Chapter 1

1. SELECTED REGIONS OF THE RUSSIAN ARCTIC AND FACTORS AFFECTING THEIR POLLUTION

According to the project objectives this study is focused on the pollution evaluation of selected regions of the Russian North. This territory occupies rather large part of the Russian Federation extended as far as about 11 000 km from Norwegian border on the western edge to the Mys Dezhneva (East Cape) on the eastern one. It includes Murmansk Oblast, Nenets Autonomous Okrug, Yamalo-Nenets and Taimyr Autonomous Okrugs, Sakha Republic (Yakutia), Chukotka Autonomous Okrug (Fig. 1.1). The model evaluation of the Russian North contamination was based on this administrative division.

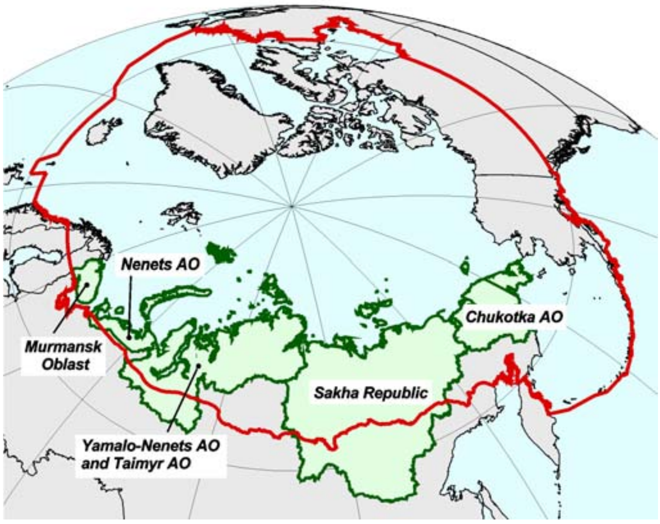


Figure 1.1 *Area of the Russian North (red line bounds the Arctic region) [AMAP, 1998]*

The territory of *Murmansk Oblast* being part of the Kola Peninsula occupies about 145 thousand km^2. The major part of indigenous population of Murmansk Oblast belongs to Saami group living in Lovozero and Kola districts of the eastern part of the Kola Peninsula.

Nenets Autonomous Okrug (Nenets AO) occupies around 177 thousand km^2. It includes the lower basin of the Pechora and Indiga Rivers. The major part of its territory is tundra and forest tundra. Most of indigenous people living in this Okrug belong to Nenets.

The territory of *Yamalo-Nenets Autonomous Okrug* (Yamalo-Nenets AO) is about 750 thousand km^2 including the Yamal Peninsula and lower basin of the Ob River. Indigenous population of the Okrug is mostly represented by Nenets, Khanty and Yukagir. As for Nenets AO the major part of its territory is tundra and forest tundra. *Taimyr Autonomous Okrug* (Taimyr AO) territory is about 862 thousand km^2. It includes the Taimyr Peninsula, lower basin of the Yenisey and Khatanga Rivers. Forests with a minor part of tundra mostly cover its area. Indigenous people living in this Okrug are Dolgan, Nenets, Nganasan, Evenk, and Enets. In computations Yamalo-Nenets AO and Taimyr AO were considered as one region.

The territory of *Sakha Republic* is about 3.1 million km^2. Its Arctic area is mostly covered by tundra and forest tundra. The indigenous population of the Republic is comprised of Yakut, Even, Evenk, Yukagir, and Chukchi.

Chukotka Autonomous Okrug (Chukotka AO) territory is about 738 thousand km^2. This Okrug is situated at the most north-eastern part of Eurasian continent. The area of this Okrug is mostly covered by tundra and forests. The indigenous population is represented by Chukchi, Eskimo (Yupik), Even, Chuvan, and Koryak.

The climate of the Russian Arctic regions is characterized by lack of solar radiation in wintertime, which leads to very low temperatures. In contrast to winter, in summer solar radiation flux is significant, but temperatures are not high because most of incoming solar energy is spent for snow or ice melting. Atmospheric circulation is characterized by cyclonic activity in all seasons, which conditions the exchange of air masses between middle and high latitudes. The western part of the Russian Arctic undergoes milding effect of the Atlantic to the highest extent in comparison with central and eastern parts because of prevailing western atmospheric flows. It is the warmest part of the Arctic and the temperature range between winter and summer is much lower than that in the eastern part of Russian North. The eastern part of the Russian North is characterized by the most severe climatic conditions.

The delivery of contaminants to the selected regions of the Russian Arctic and the Arctic as a whole depends on many factors: the atmospheric circulation, oceanic currents, ice coverage dynamic, riverine runoff to the Arctic waters, physical-geographical conditions of this region, location of emission sources, their intensity, physical-chemical properties of pollutants etc. In this section we briefly outline circulation of air masses, sea currents and ice cover dynamics in the Arctic region. More detailed analysis of processes which affect the pollution of the Arctic is given in [*AMAP*, 1998].

1.1. Atmospheric circulation in the Arctic region

The atmospheric circulation in the Arctic region is essentially different for cold and warm season. The prevailing atmospheric currents in the lower Arctic troposphere depend on the location of the following quasi-stationary baric systems in the Northern Hemisphere: Icelandic and Aleutian Low and Siberian and North American High.

In winter due to the geographical position of these systems the air parcels come to the Arctic from Europe in the northwest direction and from central Asia and Siberia (Fig. 1.2.a). The prevailing transport of air masses from the regions of North America is in the zonal direction over the North Atlantic. Thus air masses from North American continent come to the region of Scandinavia, Iceland and the Norwegian Sea and then – to the Arctic. Western regions of the Russian North (Murmansk Oblast, Nenets AO) are characterized mainly by south-western or western atmospheric flows, bringing air masses from Eastern and Central Europe as well as from central Russia. In the central regions (Yamalo-Nenets and Taimyr AO, Sakha Republic) flows with southern component prevails, thus transporting air masses from Central Russia, the Urals, South of Siberia, Central and Eastern Asia. Over easternmost region (Chukotka AO) northern flows predominate during winter.

In summer due to more uniform surface warming in comparison with the winter period the temperature gradient and consequently pressure between the pole and the equator is lower (Fig. 1.2.b). Therefore the atmospheric circulation in the Arctic is less intensive than during winter. During this period the continental high pressure systems disappear and oceanic low pressure systems weaken. Over the Arctic Ocean the high-pressure systems take place more often than in winter, defining outflow of the Arctic air in the sub-meridional direction. European region is under the impact of Azores anticyclone. Over central Eurasia and the central part of North America low-pressure systems dominate. The inflow of air masses to the Arctic mainly takes place from the Bering Sea, Aleutian Island and from the North Atlantic along the northwestern periphery of Azores anticyclone. In contrast to winter, the main peculiarity of atmospheric transport in summer over all regions of the Russian Arctic, except for Chukotka has more often the northern component. Chukotka, in its turn, is characterized by predominant transport either from the Pacific Ocean or from Eastern Asia and Russian Far East. However, the northern transport also takes place.

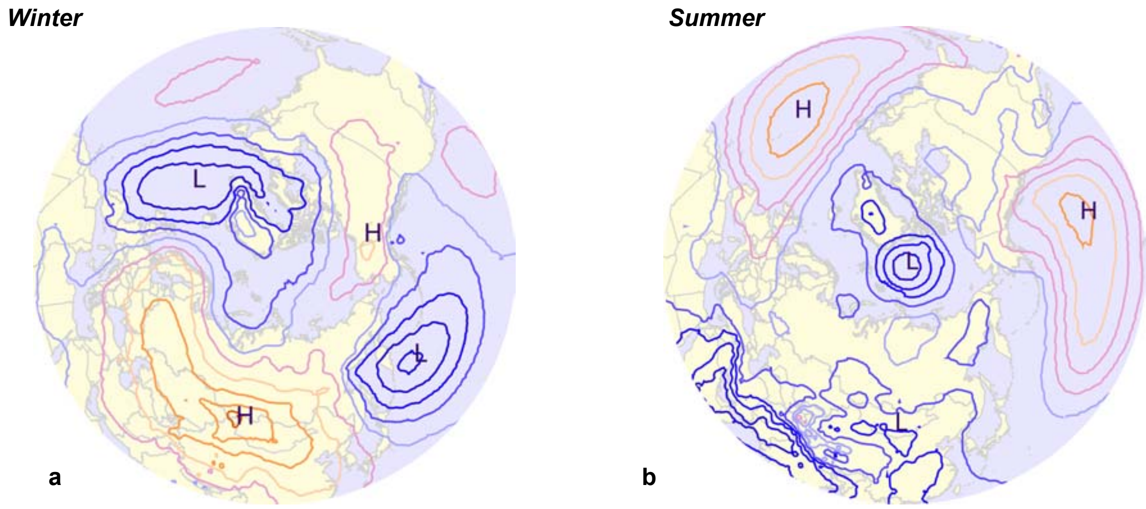


Figure 1.2. *Location of main baric systems in the Arctic region for winter (a) and summer (b) period of 1996 based on the reanalysis data [Kalnay et al., 1996]*

It is significant to note that these general features of the Arctic circulation are based on seasonal averaging. For this reason these flow directions are only most probable. Baric systems and consequently the transport direction at each specific moment can be essentially different form those estimated by averaging. It is also important to note that on the local level wind directions also can differ from prevailing directions since they can be distorted under the impact of relief, breeze circulation and other local peculiarities.

The atmospheric circulation is also responsible for precipitation pattern in the Russian Arctic. The most abundant annual precipitation take place in the western part of the Arctic and can reach 500-600 mm. From the westernmost part of the Arctic towards the east annual precipitation amount decreases. On the North of Sakha Republic precipitation are mainly within 100-150 mm. In the easternmost part of the Russian Arctic precipitation are relatively high (300 - 600 mm), which is caused by important southern transport of air masses from the Pacific Ocean, especially during summer season.

Analysis of prevailing wind directions in this or that geographical region can be made by two basic approaches – the analysis of trajectories of air particles or by typing of synoptic situations. Since in the literature comparatively little attention is given to the “climatology” of trajectories in the Russian North, the analysis of the main transport directions is based on typing of synoptic processes in the Arctic suggested by *L.A. Dydina* [1982].

The atmospheric circulation in the considered regions (the Kola, Yamal and Taimyr Peninsulas, Yakutia and the Chukotka Peninsula) first is characterized for the winter period and then for the summer.

In winter over the region of the Kola Peninsula cyclonic activity dominates. The prevailing direction of transport has the southern component – southwestern, southern, and southeastern. It implies that air parcels come from the northern part of Russia and from Europe. In some cases western and northwestern airflows take place, and air masses come from the Northern Atlantic and the Norwegian Sea. Under these transport patterns air masses from North America continent can reach the Kola Peninsula.

Over the Yamal Peninsula in winter cyclonic activity predominates. The prevailing transport direction has a distinct southern component. Air masses come mainly from southern and southwestern regions of Russia and from Kazakhstan. Under certain conditions air masses reach the Yamal Peninsula from the northern part of Europe - from the Kola Peninsula, St.-Petersburg region and Scandinavia. In relatively rare cases air masses can come from the north or southeast.

Typical wintertime air mass transport to the Taimyr Peninsula occurs from the south or southwest of Russia (the southern Urals, the Caspian region, south of West-Siberian lowland) and from Kazakhstan. However, transport from the west is also possible, and some contribution of northern regions of Russia such as St.-Petersburg region and the Kola Peninsula to pollution levels over the Taimyr Peninsula is also expected.

Yakutia in winter is influenced by Siberian anticyclone. Therefore, air masses should arrive to this region mainly from the south. In some cases, and especially in the northern part of the region, the transport from the west or northwest can take place.

The Chukotka Peninsula is affected by eastern periphery of Siberian anticyclone, which conditions northern and northeastern winds for the most part of winter. Main transport directions of air masses are from Canadian Arctic Archipelago, from the Arctic Ocean and from Alaska. In some cases the northeastern fluxes arise under the impact of Canadian anticyclone. The western peripheries of cyclones over the Chukotka and Bering Seas also condition the northern and northwestern directions of winds. Penetration of cyclones from the Sea of Okhotsk to the Bering Sea can cause transport from the south, but these situations are relatively rare for wintertime.

In summer the Barents Sea and the Kola Peninsula are characterized by cyclonic activity conditioning winds in the southern and southwestern direction. Therefore the atmospheric transport from central regions of Russia as well as from Eastern Europe is expected. Another typical situation is transport of air from the northwest. In this case air masses arrive from the northern Atlantic and Scandinavia.

Atmospheric transport patterns for the Yamal Peninsula in summer time, in contrast to winter, have more probable northern direction, when air masses penetrate to the peninsula from the Arctic Ocean. However, airflows from the south, southwest and even southeast bringing air from industrial regions of Russia are also possible.

Similar to the Yamal Peninsula, typical atmospheric transport patterns to the Taimyr Peninsula in summer are characterized either by southern or by northern flows. Airflows containing the southern component can bring air masses from the Caspian region, south of West Siberia, from the southern Urals and from Kazakhstan. More probable northern currents provide inflow of air form the Arctic Ocean.

Over Yakutia in summer the transport from the north of northwest dominates. However, under certain conditions the transport of air masses from the south or southwest can take place.

Over the Chukotka Peninsula in summer time transport both from the north or northeast (the Chukotka Sea) and from the south (the Sea of Okhotsk, the Bering Sea, the Pacific Ocean) are typical. It also happens that Okhotsk cyclones are intruded to the peninsula forming southern and southwestern air fluxes. Eastern fluxes, accompanied by the outflow of moist warm air, are formed when over Siberia low pressure system is located and over the Bering, Chukotka and East Siberian Seas high pressure dominates [*Zimich*, 1998].

This brief analysis of atmospheric transport patterns allows us to conclude, that for the western part of the Russian Arctic the transport of air masses from southern or central parts of Russia as well as Europe is more typical. In the eastern part of the Arctic the transport from southern Russia or from the Arctic Ocean is most probable.

1.2. The circulation of water and sea ice in the Arctic Ocean

Basic features of water circulation in the Arctic Ocean

The first detailed description of water circulation in the North-European basin was given in [*Nansen*, 1909; *Helland-Hansen and Nansen*, 1909]. The pattern presented by these authors has not been changed in its essential features but it was refined and complemented during the years, which followed in [*Metcalf*, 1960; *Aagaart and Coachman*, 1968; *Treshnikov and Baranov,* 1972; *Nikiforov and Shpaikher*, 1980].

According to modern conception basic elements of the horizontal circulation in the Arctic Ocean are as follows:

- Polar drift from Bering strait via the pole to the Fram strait;
- Extensive anticyclonic circulation in Amerasian Arctic sub-basin (Beaufort gyre);
- East-Greenland current; according to [*Aagaart and Coachman*, 1968] the overall transport of this current comprises about 30 Sv (Sverdrups, 1 Sv = 10^6 m^3/s), i.e. approximately half the Gulfstream ;
- West-Iceland and East-Iceland currents;
- Norwegian current (it is an extension of the Atlantic warm water flow through Faeroe-Shetland strait; northwards it divides into two branches: North Cape current and Spitsbergen current.);
- North Cape current (directed eastward along the Kola Peninsula northern shore);
- Spitsbergen current (directed northward along western Spitsbergen coast);
- The system of cyclonic currents of the North-European basin (the Norwegian and Greenland Seas).

Due to sharp vertical stratification the overall motion pattern is sufficiently more complicated than the horizontal water motion outlined above. In the structure of water masses there are several layers differing in their thermohaline properties and, as a consequence, in the circulation structure. On account of limited direct measurements the three-dimensional circulation scheme can be reproduced only in a crude way. However the key features of schemes constructed by different authors have much in common. As an example Figure 1.3 demonstrates the block scheme of three-dimensional circulation in the Arctic basin after [*Nikiforov et al.,* 1966]

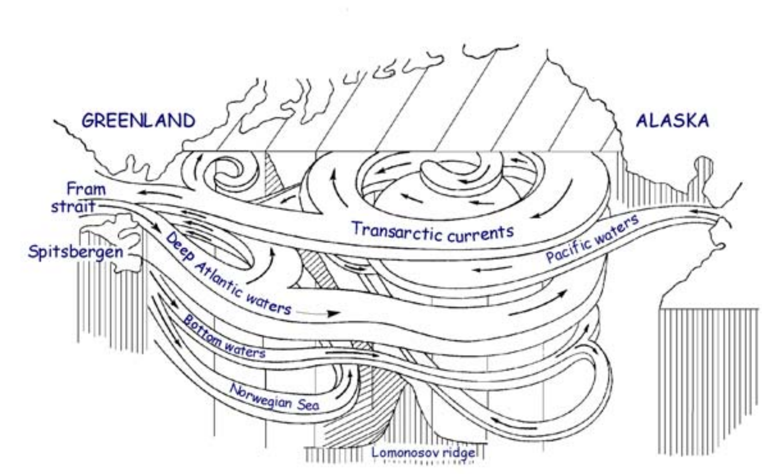


Figure 1.3. *Block scheme of circulation in the Arctic basin after [Nikiforov et al.,* 1966*]*

Three main layers differing in water masses properties stand out in the Arctic basin along the vertical: the Arctic surface water, the Atlantic water and Deep water. The Arctic surface water includes the layer of water (30-50 m) with relatively low salinity and temperature close to freezing point as well as the underlying halocline (50-

200m). The formation of this water mass is determined by the ”excess” of fresh water budget due to continental runoff. About 10% of the global runoff enters the Arctic Ocean whereas the ocean’s area is only 5%, and its volume – 1.5%. The elements of the horizontal circulation listed above are referred primarily to the Arctic surface water.

Strong density stratification in the halocline prevents from the development of deep convection like that observed to the south of Greenland, which is the source of deep-water formation. Sharp stratification essentially decreases the heat exchange rate between the upper layer and the underlying layers of relatively warm Atlantic water but at the same time it restrains the vertical redistribution of contaminants coming into the surface water from the atmosphere or with runoff.

The Atlantic water mass of the Arctic basin, as it follows from the name, comes into the Arctic basin from the Atlantic Ocean initially as a surface inflow – the extension of Norwegian current, West Spitsbergen current and then submerges under the Arctic surface water. Several places where the surface flow submerges to deeper layers are known. One of them indicated on the majority of three-dimensional circulation schemes is located to the west of Spitsbergen Island.

The water exchange between the Arctic basin and the Atlantic Ocean amounts in general to the fact that Arctic cold currents carrying enormous ice masses enter the Atlantic Ocean, and from the Atlantic warm water with high salinity flows into the Arctic Ocean as submerged flow. Thus the Arctic basin is a source of water with reduced salinity relative to the North-European basin, and the Arctic Ocean as a whole – relative to the North Atlantic. It happens for two reasons – owing to permanent ice outflow to the indicated regions and due to tremendous “excess” of fresh water budget resulted from the continental runoff.

The Pacific Ocean is another source of water inflow to the Arctic Basin through the Bering Strait. The mean inflow transport is about 0.8 Sv (1 Sv = 10^6 m^3/s.) [*Coachman and Aagaard,* 1988]. This average transport is superimposed by seasonal and interannual variations with amplitude of an order 1 Sv and 0.2 Sv respectively. According to [*Coachman,* 1993] they can reach 3 Sv to the north and 5 Sv to the south.

Evidently variations in the water transport should be directly connected with the redistribution of water contaminants.

Information about the circulation in the layer of the Atlantic waters flowing in the sub-surface layer (at depths from 200 to 900 m) is rather limited. It is deemed that the large-scale circulation is mainly counter-clockwise i.e. opposite to the general circulation of the surface water.

The Arctic deep water has two varieties: Deep water of Canadian basin and Deep water of Eurasian basin. Lomonosov ridge at depth of about 1500 m is the distinguish line between them. Water exchange with neighboring basins occurs only through the Fram strait. Its depth reaches 2600 m whereas in other places of the boundary contour (the Bering strait, straits of Canadian Archipelago, the Barents Sea) depths are essentially smaller.

In addition to the direct contaminants transport with currents there are also mechanisms of vertical mixing: turbulent mixing of convection-wind origin in the upper ocean layer, which is in action everywhere, and deep convection observed only over comparatively small regions in the Greenland, Norwegian and Labrador Seas. Deep convection is the principal source of deep water formation, which is unique for the Northern Hemisphere (in the northern latitudes of the Pacific there are no such processes). Features of the North Atlantic deep convection have been analyzed in detail by [*Killwoth*, 1983]. An essential role in these processes belongs to the evolution of sea ice, which is considered in the next section.

General information about sea ice

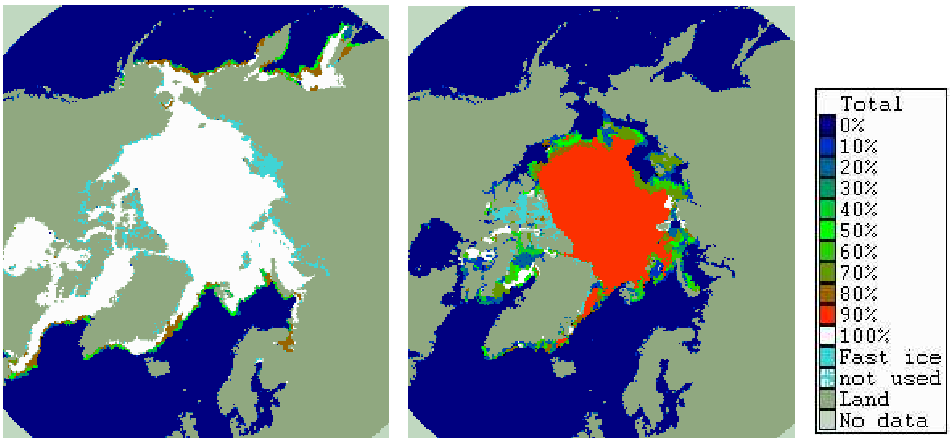
Geographical distribution

Due to the climate conditions sea ice is concentrated predominantly in the polar regions of the World Ocean. Its mean annual area is nearly 26 ml.km^2. Slightly less than half of it is accounted for the Northern Hemisphere. However, during a year the ice covered area varies drastically. The largest ice covered area in the Northern Hemisphere is observed in February-March, 15.4 ml.km^2, the smallest area – in September, 8 ml.km^2 [*Zakharov and Malinin*, 2000].

Contrary to the Southern Hemisphere where sea ice forms a broad ring surrounding the Antarctic continent, in the Northern Hemisphere ice represents a compact massive covering the ocean area around the geographical pole. The central part of this massive is made up of so called old ice i.e. two-year and multi-year ice. Along the periphery seasonal ice is located, which completely melts in summer and reaches its maximum development in February-March.

At the boundary between the Atlantic and the Pacific there are three ice tongues stretched in the meridianal direction: East-Greenland, East-Canadian and the Pacific (Fig. 1.4). Along the eastern coast of North America sea ice in winter reaches 46°N and occasionally down to 42°30′N. Along Asian continent in the Pacific Ocean ice penetrates to the south down to 43°N.

General geographical features of sea ice distribution are determined, along with seasonal cycle of incoming solar energy, by the character of circulation in polar and middle latitudes. The farthest to the south ice spreads along the eastern coast of Greenland, North America and Asia where cold sea currents flow: East Greenland, Labrador and Oya-Sio. In regions, which are under the influence of warm currents, in particular, of individual branches of North-Atlantic and Kurosio currents the ice boundary retreats to the north. As a result there is a severe asymmetry in distribution of water temperature, salinity and sea ice between the western and eastern parts of the Atlantic and the Pacific Oceans.



a b

Figure 1.4. *Sea ice compactness in the Arctic in January 1993 (a) and in August 1993 (b) from [Global Digital Sea Ice Data Bank]*

Most part of ice in the Nothern Hemisphere drifts under the impact of wind and sea currents. But in shallow water near coasts the ice is frequently attached to land and is motionless during long time. In March during the period of the most extensive development its area is 2 ml.km^2. The fast ice is mostly developed in straits of Canadian Arctic Archipelago and in shallow water surrounding New Siberian Islands.

Basic characteristics of sea ice cover

Basic characteristics of the sea ice cover state are its compactness and thickness. Up till now information about ice thickness remained quite fragmentary due to high horizontal inhomogeneity in thickness distribution and technical difficulties in its routine observations. The modern-day pattern of ice thickness distribution in the Arctic is based primarily on data sonar measurements. The accuracy of measurements of mean ice sinking (its underwater part being 80-95% of the whole thickness) at distances of 50-100 km is 0.3-0.5 m. Generalized data on wintertime sinking of sea ice determined from measurements according to Gloersen and Campball [*Zakharov and Malinin*, 2000] (an overall length of used underwater profiles is about 200 thous. km) are given in Figure 1.5.

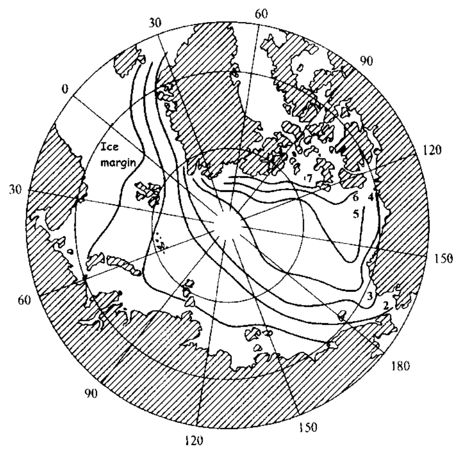


Figure 1.5. *Mean wintertime sinking of sea ice (metres) determined from measurements according to Gloersen and Campball [Zakharov and Malinin, 2000]*

Mean annual sinking for the Arctic Ocean as a whole is 2.9 m, standard deviation 1.8 m. Mean annual sinking varies greatly depending on the region within a wide range, e.g. from 1 m in the Kara Sea and the Baffin Sea to 3.4 m in the Central Arctic and up to 4 m in the region of Canadian Arctic Archipelago. Wintertime mean values reach here 7 m. A large-scale feature of the ice thickness distribution over the Arctic Ocean is a general thickness decrease from North Greenland coast and Canadian Arctic Archipelago towards Siberian coast.

Sea ice thickness varies not only with space but over time as well e.g. seasonal variations. Every year ice melts completely over the area of about 8 ml.km^2. A typical range of annual sea ice growth with subsequent melting in different regions is 0.5-2 m.

The compactness is the ratio of area covered with drifting ice to the overall area of the considered domain. It is determined by 10-ball scale according to which 0 ball means clear water and 10 balls – compact ice. The practical significance of compactness lies in the fact that it actually determines the conditions of navigation within the ice-covered areas. The scientific importance is related to the fact that it essentially governs exchange rates of substances between the atmosphere and the ocean: energy, mass and contaminants. In the Arctic basin the compactness usually rapidly increases from 1-2 balls near ice margins to 9-10 balls outside the marginal zone over the most part of the ice cover. The Arctic ice cover represents a vast area of compact ice surrounded on the outside with a narrow belt of ice with low compactness. In the Arctic Ocean seasonal compactness variations do not exceed 1.4 balls, and in the central part – 0.3 ball. Towards the margins of ice cover seasonal variations increase to 3.1 balls. This average pattern can be drastically transformed in individual years, since even in the region of the North Pole large ice-free water areas were occasionally observed.

The formation, development and decay of sea ice take place under the impact of thermodynamic (heat fluxes, phase conversions) and dynamic (ice movements under the influence of wind and sea currents) factors. This division, however, is rather conventional since, for instance, thermal state of seawater essentially depends on its dynamics. It is confirmed by the existence of vast ice-free areas in which climatic conditions are seemingly favorable for ice formation.

The analysis of present-day winter conditions in the atmosphere suggests that these conditions cannot prevent the Arctic ice cover from further expansion. Isotherm –2°C in the atmosphere corresponding to freezing point of seawater in some regions is as far from the ice edge as hundreds of kilometers [*Zakharov and Malinin*, 2000]. The climate does not prevent the sea ice cover from the development in horizontal direction. Over the entire space limited by the ice edge in the north and by air temperature isotherm –2°C in the south. A restrictive factor in this case is the advective heat coming from the south with sea currents and compensating heat losses from the ocean surface to the atmosphere . In the central part of the Arctic basin the restrictive effect of heat advection with currents disappears since the Atlantic warm waters coming to the Arctic basin submerge under lighter freshened surface water, become overlapped by the halocline from above and sharply restrain vertical heat loss. The depth of the upper freshened layer varies from 30 to 70 m [*Zakharov*, 1981].

Ice drift

Ice motion is governed by impact of wind and surface sea currents. Since the structure of surface currents, in its turn, also depends on wind impact, then large-scale features of surface water and sea ice circulation have much in common.

The first three features of large-scale water circulation listed in Section 1.1 are also distinctly expressed in the field of ice drift velocity constructed on the basis of processed data of drifting buoys (Fig. 1.6).

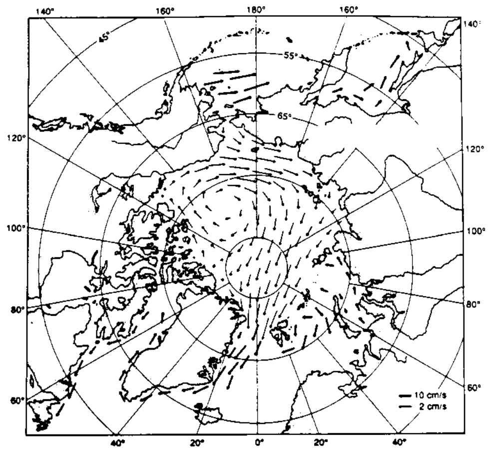


Figure 1.6. *Mean ice drift velocity in the Arctic determined on the basis of processed data from automatic drifting buoys. The data volume is equivalent to observations of one buoy drifting during 120 years [WMO/TD-No. 127, 1987]*

Ice drift velocity averaged over long time periods (about a year) can be estimated safely with the use of data on drifting stations “North Pole” (NP). The characteristic averaged velocity is 2 km/day [*Zakharov*, 1976], but it can reach 6.8 km/day as observed in the course of NP drift in 1937/38. This velocity may be accepted for the assessment of long-range transport of contaminants associated with the ice cover for the time intervals of about a year and more.

Another characteristic important for problems of the contaminants transport is an overall ice outflow from the Arctic basin to the North-European basin and to the Atlantic Ocean. This outflow has a pronounced seasonality with maximum in winter and minimum during summer half-year. During a year 650 thous.km^2 of ice come to the Greenland Sea, 420 of which fall on six winter months (November-April) and 230 – on six summer months (May-October). The mean amplitude is 530 thous.km^2. The minimum ice outflow was observed in 1953/54 and comprised 390 thous.km^2. The maximum outflow in 1961-62 amounted up to 920 thous.km^2.

In volume units the annual ice outflow from the Arctic basin to the Atlantic and the Barents Sea through various straits is about 20000 km^3 [*Knipovich*, 1938].

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