7 Elements of Carbon Balance and Cycling in the Arctic Seas of Russia

7.1 Fluxes and Balance of Masses

In this chapter, we assess the parameters of the organic and carbonate carbon cycles in the system, namely primary photosynthetic production, carbon supply from land, exchange with adjacent basins, decomposition to CO_2 in the water column and on the floor surface, and its burial in the bottom sediments. These parameters represent the fluxes of the organic carbon participating in the cycle, its masses removed from the cycling, and the equivalent amount of O_2 released into the atmosphere. The estimates are mainly based on the analysis of the data presented in the previous chapters (Figs. 7.1, 7.2, and 7.3).

According to the V.I. Vernadsky's concepts on the biosphere and the studies developing his ideas, the chemical composition of the present-day earth's hydrosphere and atmosphere, characterized by extremely high contents of oxygen and low contents of CO_2, together with the moderate temperature conditions and the acidic environment on the surface of the planet, are created and maintained by live organisms (Table 7.1) (Vernadsky 1944, 1965; Lovelock 1979; Yanshina 1966).

At present, the CO_2 exchange in the atmosphere–ice–water system of the Arctic seas of Russia (ASR) cannot be considered on a quantitative basis. We plan to perform this kind of analysis later in the course of acquisition of reliable data. This also refers to the methane fluxes.

The direction of the resulting carbon flux across the air–water interface is variable with respect to time and space. Nevertheless, over relatively short (a few years) intervals, the carbon cycling in the ocean may be assessed assuming a constant mean annual supply of CO_2. Another fact that should be taken into account when estimating the carbon balance in the Arctic is the clearly manifested seaso-

Table 7.1. Comparison of atmosphere composition and temperature condition on the Mars, Venus, Earth and hypothetic Earth without Life (Odum 1983)

	Mars	Venus	Earth without Life	Earth
Gas concentration in the atmosphere [%]				
Carbon dioxide	95	98	98	0.03
Nitrogen	2.7	1.9	1.9	79
Oxygen	0.13	trace	trace	21
Surface temperature, ºC	- 53	477	290 ± 50	13

Fluxes of TOC from land, 10^6 t C yr^{-1}
Riverine runoff, DOC – 4.7
Riverine runoff, POC - 0.5
Wave abrasion, POC – 0.8
Eolian transfer, POC – 0.27
Underground runoff, DOC – 0.40
Total fluxes of TOC from land 6.7

BARENTS AND WHITE SEAS

	Mass 10^6 t C	Primary production 10^6 t C yr^{-1}	Secondary production 10^6 t C yr^{-1}
Phytoplankton	0.68	56.5	
Ice algae		3	
Macrophytobenthos	0.12	0.13	
Microphytobenthos	0.35	4.8	
Zooplankton	3.4		8.5
Zoobenthos	8.2		3.3
Total	12.6	64.5	11.8

Mineralization in water column 42.5 10^6 t C yr^{-1} , 72% of F_{PHS}

Flux to seafloor 23.6 10^6 t C yr^{-1} , 36% of $F_{PHS} + F_{POC}$

Burial in the bottom sediments 3.8 10^6 t C yr^{-1}

Mineralization on the seafloor and in the surface layer of sediments 19.8 10^6 t C yr^{-1}, 84% of the flux to seafloor

Fossilization coefficient 5.7%

Fig. 7.1. Balance of organic carbon in the Barents Sea

Fluxes of TOC from land, 10^6 t C yr^{-1}
Riverine runoff, DOC – ?
Riverine runoff, POC - ?
Σ DOC + POC 10.8
Wave abrasion, POC – 0.35
Eolian transfer, POC – 0.10
Underground runoff, DOC – 1.0
Total fluxes of TOC from land -12.2

KARA SEA

	Mass 10^6 t C	Primary production 10^6 t C yr^{-1}	Secondary production 10^6 t C yr^{-1}
Phytoplankton	0.3	14	
Ice algae		4	
Macrophytobenthos	-	-	
Microphytobenthos	0.17	2.4	
Zooplankton	0.6		1.6
Zoobenthos	2.4		1.0
Total	3.5	20.4	9.6

Mineralization in water column 10.6 10^6 t C yr^{-1} , 59% of F_{PHS}

Flux to seafloor 11.3 10^6 t C yr^{-1}, 52% of F_{PHS} + F_{POC}

Burial in the bottom sediments 2.3 10^6 t C yr^{-1}

Mineralization on the seafloor and in the surface layer of sediments
9.0 10^{6} t C yr^{-1}, 80% of flux to seafloor

Fossilization coefficient 10.5%

Fig. 7.2. Balance of organic carbon in the Kara Sea

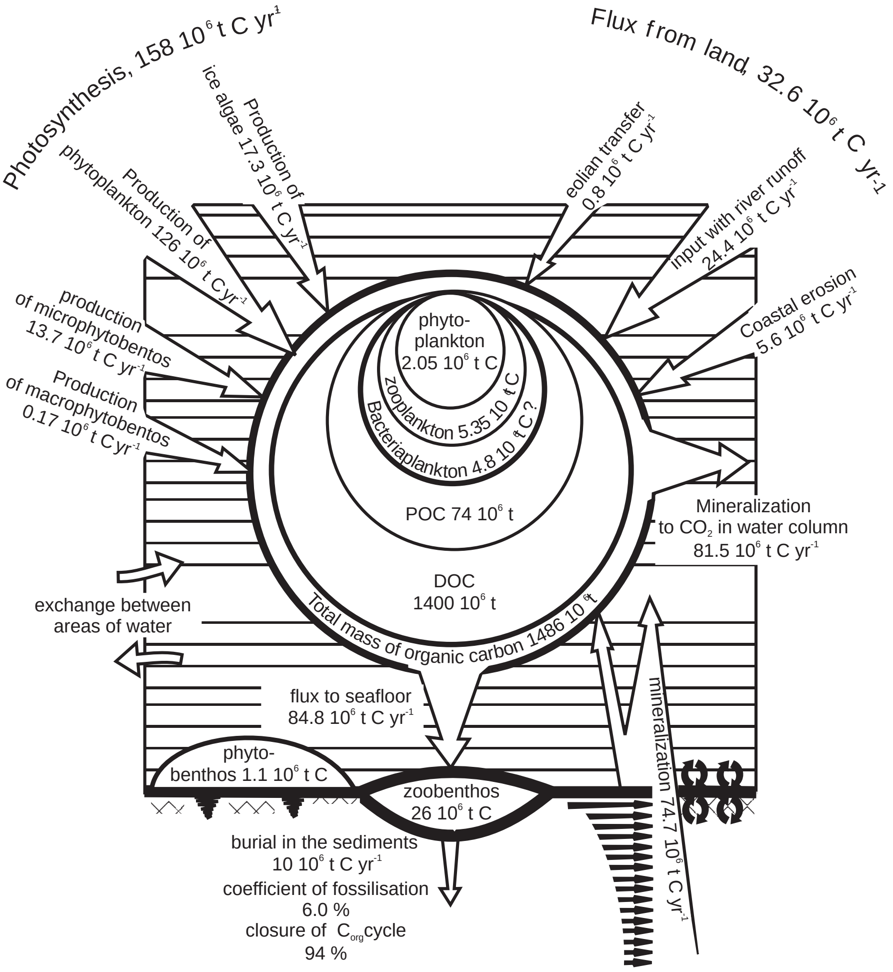

Fig. 7.3. Balance of organic carbon in ASR

nal character of the biogeochemical processes. Therefore, the assessment of the mass and energy fluxes in the ASR should be performed separately for at least two periods—the summer and the winter seasons. However, the shortness of information for the winter period does not allow one to implement this kind of approach.

The carbon cycle in the ASR consists of two closely interrelated branches represented by the cycles of C_{org} and C_{carb}. Due to the efforts of geochemists, biologists, and lithologists, the parameters of the C_{org} cycling are known better than those of the carbonate branch of the carbon cycle. It should be noted that the data on C_{carb} are no less abundant than those on C_{org}; however, to date, there are only few estimates of the primary production of $CaCO_3$, the supply from land, and the burial in the bottom sediments. The interrelation between the C_{org} and C_{carb} cycles is implemented through a complicated system of equilibrium between the hydrocarbonate ions and the final product of the C_{org} oxidation—CO_2. This issue requires an additional assessment which will represent the subsequent stage of the estimating the general distribution and fluxes of carbon.

One more simplification which we had to assume in order to avoid the temptation of operating the increments between large mass fluxes with overlapping confidence intervals of their characteristics was the rejection of the estimates obtained for the carbon exchange between the adjacent basins. The ASR represent an open system, and the water exchange between the Arctic Basin with its seas and the Atlantic and Pacific oceans is rather significant (see Chap. 2). Meanwhile, the interannual and interseasonal variations in the delivery of the Atlantic waters cover a wide range of values. During selected periods, the discharge across the Cape Nordkapp–Bear Island transect may be even negative due to the strong countercurrents. In each of the seas, the divergence of the water flux is equal to zero; meanwhile, this is not true with respect to the carbon compounds which have different concentrations in different water fluxes. Unfortunately, the quantitative data on the particulate organic carbon (POC) and dissolved organic carbon (DOC) in the ASR are extremely poor; they are mostly related to the estimates over vast aquatic areas. The approximate POC and DOC transport estimates derived from our original data are presented in Tables 7.2 and 7.3.

The supply of the Atlantic waters to the Barents Sea varies from one year to another. However, according to the most recent estimations, the resulting flux across the Scandinavia–Spitsbergen section running along 16º E makes up to 26.8 10^3 km^3 $year^{-1}$ (Yu.A. Ivanov, personal communication); this is almost equal to the value used in the calculations (30.6 10^3 km^3 $year^{-1}$, Timofeev 1963). The uncertainties in the determinations of the DOC and POC concentrations in the exchange fluxes are significantly greater. For example, rather reliable estimates of DOC are available for the central part of the White Sea and for the southwestern part of the Barents Sea; however, they cannot be used as exchange flux characteristics for calculations since the tidal flows in the White Sea Gorlo change their direction four times a day.

The C_{org} content has also been evaluated at selected sites of intensive water exchange; however, these estimates strongly differ from one another. For example, the estimates of the particulate organic matter (POM) content in the direction of the major flow of 4.0 mg l^{-1} for the Chirikov Basin and about 3.4 mg l^{-1} for the central part of the Chukchi Sea (Mosharov and Glebov, 2000) provide a value of the supply–removal increment of 8 10^6 t C $year^{-1}$; if the POM content value equal to 1.2 mg l^{-1}, as it was determined at the northeastern boundary of the sea, is used, the resulting increment is still greater.

At high flux values at the boundaries of the ASR, one cannot avoid significant errors in the estimates of the POC and DOC balance caused by the uncertainties in the determination of these quantities at the input and at the output. Nevertheless, according to the tendency to the entropy growth, larger fluxes provide the leveling of the characteristics of the water masses. In addition, the DOC mainly consists of relatively stable organic compounds; their lifetime in the ocean reaches a few tens

Table 7.2. Pattern of estimation of exchange fluxes of organic carbon between the Barents Sea and adjacent aquatories

Region	Volume of water	DOC	POC	DOC flux	POC flux	TOC flux
	$[10^3$ km^3 yr$^{-1}]$	[mg l^{-1}]	[mg l^{-1}]	[10^6 t yr^{-1}]	[10^6 t yr^{-1}]	[10^{6}t yr^{-1}
			Input			
N. Atlantic (Nordkapp – Suidkapp)	60.24 [a]	1.6 [e, g]	0.06 [e]	96.4	3.61	
Arctic Basin	1.5 [a]	1.3 [e, j, k]	0.06 [e]	2.0	0.09	
White Sea	2.2 [b]	5.5 [h]	0.16 [i]	12.1	0.4	
Pechora River	0.13 [c]	12.7 [f]	0.3 [f]	1.6	0.04	
Precipitation	0.77 [d]	-	-			
Total input	64.84			112.1	4.1	
			Discharge			
N. Atlantic (Nordkapp – Suidkapp)	29.61 [a]	1.7 [g]	0.07 [g]	50.3	2.1	
Arctic Basin (Svalbard – Franz Jozef Land)	13.81 [a]	1.7 [g, j, k]	0.06 [g]	23.5	0.8	
Kara Sea						
Cape Jelanie –Franz Josef Land)	17.13 [a]	1.3 [g]	0.08 [g]	22.3	1.37	
Karskie Vorota Strait	1.24 [a]	1.8 [g]	0.07 [g]	2.2	0.09	
Yugorskii Shar Strait	0.4 [a]	1.8 [g]	0.07 [g]	0.7	0.03	
White Sea	2 [b]	4.8 [g]	0.16 [i]	9.6	0.3	
Evaporation	0.65 [d]	-	-			
Total discharge	64.84			108.6	4.7	
Input - discharge				+3.5	-0.6	+2.9

[a] Timofeev 1963
[b] Dobrovolsky and Zalogin 1982
[c] Mikhailov 1997
[d] Ivanov 1976a
[e] Emelyanov and Romankevich 1979
[f] Artemyev 1993
[g] Present work
[h] Agatova and Kirpichev 2000
[i] Romankevich et al. 2000
[j] Andersen et al. 1994
[k] Guay et al. 1999

or a few hundreds of years. A comparison between the water exchange and the water volume in the ASR shows that the waters of the Barents and Kara seas are completely renewed over approximately five years, while in the Chukchi Sea, the water is replaced over one year and a half. Therefore, one can expect that the difference between the DOC contents at the input and at the output of the ASR should not be too great.

Similar to POC, DOC represents a dynamical system. Its concentration is determined by the balance between its formation and precipitation over the floor. In

Table 7.3. Pattern of estimation of exchange fluxes of organic carbon between the Kara Sea and adjacent aquatories

Region	Volume of water	DOC	POC	DOC flux	POC flux	TOC flux
	[10^3 km^3 yr^{-1}]	[mg l^{-1}]	[mg l^{-1}]	[10^6 t yr^{-1}]	[10^6 t yr^{-1}]	[10^6t yr^{-1}]
			Input			
Barents Sea						
Cape Jelanie –Franz Josef Land)	17.13 [a]	1.3 [d]	0.08 [d]	22.3	1.37	
Karskie Vorota Strait	1.24 [a]	1.8 [d]	0.07 [d]	2.2	0.09	
Yugorskii Shar Strait	0.4 [a]	1.8 [d]	0.07 [d]	0.7	0.03	
Continental discharge	1.48	7.3 [c, d]	-	8.7	1.1	
Precipitation	0.27 [b]	-	-			
Total input	20.52			33.9	2.6	
			Discharge			
Arctic Basin and Laptev Sea	20.36	1.8 [e]	0.08 [f]	36.4	1.6	
Evaporation	0.16 [b]	-	-			
Total discharge	20.52			36.4	1.6	
Input - discharge				-2.5	+1.0	-1.5

[a] Timofeev 1963.
[b] Ivanov 1976a.
[c] Smirnov et al. 1988.
[d] Present work.
[e] Lyutsarev et al. 1999.
[f] Shevchenko et al. 1996.

shallow-water regions, repeated suspension of particulate matter is often observed. The POC concentration features a stronger dependence on the hydrological regime and near-bottom hydrodynamics than that of DOC. In addition, POC contains a greater percentage of labile organic matter. However, its content in the water hardly reaches a few percent of that of DOC; therefore, ignoring the water exchange with adjacent basins results in smaller errors.

Tables 7.2 and 7.3 allow one to realize the approximate intensity of the water and organic carbon exchange between adjacent water basins; however, these data cannot be used for quantitative estimates of the C_{org} balance. The positive conclusion that can be drawn from these data is the compatibility of the resulting C_{org} flux values with those of the riverine runoff delivery at enormous intensity of the water exchange with adjacent basins. The calculated approximate values of the annual C_{org} fluxes cannot be used to judge upon the DOC accumulation or CO_2 release at its mineralization; to do this, more reliable characteristics of the water exchange for POC and DOC are required.

In Table 7.4, we present the results obtained in this study concerning the estimation of the masses and fluxes of C_{org} in the ASR under the above-described assumptions. The techniques and results of the estimation of the annual fluxes of different forms of carbon generated in the course of photosynthesis, the fluxes

Table 7.4. Fluxes and masses of organic carbon in ASR

<table>
<tr><th>Fluxes and masses</th><th>Barents</th><th>White</th><th>Kara</th><th>Laptev</th><th>East Siberian</th><th>Chukchi</th><th>ASR as a whole</th></tr>
<tr><td>TOC flux from Land [10^6 t yr^{-1}]</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>including:</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>DOC of riverine runoff</td><td colspan="2">4.7</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>POC of riverine runoff</td><td colspan="2">0.5</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>TOC of riverine runoff</td><td colspan="2">5.3</td><td>10.8</td><td>6.3</td><td>1.9</td><td>0.14</td><td>24.4</td></tr>
<tr><td>POC of coastal abrasion</td><td>0.5</td><td>0.3</td><td>0.35</td><td>1.8</td><td>2.2</td><td>0.4</td><td>5.6</td></tr>
<tr><td>Eolian transfer (POC)</td><td>0.25</td><td>0.02</td><td>0.10</td><td>0.15</td><td>0.16</td><td>0.11</td><td>0.8</td></tr>
<tr><td>DOC underground discharge</td><td colspan="2">0.40</td><td>1.00</td><td>0.33</td><td>0.10</td><td>0.008</td><td>1.8</td></tr>
<tr><td>Σ DOC input (F_{DOC})</td><td colspan="2">5.1</td><td>10.7</td><td>6.0</td><td>1.8</td><td>0.14</td><td>23.7</td></tr>
<tr><td>Σ POC input (F_{POC})</td><td colspan="2">1.6</td><td>1.5</td><td>2.6</td><td>2.6</td><td>0.52</td><td>8.8</td></tr>
<tr><td>Σ TOC input from Land (F_{TER})</td><td colspan="2">6.7</td><td>12.2</td><td>8.6</td><td>4.4</td><td>0.7</td><td>32.6</td></tr>
<tr><td>Bioproduction [10^6 t yr^{-1}] [a]</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Phytoplankton</td><td>55</td><td>1.5</td><td>14</td><td>7</td><td>7</td><td>42</td><td>126.5</td></tr>
<tr><td></td><td>(0.66)</td><td>(0.02)</td><td>(0.3)</td><td>(0.17)</td><td>(0.2)</td><td>(0.7)</td><td>(2.05)</td></tr>
<tr><td>Ice algae</td><td>3</td><td></td><td>4</td><td>3</td><td>4.7</td><td>2.6</td><td>17.3</td></tr>
<tr><td>Macrophytobenthos</td><td>0.066</td><td>0.064</td><td></td><td></td><td></td><td>0.04</td><td>0.17</td></tr>
<tr><td></td><td>(0.063)</td><td>(0.056)</td><td></td><td></td><td></td><td>(0.038)</td><td>(0.16)</td></tr>
<tr><td>Microphytobenthos</td><td>4.8</td><td>0.009</td><td>2.4</td><td>0.53</td><td>3.5</td><td>2.5</td><td>13.7</td></tr>
<tr><td></td><td>(0.35)</td><td>(0.0009)</td><td>(0.17)</td><td>(0.04)</td><td>(0.28)</td><td>(0.08)</td><td>(0.92)</td></tr>
<tr><td>Zooplankton</td><td>8.3</td><td>0.22</td><td>1.6</td><td>0.6</td><td>0.5</td><td>2</td><td>13.2</td></tr>
<tr><td></td><td>(3.3)</td><td>(0.1)</td><td>(0.6)</td><td>(0.25)</td><td>(0.2)</td><td>(0.9)</td><td>(5.35)</td></tr>
<tr><td>Zoobenthos</td><td>3.2</td><td>0.1</td><td>1.0</td><td>1.6</td><td>1.6</td><td>2.8</td><td>10.3</td></tr>
<tr><td></td><td>(7.9)</td><td>(0.3)</td><td>(2.4)</td><td>(4.1)</td><td>(4.1)</td><td>(7.0)</td><td>(25.8)</td></tr>
</table>

Table 7.4. (cont.)

Fluxes and masses	Barents	White	Kara	Laptev	East-Siberian	Chukchi	ASR as a whole
Photosynthetic flux (F_{PHS}) [10^6 t yr^{-1}]	62.9	1.6	20.4	10.5	15.2	47.1	157.7
$F_{PHS} + F_{POC}$ [10^6 t yr^{-1}]	66.1		21.9	13.1	17.8	47.6	166.5
$F_{PHS} : F_{TER}$	100 : 10		100 : 60	100 : 82	100 : 29	100 : 1.5	100 : 21
$F_{PHS} : F_{POC}$	100 : 2.5		100 : 7.3	100 : 25	100 : 17	100 : 1.1	100: 5.6
Mass of DOC [10^6 t]	550	45	175	445	100 ?	85	1400
Mass of POC [10^6 t]	20	1.4	6	35	5 ?	6.3	74
Flux to seafloor [10^6 t yr^{-1}] taking into account [b]:							
Production of phytoplankton (PhP)	15.3 (28%)	0.9 (60%)	5.8 (41%)	3.0 (43%)	4.6 (66%)	24.3 (58%)	53.9 (43%)
PhP + production of ice algae (PIA)	16.1 (28%)	0.9 (60%)	7.4 (41%)	4.3 (43%)	7.7 (66%)	25.9 (58%)	62.3 (43%)
PhP + PIA + production of phytobenthos	21.0 (33%)	0.97 (61%)	9.8 (48%)	4.9 (47%)	11.2 (74%)	28.1 (60%)	76.0 (48%)
Total flux to seafloor (F_{SEAFL}) [c]	23.6 (36%)		11.3 (52%)	7.5 (57%)	13.8 (77%)	28.6 (60%)	84.8 (51%)
Mineralization PhP + PIA in water column [10^6 t yr^{-1}] (% of PhP + PIA)	41.9 (72%)	0.6 (40%)	10.6 (59%)	5.7 (57%)	4.0 (34%)	18.7 (42%)	81.5 (57%)
Mineralization on seafloor [10^6 t yr^{-1}] (% of F_{SEAFL})	19.8 (84%)		9.0 (80%)	6.3 (84%)	12.8 (93%)	26.7 (93%)	74.7 (88%)
Burial in bottom sediments [10^6 t yr^{-1}]	3.4	0.37	2.3	1.18 [d]	1.0 [e]	1.9	10.1
Fossilization coefficient (FC) [% of F_{PHS}]	5.4	23	11.3	11.2	6.6	4.0	6.4
FC ' [% of F_{POC}]	236		153	45	38	365	115
FC '' [% of $F_{PHS} + F_{POC}$]	5.7		10.5	9.0	5.6	4.0	6.0

[a] The maximal biomass in summer is shown in parenthesis.

[b] The share of initial flux [%] is shown in parenthesis.

[c] including total primary production (F_{PHS}) and POC of riverine runoff, coastal erosion, and eolian matter

[d] Stein and Fahl 2000

[e] Petrova et al. 2004

from land, and the rates of burial of C_{org} and C_{carb} in the bottom sediments (accumulation rate) are assessed in chapters 3, 5, and 6, respectively. To estimate the total masses of POC and DOC, we used mean concentration values averaged over each of the seas.

For the Barents Sea, the estimation of the POC and DOC contents was implemented through summing up their contents in the layers 0–50 m, 50–100 m, and 100 m–bottom. In so doing, mean concentrations for these layers determined in the Murmansk–Franz Josef Land transect (see Table 4.1) were used; they were equal to 2.27, 1.74, and 1.54 mg l^{-1} for DOC and 0.136, 0.54, and 0.040 mg l^{-1} for POC, respectively. For the White Sea, respective mean concentrations of DOC and POC were 8 and 0.25 mg l^{-1}. The total masses of DOC and POC in the Barents Sea were estimated at 550 10^6 and 20 10^6 t, respectively.

In the Kara Sea, the DOC concentrations at the surface in the Ob and Yenisei river estuaries are high—up to 6.9–11.4 and 6.8–8.6 mg l^{-1}, respectively. In the central part of the sea, this value ranges from 1.5 to 2.1 mg l^{-1}. The POC concentrations in the Ob and Yenisei estuaries are also high—up to 4 and 0.8 mg l^{-1}, respectively. Meanwhile, in most of the regions of the sea this value never exceeds 0.1 mg l^{-1}. Since the total area of the estuaries is relatively small, mean concentration values of DOC and POC for the Kara Sea were assumed to be 1.8 and 0.06 mg C l^{-1}. Under this assumption, the total masses resulted to be 175 10^6 t of DOC and 6 10^6 t of POC.

In the Laptev Sea, in the Lena River estuary, the DOC concentrations in the surface layer change from 8 mg l^{-1} at the exit from the river channels up to 3.6–4.8 mg l^{-1} at the seaward boundary of the estuary. The corresponding values for the POC concentrations are 1.43 and 0.06 mg l^{-1}. In the pelagic zone, the concentrations of DOC and POC are 1.0–1.5 and less than 0.1 mg l^{-1}, respectively. In order to estimate the total contents of DOC and POC, their mean concentrations over the sea were assumed to be 1.25 and 0.1 mg l^{-1}, respectively. Using these values, we obtain the total carbon content in the Laptev Sea to be presented by 445 10^6 t of DOC and 35 10^6 t of POC.

For the East Siberian Sea, practically no estimates of the concentrations of DOC and POC are available. We suppose that the waters of the East Siberian Sea contain 100 10^6 t of DOC and 5 10^6 t of POC. These estimates can be refined with acquisition of more reliable data on the organic carbon distribution over the East Siberian Sea.

For the Chukchi Sea, the mean DOC and POC concentrations were estimated at 2.0 and 0.15 mg l^{-1}, respectively (Hood and Reeburgh 1974; Walsh 1995). The total carbon mass in the sea is presented by 85 10^6 t of DOC and 6.3 10^6 t of POC.

The above estimates allow one to outline the relations between the masses and fluxes of C_{org} in individual seas and in the ASR on the whole (Table 7.4, Figs. 7.1–7.3).

The principal sources of C_{org} in the ASR are the production of photosynthesis, which reaches about 160 10^6 t C_{org} year^{-1}, and the riverine runoff (24.4 10^6 t C_{org} year^{-1}, DOC + POC), as well as the wave abrasion (5.6 10^6 t C_{org} year^{-1}). Significantly smaller contributions are made by the underground discharge beyond the rivers (1.8 10^6 t C_{org} year^{-1}) and the eolian supply (0.8 10^6 t C_{org} year^{-1}).

The total flux of DOC from different sources to the ASR is approximately 23.7 10^6 t C_{org} year^{-1}; for POC, the corresponding value is 8.8 10^6 t C_{org} year^{-1}. The POC-to-DOC ratio in the total flux is thus estimated at 1 : 2.7. The ratio of the masses of POC (7.4 10^6 t) and DOC (1400 10^6 t) differs from that for the fluxes and comprises 1 : 19. The significantly different POC-to-DOC ratio in terms of masses is related to the conservative character of DOC, which is hardly mineralized. However, judging from the interrelation between POC (55 10^9 t) and DOC (1600 10^9 t) in the World Ocean (1 : 29), the DOC of the ASR is less conservative and seems to be a younger substance (Romankevich and Vetrov 1997).

The total supply of C_{org} to the ASR from various sources on land amounts to approximately 32.6 10^6 t C_{org} year^{-1}.

As it was mentioned before, the primary production of C_{org} is estimated at 160 10^6 t C_{org} year^{-1}.

The main contribution to the primary production is provided by phytoplankton (80% of the overall photosynthetic flux of C_{org}). The greatest production rates are characteristic of the Barents (55 10^6 t C_{org} year^{-1}) and Chukchi (42 10^6 t C_{org} year^{-1}) seas subjected to the influence of the relatively warm waters supplied from the Atlantic and Pacific oceans favoring the development of all kinds of biocoenoses. Everywhere, a significant share of the primary production belongs to the ice algae (see Table 7.4). In the East Siberian and Laptev seas, their production (4.7 10^6 and 3.0 10^6 t C_{org} year^{-1}, respectively) equals or even exceeds (East Siberian Sea) a half of the total phytoplankton production.

Macrophytobenthos produces the photosynthetic matter in the near-shore regions of the seas. Here, its contribution may exceed that of the primary production of phytoplankton. The distribution of macrophytobenthos is mainly restricted by the Barents, White, and Chukchi seas. In these seas, the relative share of their production is small (0.1% in the Barents and Chukchi seas). However, in the White Sea, the production of macrophytes comprises a noticeable portion (4.3%) of the phytoplankton production (1.5 10^6 t C_{org} year^{-1}). On the whole, in the ASR, the contribution of macrophytes to the overall phytoplankton production is slightly greater than 0.13%.

The production of microphytobenthos in the ASR is approximately by a factor of 10^2 greater (13.7 10^6 t C_{org} year^{-1} or 11% of the overall phytoplankton production). The great extension of shallow-water areas in the ASR together with the widely spread soft grounds creates favorable conditions for the bottom macrophytes in some biotopes of the ASR.

The secondary production created by zooplankton and zoobenthos in the ASR is estimated at 13.2 10^6 and 10.3 10^6 t C_{org} year^{-1}. The zooplankton production comprises about 10% of that of phytoplankton. The production of phytobenthos is smaller than that of microphytobenthos. Various estimates of the bacterial production are so contradictory that it is impossible to derive any reliable average value.

The total C_{org} flux created in the course of photosynthesis (158 10^6 t C year^{-1}) and due to the DOC and POC supply from land (32.6±6.5 10^6 t C year^{-1}) comprises 191 10^6 t C year^{-1}.

The proportions of the overall marine photosynthetic (F_{PHS}) and the overall terrigenous (allochtonous—F_{TER}) fluxes of C_{org} are strongly variable (see Table 7.4,

F_{PHS} : F_{TER} ratio). Sorted with respect to this ratio, the ASR form the following sequence: the Chukchi Sea (100 : 1.5), the Barents Sea (100 : 10), the East Siberian Sea (100 : 29), the Kara Sea (100 : 60), and the Laptev Sea (100 : 82). On the whole, the ASR are characterized by an average value of the F_{PHS} : F_{TER} ratio of 100 : 21.

A very indicative characteristic of the ASR is also represented by the proportion between the fluxes F_{PHS} and F_{POC}. In the Chukchi Sea, this ratio is of maximum (100 : 1.1); it is smaller in the Barents (100 : 2.5), the Kara (100 : 7.3) and the East Siberian (100 : 17) seas, and reaches its minimum in the Laptev Sea (100 : 25). Therefore, it is not surprising that this difference in the proportions between the hydrogenous and terrigenous matter is clearly reflected in the group, molecular, and isotopic fluxes ($\delta^{13}C$) of the organic matter in the suspension and in the bottom sediments, which allowed us to distinguish three types of organic matter (see Chaps. 4 and 6). Hence, the balance of fluxes in the ASR suggests the existence of two initially different pools of two genetically different components of organic matter in the bottom sediments. This is unambiguously reflected in their fluxes reaching the floor and in those transmitted to the sedimentary reservoirs of the ASR.

The total C_{org} flux reaching the floor incorporates autochtonous (hydrogenous) and allochtonous components.

In order to estimate the C_{org} fluxes directed toward the bottom, the data obtained with sediment traps are commonly used. Unfortunately, in the ASR, these measurements are few and, in addition, the shallowness of the Arctic seas results in significant distortions of the fluxes measured caused by the repeated suspension of the sedimentary matter (see Chap. 4).

In the pelagic zones of the World Ocean, we estimated the downward fluxes of C_{org} (Romankevich et al. 1999) using the dependence of the C_{org} fluxes on depth and primary production value (Tseitlin 1993). There is about a dozen of empiric dependences derived for the pelagic zone of the ocean relating these characteristics (Romankevich and Vetrov 1997) valid for the water masses located beneath the photic layer. Due to the above-mentioned reasons, using the sediment trap data in the ASR did not allow us neither to check the applicability of these relations for the Arctic seas nor to derive new ones.

In the Greenland and Norwegian seas, sediment fluxes of C_{org} toward the floor were calculated on the basis of the relations between primary production and vertical oxygen profiles (Schluter and Rfannkuche 2000; Schluter et al. 2000). The resulting C_{org} fluxes at the levels 500 and 1000 m (10.3 and 4.5 10^6 t C year^{-1}) at a primary production value of 150–160 10^6 t C year^{-1} allow one to check the applicability of the relations derived for temperate and low latitudes to the northern seas. Estimation of the flux across the levels cited (Z) by the Berger’s formula $F_C = 9\ PP/Z + 0.7\ PP/Z^{1/2}$ (Bishop 1989) provides values of 7.8 10^6 and 4.8 10^6 t C year^{-1}, while application of the formula $F_C = 33\ PP/Z$ (Tseitlin 1993) results in values of 10.2 10^6 and 5.1 10^6 t C year^{-1}. The latter formula was used for the estimation of the C_{org} fluxes in the ASR from mean annual primary production values as it allows one to minimize the discrepancies at smaller depths. In the cases when sea depth was less than 50 m, the value of Z was assumed equal to 50 m.

In Table 7.4, we present selected estimates of the C_{org} fluxes to the seafloor with account for (a) phytoplankton production, (b) phytoplankton production + production of the ice flora, and (c) overall flux to the bottom including the entire photosynthetic production, POC of the riverine runoff, coastal abrasion, and eolian supply (F_{SEAFL}).

Direct estimates of the riverine fluxes of POC were performed for selected rivers of the basins of the White, Barents, Kara, and Laptev seas. In the Barents Sea, the proportion of POC in the total sum DOC + POC is about 10%; the corresponding values for the Kara and Laptev seas are 3.5 and 25%, respectively. However, the data on the Lena River need confirmation by observations in various years and seasons. Up to date, for the rivers where no direct measurements of POC are available, one may accept a value of 10% as the POC content in the sum DOC + POC.

Dissolved OM of different fluxes is partly decomposed to CO_2 and nutrients, partly removed to the adjacent water areas, and partly transfers to colloids and particulate matter and, in this form, is buried in the sediments. One can suggest that the DOC transferred into particulate matter (> 0.4–0.6 µm) is already accounted in the calculations. The main transformation of DOC and its transfer into particulate matter occurs in the land–sea interface zone and other biochemically active zones (estuaries, water–bottom interface, and others). Up to 20% of DOC seems to transfer into particulate matter through trophic webs, flocculation, and sorption. The fate of the rest part of the DOC of the riverine runoff remains unclear.

The overall total C_{org} flux to the seafloor (F_{SEAFL}) in the ASR comprises about 85 10^6 t year^{-1}. To calculate it, we accounted for the total production of photosynthesis (F_{PHS} = 158 10^6 t year^{-1}), POC of the riverine runoff (F_{POC} = 2.5 10^6 t year^{-1}), the content of C_{org} in the solid matter of abrasion (5.6 10^6 t year^{-1}), and eolian supply (0.8 10^6 t C_{org} year^{-1}), which made up about 167 10^6 t year^{-1}. In different seas, from 28 to 66 % of the initial flux of the phytoplankton OM and, probably, ice flora reach the bottom.

The total flux toward the bottom comprises about 50% of the initial flux. The C_{org} flux reaching the bottom that great is caused by the set of special conditions existing in the ASR. Among them, in our opinion, the principal are; the shallowness of the seas, the great (unique per unit sea area) terrigenous matter runoff (both riverine and abrasive), the short trophic webs, and the temperature conditions preventing OM from destruction both in the water column and on the bottom. The latter factor defines the amounts of the OM buried.

At the surface of the floor, one of the principal (second after the photic layer) zones of transformation and destruction of different forms of carbon is located. In the ASR, here, the major part of the C_{org} supplied to the bottom is mineralized: up to 84% in the Barents Sea and 80% in the Kara Sea.

The value of C_{org} flux to the seafloor in the Kara Sea 11.8 10^6 t year^{-1} is in accordance to estimated values of the macrozoobenthos and benthic microbial community organic carbon demand 5–7 10^6 and 3.6 10^6 t C year^{-1}, respectively (Klages et al. 2003). An assessment of total organic carbon demand needs considerations of meiofauna and trophic relations between benthic communities.

On the average, 75 10^6 t year^{-1} C_{org} or 88% of the organic carbon supplied to the bottom is mineralized in the ASR. This parameter was calculated from the difference between the C_{org} supplied to the bottom and that transferred to the bottom sediments (buried OM fluxes). On the whole, about 10 10^6 t C_{org} year^{-1} is accumulated in the bottom sediments of the ASR, which approximately equals the amount accumulated over the entire pelagic zone of the World Ocean. Of this amount, 3.4 10^6 t year^{-1} is accumulated in the Barents Sea and 2.3 10^6 t year^{-1} is accumulated in the Kara Sea.

In the ASR, the fossilization coefficient (FC) of the photosynthetic C_{org} flux (F_{PHS}), that is, the percentage of the initial flux of the photosynthetic production, equals 6.4%. The FC for the sum of the photosynthetic flux and the POC flux ($F_{PHS} + F_{POC}$) in the ASR is 6.0%, which is significantly greater than in the pelagic zones of the ocean (FC = 0.02%) and continental margin of the World Ocean (0.8–1.3%; Romankevich and Vetrov 1997). The values that high imply an unbalance in the biosynthesis (+ land supply)–burial on the bottom system and represent one of the distinctive characteristics of the carbon cycling in the ASR. In addition to the factors defining the C_{org} flux reaching the bottom (see above), these high values of FC in the ASR are caused by a series of features of the polar lithogenesis and of the composition of the buried OM. The latter mostly consists of a mixed hydrobiont–terrigenous OM, which has executed a distant route of migration with riverine and abrasive fluxes accompanied by destruction in trophic webs.

The coefficient of C_{org} fossilization in the bottom sediments FC′ calculated as the percentage of the total POC flux from land (F_{POC}) in the Barents Sea equals 236 %. This evidently implies a significant role of hydrobiont OM in the composition of OM in the sediments of this sea—planktonogenic OM makes up no less than 70% of the total OM, while terrigenous OM comprises 30% of it. In the Kara, Laptev, and East Siberian seas, terrigenous OM seems to comprise more than 70% of the total OM in the bottom sediments.

The results of the estimation of the flux and masses of C_{carb} are presented in Table 7.5. At present, the supply of C_{carb} with the riverine runoff, the contents of C_{carb} in the bottom sediments of the Barents, Kara, and Chukchi seas, the mass and production of C_{carb} produced by zoobenthos in the ASR are calculated. The undersaturation of the cold waters of the ASR with calcium carbonate does not favor the development of the organism which use calcium carbonate for constructing supporting tissues. According to our data, the biological production of C_{carb} in the ASR annually produced by benthos, which is the main carbonate-synthezing and accumulating element of the ecosystem, reaches 4.8 10^6 t year^{-1} (the production of coralline algae is still unknown). The zoobenthos production of C_{carb} in the ASR is by an order of magnitude smaller than the amount of DIC supplied with the riverine and underground runoffs. These 10% are partially produced by zoobenthos at the expense of utilization of the DIC of the riverine and underground runoffs; this should be accounted when assessing the total budget of the forms of carbon in the ASR. The proportions of C_{inorg} supplied to the turnover due to abrasion and eolian transport is not estimated yet. The $C_{org} : C_{carb}$ ratio in the bottom sediments is approximately equal to 5 : 1. In the bottom sediments of the World Ocean, inverse $C_{org} : C_{carb}$ relations are observed. Thus, the high values of the $C_{org} : C_{carb}$ ratio in

Table 7.5. Fluxes and masses of carbonate carbon into ASR

Fluxes $[10^6\ t\ yr^{-1}]$ and masses $[10^6\ t]$	Barents	White	Kara	Laptev	East Siberian	Chukchi	ASR as a whole
Riverine runoff (dissolved C_{carb})	6.1		20	8.4	1.5	0.03	36
Underground discharge	1.8		4.4	1.5	0.5	0.04	8.2
Total C_{carb} flux from Land	7.9		24.4	9.9	2.0	0.07	44.2
Zoobenthos (mass)	3.1	0.1	0.9	1.6	1.6	2.8	10.1
Zoobenthos (production)	1.5	0.05	0.4	0.8	0.8	1.3	4.8
C_{carb} in bottom sediments	1.1	-	0.46	-	-	0.4	-

the sediments is a characteristic feature of the polar lithogenesis. These features also include the high C : N ratio, the peculiarities of the group and molecular compositions of bituminoids, lipids, and hydrocarbons, the poor equilibrium in the carbon cycling, and the high values of the C_{org} fluxes toward the pools of sedimentation.

Thus, the climatic, hydrodynamical, geomorphological, bioproductional, and biogeochemical characteristics of the Arctic seas which form the features of the polar lithogenesis determine the originality of the carbon cycling, its parameters and features in this region of the biosphere. The Arctic seas are characterized by a distinctly manifested seasonality in the vegetation processes and in the OM supply to the bottom, a great role of horizontal fluxes from land, great absolute masses of C_{org}, high fossilization coefficients of OM, and relatively poor closure of the carbon cycle. Combination of these factors leads to a long-term removal of great amounts of C_{org} from biotic cycling, which are transferred to the bottom sediment reserve.

7.2 Ecological Features of the Arctic Seas and their Influence on Carbon Cycling

Climatic changes and direct anthropogenic impact on the biota affect the ecological situation in the ASR and lead to sharp changes in the trophic links, matter fluxes, and element cycling. This influences the rates of matter exchange between reservoirs and the parameters of carbon cycling.

The evolution of the ASR ecosystem at the recent stage of development lasts over a relatively short period—about 7–10 ky. At the beginning of the Holocene, the entire Arctic shelf represented a land area. During this relatively short-term geological period, the biocoenosis of the ASR had to adapt itself to the changing climatic and geological conditions. The flora and fauna of the ASR is mostly represented by species gradually introduced from the Atlantic Ocean with the climate warming. Meanwhile, properly Arctic species also seem to exist, since, according to the present-day concepts, the Arctic Ocean has never been completely frozen through.

The principal features of the ASR defining peculiarities of their ecosystems and carbon fluxes are the low temperatures and irregular illumination regime throughout the year, the presence of an ice cover over the major part of the year, and the vertical structure of the water column varying over the greater part of he area from clearly manifested stratification to complete homogeneity. Due to the great area of the ASR and significant changes in the climatic conditions not only from the south to the north but also from the west to the east, the ecosystem of the ASR may be separated into a series of subsystems differing in the species composition and degree of extremity of the dwelling conditions. Among them, the largest are the systems subjected to the influence of the Atlantic and Pacific waters and those where this influence is almost absent.

In the Arctic, the seasonality of the climatic changes caused by the great variability of the solar irradiance over the year from the polar day to the polar night is most dramatically expressed. In the ASR, light is the limiting ecological factor for photosynthesis. In the winter, photosynthesis is virtually impossible, while in the summer, significant parts of the seas are covered with ice; the ice, as a rule, is covered with snow reflecting sunrays. The amount of solar irradiance accepted by the ASR (80 kcal cm^{-2} year^{-1}) is approximately by a factor of 2.5 smaller than in the tropical latitudes. The distinct seasonality in the ASR results in the changes in the dominant age stages and species of plankton over the year; therefore, a complete knowledge on the fauna composition in the ASR, on the matter fluxes, and, hence, on the biomass, production, and balance of carbon may be obtained only from observations covering all the seasons of the year.

In the ASR, ice does not present an insuperable obstacle for life. The intensive phytoplankton development near ice edges and the strong carbon flux (mostly of C$_{org}$) from these areas may be related to a series of poorly studied factors: changes in the water structure, enhanced nutrient concentrations due to the water circulation near ice edges and to wind-induced upwellings, and others (Garrison et al. 1984; Slagstad 1984; Spies 1987; Frolova and Gavrilo 1997). Meanwhile, an alterative opinion exists; it suggests that the outburst of the activity of Arctic phytoplankton near ice edges is mostly caused by genetically intrinsic seasonal character of this activity and phytoplankton awakening in the spring, because in selected cases, no outburst is observed even at the presence of all the conditions favorable for phytoplankton development, including the sites located near the edges of the melting ice driven by drift (for example, Shirshov 1937; Bogorov 1974).

In the Arctic seas, ice should be regarded as a special subsystem of carbon cycling. The body of sea ice is inhabited by communities of bacteria, phyto- and zooplankton, and phyto- and zoobenthos. Their about is subjected to seasonal variations. As a rule, the salinity of sea ice differs from that of seawater; in young ice it makes about 12‰, while in perennial ice it equals 2.6‰ The chlorophyll *a* in ice is significantly (sometimes two orders of magnitude) greater than in seawater (Mel'nikov et al. 1985; Gosselin et al. 1997). Life in ice is mostly concentrated in cavities filled with water formed at the ice melting. Among the ice-dwelling algae, one can encountered endemic species which sink with the brine from snow through ice and diatoms of a planktonic origin. The diatomaceous flora inhabits the lower ice layers where salinity in selected cells may reach 35‰ in the summer and 50‰ in the winter. Endemic green and blue–green algae dominate over the upper layers where salinity changes from 10‰ in the summer to 100‰ in the winter (Matishov and Pavlova 1990). The nutrient flux in the ice is directed upward, while the fluxes of POC and DOC are directed downward. The diatoms of a planktonic origin contained in ice provide the initial spring bloom around the melting ice floes. Ice algae serve as a food source for heterotrophic organisms (nematods, harpacticides, juveniles of amphipods and copepods, larvae of polychaets, and others) and form the basis of the ice ecosystem and initial sources of the carbon fluxes to the biotope.

For each type of the organisms, there exists an optimal temperature range within which their growth is provided. In the Barents Sea, mass phytoplankton bloom starts at a water temperature of about 0°C. Heterotrophic organisms require somewhat greater temperatures for their activity. Therefore, in the Barents Sea, two principal peaks of phytoplankton bloom are observed—the spring one, when the efficiency of heterotrophs eating out phytoplankton is still smaller than the greatest possible, and the fall one, when the metabolic processes in zooplankton decrease, while the conditions for phytoplankton development are still favorable. In accordance with this, pulsations in the POC and, probably, DOC fluxes are observed. The heterotrophic of Arctic ecosystems are dominated by the organisms with a retarded life rate. L.A. Zenkevich (1956) referred to the fauna of the Arctic seas as to the "fauna of the ages." The life span of the Arctic heterotrophs is several times as great as that of heterotrophs of the low latitudes.

Since the biomass of multicellular algae is small and their development is restricted by small depths, where the illumination necessary for photosynthesis is provided, they produce a small flux of C_{org}. In the ASR, this zone is somewhat reduced due to the abrasive action of mobile ice near the shores. A displacement of macrophytes toward deeper parts of the floor is observed. The habitat of macrophytes in the ASR is mostly limited by the southern coastal zone of the Barents Sea and the western part of the coasts of the Kara Sea. Their distribution further to the east is restrained by the severe climate and low water transparency due to the intensive riverine runoff and the matter of thermal abrasion. Only in the eastern part of the Chukchi Sea, life conditions become favorable for macrophytes and the weak flux of photosynthetic carbon increases. One of important ecological niches, where C_{inorg} is transferred into C_{org} and primary production of OM is implemented, is the system of microphytobenthos. Microalgae (diatomaceous and others) dwell in the sediments at small depths and, at selected sites, their contribution to the primary production is several times as great as that of phytoplankton.

In the ASR, the bacterial destruction of the OM synthesized during the summer and occurring in form of detritus continues to proceed in the winter. Bacteria replenish the nutrient stock in the water column and synthesize OM through increasing their own biomass. In the Bering Sea, the proportion of the local bacterial production makes up 0.5–150% of the primary production due to photosynthesis

(Tsyban' and Korsak 1987). Due to the development of psychrophilic enzymatic systems, the Arctic bacterioplankton shows a significant metabolic activity even at low water temperatures, which is its characteristic feature. During the long polar night, bacterioplankton compensates the food deficit of filtering zooplankton serving as a perfect food for it. Under these conditions, the trophic web as an element of the biotic carbon cycling is partially switched over from pasturable forms to a detrital one. Bacteria mostly perform secondary OM synthesis. The role of chemosynthesizing bacteria, which use OM buried in the sediments or OM of an abiogenic origin, in the ASR is unknown.

In the ASR, as in the ocean on the whole, life is concentrated in frontal zones, which are related to sharp changes in the properties, composition, and concentrations of various forms of carbon. These are the zones of upwellings, water convergence, mixing between riverine and marine waters, areas near ice edges, boundaries of stratified layers, water–bottom interface, etc. In the Barents Sea, intensive fronts between the Atlantic and Arctic waters are observed, while in the Chukchi Sea, fronts separate the Pacific and Arctic waters. In these zones, the nutrient stocks contained in deep waters are involved into carbon cycling. Vast vertical and horizontal fronts exist in the seas of the East Arctic in the zones adjacent to the mouths of the largest Siberian rivers.

An important feature of the waters of the ASR is the clearly expressed seasonal thermocline; it is formed in the spring in the process of ice melting and destroyed in the winter due to the cooling of the surface water layers and wind-induced mixing. It strongly influence the distribution of different forms of carbon and their migration. The seasonal character of the thermocline favors the spring phytoplankton development. However, with time, it prevents the photic layer from replenishment with nutrients and represents an obstacle in the way of new OM formation. After a while, high concentrations of POC (and sometimes of DOC) may be observed only at the surface in frontal zones and in the boundary zone between the warm surface layer poor in nutrients and the colder mixed underlying water.

The location of fronts is strictly controlled by the bottom topography; in the case of irregular topography and sharp depth increments, the currents interacting with the topographic features may induce upwelling of waters rich in nutrients to the surface and new formation of DOC, POC, and C_{carb}. One can distinguish the upper zone of the continental slope, where the great depth increment favors the upgoing water flows and, all the other necessary conditions being met, leads to the synthesis of additional masses of POC and DOC. The concentration of biomass and OM production over banks is, to a great extent, conditioned by the hydrodynamics of the permanent currents in the regions of these major topography features. Above the banks, columns of rotating seawater are located, generated at the flowing about these underwater rises; this affect both the masses and the flows of C_{inorg}, DOC. and POC in the ocean.

The characteristics of the bottom sediments also represent an important ecological factor controlling the development of bottom communities in the ASR. They first include the grain-size and chemical compositions of the sediments and acid–alkaline and oxidation–reduction conditions. The most important characteristic of the chemical composition of the sediments is the content of OM, which serves as a source of energy and construction elements for benthic organisms. In the ASR, a correlation between the C_{org} content in the sediments and the benthos density was found (for example, Husmann 1978). The grain-size composition of the sediments determines their sorption properties. The finer the sediments the better the conditions for OM accumulation. Benthos not only consumes and transforms the planktonogenic OM flux but also mechanically stirs the upper layer of the sediments thus providing its even stronger influence on the processes of diagenesis, element migration, and carbon burial in the sediments.

In the course of evolution, the ASR ecosystems adjusted themselves to functioning under extreme conditions. Recently, approximately beginning from the 1960s, these unfavorable conditions of the far north are aggravated by the growing human activity. Among the disastrous sources of the anthropogenic impact one should distinguish the operation of the fishery fleet, oil pollution from ships and oil and gas industry, seismic soundings and electric surveys on shelves, coastal runoff of domestic and industrial waste waters, acid rains, anthropogenic aerosols, polluted waters of the Gulf Stream, and contamination with radioactive substances. From the point of view of evolution, the changes produced in the ecosystem by man may be characterized as violent. Taking into account that the life processes in the Arctic are generally decelerated as compared to warmer seas, the restoration of the distorted links of the Arctic ecosystem will require a significantly longer period.

The Barents and Kara seas are most subjected to the anthropogenic impact in the West Arctic, which has already been manifested in its carbon cycling. In the Barents Sea, a large-scale surveying of oil and gas fields proceeds accompanied by corresponding negative after-effects (Matishov 1998). The waters of the Pechora Sea directly join the Timan–Pechora oil and gas province, where intensive oil and gas production is under progress (Borovinskikh et al. 1998); its side products are supplied into the sea immediately or with the Pechora River runoff (Romankevich 1999; Romankevich et al. 2003). The chemical changes in the riverine runoff, in turn, result in the changes in the sedimentation basins, first, in the coastal water areas, where violations in the carbonate and organic carbon are observed (Zavarzin and Kotlyakov 1998). A negative influence on the ASR ecology is also contributed by the enhancement of traffic over the Northern Sea Route. Along the shores, heaps of lost and driven timber gradually grow; the concentrations of various poisonous compounds both of a local origin and driven from the North Atlantic with currents increase; and mass diseases of fishes, including blood cancer, are observed (Bezumov 1998; Chuksina 1998).

The greatest danger for the ecosystems is represented by the polluting substances of a global distribution—oil and oil products, heavy and transition metals, and chlorinated hydrocarbons. In addition to dissolved oil products and oil film, in the ASR, floating oil aggregates are observed. Their subsequent destruction and decomposition lasts over several years.

The ASR, where about 75–80% of the hydrocarbon reserves of Russia are concentrated, are prone to danger to the greatest degree. In the course of oil and gas drilling and production of oil, gas, and gas condensate, one meets special difficulties related to the presence of ice, shortness of the warm season, and frequent storms. These reasons also complicate the cleaning operations in emergency situations under the ice conditions of the Arctic seas (Romankevich et al. 2003). With the decrease in the water temperature and increase in the water salinity, the rate of oil destruction decreases and this affects the CO_2 exchange in the water–atmosphere system. Saline water eliminates the ionic charge of the suspended oil particles causing their coagulation and precipitation. As a result, oil products are accumulated in the sediments; they slow down the diffusion processes and produce oxygen deficiency; this, in turn, restricts the process of oil degradation. The low water and air temperatures hamper the natural processes of chemical oxidation of hydrocarbons in the Arctic seas even in the summer period (for example, Nesterova and Simonov 1979; Tsyban' 1996). The area most contaminated with oil products is Kola Bay (up to 10 maximum permissible concentrations). The local people are warned about the danger of consuming any type of seafood from Kola Bay. The White Sea annually accepts about 3.5 th. t of oil products with the riverine runoff (Tsyban' 1996); the Northern Sea Route is also significantly polluted. That is why the "World Ocean" Federal Purposive Program and its supplement ("The Northern Sea Route Development" subprogram) should anticipate multidisciplinary studies in order to provide their ecological security (Aleksin 2000; Denisov 2002).

Oil and oil products seriously distort the natural carbon cycling in the ASR and jeopardize the Arctic ecosystems (for example, Savinova et al. 1985; Romankevich et al. 2003). Oil film intervenes the energy and heat regimes and gas exchange with the atmosphere. Oil products violate the structural and functional characteristics of phytoplankton; at their concentration equal to the maximum permissible value, the rate of the C_{org} primary production is reduced by a factor of 4–8. They also suppress the process of OM synthesis by macrophytes. Emulsified oil causes mass destruction of hydrobionts and increased mortality of spawn and juveniles of fishes. Oil products are accumulated in all the links of the trophic web. In the coastal zone of the Barents Sea, zooplankton accumulates up to 3–5% of oil hydrocarbons contained in the water. The development of oil production provides conditions under which salmons can loose their way while moving to spawning sites due to the loss of their smell-based sense of orientation. Sometimes, mass death of seabirds results from pollution of their feathering with oil.

Since the oil composition also includes phenols and polynuclear aromatic hydrocarbons (PAH), the oil pollution is also accompanied by phenol and PAH contaminations. Submerged and floating timber serve as additional sources of phenols; contamination of this origin is most important in the coastal regions of the Laptev Sea, especially off the Lena and Yana river deltas (Tsyban' 1996). Many of PAH feature clearly manifested toxic, mutagenic, and carcinogenic properties. Serious negative after-effects of the oil pollution of the ASR are related to the active circulation of PAH in marine waters, their accumulation in the surface microlayer, marine biota, and bottom sediments (Aibulatov and Artyukhin 1993; Izrael and Tsyban' 2000).

Heavy and transitive metals Hg, Pb, Cd, Cu, Zn, Ni, Co, Sb, Cr, Mn, Fe, and others in microgram amounts participate in the composition of many biologically important compounds—enzymes, hormones, vitamins, pigments, and others. The normal passing of the processes of biosynthesis requires not only the presence of a special chemical element in the environment but also the certain proportions of the elements (Khristoforova 1989; Saenko 1992). In particular, an increase in the concentration of one or a few metals may make them toxic and leads to a distortion of the trophic links in the carbon cycling.

Among the toxicants of a global distribution, the group of chlorinated hydrocarbons is distinguished; contrary to oil and heavy metals, they have no natural analogs. This group includes chlorine–organic pesticides and polychlorinated biphenyls—substances widely applied in industry and agriculture. One of the principal sources of chlorine–organic pesticides is the water supplied to the ASR from the Atlantic Ocean. The highest concentrations of these compounds are encountered in the Barents and White seas; meanwhile, the content of chlorinated hydrocarbons in the Chukchi Sea also causes a serious anxiety (Izrael' and Tsyban' 2000). These substances, insoluble in the water but well soluble in lipids, are able to form stable and toxic metabolites. The half-value period of chlorinated hydrocarbons in cold seawater and ice ecosystems makes up tens and hundreds of years. Since the natural microflora does not contain species able to use these compounds as a food substrate, their decomposition under the natural conditions of the ASR proceeds slowly under the action of physical and physicochemical factors. During the recent years, due to the ban of the application of dichlorodiphenyltrichloroethane, its content in the water has decreased; however, it still remains rather high because of it high stability. For example, in Kola Bay, its concentration is 5–6 times as high as its maximum permissible value.

The response of the ASR ecosystem to the anthropogenic pollution is manifested in the decrease in the OM productivity, changes in the species diversity, trophic links, and structure of the populations of mass species of benthos and plankton. This is a clear evidence on the incipient rapid changes in the carbon cycling parameters (for example, Matishov et al. 1994; Dodin and Sadikov 2000; Saenko 2001).

Along with the chemical effects on the ecosystem resulting in violation of different levels of the OM production, there exist equally ruinous human impacts which weaken one or a few links in the carbon cycling system. As a result, an extended train of events begins, which makes difficult restoration of the initial condition of the carbon cycling.

Thus, the ecosystem of the ASR undergoes a complicated and very active period of its evolution. It faces the stage of the mass development of oil and gas resources, the growth of the pollution related to their production and processing, the increase in the fluxes of greenhouse gases at climate warming, and other natural and anthropogenic of the biosphere changes negative from the point of view of the mankind. All this should be taken into account when estimating and forecasting the changes in the carbon cycling parameters in the future.

The objectives of the further studies of the carbon cycling are:

—refinement of the values of concentrations and fluxes of DOC and POC in the ASR, their distribution, and removal to the Atlantic Ocean;

—accumulation and generalization of the data on the gas exchange in the ASR (carbon dioxide, methane) in the water surface–atmosphere system;

—estimation of the ecological dynamics of carbon compounds in the Arctic seas;

—estimation of the biogeochemical and organochemical parameters of carbon cycling as indicators of climate changes;

—development of a prognostic model for carbon cycling in the Arctic Basin.

Many of these questions would be considered to our mind during International Polar Year 2007/8 that will mark the 125th anniversary of the First International Polar Year (1882/3) and the 50th anniversary of the International Geophysical Year (1957/8).