of runoff and sediments from rivers but has a considerably larger supply of terrestrial sediment from coastal erosion (Tables 6.2.1, 6.2.2, Fig. 6.2.2a). The nutrient flux from land sources, including the Yukon River via Bering Strait, is miniscule (Table 6.2.3) when compared to the nutrient requirements to sustain primary production (Table 6.2.4). Similarly, the potential to bury organic matter in Chukchi Shelf sediments (Fig. 6.2.2a) is small simply due to the poor supply of inorganic sediment to support the burial (Naidu et al. 2004). This shelf sustains its high marine productivity partly from nutrient-rich inflow from the Pacific Ocean (Table 6.2.4), particularly from the Anadyr Current which feeds the western side of Bering Strait, and partly from shelf–edge exchange and upwelling (Codispoti et al. 2005; Hill and Cota 2005; Walsh et al. 2005). The primary production is large in this sea (Table 6.2.4), with new production estimated at $2600 \times 10^9\,\mathrm{mol\,yr^{-1}}$. The estimated exogenous supply of nutrients carried by Bering Strait inflow (~0.8 Sv (Roach et al. 1995)) appears large enough to support the estimated new production, but this inflow is an annual average, including both summer waters with low nutrient concentrations, as well high-nutrient winter waters, and Pacific waters reside on this shelf for only a short time (Table 6.2.1). Accordingly, the new production for the Chukchi is likely supported largely by the Bering Strait inflow but shelf–edge exchange including upwelling should not be neglected (e.g., see Walsh et al. 2005). The organic carbon and nitrogen burial fluxes (Table 6.2.5), which account for only a very small portion of the new production, are still sufficient to account for the organic carbon composition observed within Chukchi sediments (Tables 6.2.2 and 6.2.5 (Belicka et al. 2002; Belicka et al. 2004)). Estimates of denitrification based on sediment fluxes (Devol et al. 1997) and water-column measurements (Codispoti et al. 2005) on this shelf ($226 \times 10^9\,\mathrm{mol\,yr^{-1}}$; Table 6.2.5, Fig. 6.2.2a) indicate that this process may be an important sink for fixed nitrogen, probably the result of an exceptionally strong labile organic carbon supply to sediments. A recent study by Eicken and co-workers (2005) suggests that the export of sediments from the Chukchi and Beaufort Shelves to the basin by ice drift ($5\text{–}8\,\mathrm{Mt\,yr^{-1}}$) is significant (~10% of the sediment supply); nevertheless, ice plays a minor role in Chukchi Shelf budgets (Table 6.2.6).

Kaltin and Anderson (2005) estimated the CO_2 uptake by ocean water passing over the Bering–Chukchi shelves as $1800 \times 10^9\,\mathrm{mol\,yr^{-1}}$ based on the difference between the change caused by biological activity and the observed change in total dissolved inorganic carbon. Direct measurements of CO_2 uptake from atmosphere during open-water season have been observed in the range of -18 to $+3\,\mathrm{mmol\,m^{-2}\,d^{-1}}$ (Murata and Takizawa 2003; Semiletov et al. 2006) with the latter authors suggesting that flux into the ocean was greater during the relatively cold years of 1996 and 2000 compared to the warmer 2002. In agreement with this, Murata and Takizawa (2003) proposed that the forcing for CO_2 invasion depended on low water temperature and mixing rather than biological production.

6.2.4.2 East Siberian Shelf

The East Siberian Sea is an enormous, shallow shelf that receives most of its particulate supply from coastal erosion (Table 6.2.2; Fig. 6.2.2b). As implied by Table 6.2.2, all of the Russian Shelves depend predominantly on coastal erosion for the supply of inorganic solids, which then provide the means to bury organic carbon (Rachold et al. 2004; Rachold et al. 2000). Based on chemical and hydrological data, this shelf may be divided into two domains; the eastern area is strongly influenced by Pacific inflow (Petrova et al. 2004; Semiletov et al. 2005), whereas

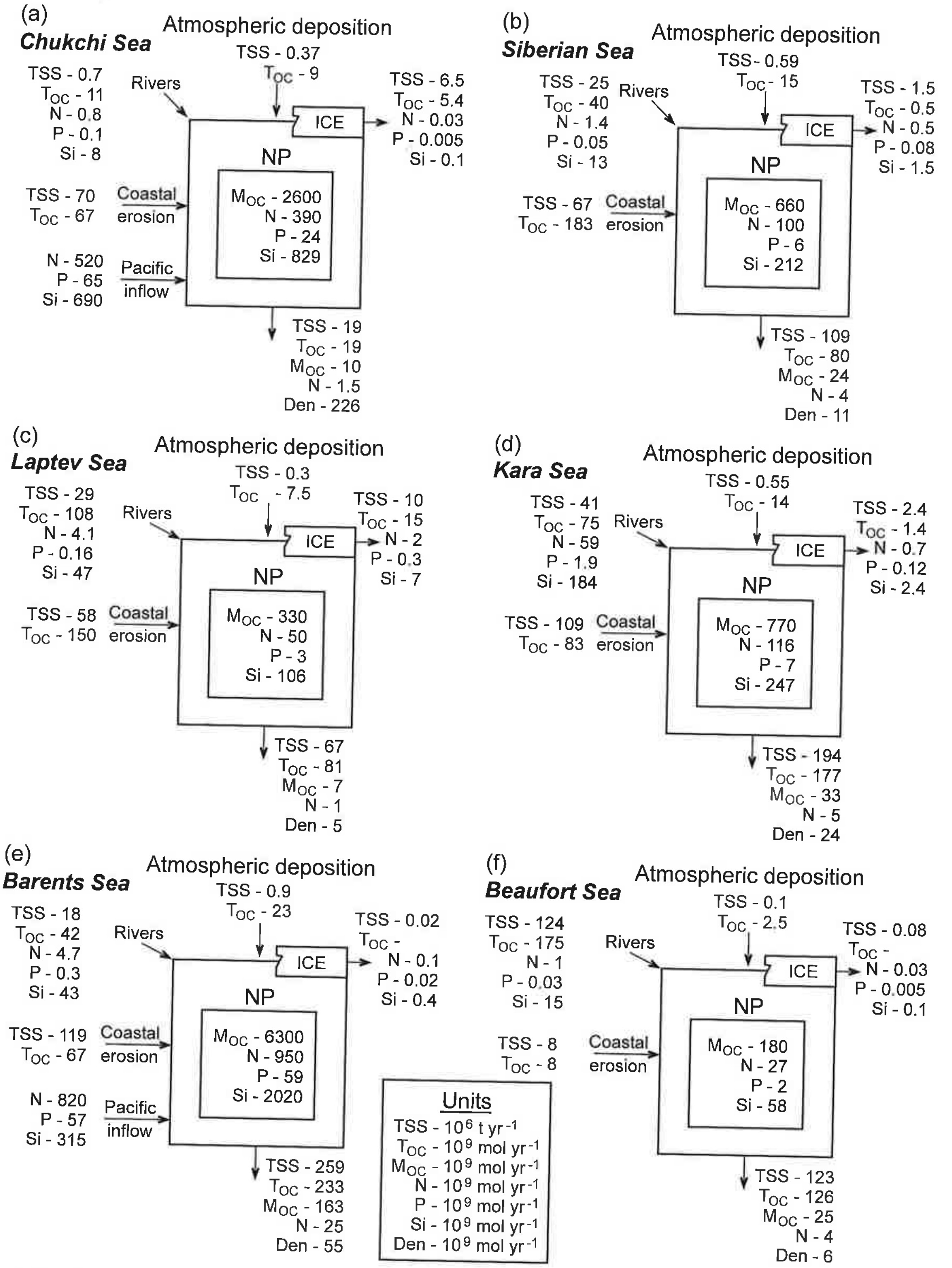

Fig. 6.2.2 Biogeochemical fluxes for (**a**) The Chukchi Shelf, (**b**) The East Siberian Shelf, (**c**) The Laptev Shelf, (**d**) The Kara Shelf, (**e**) The Barents Shelf, and (**f**) The Beaufort Shelf. Abbreviations are TTS = Total Suspended Sediments, T_{OC} = Total Organic Carbon, M_{OC} = Marine Organic Carbon, Den = Denitrification, N = Nitrogen, P = Phosphorus, and Si = Silicate

the western area is influenced strongly by fresh water flux and particulate material from coastal erosion (the Lena solids discharge signal is negligible). Freshwater runoff is collected into an eastward flowing coastal current (Petrova et al. 2004; Weingartner et al. 1999).

The supply of riverborne nutrients is clearly insufficient to support the estimated new production of this shelf (Tables 6.2.3, 6.2.4; Fig. 6.2.2b) implying that upwelling and exchange must predominate. In addition to shelf–edge exchange, this shelf probably also benefits from nutrients imported through Bering Strait, particularly over the eastern portions of the shelf (Petrova et al. 2004; Semiletov et al. 2005). Marine new production ($660 \times 10^9\,\mathrm{mol\,yr^{-1}}$) is accompanied by a very small marine organic carbon burial flux ($24 \times 10^9\,\mathrm{mol\,yr^{-1}}$) suggesting that most of the primary production is regenerated and/or exported to the interior ocean. The supply of organic carbon from rivers and coastal erosion ($\sim 80 \times 10^9\,\mathrm{mol\,yr^{-1}}$) is much smaller than that produced within the system, but it is this carbon that tends to be preserved in the accumulating sediments of the shelf (Guo et al. 2004). Given the relatively low production of labile organic carbon, denitrification rate over this shelf is likely to be small, similar to rates estimated for the Laptev Sea (Nitishinsky et al. 2005), and probably accounts for only a small proportion of the nitrogen (Table 6.2.5; Fig. 6.2.2b). Export by ice accounts for 1% or less of the nutrient budget (Table 6.2.6).

Measurements of the CO_2 system in September of 2003 and 2004 (Semiletov et al. 2006) suggest that the partitioning of water-masses in the East Siberian Sea is also reflected in the net direction of CO_2 flux with the western area evading CO_2 to the atmosphere while the Eastern, Pacific-dominated area is a sink. Mean CO_2 fluxes from surface water to atmosphere were estimated at $1 \pm 1.6\,\mathrm{mmol\,m^{-2}\,d^{-1}}$ (2003) and $10.9 \pm 12.6\,\mathrm{mmol\,m^{-2}\,d^{-1}}$ (2004). The larger efflux observed in 2004 corresponded with relatively warm and windy conditions, possibly associated with a 30% increase in Lena and Kolyma river discharge for that year.

6.2.4.3 Laptev Shelf

The Laptev Sea provides the terminus for one of the world's great rivers, the Lena. This shelf is dominated by waters of Atlantic origin and is noteworthy as the Arctic Ocean's greatest exporter of ice (Table 6.2.6, AMAP 1998; Eicken 2004; Eicken et al. 2000). Ice, which has entrained resuspended sediment from shallow (<20 m) mid-shelf regions, results in a significant export of particles from this shelf into the Transpolar Drift (Eicken et al. 2000; Eicken et al. 1997). The large source of fresh water to this shelf ($\sim 770\,\mathrm{km^3\,yr^{-1}}$) is accompanied by $\sim 30\,\mathrm{Mt\,yr^{-1}}$ of suspended sediments which are further augmented from coastal erosion ($\sim 60\,\mathrm{Mt\,yr^{-1}}$). The large quantities of sediments and particulate organic carbon from the Lena River (Cauwet and Sidorov 1996; Gordeev et al. 1996) are predominantly trapped in the delta region (Lisitzin 1995). Much of the Lena river water enters the Transpolar Drift with time lags of about 1–2 years over the shelf and a further 2–3 years to reach Fram Strait (Semiletov et al. 2000). Surface water from the Laptev Sea shelf, rich in runoff and dissolved organic matter (DOM) likely contributes to the high concentrations of DOM measured over the Arctic Basin (Opsahl et al. 1999).

New production on this shelf is low ($\sim 330 \times 10^9\,\mathrm{mol\,yr^{-1}}$) and predominantly supported by nitrate and phosphate exchanged at the shelf edges rather than supplied from land (Tables 6.2.3 and 6.2.4). The input of $Si(OH)_4$ from land ($47 \times 10^9\,\mathrm{mol\,yr^{-1}}$), however, appears capable of supplying a considerable proportion of the $Si(OH)_4$ required for primary production ($\sim 106 \times 10^9\,\mathrm{mol\,yr^{-1}}$). The burial of organic carbon and nitrogen from marine sources accounts for only a very small proportion of the budget with the sediment organic carbon flux being made up predominantly of organic carbon from terrigenous sources (~90%). In agreement with the low primary production of this shelf, denitrification is a relatively small component of the nitrogen budget (Table 6.2.5, Nitishinsky et al. 2005). Even though the Laptev Sea sustains the largest export of sea ice within the Arctic, the export of material directly by ice remains a relatively small budgetary component (10% of sediment supply, <1% for nutrient supply).

6.2.4.4 Kara Shelf

Like the Laptev Sea, the Kara Sea is strongly affected by the large inflow from Russian Rivers (Ob and Yenesei Rivers, Table 6.2.1, Fig. 6.2.2d, Stein et al. 2004). Although these rivers supply a considerable quantity of suspended sediments (41 Mt yr^{-1}), coastal erosion (109 Mt yr^{-1}) (Table 6.2.2) dominates the sediment sources for this shelf. Unlike the other Siberian shelves, however, the supply of DIN from land (~59 × 10^9 mol yr^{-1}) could account for perhaps half of the estimated requirements to support new production (116 × 10^9 mol yr^{-1}). Likewise, $Si(OH)_4$ supplied by the rivers (184 × 10^9 mol yr^{-1}) must play an important role in this shelf's budget, accounting for almost 75% of that required by new production (Table 6.2.4). Considering the silicate import by rivers, both the Laptev and the Kara shelves appear to be favorable locations for diatom production. The burial of marine organic carbon (33 × 10^9 mol yr^{-1}) accounts for only ~5% of the new production, and within the sediments the burial flux is estimated to comprise only ~20% marine carbon with the remainder made up of terrigenous organic carbon. Based on a slightly higher new production rate for this shelf than the Laptev and East Siberian Shelves, denitrification is likely to be slightly higher, although still a minor (~20%) component of the nitrogen budget.

6.2.4.5 Barents Shelf

The Barents Sea has a relatively low freshwater inflow compared with its area and the shelf also depends on coastal erosion for inorganic sediment supply (Tables 6.2.1 and 6.2.2). Of the Arctic shelves, the Barents has the highest mean depth (Table 6.2.1) and like the Chukchi Sea, it supports a healthy primary production based on the import of nutrients by Atlantic inflow. The Barents Sea has long sustained an industrial fishery for capelin and herring (Gjøesaeter 1995) although that fishery has suffered collapse due to the combined effect of overexploitation and climate variability. Sediment supply to support burial comes primarily from coastal erosion. The large primary production (~6300 × 10^9 mol C yr^{-1}) must be supported predominantly by Atlantic inflow (~820 × 10^9 mol yr^{-1} DIN) together with shelf-edge exchange and upwelling, with rivers providing but a minor supply (4.7 × 10^9 mol yr^{-1} DIN). The burial of marine organic carbon (25 × 10^9 mol C yr^{-1}) accounts for a negligible part of the new production. Despite its relatively high primary production, there is little evidence in, for example, the N:P relationship of bottom waters or lower halocline waters (see, e.g., Jones et al. 1998) that denitrification is an important process for this shelf. The difference between the Barents and Chukchi Shelves, both of which sustain large export production, is that the Barents Sea is relatively deep, allowing organic regeneration to occur within the water column, and the bottom water circulation is sufficiently vigorous to maintain oxic conditions near the bottom.

6.2.4.6 Canadian Archipelago Shelf

The shelf regions of the Arctic Ocean north of Greenland and the Archipelago comprise a mere 5% of the total Arctic shelf (Table 6.2.1) suggesting that shelf burial and exchange are likely to contribute a similarly relatively small component to the Arctic budgets. Nevertheless, because these regions provide an important outflow for shallow water from the Arctic to the Atlantic Ocean, they should not be neglected. The Archipelago outer shelves are likely to remain woefully under-sampled, especially for biogeochemical properties and processes and, therefore, there is little information by which to estimate terrestrial inputs, exchanges, and primary production. In the tables, we have divided the Archipelago shelves into the northern portion facing the Arctic Ocean, and the shelf collectively contained within the Archipelago Passages (Fig. 6.2.1; Tables 6.2.2, 6.2.3, and 6.2.4). The mean flow through the Archipelago, estimated at between 0.7 and 1.7 Sv (1 Sv $=10^6$ m^3 s^{-1}, e.g., see McLaughlin et al. 2006; Melling 2000; Rudels and Friedrich 2000), is out of the Arctic and this route is likely the predominant exit for Pacific water that has entered the Arctic through Bering Strait and for a substantial component of the freshwater from rivers especially those in the Western Arctic (Mackenzie, Yukon). The sill depths in the Archipelago, ~100 m for Lancaster/Jones Sound and ~200 m for Nares Strait, limit the outflow to low-density surface water containing runoff, ice melt, and Pacific water. Estimates of primary production for this region (McLaughlin et al. 2006; Michel et al. 2006; Sakshaug 2004; Welch et al. 1992) suggest that relatively high values (40 g C m^{-2} yr^{-1} new production or more) are sustained by imported nutrients from the Arctic Ocean and by mixing and upwelling within the Archipelago's passages with an important component of that production occurring in ice (Michel et al. 2006; Smith et al. 1988). Products of primary production and regeneration, however, are likely exported out of the Arctic Ocean with the mean flow. The volume of water contained within the Archipelago

($0.38 \times 10^6\,\mathrm{km}^3$) together with the mean flow (~1 Sv) imply a 12-year residence time, which suggests that the Archipelago channels considerably modify the water over the numerous annual cycles of light and temperature.

In the absence of data for this region, we have estimated the supply of materials from runoff and atmospheric deposition using averages for rivers and deposition in other Arctic regions excluding the Mackenzie River for the particle estimate (anomalously high particulate load), the Kara Sea inflow for nutrients (anomalously high nutrients), and the Laptev Sea for atmospheric deposition (anomalously high particle deposition). Some of the modern runoff in the Archipelago involves stored water deriving from recent glacial melt-back estimated to be approximately $800\,\mathrm{km}^3$ since about 1960 (Dyurgerov and Meier 1997) or, on average, about $20\,\mathrm{km}^3\,\mathrm{yr}^{-1}$. This water likely contains low nutrient and organic carbon content. Presently there are no data with which to evaluate the importance of sedimentation on the Archipelago shelves. Seismic profiles suggest that a number of basins within the channels sequester Holocene sediments (dating from ~10,500 years ago) but that much of the bottom is not presently accumulating material. Transport of material with the ice drift appears small relative to the other sources.

6.2.4.7 Beaufort Shelf

The Beaufort Sea is exceptional in the Arctic Ocean in that it is fed by a large, sediment-rich river, the Mackenzie River (Fig. 6.2.2f). This single source of sediments and fresh water dominates the oceanography of the adjacent shelf (Carmack and Macdonald 2002) and provides, by far, the largest single source of terrigenous sediment – about 50% of the entire supply by rivers to the Arctic Ocean (Macdonald et al. 1998). A consequence is that this region has the potential to sustain a healthy burial flux supported by the terrestrial inorganic material trapped over the shelf and in the canyons. The regional sediments of the Beaufort Sea and even those of the adjacent basin reflect their provenance in a strong suite of terrestrial biomarkers (Drenzek et al. 2007; Goñi et al. 2005; Grantz et al. 1996; Yunker et al. 1995). The new production of this shelf appears low at $3\text{–}17\,\mathrm{g\,C\,m}^{-2}\,\mathrm{yr}^{-1}$ (Arrigo and van Dijken 2004; Carmack et al. 2004; Forest et al. 2007; O'Brien et al. 2006; Sakshaug 2004). Despite the dominating influence of the Mackenzie River on regional oceanography (Carmack and Macdonald 2002) and sediment organic supply (Goñi et al. 2000; Goñi et al. 2005; Guo et al. 2007; Raymond et al. 2007), the river accounts for but a small component of the DIN and DIP required to sustain the new production. It does, however, supply a substantial (~30%) component of the required $\mathrm{Si(OH)_4}$. For this shelf, upwelling at the shelf edge or within the Mackenzie Canyon is likely the most important process to supply nutrients (Carmack et al. 2004; Macdonald et al. 1987; Williams et al. 2006) with this process potentially accessing Pacific-derived nutrient-rich water (100–200 m) (Macdonald et al. 1989). Like other shelves of the Arctic, burial of marine organic carbon and nitrogen accounts for very little of marine primary production implying that regeneration and export must occur (Goñi et al. 2005). Finally, the organic composition of the sediments is dominated by terrestrial organic carbon (~80% by composition).

6.2.5 The Total Arctic Ocean Budgets and Fluxes

6.2.5.1 The Influence of Terrigenous Supply

Inorganic sediment inputs to the Arctic Ocean (Fig. 6.2.3) are dominated by coastal erosion ($430\,\mathrm{Mt\,yr}^{-1}$) and river inflow ($237\,\mathrm{Mt\,yr}^{-1}$) with eolian sources playing only a very small role ($5.7\,\mathrm{Mt\,yr}^{-1}$). Noteworthy, the total sediment input to the Arctic Ocean cannot support the total estimated sediment sink (cf. $673\,\mathrm{Mt\,yr}^{-1}$ versus $1008\,\mathrm{Mt\,yr}^{-1}$ in Table 6.2.2). The imbalance between modern sediment supply and the sedimentation rate was suggested by Stein and Macdonald (2004) to arise from bias in the estimation of the sinks. Shelf sedimentation rates often have been assigned based on average Holocene accumulation rates, but recent rates have probably been lower than those in the earlier phases of deglaciation. The organic carbon budget reveals a very large marine labile carbon source (total production of $31{,}800 \times 10^9\,\mathrm{mol\,yr}^{-1}$), of which most is recycled, and only $\sim 301 \times 10^9\,\mathrm{mol\,yr}^{-1}$ is buried. On the other hand, the total supply of terrigenous organic carbon is far less ($1094 \times 10^9\,\mathrm{mol\,yr}^{-1}$), but far more of it is preserved through burial ($917 \times 10^9\,\mathrm{mol\,yr}^{-1}$).

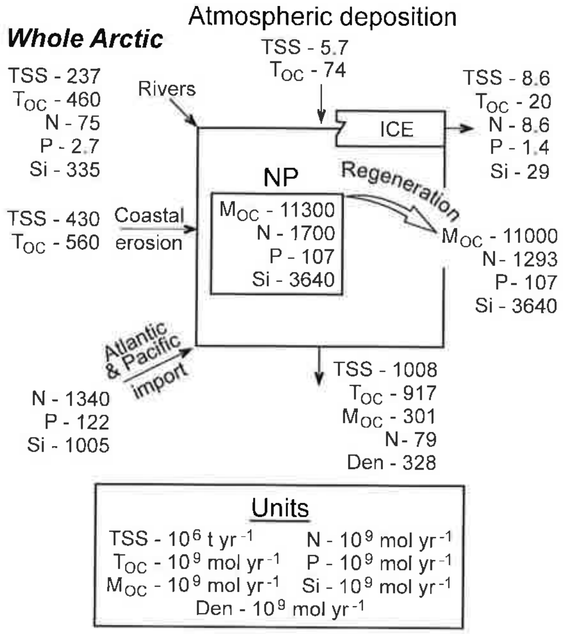

Fig. 6.2.3 Biogeochemical budget for the entire Arctic Ocean, with abbreviations the same as in Fig. 6.2.2

The total supply of DIN from rivers is about 75×10^9 mol yr^{-1} and this is augmented by approximately a further 38×10^9 mol yr^{-1} of DON. Together, these two sources of terrigenous fixed nitrogen could support only a very small proportion of the nitrogen required for the estimated new production of the Arctic Ocean (1700×10^9 mol yr^{-1}) and, indeed, this source does not even offset the total loss of nitrogen through denitrification and burial over shelves ($\sim 400 \times 10^9$ mol yr^{-1}). Although change in river inflow, recently demonstrated to be ± 10–20% over several decades (Déry and Wood 2005; Peterson et al. 2002), has often been proposed as an important manifestation of climate change (Vörösmarty et al. 2001), it is clear from the shelf budgets presented here that this magnitude of alteration in river flow has very little leverage for directly changing the nutrient budget of the Arctic Ocean. Finally, atmospheric deposition of reactive nitrogen from human activities appears to play almost no role in the Arctic budget (assuming deposition of ~ 1 mmol m^{-2} yr^{-1} (Levy and Moxim 1989) over an area of 10×10^6 km^2 implies a total deposition of $\sim 10 \times 10^9$ mol yr^{-1}).

6.2.5.2 The Influence of the Marine Supply

The predominant role of inflowing water from the Atlantic and Pacific Oceans and the shelf–edge exchange/upwelling in the Arctic Ocean nutrient budgets (Fig. 6.2.3) imply that alteration of the biogeochemical cycling though climate change and variability is more likely to occur via these parameters. We have seen decadal-scale variation in both the Atlantic (Swift et al. 1997) and the Pacific (Macdonald et al. 2005) inflows that suggest ±20% in these terms could easily be produced by, for example, changes in atmospheric pressure fields (North Atlantic Oscillation/Arctic Oscillation). Perhaps of greater interest would be the alteration of stratification in the Arctic Ocean either through change in river inflow or change in ocean storage of freshwater, which would then affect the return of deep nutrients to surface waters. Similarly, the loss of ice cover, as observed and projected in models (ACIA 2004), would change wind mixing, shelf-edge exchange, and upwelling (Carmack and Chapman 2003).

The estimated total new production for the shelves of the Arctic Ocean ($11{,}300 \times 10^9$ mol yr^{-1}; Fig. 6.2.3) suggests an export from the Arctic shelf surface of this amount of organic carbon together with 1700×10^9 mol yr^{-1} of nitrogen, 107×10^9 mol yr^{-1} of phosphorus, and 3640×10^9 mol yr^{-1} of silicate. The further loss of nitrogen and organic carbon to sediments leaves $11{,}000 \times 10^9$ mol yr^{-1} of organic carbon and 1280×10^9 mol yr^{-1} of nitrogen to be exported off the shelf as regenerated products. Taking Melling's (1993) estimate for halocline nourishment within the Arctic (37.8 km^3 yr^{-1}) and assuming, for example, an average nutrient content of such water to be 14 mmol m^{-3} (DIN), 1.3 mmol m^{-3} (DIP), and 26 mmol m^{-3} ($Si(OH)_4$) imply transports of 529, 49, and 983 (in units of 10^9 mol yr^{-1}) respectively, which accounts for perhaps half of the regenerated nutrients. It seems likely that salinification of shelf waters in winter to feed the halocline could account for perhaps half of the regenerated material leaving shelf–edge exchange or export particulate organic carbon from the shelf to account for the rest. In the case of silicate, two previous efforts to produce an arctic-wide budget (Anderson et al. 1983; Codispoti and Lowman 1973; Codispoti and Owens 1975) have discussed the difficulty of estimating the sedimentation flux, which falls within the errors in the differences between inflows and outflows. Perhaps 10% of the silicate entering primary production becomes buried (Codispoti and Owens 1975).

6.2.5.3 The Inorganic Carbon Budget with Emphasis on Greenhouse Gas Exchange

The inorganic carbon budget for the Arctic Ocean appears to be near balance, according to our current understanding of the various fluxes (Table 6.2.7; Anderson et al. 1990; Anderson et al. 1998b). Particularly strong uncertainties in the inorganic carbon budget lie with the sedimentation flux (i.e., possible changes in phytoplanktonic species progression that can result from variable environmental controls such as temperature and light availability) and with the air–sea exchange flux, including the extent to which sea ice is truly a barrier to gas fluxes. As noted in the introduction, estimates of annual CO_2 uptake from the atmosphere vary widely from 2250 to 14,700 × 10^9 mol yr^{-1}. However, even the low estimate of CO_2 uptake from the atmosphere made by Anderson et al. (1998b) is significantly larger than the terrigenous organic carbon preserved through burial (917 × 10^9 mol yr^{-1}, Table 6.2.2). Data for the individual shelves remain too sparse in space and time to assess with confidence to what extent each shelf area may act on average over a full year as an inorganic carbon source or sink. High latitude ocean surface waters display exceptionally low CO_2 concentration in summer with the degree of undersaturation varying from about 100 μatm in the Greenland Sea (Miller et al. 1999) to 150–200 μatm (~50% saturation) in the Chukchi, Laptev, and Kara Seas (Murata and Takizawa 2003; Pipko et al. 2002; Semiletov 1999a). In contrast, the Arctic Ocean in winter appears to be a source of CO_2 to the atmosphere (see, for example, Pipko et al. 2002; Semiletov et al. 2007), implying that yearlong records of fluxes will be required to make unbiased estimates of annual net CO_2 flux.

Table 6.2.7 Inorganic carbon budget[a]

	Input (10^{12} mol yr^{-1})	Output (10^{12} mol yr^{-1})
Net atmospheric exchange	2.0	
Pacific inflow	56.7	
Atlantic inflow	215.2	
Rivers	2.8	
Atlantic outflow		273
Ice export		0.8
Sedimentation		0.2
Total	276.7	274.0

[a] Based on Anderson et al. (1998b).

6.2.5.4 Arctic Shelves as Sources of Methane

Where measurements have been made, Arctic shelf sediments have been shown to be sources of methane (Damm et al. 2005; Kvenvolden and Grantz 1990; Kvenvolden et al. 1993; Macdonald 1976; Semiletov et al. 1996; Shakhova and Semiletov 2007; Shakhova et al. 2005). In the case of the Laptev and East Siberian Seas, methane supersaturation of surface water up to 2500% has been observed, implying that strong air-to-sea fluxes must occur at times. Methane fluxes from the sea floor measured for the Laptev and East Siberian shelves (Shakhova et al. 2005) ranged from 0.025 to 0.09 mol CH_4 m^{-2} yr^{-1} which, if prorated for the shallow parts of the Arctic shelves (~3000 × 10^3 km^2), implies a methane flux of 75–280 × 10^9 mol yr^{-1}. This estimate exceeds by up to four times the annual flux estimated for all coastal seas (Cynar and Yayanos 1993).

6.3 The Ross Sea[1]

Giulio Catalano, Giorgio Budillon,
Rosabruna La Ferla, Paolo Povero,
Mariangela Ravaioli,
Vincenzo Saggiomo,
Alessandra Accornero, Maurizio Azzaro,
Gian Carlo Carrada, Federico Giglio,
Leonardo Langone, Olga Mangoni,
Cristina Misic and Monica Modigh

We present budgets of carbon and nitrogen for the Ross Sea, Antarctica. The novelty of this study consists in estimating both vertical water column to sedimentary fluxes as well as horizontal exchanges due to water mass lateral transport between the continental shelf

---

G. Catalano (✉)
CNR – ISMAR – Office of Trieste, Viale Gessi, 2, 34123
Trieste, Italy
e-mail: giulio.catalano@ts.ismar.cnr.it

[1] This research was carried out in the frame of Italian National Antarctic Research Program (PNRA), within CLIMA, ROSSMIZE, and BIOSESO Projects. Thanks are due to Robert Dunbar for ROAVERRS data on sediment traps. The consultation of the web site of US JGOFS Project has been a very useful tool for the comparison of data sets used for this work.