

# The Arctic Ocean Estuary

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**Abstract** Large freshwater contributions to the Arctic Ocean from a variety of sources combine in what is, by global standards, a remarkably small ocean basin. Indeed, the Arctic Ocean receives ~11% of global river discharge while accounting for only ~1% of global ocean volume. As a consequence, estuarine gradients are a defining feature not only near-shore, but throughout the Arctic Ocean. Sea-ice dynamics also play a pivotal role in the salinity regime, adding salt to the underlying water during ice formation and releasing fresh water during ice thaw. Our understanding of physical–chemical–biological interactions within this complex system is rapidly advancing. However, much of the estuarine research to date has focused on summer, open water conditions. Furthermore, our current conceptual model for Arctic estuaries is primarily based on studies of a few major river inflows. Future advancement of estuarine research in the Arctic requires concerted seasonal coverage as well as a commitment to working within a broader range of systems. With clear signals of climate change occurring in the Arctic and greater changes anticipated in the future, there is good reason to accelerate estuarine research efforts in the region. In particular, elucidating estuarine dynamics across the near-shore to ocean-wide domains is vital for

understanding potential climate impacts on local ecosystems as well as broader climate feedbacks associated with storage and release of fresh water and carbon.

**Keywords** Arctic · Estuary · Ocean · River · Watershed · Inorganic nutrients · Organic matter · DOC · DON · Nitrate · Phosphate · Silica · Productivity · Ice

## Introduction

While the term “estuary” typically evokes images of the near-shore environment where continental runoff first mixes with ocean water, the scientific community has also considered estuarine processes over a range of larger spatial scales. Estuarine gradients associated with major river plumes are often studied over the continental shelf domain. Broader still, estuarine qualities of major ocean basins have been considered. For example, Tully and Barber (1960) described the North Pacific as an estuary, and Stigebrandt (1984) described exchange of Pacific and Arctic Ocean waters within an estuarine context. Aagaard and Carmack (1994) considered the estuarine character of the Arctic Ocean more fully, including the importance of freshwater export from the Arctic Ocean to the North Atlantic. Physical, chemical, and biological attributes of the Arctic Ocean estuary are developed further in papers by Macdonald (2000), Carmack and Wassmann (2006), and Carmack (2007). Sea-ice dynamics are an important focal point in all three of these papers. Carmack (2007) also places the Arctic Ocean estuary into a global context, pointing out that stratification of high-latitude seas in both hemispheres is predominantly controlled by salinity (*beta oceans*) whereas stratification of subtropical seas is predominantly controlled by temperature (*alpha oceans*).

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This paper describes the physical and biogeochemical characteristics that define Arctic estuaries (in the classical sense) and the estuarine character of the Arctic Ocean as a whole. It also includes discussion of the strengths and limitations of our current knowledge across the physical–chemical–biological realm and potential changes that we may see in the future. Finally, this paper provides a broad context for four synthesis papers organized around the Arctic Estuary theme. The synthesis papers address biogeochemical export from rivers (Holmes et al. 2011, this issue), coastal erosion (Lantuit et al. 2011, this issue), linkages between river-supplied nutrients and productivity (Tank et al. 2011, this issue), and near-shore ecosystem dynamics (Dunton et al. 2012, this issue). The first three papers consider the pan-Arctic domain as a whole, while the last one focuses in on the Beaufort and Chukchi Sea regions. Although estuarine ecology is not a major focal point herein, the subject is given significant attention by Dunton et al. (2012, this issue).

The Arctic Ocean receives massive inputs of fresh water from continental runoff as well as relatively low-salinity Pacific waters delivered through the Bering Strait (Fig. 1). Net precipitation on the ocean surface and inputs from the Norwegian Coastal Current and Fram Strait deep water also contribute to the freshwater budget of the Arctic Ocean (Serreze et al. 2006). These inputs combine in what is, by global standards, a remarkably small ocean basin. While the

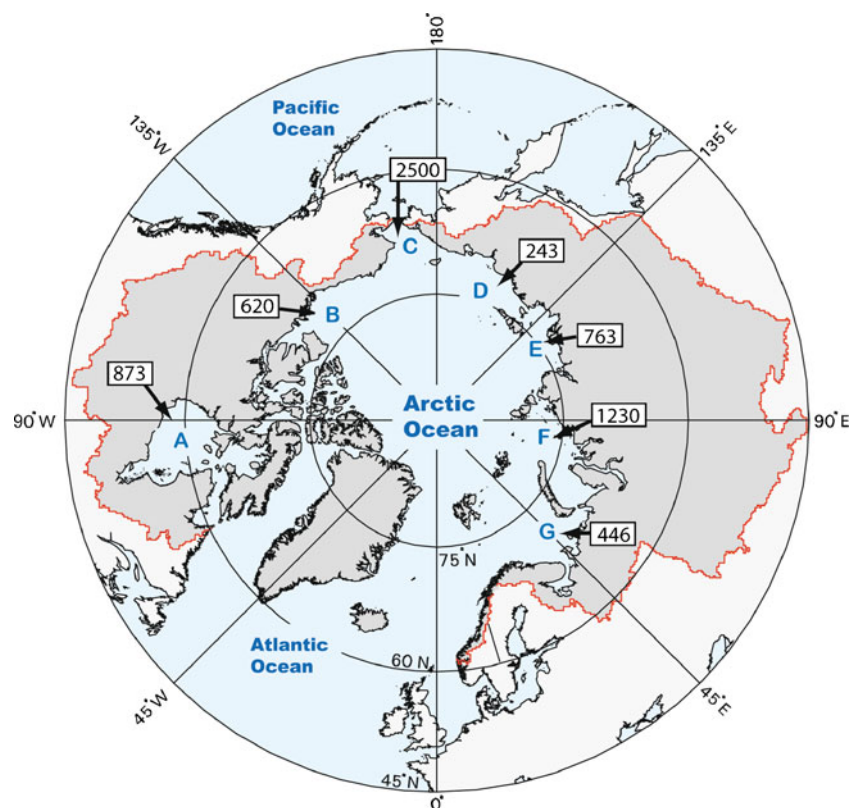
Arctic Ocean receives ~11% of the world's river discharge, it accounts for only about 1% of the world's ocean volume (Menard and Smith 1966; Aagaard and Carmack 1989). As a consequence, estuarine gradients are a defining feature not only near-shore, but throughout the Arctic Ocean. Sea-ice dynamics also play a pivotal role in the salinity regime, adding salt to the underlying water during ice formation and releasing fresh water during ice thaw (Macdonald 2000).

## River Inputs

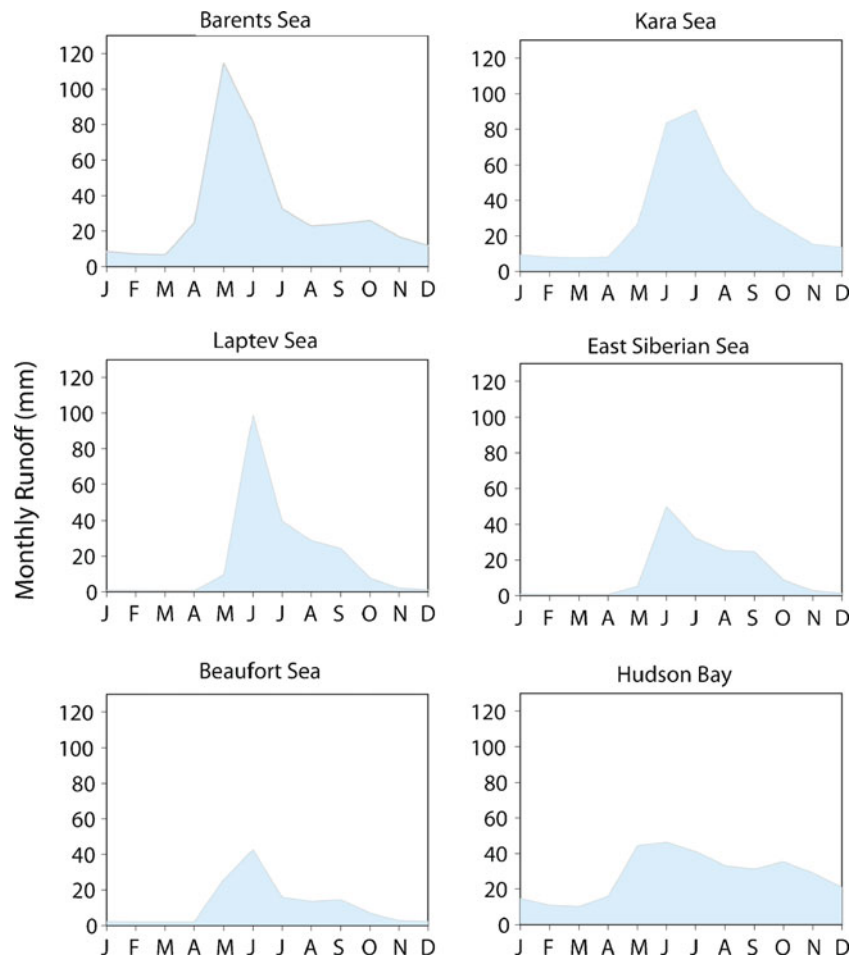
Marked seasonal variations in continental runoff are a defining feature around the pan-Arctic domain (Fig. 2). Most notably, runoff is relatively low during winter months and peaks with snowmelt in the spring. There are, however, distinct differences in runoff climatology among regions. For example, the winter–spring transition in runoff occurs during the March to May timeframe in the Barents Sea and Hudson Bay regions, whereas the winter–spring transition in runoff occurs in the April to June timeframe in the Kara Sea, Laptev Sea, East Siberian Sea, and Beaufort Sea regions. There are also distinct regional differences in the distribution of runoff among months (Fig. 2).

The regional differences in runoff reflect differences in precipitation regimes as well as differences in watershed

**Fig. 1** The pan-Arctic drainage basin and major freshwater inflows (cubic kilometers per year, as shown in boxes) to the Arctic Ocean and surrounding seas. Red line watershed boundary, A Hudson Bay, B Beaufort Sea, C Chukchi Sea, D East Siberian Sea, E Laptev Sea, F Kara Sea, G Barents Sea. Inputs from land were calculated from the regional runoff estimates of Lammers et al. (2001). The 2,500 km<sup>3</sup>/year input to the Chukchi Sea is the freshwater content of Bering Sea water flowing into the Arctic Ocean via Bering Strait based on a reference salinity of 34.8 (Serreze et al., 2006)



**Fig. 2** River runoff climatologies (millimeters per month) for six regions around the pan-Arctic domain. Data are average monthly runoff for 1990–1999. Regional runoff climatologies were calculated using the following rivers: Barents Sea (Mezen, Norway Tana, Onega, Pechora, and Severnaya Dvina), Kara Sea (Norilka, Ob, Pur, and Yenisey), Laptev Sea (Anabar, Lena, Olenek, and Yana), East Siberian Sea (Alazeya, Indigirka, Kolyma), Beaufort Sea (Anderson, Kuparuk, Mackenzie), Hudson Bay (Churchill, Hayes, Saskatchewan, Seal, Thlewiaza, Missinaibi, Kazan, Red, Winnipeg, Notaway, Eastmain, Grande Baleine, Harricana, Broadback, Nastapoca, Kogaluc, Innuksuac, Thelon). Data from R-ArcticNet (<http://www.r-arcticnet.sr.unh.edu/>), Arctic RIMS (<http://rims/unh.edu>), the US Geological Survey (<http://waterdata.usgs.gov/nwis>), and Water Survey of Canada's Hydrometric Database-YDAT ([www.wsc.ec.gc.ca/](http://www.wsc.ec.gc.ca/))

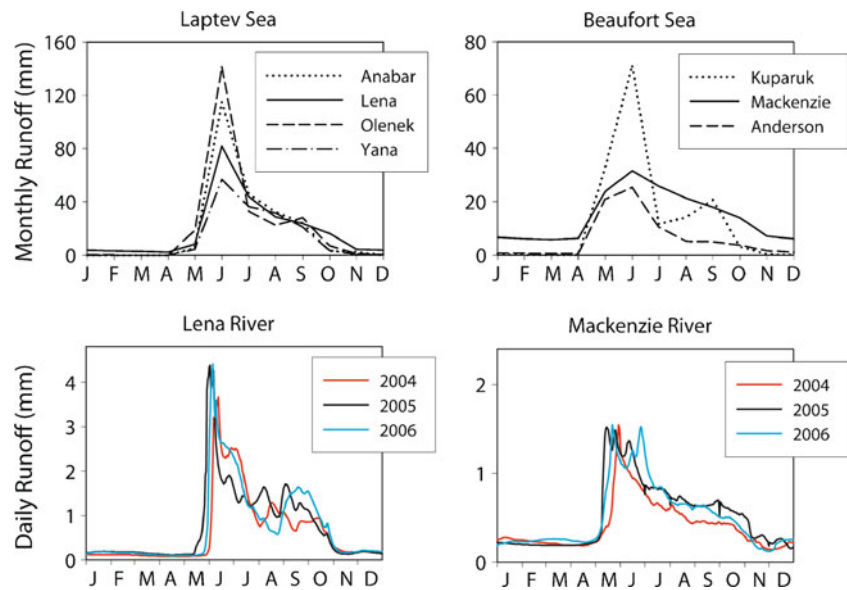


characteristics. The southern and northern boundaries of the pan-Arctic drainage basin vary substantially from region to region (Fig. 1), and the proportion of annual precipitation falling as rain versus snow in the regional watersheds is, in part, dependent on latitude (i.e., the latitudinal coverage of each drainage basin). Permafrost extent is also related to the latitudinal coverage of each drainage basin (Frey and McClelland 2009). For example, less than 20% of the area draining to Hudson Bay is underlain by continuous permafrost, whereas greater than 80% of the area draining to the Laptev Sea is underlain by continuous permafrost. Such differences in permafrost coverage contribute to differences in runoff among regions because drainage basins with permafrost typically have greater surface water flow in comparison to drainage basins without permafrost (McNamara et al. 1997; McNamara et al. 1998). In drainage basins with large reservoirs, regulation of flow through dams is an additional factor contributing to seasonal patterns in Arctic river discharge. For example, increases in winter discharge from several of the major Eurasian Arctic rivers are largely attributed to release of stored spring/summer runoff from reservoirs during winter months (Ye et al. 2003; McClelland et al. 2004; Yang et al.

2004). Reservoir effects have also been documented in the Mackenzie River basin and the Hudson Bay region (Woo and Thorne 2003; Déry and Wood 2005).

While the climatologies shown in Fig. 2 highlight broad similarities and differences in runoff regimes around the pan-Arctic domain, combining multiple rivers and binning the data in monthly increments mask some notable features within regions. A comparison of runoff data from the Laptev Sea and Beaufort Sea regions exemplify variability underlying the regional climatologies (Fig. 3). In both cases, there is remarkable synchrony in terms of the timing of peak runoff among rivers, but the proportion of runoff occurring during June as compared with other months varies widely among rivers (Fig. 3, top panels). When considering daily runoff, it is also apparent that the winter–spring transition is very abrupt in any given year (Fig. 3, bottom panels). The more gradual representation of the winter–spring transition shown in the monthly climatologies is a reflection of averaging among years. Although these patterns represent runoff from catchments of vastly different sizes, ranging from 78,800 to 2,430,000 km<sup>2</sup> in the Laptev case and 8,400 to 1,680,000 km<sup>2</sup> in the Beaufort case, it is important to keep in mind that runoff patterns

**Fig. 3** Comparison of runoff climatologies, average millimeters per month for 1990–1999, for individual rivers in the Laptev Sea and Beaufort Sea regions (*top panels*) and daily runoff for 2004, 2005, and 2006 in the Lena and Mackenzie rivers (*bottom panels*). Data sources are as described for Fig. 2



become more variable at smaller scales. For example, only about one third of the annual runoff within the upper Kuparuk River basin (140 km<sup>2</sup>) is contributed by snowmelt (Kane et al. 2000). The dominant spring peaks we see in most of the larger Arctic rivers reflect the fact that onset of snowmelt is similar across broad areas whereas rainfall patterns vary substantially over smaller scales.

Differences in geomorphology also contribute to variations in runoff patterns among drainage basins within the pan-Arctic watershed. For example, drainage basins in western and eastern Siberia differ substantially with respect to large-scale relief (Gordeev 2006). Most notably, the Western Siberian Lowlands cover an area of ~1.8 million km<sup>2</sup> that accounts for ~2/3 of the total area of West Siberia (Kremenetski et al. 2003). A large proportion of the lowland area lies within the Ob River drainage basin. Smaller proportions lie within the Nadyam, Pur, Taz, and Yenisey drainage basins. The gentle relief in this vast lowland area has a direct impact on flow rates and runoff ratios. In addition, extensive growth of wetland vegetation and build-up of peat deposits within the lowlands mediates water flow through the region. While effects of large-scale topography are emphasized here, it is also important to keep in mind that permafrost has a strong influence on patterns of water flow through the landscape. Indeed local geomorphology related to formation and maintenance of river channel networks differs substantially between areas with and without permafrost (McNamara et al. 1999).

The large seasonal variations in continental runoff in the Arctic are accompanied by large seasonal variations in nutrient and organic matter inputs from rivers to the coastal ocean. Holmes et al. (2011, this issue) describe these inputs in detail. Here, we highlight some general characteristics of nutrient and organic matter fluxes from Arctic rivers.

Seasonal changes in water discharge alone account for much of the variation in constituent fluxes. In addition, seasonally varying concentrations of dissolved and particulate material contribute to variations in constituent fluxes. For example, organic matter concentrations increase dramatically during the spring freshet, while nitrate and silica concentrations show the opposite pattern. These concentration changes are tightly coupled to seasonal changes in water flow paths through the landscape (MacLean et al. 1999; Frey and McClelland 2009; Guo and Macdonald 2006; Guo et al. 2007). Frozen ground constrains water flow to organic rich surface layers during the spring snowmelt period. As the ground thaws, an increasing proportion of the water moves through mineral soils along deeper flow paths. Where there is permafrost, flow paths are constrained to the seasonally thawed portion of the soil profile (active layer), and deep groundwater contributions (i.e., via springs) are relatively small.

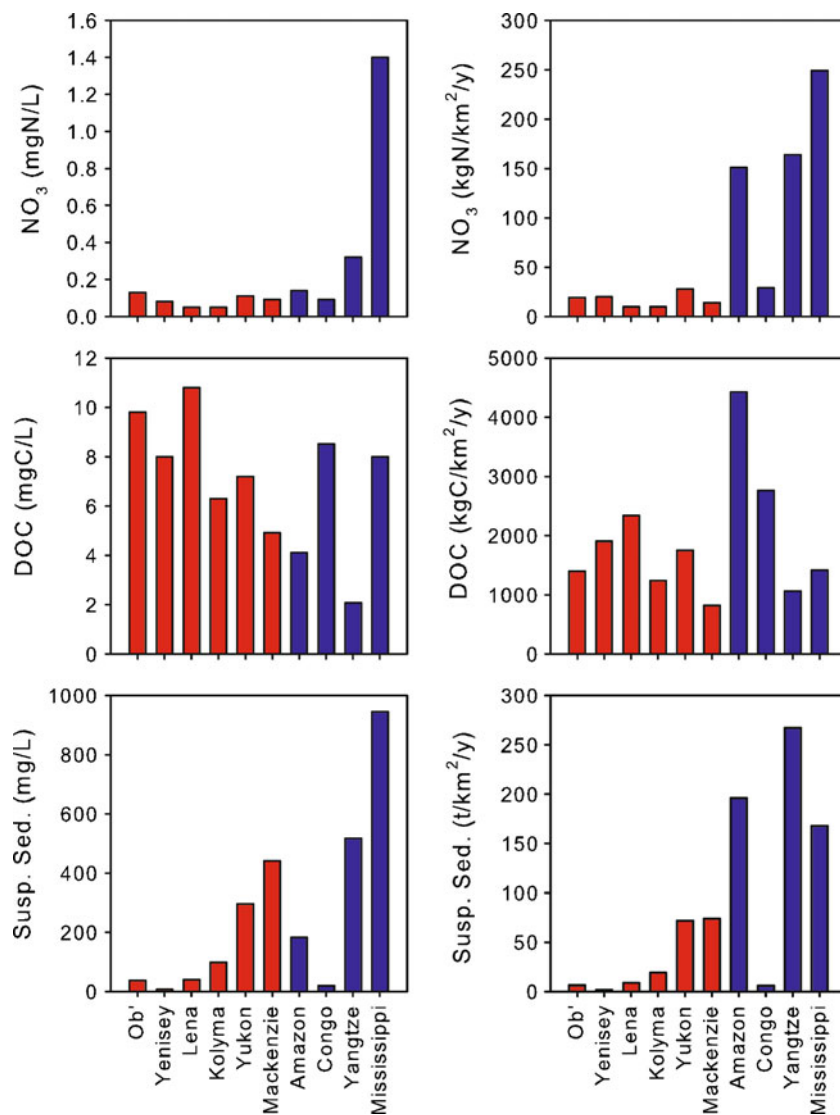
Seasonal vegetation growth and microbial activity also contribute to variations in nutrient and organic matter concentrations in arctic rivers. For example, growth of tundra vegetation on the North Slope of Alaska is nitrogen-limited during summer months, and loss of inorganic nitrogen from soils to tundra streams is relatively low during the growing season (Peterson et al. 1992; Rastetter and Shaver 1992; Williams et al. 2000). Increased microbial activity during summer months provides a source of inorganic nitrogen through mineralization of organic matter, but much of this nitrogen is taken up by the vegetation. Likewise, while decomposition of detritus generates dissolved organic matter, net uptake and mineralization of dissolved organic matter by microbes may be a contributing factor to lower dissolved organic matter concentrations observed in arctic river waters during the summer (Striegl et

al. 2005). Higher temperatures and longer residence times (in both soils and stream/river networks) during summer base-flow conditions combine to facilitate microbial decomposition of dissolved organic matter. Holmes et al. (2008) demonstrated that dissolved organic carbon (DOC) in rivers on the North Slope of Alaska is much more labile during the spring freshet than later in the summer. This finding is consistent with greater net mineralization of dissolved organic matter during watershed transit over the summer months.

In general, river waters entering the Arctic Ocean are rich in organic matter and depleted in inorganic nitrogen. This is demonstrated in Fig. 4 by a comparison of DOC and nitrate concentrations in the six largest rivers draining the pan-Arctic watershed (Ob, Yenisey, Lena, Kolyma, Yukon, and Mackenzie) with several other major rivers around the world (Amazon, Congo, Yangtze, and Mississippi). Ranked by discharge, the Amazon, Congo, and Yangtze are among

the five largest rivers in the world. The Mississippi River ranks within the top ten. Nitrate concentrations in the arctic rivers consistently fall toward the lower end of the overall concentration range in this comparison. Furthermore, the nitrate yields (kilograms nitrogen per square kilometer per year) from the drainage basins of the major arctic rivers are much lower than the yields from the Amazon, Yangtze, and Mississippi drainage basins. The relatively low nitrate yields from the arctic drainage basins are a reflection of much lower annual runoff in the arctic basins as compared with the other basins. In contrast with nitrate, DOC concentrations in the arctic rivers fall within the upper half of the overall concentration range, and DOC yields from the arctic basins fall in the middle of the overall yield range (Fig. 4). In this case, relatively high DOC concentrations in the arctic rivers compensate for low runoff to maintain intermediate yields. The pattern for dissolved inorganic phosphorus is similar to that of nitrate (i.e., low concentra-

**Fig. 4** Concentrations (left column) and yields (right column) of nitrate, dissolved organic carbon, and total suspended sediment in the six largest rivers draining the pan-Arctic watershed (red bars) as well as several other major rivers around the world (blue bars). Average annual water discharge: Amazon (6,590), Congo (1,200), Yangtze (928), Yenisey (620), Lena (530), Mississippi (529), Ob (404), Mackenzie (307), Yukon (205), and Kolyma (132 km<sup>3</sup>/year). Data from: Holmes et al. (2002), (2011, this issue); Meybeck and Ragu (1996)



tion, low yield), and the pattern for dissolved organic nitrogen is similar to that of DOC (i.e., high concentration, intermediate yield). Dissolved silica concentrations in the major arctic rivers are not remarkably different than those found in the other major rivers. While these comparisons between the largest arctic rivers and other major rivers of the world highlight key differences that are important to consider in the development of estuarine research programs in the Arctic, it is also important to keep in mind that unique aspects of smaller arctic rivers may not be well-represented. Furthermore, we still have a tremendous amount to learn about the soil and in-stream processes contributing to the unique biogeochemistry of arctic rivers.

Suspended sediment in the major arctic rivers show a distinct dichotomy between higher concentrations in the North American rivers (Yukon and Mackenzie) and lower concentrations in the Eurasian rivers (Ob, Yenisey, Lena, Kolyma). This dichotomy is primarily a consequence of greater proportional runoff from mountainous terrain in the Yukon and Mackenzie basins as compared with the other basins (Holmes et al. 2002). In comparison with the Amazon, Congo, Yangtze, and Mississippi, sediment concentrations in the Eurasian arctic rivers are most similar to the Congo River, whereas sediment concentrations in the North American arctic rivers are intermediate between the Amazon and Yangtze rivers (Fig. 4). As discussed above for nitrate, lower runoff in the arctic basins leads to markedly lower yields from these basins compared with the Amazon, Yangtze, and Mississippi.

### Estuaries within the Arctic

This section focuses on river-to-shelf salinity gradients, including major river plumes as well as smaller estuaries more intimately associated with the near-shore environment. Classical estuarine studies have been relatively rare in the Arctic. A query of the *ISI Web of Science* database (done in November 2009) using “arctic” and “estuary” as search terms returned 256 hits. However, only 65 papers emphasized estuarine processes within the river-to-shelf domain of the Arctic. Out of the 65 papers, 35% dealt with Mackenzie River inputs, 22% dealt with Ob/Yenisey River inputs, and 17% dealt with Lena River inputs. The remaining 26% covered a variety of smaller estuaries around the Arctic. While this query undoubtedly missed some studies, the results do serve to highlight a relative emphasis on estuarine dynamics associated with inputs from a few very large rivers, all of which have large watersheds that extend south of what is typically considered to be “Arctic”. Furthermore, it should be noted that most of the papers (~2/3) identified in the query emphasized findings from field efforts conducted during mid- to late summer.

While seasonality has long been recognized as a defining feature in the Arctic, much of the work done on estuaries has been constrained to summer as a consequence of logistical challenges. There has been a major effort to improve our understanding of seasonal variations in the chemistry of river inputs to the Arctic Ocean during recent years (McClelland et al. 2008), but additional complexities associated with coastal ocean work in the Arctic make it difficult to conduct parallel studies in estuarine waters. Our current conceptual model of seasonal dynamics in arctic estuaries was largely formed from early studies in the Mackenzie system (Macdonald 2000; Carmack et al. 2004). However, more general models based on work in a range of Arctic and sub-Arctic estuaries are beginning to emerge (Kuzyk et al. 2008). We have also gained important insight (albeit largely during summer) about the transport, fate, and effects of river inputs in coastal and shelf waters from major coordinated efforts such as the Siberian river runoff (SIRRO) project focusing on the Kara Sea system (Stein et al. 2003), an earlier German–Russian program in the Laptev Sea system (Kassens et al. 1999), and the Canadian Arctic Shelf Exchange Study (CASES)/Arctic River-Delta Experiment (ARDEX) focusing on Mackenzie River inputs to the Beaufort Sea (Emmerton et al. 2008; Retamal et al. 2008; Vallières et al. 2008).

### Physical Characteristics of Arctic Estuaries

While geomorphology and the relative magnitudes of freshwater inflow and tidal mixing are fundamental determinants of estuarine gradients throughout the world, seasonal ice dynamics in coastal waters add to the complexity of Arctic estuaries through effects on wind mixing, buoyancy, and circulation (Macdonald 2000). During periods of ice cover (~9 months each year around much of the Arctic), coastal waters are not subject to wind mixing and thus stratification associated with river water inputs is enhanced. Ice formation reduces buoyancy by injecting salt into the underlying water column whereas ice melt increases buoyancy by adding fresh water. Some salt is retained as sea-ice forms, but the majority is rejected as brine. Sea-ice melt typically adds back brackish water with a salinity of around 5 (Macdonald et al. 1989; Alkire and Trefry 2006). Freeze/thaw effects on the salt balance are relatively small at the head of the estuary. However, they become more important as salinity increases along the estuarine gradient. The freezing and thawing effects may balance each other over annual timeframes. However, ice and the water from which it was formed are often spatially separated (i.e., the underlying water moves on) during the long winter months so that, when the ice does thaw, it represents a net freshwater source to the local environment. At the same time, the salt that was excluded effectively reduces the freshwater inventory at another location.

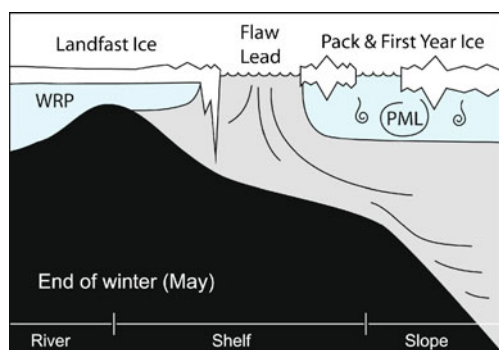
Ice production is greatest at the interface between landfast ice and drifting ice (Fig. 5). Open water areas (flaw lead polynyas) are maintained over much of the winter along this interface and thus new ice continues to form throughout the winter. Brine rejected during ice formation at the polynyas can drive deep convection, but the magnitude of this effect (or even whether or not deep convection occurs) depends strongly on the salinity of the water at the site of ice formation. The polynyas typically form over the mid-shelf, and any freshwater contributions from rivers that reach these areas work against deep convection. In general, one might expect river waters to influence convection mostly in areas where the polynyas are relatively close to shore and river water inputs are large. However, rubble ice (stamukhi) generated by convergence of landfast and drifting ice can form an inverted dam that traps river water on the landward side of the polynya during the winter months (Fig. 5). This has been well-documented in the Mackenzie River/Beaufort Sea system (Macdonald and Carmack 1991; Macdonald et al. 1995; Carmack and Macdonald 2002). In other areas, such as the Lena River/Laptev Sea system (Eicken et al. 2005), the Alaskan Beaufort Sea coast (Alkire and Trefry 2006), and the Churchill River region of the Hudson Bay (Kuzyk et al. 2008), stamukhi dams appear to be less important in controlling river water spread over the shelf. Aside from the presence or absence of seasonal effects related to ice dams, river water residence times over different shelf regions are an important consideration with respect to convection. Where residence times are greater than 1 year, river inputs from preceding years help set the stage for whether sea-ice formation can produce penetrative convection during any given ice growth season. River water residence times in the Kara, Laptev, and East Siberian shelf regions are around 2–4 years whereas river water residence

times over the Beaufort and Chukchi shelves are typically less than 1 year (Macdonald 2000).

#### Nutrient and Organic Matter Dynamics in Arctic Estuaries

The nutrient and organic matter concentrations of ocean end-members for Arctic estuaries can be coarsely separated into a Pacific water source that mixes with freshwater inputs from North America and an Atlantic water source that mixes with freshwater inputs from Eurasia; the ocean end-members have different nutrient concentrations (Macdonald et al. 1989) and different ratios between the nutrients (Jones et al. 2003). Below the mixed layer, the Pacific source is characterized by  $\sim 15$  nitrate,  $\sim 2$  phosphate, and  $\sim 30$   $\mu\text{M}$  silica at salinities near 33.1 (Macdonald et al. 1989; Carmack et al. 2004), while the Atlantic source is characterized by  $\sim 8$  nitrate,  $\sim 1$  phosphate, and  $\sim 6$   $\mu\text{M}$  silica at a salinity of 34.9 (Cauwet and Sidorov 1996; Dittmar et al. 2001). DOC concentrations are 50–60  $\mu\text{M}$  in both sources (Dittmar et al. 2001; Emmerton et al. 2008). Average (discharge-weighted) concentrations of nitrate and phosphate in arctic rivers are lower than these ocean end-members, and average (discharge-weighted) concentrations of silica and DOC are higher than these ocean end-members (Holmes et al. 2011, this issue). Thus, river inputs act to dilute the Arctic Ocean with respect to nitrate and phosphate and enrich the Arctic Ocean with respect to silica and DOC. That said, it is important to keep in mind that stratification and biological uptake in surface waters can leave effective ocean end-member concentrations much lower with respect to nitrate, phosphate, and silica during summer months. While nitrate and phosphate availability have the potential to limit total primary production in the photic zone, availability of silica can limit diatom growth and thus influence the proportion of total production contributed by diatoms (Davis et al. 1978; Egge 1998; Officer and Ryther 1980). High dissolved inorganic Si/N and Si/P ratios in Arctic rivers relative to diatom stoichiometry (Si/N/P of  $\sim 17:16:1$ ) set the stage for unrestricted competition between diatoms and other primary producers in coastal waters. However, different patterns of Si, N, and P cycling along estuarine gradients lead to temporal and spatial variability in nutrient limitation.

During the open water season, distributions of inorganic nutrients in Arctic estuaries are not strikingly different than observed in many other estuaries (particularly those with low nutrient loads) around the world. For example, concentrations of dissolved phosphate and nitrate fall below estimated values for conservative mixing across wide salinity ranges in the Lena and Mackenzie estuaries (Cauwet and Sidorov 1996; Carmack et al. 2004; Emmerton et al. 2008). Extra care must be taken when interpreting salinity-property plots in the Arctic because formation and thawing of sea-ice can significantly alter the salinity regime.



**Fig. 5** Schematic diagram showing major features of frozen estuaries in the Arctic. Note that the ice dam depicted at the seaward extent of the landfast ice is a prominent feature of the Mackenzie estuary that constrains spreading of river water over the shelf. This damming effect varies among Arctic estuaries depending on the location of the flaw lead and the amount of rubble ice (stamukhi) that forms at the landfast ice edge. *WRP* Winter River Plume, *PML* Polar Mixed Layer

Additional freshwater tracers such as stable oxygen isotope ratios in water ( $\text{H}_2\text{O}-\delta^{18}\text{O}$ ) help separate runoff from sea-ice effects (Östlund and Hut 1984; Macdonald et al. 1995; Cooper et al. 2008). In any case, variations in dissolved nitrate and phosphate concentrations relative to the Redfield ratio (N/P of 16:1) suggest that phosphorus limits total primary production at the lower end of the estuarine gradient (salinities from  $\sim 0$  to 10) and nitrogen limits total primary production further off-shore in the Mackenzie/Beaufort system. In the Lena/Laptev system, nitrogen appears to be the limiting nutrient for total primary production throughout the estuary. Distributions of dissolved silica also reflect effects of biological uptake in the estuaries, but the silica concentrations are much higher than the nitrate and phosphate concentrations over most of the salinity range. In waters over the Canadian Shelf of the Beaufort Sea, spatial variations in nutrient ratios suggest that silica delivered from the Mackenzie River is sufficient to support optimum diatom growth over the inner shelf, but becomes a limiting factor over the middle to outer shelf (Carmack et al. 2004).

In contrast with the non-conservative behavior of inorganic nutrients discussed above, several studies have shown that DOC concentrations in Arctic estuaries fall along conservative mixing lines from high concentrations in river waters to much lower concentrations at the marine end (Cauwet and Sidorov 1996; Emmerton et al. 2008; Köhler et al. 2003). In some cases, these results have been cited as evidence that river-borne dissolved organic matter is highly refractory and passes through the estuaries largely unaltered. Several studies have estimated significant losses of terrigenous DOC within the Arctic Ocean over longer timeframes (Opsahl et al. 1999; Hansell et al. 2004; Cooper et al. 2005), but losses in the near-shore and shelf environments have generally been considered negligible. However, recent studies of photomineralization (Osburn et al. 2009) and bacterial consumption (Holmes et al. 2008) of river-borne DOC exported to Arctic estuaries have demonstrated substantial losses over relatively short timeframes during bottle incubation experiments. Furthermore, Granskog et al. (2009) showed that over 50% of the chromophoric dissolved organic matter delivered by rivers was photo-bleached within months as it was transported under ice-free conditions in the Hudson Bay coastal current. Seasonal variations may help reconcile the conservative mixing results with the results showing substantial short-term losses of dissolved organic matter. In the bottle incubation experiments (Holmes et al. 2008; Osburn et al. 2009), losses were much higher in water collected during spring as compared with late summer. The more reactive fraction of DOC delivered to the estuaries during the spring freshet may largely be gone by mid- to late summer, when most of the research on Arctic estuaries has been done.

Dissolved organic nitrogen (DON) shows similar pattern to DOC in the Ob and Yenisey estuaries (Köhler et al. 2003), but very different patterns than DOC in the Mackenzie (Emmerton et al. 2008) and Lena (Cauwet and Sidorov 1996) estuaries. In the Lena case, non-conservative behavior of DON suggests major losses within the lower end of the salinity range (0 to  $\sim 10$ ). In the Mackenzie case, DON concentrations are positively correlated with salinity, increasing toward remarkably high DON concentrations ( $\sim 20$  to  $25 \mu\text{M}$ ) over the shelf. The different patterns for DON relative to those observed for DOC serve as a reminder that the dissolved organic matter pool contains a complex mixture of molecules that range widely in their reactivity. In a study of 12 Russian arctic rivers and associated shelf waters, Dittmar et al. (2001) reported that dissolved hydrolyzable amino acids (DHAA) account for  $\sim 10\%$  (ocean) to  $\sim 40\%$  (river) of the total DON. The composition of the DHAA pool suggested that these amino acids were largely recalcitrant. However, as discussed with respect to DOC, more reactive fractions delivered during the spring freshet may have been missed as a consequence of sampling during mid- to late summer. Tank et al. (2011, this issue) use a modeling approach to examine the potential of river-supplied DON to support production across the near-shore, shelf, and basin domains of the Arctic Ocean. This approach accounts for seasonally varying inputs of DON and explicitly considers the roles of photomineralization and microbial processing.

Bulk particulate concentrations in Arctic estuaries decrease rapidly in the near-shore environment (referred to as the “marginal filter” by Lisitsyn 1995) due to net sedimentation. As observed globally, this process is facilitated by flocculation as freshwater and saltwater mix. Particulate organic matter concentrations decrease with the bulk suspended material (Macdonald and Yu 2006; Emmerton et al. 2008), and the proportion of phytoplankton contributing to the suspended organic matter pool increases (Nöthig et al. 2003; Retamal et al. 2008). However, there are also some notable differences among Arctic estuaries with respect to phytoplankton distributions during the open water season (as indicated by chlorophyll and/or biomass). Concentrations of phytoplankton peak strongly at the freshwater ends of the Ob, Yenisey, and Lena estuaries (Sorokin and Sorokin 1996; Nöthig et al. 2003; Makarevich et al. 2003), whereas phytoplankton concentrations remain relatively level across the river-to-estuary transition in the Mackenzie system, and there is a marked chlorophyll maximum at a depth of  $\sim 25$  m farther off-shore (Carmack et al. 2004; Retamal et al. 2008; Emmerton et al. 2008). This difference may be related to greater light attenuation in near-shore waters of the Mackenzie River estuary as a consequence of much higher suspended sediment inputs compared with the other estuaries.

While the above discussion, and most of the research on biogeochemistry of Arctic estuaries to date, has emphasized



nutrient and organic matter dynamics during mid- to late summer, the marked seasonality of Arctic estuaries is what makes them truly unique. Short daylight hours and thick ice/snow cover strongly limit light availability in the water column during 8–9 months each year. Under these conditions, nutrients delivered to coastal waters via rivers (i.e., rivers large enough to maintain year-round flow) are not rapidly consumed and thus spread out and build-up under the ice (Cauwet and Sidorov 1996; Carmack et al. 2004; Kuzyk et al. 2008). The distribution of river-supplied nutrients over the shelf can be tightly constrained by stamukhi dams, as in the Mackenzie case, or much less so where flaw leads are further off-shore and/or there is less ice deformation. In any case, these nutrients are a potentially important resource supporting primary production as day length increases and ice cover thins. Growth of algae within brine channels and attached to the bottom of the ice provide an important food source to consumers during the early growing season (Horner and Schrader 1982; Juul-Pedersen et al. 2008; Rozanska et al. 2009), and this ice algae is well situated to take advantage of a winter build-up of nutrients. Nutrients supplied by rivers during winter may also help support early phytoplankton blooms in the water column at flaw lead polynyas, but again, this depends on the location of the flaw lead and the extent to which stamukhi dams constrain winter river plumes.

Inputs of organic matter from arctic rivers have the potential to contribute to secondary production throughout the year, and in the absence of primary production (i.e., during the winter), these inputs may provide a particularly important subsidy to estuarine communities. Stable isotopic evidence suggests that land-derived organic matter contributes to the food webs of Alaskan Beaufort Sea lagoons (Dunton et al. 2006). Likewise, studies of heterotrophic production and food web relationships in the Mackenzie estuary have demonstrated that river-supplied organic matter is a significant resource for plankton communities near the river mouth (Parsons et al. 1988, 1989; Garneau et al. 2006). Furthermore, analyses of carbon quantity and quality in sediment samples from the Mackenzie River and Beaufort Shelf point to significant annualized losses of river-supplied particulate organic matter in the coastal ocean (Goñi et al. 2005). The Goñi et al. (2005) study did not separate losses due to burial within the delta from leaching and/or net respiration. However, larger percentage loss of modern carbon as compared with ancient carbon in this study suggests that a significant proportion of the modern carbon in the particle load delivered by the Mackenzie River is respired. The extent to which land-derived organic matter specifically supports heterotrophic activity during the winter remains to be seen. One might reasonably assume that lower temperatures and organic matter inputs limit heterotrophic activity during the long arctic winter. Yet, non-conservative behavior of ammonium

and nitrate within the Lena estuary during the winter suggest that significant nitrification and denitrification occur over this time period (Cauwet and Sidorov 1996). Dunton et al. (2012, this issue) address near-shore ecosystem dynamics in the Arctic, including seasonality and potential trophic linkages with terrestrial organic matter, in greater detail.

At the onset of the spring freshet, landfast ice is still in place around much of the pan-Arctic domain. Increased river discharge can accelerate ice melt when river water temperatures are higher than the coastal waters they flow into, and river water that flows out over the ice surface accelerates melting through effects on albedo (Dean et al. 1994). However, most of the river water delivered during the spring freshet pushes out under the ice, mixing with and/or displacing the river water that built up slowly during the winter (Macdonald 2000). This has interesting consequences for the estuarine nutrient regime because the river waters delivered during the spring freshet have much lower inorganic nutrient concentrations and much higher organic matter concentrations than the river waters delivered during the winter (Holmes et al. 2011, this issue). When the ice breaks up and primary production in the water column is able to begin in earnest, nutrient concentrations may be higher off-shore than near-shore. Carmack et al. (2004) demonstrated that landfast ice in the Mackenzie River region delays the onset of phytoplankton production in the water column by ~1 month over the inner shelf compared with the outer shelf. While this delay is largely a function of light availability, the off-shore nutrient regime supports more primary production as well. The patterns in phytoplankton production reported in Carmack et al. (2004) are broadly corroborated by sediment trap data (O'Brien et al. 2006). In addition, O'Brien et al. (2006) demonstrate the importance of coastal erosion and sediment re-suspension as contributors to organic matter content in the water column after the ice retreats.

As winter approaches and ice once again forms over Arctic estuaries, brine rejection concentrates nutrients and organic matter in surface waters (Macdonald and Yu 2006). This process is most evident for constituents that are already at relatively high concentrations when the ice begins to form. For example, a positive offset in mixing lines for dissolved silica between summer and winter in the Mackenzie estuary has been attributed to rejection of dissolved silica from the accumulating ice. A maximum ice thickness of approximately 2 m ultimately limits this effect over the inner shelf, while it continues with ice production throughout the winter at flaw lead polynyas.

### Estuarine Character of the Arctic Ocean as a Whole

In the [Introduction](#), we identified continental runoff, inflow of Pacific waters through Bering Strait, and net precipitation

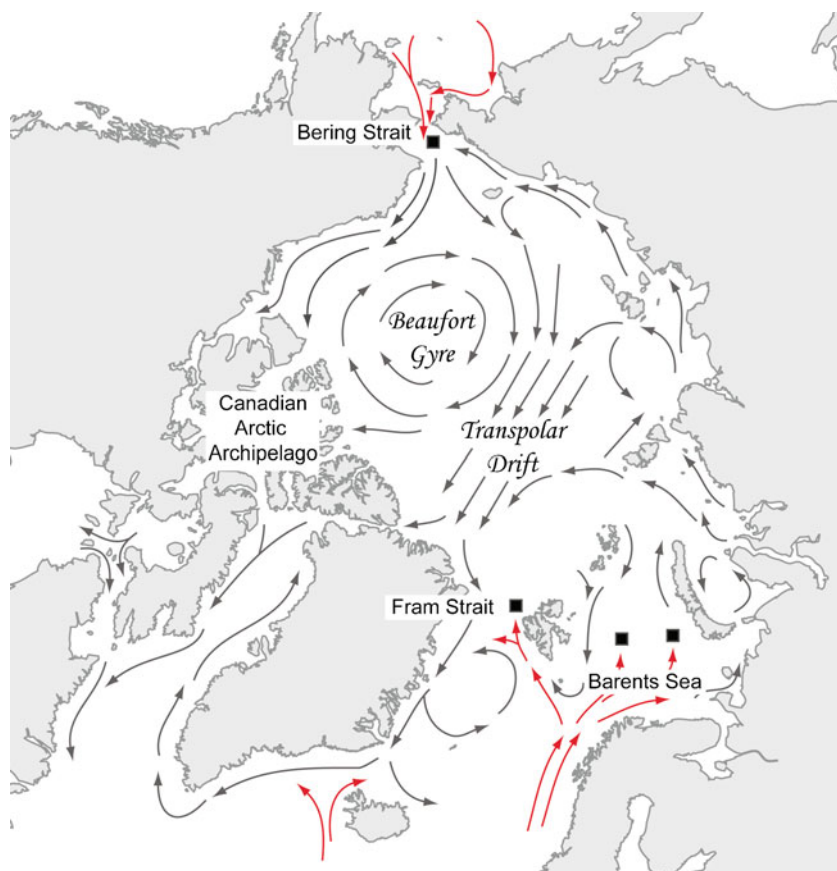
on the ocean surface as the major freshwater sources to the Arctic Ocean. The salty end of this great estuary is the northern Atlantic Ocean. In general, stratification of the Arctic Ocean consists of a seasonally variable surface mixed layer occupying the upper ~30 to 50 m of the water column, a complex of cold, salt stratified layers that define the halocline, a saline but warmer Atlantic layer, and deepwater below 1,600 m (Carmack 2000). The mixed layer is fresher and the halocline extends deeper in the western Arctic as compared with the eastern Arctic. The halocline in the western Arctic also exhibits more structure. These differences largely reflect the influence of Pacific water inflow to the western Arctic. The Atlantic layer is primarily derived from inflow of North Atlantic water through Fram Strait and the Barents Sea. The surface water inflows from the Pacific and North Atlantic are shown as red arrows in Fig. 6. In all cases, the inflowing waters submerge under more buoyant surface waters as they enter the Arctic Ocean basin.

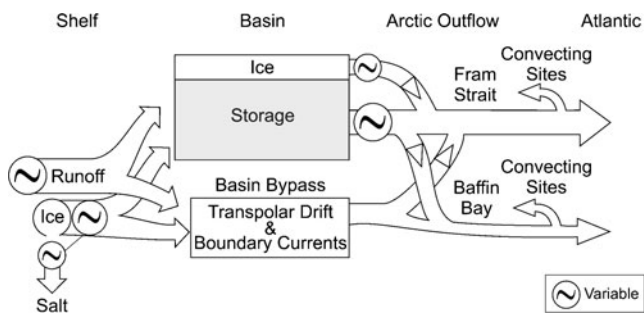
Within the interior basins of the Arctic Ocean, there are two main flow fields for surface waters. Waters on the Eurasian side primarily move from the Siberian shelf toward Greenland along the Transpolar Drift, whereas waters on the North American side circulate through the Beaufort Gyre (Fig. 6). The Arctic Ocean also supports a large-scale connected network of coastal currents that facilitate movement of continental runoff out of the Arctic (e.g., Carmack et al. 2008; McLaughlin et al.

2006). Depending on winds, river inflow can be constrained to the coastal currents or form lengthy plumes that efficiently transport runoff into the ocean's interior (Macdonald et al. 1999, 2002; Macdonald & Yu 2006). Approximately 50% of the freshwater exported from the Arctic Ocean rides out over the Atlantic water through Fram Strait (Serreze et al. 2006). Most of the remaining freshwater export occurs via the Canadian Arctic Archipelago (~36%). Roughly half of the freshwater exported through Fram Strait is in the form of ice, whereas freshwater export through the Canadian Arctic Archipelago is mostly liquid.

The various routes that river waters take as they circulate through the Arctic Ocean have important implications with respect to freshwater storage within and release from the ocean basin (Fig. 7). In general, runoff entrained into rapidly transporting coastal currents (Granskog et al. 2009) is exported more quickly than runoff that is shunted into the ocean's interior (Proshutinsky et al. 2002). Furthermore, runoff that enters the Beaufort Gyre has a much longer residence time (~10 years) than runoff transported via the Transpolar Drift (~2 years). For the Eurasian rivers, it appears that the state of the Arctic Oscillation (AO) can impact where river waters enter the ocean interior (Johnson and Polyakov 2001): a high AO index forces runoff eastward and into the Beaufort Gyre and a low AO index forces runoff directly into the Transpolar Drift. The

**Fig. 6** Surface currents in the Arctic Ocean and surrounding seas. Boxes mark general locations where denser inflowing waters submerge under more buoyant surface waters in the Arctic Ocean. Red arrows warm currents. Black arrows cold currents. Adapted from Fig. 3.29 in AMAP (1998)





**Fig. 7** Schematic diagram showing switches (bifurcations) and oscillations (temporal trends) possible in the runoff and ice components of the Arctic's freshwater cycle. Runoff entering the shelf may exit the Arctic rapidly in boundary currents or the Transpolar Drift, or it may enter the basin to be stored. Likewise, ice production may generate fresh water that is stored in the interior ocean or swept rapidly out of the ocean. Upon exiting the Arctic Ocean, fresh water may enter convecting areas or bypass them on the way south

bifurcations in river water transport then have effects on the interior ocean structure of the receiving basins (Steele and Boyd 1998; Schlosser et al. 2002). Storage and release of ice is similarly affected by transport pathways through the Arctic Ocean (Fig. 7).

While Pacific water was identified as a marine end-member in our earlier discussion of individual Arctic estuaries, it is important to recall that this nutrient-rich water serves as a freshwater end-member with respect to the Atlantic water in the Arctic Ocean estuary more generally (Fig. 1) and is a crucial contributor to the stratification in the Canada Basin, lying as it does between the surface mixed layer and the Atlantic water (Macdonald et al. 1989). During winter, surface waters rich in nitrate, phosphate, and silica pass through the Bering Strait and spread out over the Chukchi shelf (Codispoti et al. 2005, 2009). These nutrients fuel intense phytoplankton blooms in the spring and early summer (as the sea-ice recedes) that support productive microbial and metazoan communities in the Chukchi Sea (Mathis et al. 2009; Sukhanova et al. 2009; Kirchman et al. 2009; Dyda et al. 2009; Sherr et al. 2009; Campbell et al. 2009). In contrast, the surface waters of the Canada Basin, which store fresh water, have far less opportunity to access the Pacific nutrients and, as a result, exhibit exceptionally low export production (Honjo et al. 2010). Where freshwater moves, entrainment and mixing enhance production; where freshwater accumulates, entrainment and mixing are prevented and low production ensues.

### Climate Change

Arctic estuaries, from the small scale of coastal embayments to the large-scale of the entire Arctic Ocean, are vulnerable to climate variability and change. We are already seeing significant climate-driven changes throughout the

Arctic and more are predicted for the future (ACIA 2005). Many of these changes involve storage and cycling of fresh water, including changes in the timing and magnitude of river discharge and sea-ice coverage. Annual river discharge to the Arctic Ocean increased by an average of  $\sim 7 \text{ km}^3$  each year over the 1964–2000 time period, with a large increase from Eurasia tempered by a small decrease from North America (McClelland et al. 2006). Summertime sea-ice cover around the pan-Arctic domain decreased by  $\sim 8\%$  per decade over the 1979–2005 time period, with most extensive losses in the Eurasian sector (Parkinson et al. 1999) and extreme minima observed in the 2000s (Stroeve et al. 2008). Changes in precipitation, evaporation, and a variety of permafrost characteristics have been identified as likely contributors to the changes in annual river discharge, with the relative importance of these different drivers varying across watersheds. Changes in the seasonality of river discharge are also dependent on the above-mentioned drivers. However, snow cover characteristics (i.e., extent, water equivalent, and timing of melt) are particularly important with respect to the timing and magnitude of the spring freshet (Kane et al. 2000; Woo 1986; Yang et al. 2003). Warming has caused snowmelt to begin earlier in northern regions during recent decades (Yang et al. 2002, 2003; Zhang et al. 2000). Likewise, sea-ice thaw/break-up is occurring earlier. See White et al. (2007) for a comprehensive tabulation and analysis of changes in terrestrial and marine components of the arctic freshwater system.

As Arctic river discharge increases, changes in the physical and biogeochemical properties of coastal, shelf, and basin waters of the Arctic Ocean are anticipated. Greater freshwater inflow will support stronger stratification, but will also support stronger estuarine entrainment of deeper water. At the same time, concentrations of nutrients and organic matter in the river inputs are likely to change as consequence of warmer temperatures and thawing permafrost (Frey and McClelland, 2009). There is general agreement that soluble reactive phosphorus and silica concentrations in arctic rivers will increase. There is less agreement about how concentrations of inorganic nitrogen and organic matter in arctic rivers will change, but it is likely that export will increase in some regions and decrease in others depending on vegetation, soil composition, microbial activity, and changes in water flow paths as permafrost thaws. Such changes in nutrient and organic matter export from rivers to the Arctic Ocean have the potential to significantly influence productivity in Arctic coastal waters, whereas river-induced changes in the productivity of outer shelf and basin waters would largely be limited to effects of freshwater inflow on circulation.

In addition to potential changes in productivity associated with overall river inputs, changes in seasonality are

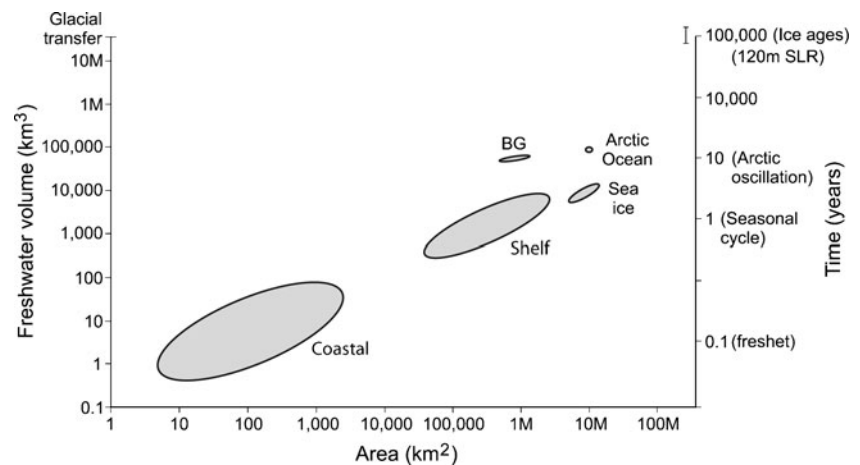
likely to have (and may already be having) a significant impact on the timing, magnitude, and distribution of ecosystem production in coastal and shelf waters of the Arctic (Loeng et al. 2005; Carmack et al. 2006). In particular, shifts in the timing of the spring freshet and ice break-up could lead to a variety of contrasting outcomes. If the spring freshet occurs earlier relative to sea-ice break-up, more of the nutrient-rich river water from winter discharge will be displaced/diluted by nutrient-poor water from the freshet before the onset of the phytoplankton bloom. Under this scenario, peak production would occur farther from shore, and the relative importance of river-borne organic matter versus inorganic nutrient contributions to production in near-shore waters would increase. On the other hand, if the spring freshet occurs later relative to sea-ice break-up, less of the nutrient-rich river water from winter discharge will be displaced/diluted by nutrient-poor water from the freshet before the onset of the phytoplankton bloom. In this case, peak production would occur nearer to shore, and the relative importance of river-borne organic matter versus inorganic nutrient contributions to production in near-shore waters would decrease. Even if the relative timing of the spring freshet and ice break-up remain constant as they shift to earlier in the year, lower incident light levels during ice retreat would change the progression of the phytoplankton bloom, lessening its initial intensity, slowing the drawdown of nutrients, and smoothing the on-shore to off-shore gradient in production.

Changes in wind-driven mixing associated with decreasing ice cover are also likely to effect productivity in coastal, shelf, and basin waters. Increased mixing will work against the stratification effect of greater freshwater inflows. At the same time, increased shoreline erosion associated with decreasing ice cover will enhance sediment, nutrient, and organic matter contributions to coastal waters (Lantuit et al. 2011, this issue). The added nutrients and organic

matter have the potential to increase biological production, but greater light attenuation as a consequence of enhanced sediment loads may limit this effect near-shore.

Finally, climate change is likely to affect the balance between freshwater storage within the Arctic Ocean and export of fresh water to the North Atlantic. Each of the switches and oscillations depicted in Fig. 7 is sensitive to changes in runoff, ice dynamics, and large-scale wind patterns. However, given that changes in some switches/oscillations will enhance freshwater storage while others will facilitate export, it is difficult to predict the overall outcome of these effects. For example, greater runoff will work against brine formation during seasonal ice growth, making conditions less favorable for deep convection (which supports long-term separation of sea-ice from the salt rejected during its formation) and thus diminishing the capacity for sea-ice to serve as an exportable freshwater source. At the same time, diminished ice cover in the fall together with more open water storms may help to remove freshwater inventories from the shelves and precondition them toward a greater potential to generate dense water from ice production in the ensuing winter. In any case, changes in freshwater export from the Arctic Ocean have potential consequences for North Atlantic Deep Water formation and associated larger-scale ocean circulation and climate patterns (Manabe and Stouffer 1994; Rahmstorf 1995; Broecker 1997). Changes in regional climate, including a relative cooling of Europe and enhanced warming in the equatorial Atlantic as consequences of reduced meridional overturning circulation triggered by greater freshwater export from the Arctic have been given particular attention. However, the severity of these consequences will depend strongly on the magnitudes of the changes in freshwater export as well as the timeframes over which they occur. An estimate of the storage capacities and residence times of freshwater in the Arctic Ocean (Fig. 8)

**Fig. 8** Schematic diagram showing the potential of various Arctic domains to store fresh water (BG Beaufort Gyre)



suggests that shelves can be affected quite quickly by change in, for example, wind fields (Johnson and Polyakov 2001), whereas the Beaufort Gyre takes longer to store and shed its freshwater inventory (decadal), but is capable of storing larger quantities, which, when released, have a greater potential to affect thermohaline circulation in the Greenland–Iceland–Norwegian Seas. Effects of increasing freshwater inputs may not, therefore, be felt immediately, but later as the Beaufort Gyre begins to store and release larger quantities of freshwater at the decadal scale in response to variability in, for example, the Arctic Oscillation. The complexity of bifurcations in freshwater pathways (Fig. 7) and in the capacity to store and release freshwater (Fig. 8) are what make the Arctic Ocean Estuary one of the most important components of feedback in Arctic as well as global change.

### Concluding Remarks

Estuarine science in the Arctic is young in comparison to many other regions of the world where major human population centers are situated along the coastline and scientists are able to access field sites with relative ease and regularity. Our current knowledge of Arctic estuaries is largely based on studies of a few major systems (i.e., estuaries associated with major river inputs). Furthermore, seasonal coverage of Arctic estuarine dynamics has been very limited. However, with clear signals of climate change occurring in the Arctic and greater changes anticipated in the future, there is good reason to accelerate estuarine research efforts in the region. In particular, elucidating estuarine dynamics across the near-shore to ocean-wide domains is an important pre-requisite for understanding potential climate feedbacks associated with storage and release of fresh water and carbon. Changes in freshwater export from the Arctic Ocean have the potential to alter ocean convection in the North Atlantic, while mobilization of large organic carbon stocks in arctic watersheds (most notably those trapped in permafrost) have the potential to accelerate the build-up of atmospheric CO<sub>2</sub>. Much of the mobilized carbon might be processed and released to the atmosphere within the continental domain, but the fate of terrigenous carbon within the ocean domain is also an important consideration with respect to the carbon budget of the Arctic.

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