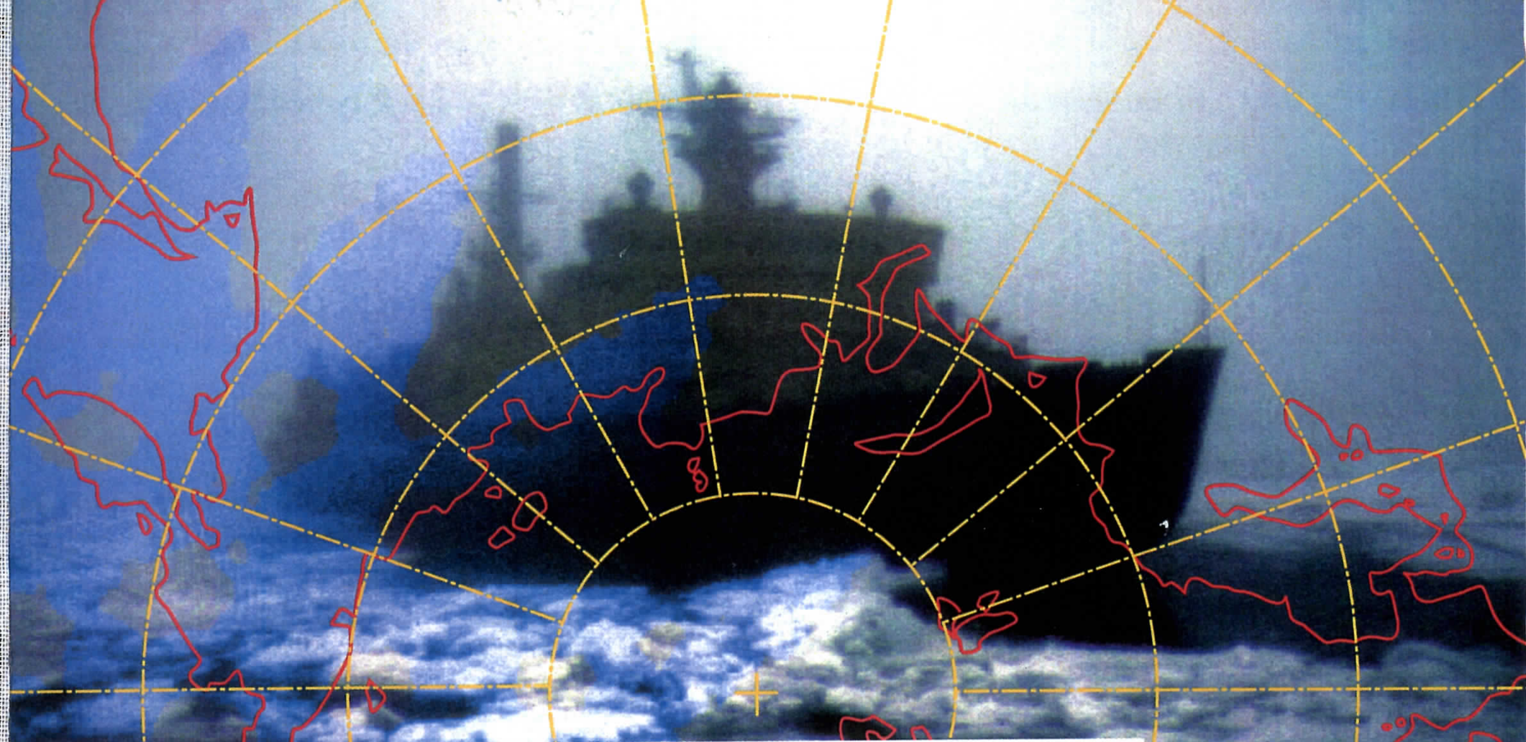

INSROP WORKING PAPER
NO. 69 - 1996, I.7.1

Perspective Research

Part I: Changes in Climate, Ice and Shipping Conditions along the NSR during the XXth Century.

Part II: Accurate Positioning in the Arctic.

By V.F. Zakharov, A. Baskin, G.V. Alekseyev, A.Y. Buzuyev and S. Samonenko

INSROP International Northern Sea Route Programme

Central Marine Research & Design Institute, Russia

The Fridtjof Nansen Institute, Norway

Ship and Ocean Foundation, Japan

International Northern Sea Route Programme (INSROP)

Central Marine Research & Design Institute, Russia

The Fridtjof Nansen Institute, Norway

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INSROP WORKING PAPER NO. 69-1996

Sub-programme I:	Natural Conditions and Ice Navigation
Project I.7.1:	Perspective Research
Supervisors:	V.F. Zakharov and A.Baskin
Title:	**Perspective Research** **Part I: Changes in Climate, Ice and Shipping Conditions along the NSR during the XXth Century.** **Part II: Accurate Positioning in the Arctic.**
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Date:	14 November 1996
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FOREWORD - INSROP WORKING PAPER

INSROP is a five-year multidisciplinary and multilateral research programme, the main phase of which commenced in June 1993. The three principal cooperating partners are **Central Marine Research & Design Institute (CNIIMF)**, St. Petersburg, Russia; **Ship and Ocean Foundation (SOF)**, Tokyo, Japan; and **Fridtjof Nansen Institute (FNI)**, Lysaker, Norway. The INSROP Secretariat is shared between CNIIMF and FNI and is located at FNI.

INSROP is split into four main projects: 1) Natural Conditions and Ice Navigation; 2) Environmental Factors; 3) Trade and Commercial Shipping Aspects of the NSR; and 4) Political, Legal and Strategic Factors. The aim of INSROP is to build up a knowledge base adequate to provide a foundation for long-term planning and decision-making by state agencies as well as private companies etc., for purposes of promoting rational decisionmaking concerning the use of the Northern Sea Route for transit and regional development.

INSROP is a direct result of the normalization of the international situation and the Murmansk initiatives of the former Soviet Union in 1987, when the readiness of the USSR to open the NSR for international shipping was officially declared. The Murmansk Initiatives enabled the continuation, expansion and intensification of traditional collaboration between the states in the Arctic, including safety and efficiency of shipping. Russia, being the successor state to the USSR, supports the Murmansk Initiatives. The initiatives stimulated contact and cooperation between CNIIMF and FNI in 1988 and resulted in a pilot study of the NSR in 1991. In 1992 SOF entered INSROP as a third partner on an equal basis with CNIIMF and FNI.

The complete series of publications may be obtained from the Fridtjof Nansen Institute.

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International Northern Sea Route Programme (INSROP)

Central Marine Research & Design Institute, Russia
The Fridtjof Nansen Institute, Norway
Ship & Ocean Foundation, Japan

NATURAL CONDITIONS AND ICE NAVIGATION

SUB-PROGRAMME I

Project I.7.1

PERSPECTIVE STUDIES

Annual 1995 working paper

**PREPARED FOR
THE JOINT
RESEARCH COMMITTEE
AND
SPONSOR COMMITTEE**

Supervisors:
Professor V.F.Zakharov, AARI
Dr. A.Baskin, CNIIMF

ST.PETERSBURG
1995

PREFACE

The Report on the second stage of Project 1.7.1 "Perspective studies" consists of two parts:

Part I "Changes in climate, ice and shipping conditions along the NSR during the XXth century". Prepared at the AARI under the supervision of Professor V.F. Zakharov.

Section 1 prepared by Dr. G.V. Alekseyev, section 2 - Prof. V.F.Zakharov, section 3 - Dr. A.Ya.Buzuyev, section 4 - Dr. A.Ya.Buzuyev and Prof. V.F.Zakharov.

Part II "Organization of shipping using electronic charts". Prepared at CNIIMF under the supervision of Dr. A. Baskin.

PART I

CHANGES IN CLIMATE, ICE AND SHIPPING CONDITIONS ALONG THE NSR DURING THE XXTH CENTURY

LIST OF FIGURES AND TABLES

Figure captions

Tables

TABLE OF CONTENTS

INTRODUCTION

The Report contains the results of the studies at the second stage of Project 1.7.1, its ultimate goal being an assessment of possible changes of climate, ice conditions and shipping along the NSR during the forthcoming decade (up to 2005). The need for such an assessment is quite evident. The opinions about the global warming being inevitable as a result of increased carbon dioxide concentration in the atmosphere, a distinct reduction in sea ice area and the need for a drastic reassessment of the conditions for economic activities in polar waters become increasingly popular. We have to work out our attitude to all these problems. Are we really on the way to an ice-free ocean? And are current changes of climate and ice conditions really consistent with these viewpoints?

The study was planned to be fulfilled in three stages:

1. Review and a critical analysis of the existing understanding of the forthcoming changes in climate and ice conditions along the NSR (April 1993-March 1994);
2. Changes in climate, ice conditions and shipping conditions along the NSR during the XXth century April 1994 - March 1995);
3. Assessment of changes in climate, ice state and shipping conditions along the NSR up to 2005 (from April 1995).

An analysis of the past and present environmental changes performed at the first stage has not revealed any obvious traces of the influence of increasing levels of carbon dioxide and other greenhouse gases in the atmosphere on climate and ice conditions in the Arctic. Already due to this fact, forecasting of the state of the latter for the immediate 10-15 years cannot be based predominantly on the assumption that future changes will be governed by anthropogenic impact. On the contrary, before finding out the real role of carbon dioxide in the changes of present climate, it is, probably, necessary to assume as before, a precondition of the leading role of factors of natural origin in the environmental evolution. The basic forecasting principle "the past is a key to the future" is still valid during the epoch of industrial development. To investigate typical features in the development of the phenomenon under prediction on the basis of retrospective data is still one of the most important conditions for foreseeing its future state.

This goal was addressed at the second stage of Project 1.7.1.

1 CLIMATE CHANGES

1.1 Characteristics of climate along the NSR

The climate over the area of the Siberian Arctic Seas is formed, as over the whole of the Arctic, under conditions of solar radiation deficit being strongly affected by heat and moisture advection from temperate latitudes.

Western seas - the Kara and Laptev Seas are influenced by atmospheric heat and moisture transfers from the North Atlantic and the North-European Basin related to the Icelandic Low. The Chukchi and, partly, the East-Siberian Seas are influenced by heat and moisture transfers from the northern Pacific Ocean connected with the Aleutian depression.

According to data (Atlas, 1985; Treshnikov and Sal'nikov, 1985), the climate of the study area is on the whole characterised by moderate winds with a mean speed of 5-7 m in the summer (navigation) season. The occurrence frequency of storms is 2% on the average, being 8% in some zones near the shores. The duration of summertime with a stable positive air temperature varies from 30 days in the northern sea zones up to 80-100 days near the shores. Maximum summer air temperature reaches 28°C in coastal regions and 15°C in the northern sea zones. Fig. 1.1. illustrates the thermal regime over the sea area.

The distribution functions of mean daily air temperature in the data of weather stations along the NSR are close to normal for all seas in May-September. In October the form of the distribution function considerably changes and becomes asymmetric and the probability of positive anomalies does not exceed root-mean-square deviation increases.

Relative air humidity reaches 90-95%, on the average, for a month over the seas under consideration resulting in frequent fogs (up to 35% in the northern sea zones). In June-July cloud cover is about 80%, on the average, decreasing to 70% near the coast. For more detailed characteristics of the main climate parameters for each of the seas see below.

The Kara Sea

During the warm period the cold sea surface covered by melting ice plays the main role in the formation of the meteorological regime. The transition to prevailing positive mean daily temperatures occurs near the coast in the first 10-day period of June and in the northern sea region at the end of the first 10-day period of June. July is most warm, although August is insignificantly colder than July. A spatial change of mean monthly temperature during the warm period is small. In June almost a non-gradient field with a temperature within -1 to -2°C is located over the sea. Near the coast the temperature increases in July being from 7° C in the south-west to 2°C in the vicinity of the Vil'kitsky strait in the data of coastal stations. Mean monthly temperatures are very stable. Their variability does not exceed 1.0, 1.5° C in the southern region of the sea. Temperature variability from day-to-day is the least in summer, especially in July and August.

Absolute temperature minimum in July can reach -5, -6°C. Absolute temperature maximum can reach 10°C in the central sea region and 26-27°C at the south-western coast.

The climatic data for each of the seas by the weather stations located along the NSR are given below.

Table 1.1. Parameters of mean daily air temperature distribution at the Dikson station from 1948 to 1992, °C.

month	air temperature			
	mean	root-mean-	maximum	minimum
June	-0.1	2.9	16.0	-13.0
July	4.5	4.1	21.1	-1.8
August	4.8	3.4	18.6	-1.8
September	1.3	3.2	12.3	-8.6
October	-8.4	6.4	4.5	-28.1

Winds in the Kara Sea are governed by the location of pressure systems and related air pressure gradients.

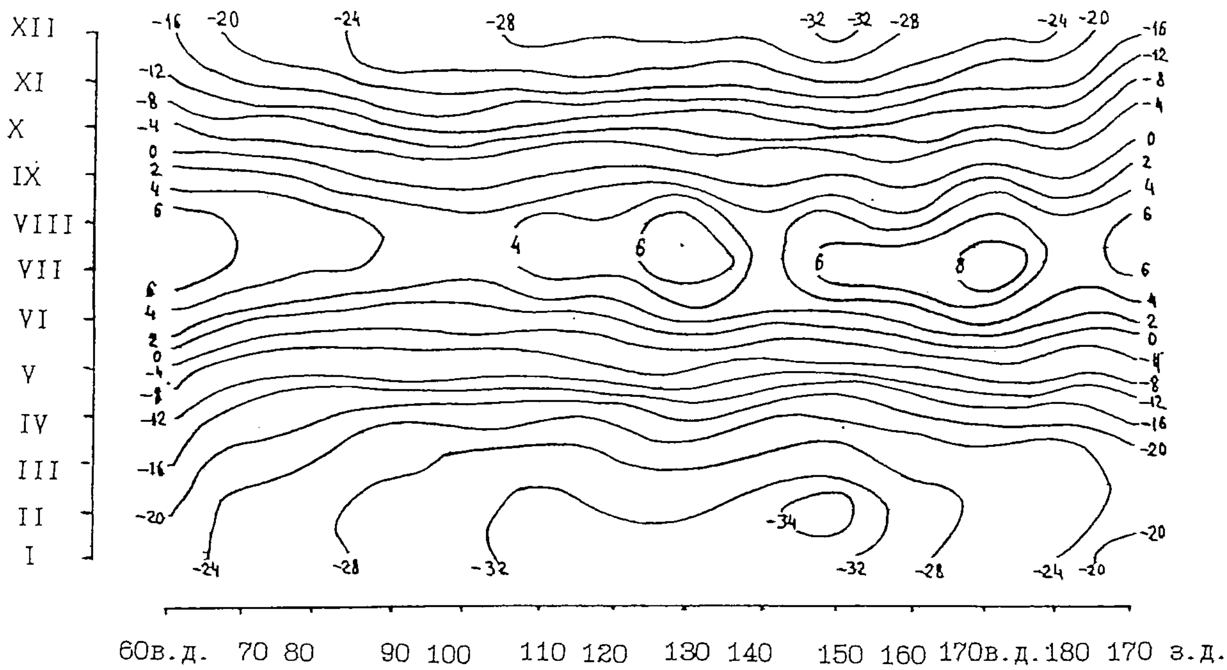


Fig. 1.1. Profile of mean monthly air temperature at coastal stations along the NSR, °C.

Table 1.2. Occurrence (%) of wind speed in the Kara Sea

Month	Speed, m/s						
	0-1	2-5	6-9	10-15	16-20	21-29	30-40
Dikson							
June	6.4	32.0	35.8	22.7	2.8	0.3	0
July	6.7	34.4	40.6	16.8	1.4	0.1	0
August	6.1	35.8	35.5	20.2	2.2	0.2	0.03
September	5.9	29.3	35.8	24.1	4.4	0.5	0
October	8.4	25.1	30.0	27.6	7.9	1.0	0.03
Cheluskin cape							
June	8.1	35.8	37.5	17.0	1.4	0.2	0
July	8.6	35.3	36.4	18.3	1.3	0.1	0
August	7.6	32.8	36.9	20.3	1.2	0.0	0
September	6.9	31.3	35.5	21.7	3.2	0.4	0
October	6.8	28.6	36.4	22.4	4.8	0.9	0.1

The duration of storm conditions is about 7%. In 80% of days moderate winds (<15 m/s) are observed. Wind speed (>15 m/s) is relatively seldom observed (Table 1.3).

Table 1.3. Mean (numerator) and maximum (denominator) number of days with wind >15 m/s.

Dikson	6/17	4/15	2/10	5/14	8/19
Cheluskin	4/7	4/9	3/7	4/12	6/14

Storm winds (>25 m/s) are rather rare, being observed less than 1 day (maximum 3 days), on the average, in September and October. The strongest wind speed reached 40 m/s in October.

The horizontal visibility along the NSR in the Kara Sea for 60-80% of the time of navigation exceeds 10 km, while visibility of less than 1 km is observed for 8-15% of days. The main cause of bad visibility is fogs. In June-October the number of days with fog is 63 , on the average, and the largest number on the average, for all months is 114 days. Mean fog duration during 24 h when fog is observed, is about 7 hours. Dense fogs with visibility up to 100-200 m and less are observed 2-3 days on the average, in summer (June-September). The largest number of days with such fog can reach 10 days a month.

The Laptev Sea

During the warm period a transition to prevailing positive mean daily temperatures occurs near the coast in the first 10 days of June and in the northern sea region at the end of the first 10-day period of July.

In July over much of the sea mean monthly temperature is steadily in the range from 2 to 0°C, this being connected with large ice cover extent in July and ice accumulation in some regions of the southern zone of the sea. But near the coast there is a rapid temperature increase reaching 6-7°C on the southern coast. A temperature increase also occurs at large islands. Thus, at the coast of the Kotel'ny island it is almost equal to 3°C and over the sea at the same latitude it is below 1°C. In August temperature gradients over the coast decrease in connection with a lesser land heating, as compared with July. And over the sea they increase mainly due to an increase in temperature in the southern and central sea regions. Warm water of the Lena river, creating a strong warm current directed north-east, plays a significant role in the air temperature increase. A decrease in air temperature in the western sea region occurs under the influence of the cold Taimyr current. Variability of summer temperatures is insignificant. It is 1.0, 1.5°C in July, on the average. From day-to-day variability in the northern region is smaller (about 1°C) than in the southern region (about 2.0, 2.5°C).

An absolute minimum in July can reach -1, -3°C in the southern sea region and -4, -6°C in the northern part. An absolute temperature maximum can reach, although very seldom does, 22-24°C in the north, 28-30°C at the southern coast and 33-34°C in deep bays. Temperature variations are closely related to wind direction. Thus, in the Tiksi inlet in July mean temperature at southerly wind is equal to 15.5°C and at north-easterly wind 5.5°C. Sharp warmings with outflows of warm and dry masses of continental air are often increased by a foehn effect when they cross the upland surrounding the inlet. As a result, air temperature sometimes increases to 23-30°C.

Winds in the Laptev Sea (Table 1.4) are weaker than in the Kara Sea, this being related to a lower occurrence frequency of deep cyclones here.

Table 1.4. Occurrence of wind speed (%) at the Kotel'ny Island

Month	Speed, m/s					
	0-1	2-5	6-9	10-15	16-20	21-25
June	8.2	40.0	34.7	14.3	2.1	0.1
July	7.4	42.0	36.3	12.6	1.6	0.1
August	7.5	36.1	37.3	16.1	2.8	0.1
September	7.1	35.4	37.8	17.5	2.2	0.0
October	11.2	36.4	33.3	16.7	2.2	0.2

Wind speed exceeding 15 m/s is observed 3-4 days on the average, for summertime (June-October) and storm speeds (25 m/s and more) - less than one day a month.

A number of days with fogs on the NSR segment in the Laptev Sea is the least, as compared with other seas, being 50 days on the average, in June-October. Mean fog duration is 5-6 h. Dense fogs are observed not more than 1 day a month. Their largest occurrence can reach 3-4 days in the open area and up to 10 days near the sea coast.

The East-Siberian Sea

During the warm period the meteorological conditions of the sea are under a complicated influence of all main factors composing climate. A transition to prevailing positive values of mean daily temperature occurs in the second 10-day period of June and in the northern sea region in the first 10-day period of July. July is the warmest month, but August is insignificantly cooler. Mean monthly air temperature in the southern sea is only 0.7°C warmer in July than in August; at the coast this difference increases up to 1.5-2°C. Only in those areas where ice often accumulates in July, is the July temperature lower than in August. A sharp increase in mean monthly air temperature in July occurs only near the coast and on the mainland coast itself. Thus, in open zones of the shore it is 4-5°C, being 10-12°C in deep bays. In August large temperature gradients are preserved over the coast. The temperature at sea quite rapidly decreases from 3-4°C at the coast to 0°C, but further north it is preserved within 0 -1°C. Variability of summer temperatures is very small. It is 0.5-0.8°C, on the average, over the whole sea in July, slightly exceeding 1°C at the south-western coast. In August near the coast variability increases to 1.5°C.

Wind direction plays a significant role in mean daily air temperature variations. In the Pevek inlet in July mean air temperature at north-west wind is equal to 3.2°C and at south-east wind 14.3°C. These sharp temperature increases are related to advection of warm continental air in cyclones enhanced by the foehn effect.

An absolute temperature minimum both at sea and on the coast reaches -4, -6°C. An absolute maximum can reach 28-30°C on the coast.

Table 1.5. Parameters of mean daily air temperature distribution at the station Chetyrekhstolbovoy Island, 1948-1984,°C

Month	Air temperature			
	mean	root-mean-	maximum	minimum
June	0.5	3.1	15.7	-8.4
July	4.3	3.4	22.8	-1.3
August	3.1	3.0	19.5	-3.4
September	-0.3	3.0	12.3	-12.9
October	-8.8	5.7	6.8	-28.6

In summertime (June-September) no storm winds are actually observed here. Winds from 2 to 15 m/s (more than 70%) prevail here (Table 1.6).

Table 1.6. Occurrence of wind speed (%) at the Chetyrekhstolbovoy Island

Month	Speed, m/s					
	0-1	2-5	6-9	10-15	16-20	21-25
June	8.8	33.0	38.5	18.7	1.0	0
July	10.2	31.9	37.6	18.4	0.9	0
August	7.5	34.4	37.4	17.7	1.0	0
September	11.1	35.3	34.7	17.4	1.5	0
October	11.1	29.6	34.7	20.2	4.0	0.4

The number of days with a wind speed exceeding 15 m/s is 1-2, maximum 6-8 days a month.

The maximum wind speeds here do not exceed 22 m/s in summer. A horizontal visibility in summer in 75-83% of days is 10 km and more. A poor visibility (less than 1 km) is observed in 3-8% of days, on the average, for June-October. The mean number of days with fogs for this period is 62 at a mean fog duration of about 7 hours.

The Chukchi Sea

The Chukchi sea receives a large amount of heat during the warm period, both radiation heat and heat transported by water and air masses. A temperature transition to prevailing positive mean daily value occurs in the Bering Sea and at the coast of the Chukchi peninsula during the first 10-day period of June. In the north of the sea the transition is noted at the end of the first-beginning of the second 10-day period. The warmest month in the Chukchi sea is July. In August mean monthly air temperature is only 0.5-0.7°C less. Spatial change in air temperature over the sea is small, significant changes take place only off the mainland coast. In July and August the spatial distribution of temperature in considerably influenced by the warm current from the Bering Strait directed to the central and eastern zone of the sea and by the cold current directed to the south-east along the coast of the Chukchi Peninsula. Mean air temperature in the Bering strait and in the eastern zone of the sea is 6°C, exceeding 8°C in the south-easternmost sea region. The temperature gradients are mainly directed to the north and west. As a result, the temperature in the northern and western sea regions decreases to 1-2°C. At the coast it decreases slower from 5°C in the Uelen to 3°C at the Shmidt Cape. Variability of mean monthly temperature in summer is very small, especially in July when it is 0.8-1.0°C.

An absolute temperature minimum in the Long strait can reach -5, -6°C and in the Bering strait -1, -2°C. An absolute maximum on the coast can reach 25-26°C. Such high temperatures are related not only to heat advection in cyclones but also to the foehn effect.

Table 1.7. Parameters of mean daily air temperature distribution at the Shmidt Cape station, 1948-1991,°C

Month	Air temperature			
	mean	root-mean-	maximum	minimum
June	1.5	3.1	15.7	-8.4
July	4.3	3.4	22.8	-1.3
August	3.1	3.0	19.5	-3.4
September	-0.3	3.0	12.3	-12.9
October	-8.8	5.7	6.8	-28.6

Wind speed in summer is mostly within 2-10 m/s (Table 1.8)

Table 1.8. Occurrence of wind speed (%) at Vrangel Island

Month	Speed, m/s						
	0-1	2-5	6-9	10-15	16-20	21-25	> 25
June	28.6	46.9	18.1	5.4	0.9		
July	27.7	42.7	21.1	11.0	1.4		
August	28.4	39.7	19.9	9.2	2.8	0.1	0.03
September	23.2	37.4	23.0	11.9	4.0	0.3	0.2
October	14.0	28.4	28.2	18.4	8.7	1.2	1.2

The number of days with wind exceeding 15 m/s is 1-2 a month on the average, maximum 6-8 days.

Maximum wind speeds here in summer do not exceed 22 m/s. Horizontal visibility in summer is 10 km in 75-83% of days and more. Poor visibility (less than 1 km) is observed in 3-8% of days, on the average, in June-October. Mean number of days with fog is 62 for this period at an average duration of fog of about 7 h.

1.2 Climate changes in the Arctic over the area of the Siberian Seas

The most significant climate changes in the Northern Hemisphere in the XXth century were observed in the Arctic. They are particularly evident in the changes of air temperature, Arctic sea ice area and atmospheric pressure distribution. The main reasons for increased climatic changes in high latitudes of the Earth are related to a strong dependence of their energy budget on the influx of heat and moisture from lower latitudes and to a special role of sea ice in the climatic system of the Earth (Alekseyev and Svyashennikov, 1991; Climatic regime, 1991; Zakharov, 1981; Khrol, 1993). Probably, the same causes are responsible for the expected increase in the Arctic of the green house warming of the Earth's climate which is predicted by means of climate models (Report, 1990).

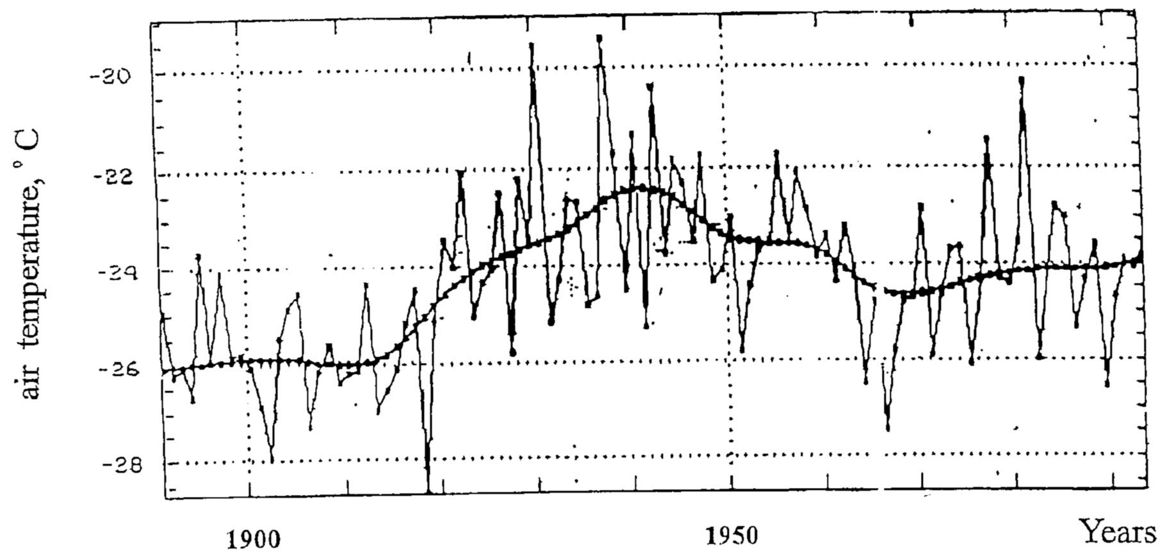
Climatic series of mean air temperatures over the Arctic show (Fig. 1.2) their strong interannual variations, a considerable warming in the 30-40s, especially in winter, and a moderately rapid increase in summer temperature in 1980-1990. An analysis of mean temperature changes relative to the mean for the period 1981-1991 has shown (Table 1.9) that these years had the warmest summer seasons (June-August). In other months of the year the Arctic was the warmest in 1937-1947, especially from October to January. The latter is not in agreement with model estimates of the distribution within a year of the expected green house warming of the Arctic that indicate a multiple excess of the winter green house warming over the summer one.

Recent model calculations of the temperature response of the Arctic atmosphere to an increase in the level of carbon dioxide and aerosols showed the latter to induce an increase in the tropospheric temperature in summer and enhance surface temperature inversions. This conclusion confirms the suggestion that an increase in summer air temperature during the last decade is connected with an increase in aerosol level in the Arctic atmosphere rather than with the green house effect. However, it is obvious that most variations in the temperature regime of the Arctic over the XXth century are related to natural causes and, primarily, to the internal dynamics of the complicated climatic system of the Earth.

Table 1.9. Differences in mean air temperatures in the Arctic over 1981-1991 and over the preceding periods

	Months											
	1	2	3	4	5	6	7	8	9	10	11	12
1970-81	0.02	1.06	0.57	0.30	0.41	0.46	0.33	0.06	0.24	0.48	0.11	0.74
1959-69	0.75	1.03	1.37	0.41	0.63	0.82	0.67	0.46	0.48	0.08	-0.27	0.01
1948-58	-0.50	0.82	0.05	-0.72	0.06	0.78	0.95	0.51	0.26	-0.68	-0.65	0.21
1937-47	-1.72	-0.33	-0.12	-1.02	-0.29	0.57	0.76	0.54	-0.08	-1.44	-1.71	-1.23
1926-36	-0.63	-0.50	0.03	-0.37	0.32	0.67	0.49	0.27	-0.15	-0.81	-1.37	-0.88
1915-25	0.73	1.20	0.71	0.13	0.54	1.00	0.95	0.57	0.22	-0.08	-0.54	1.46
1904-14	1.86	0.96	0.91	-0.15	0.53	0.87	1.13	0.50	0.43	-0.40	0.01	1.05
1893-03	1.82	1.51	1.25	0.41	0.24	0.94	1.02	1.20	0.42	-0.20	-0.19	1.28

a)



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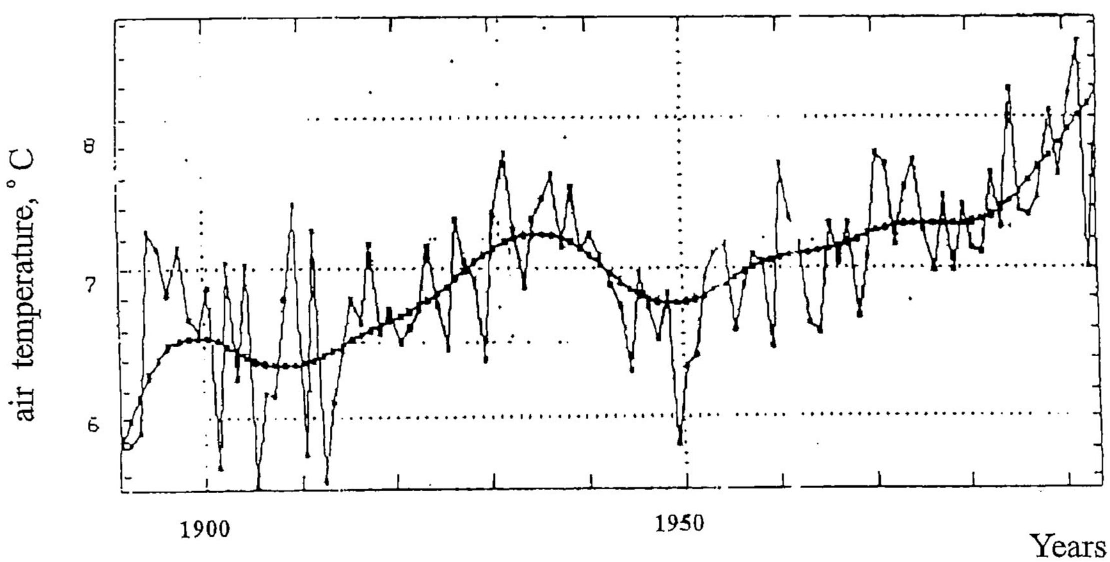
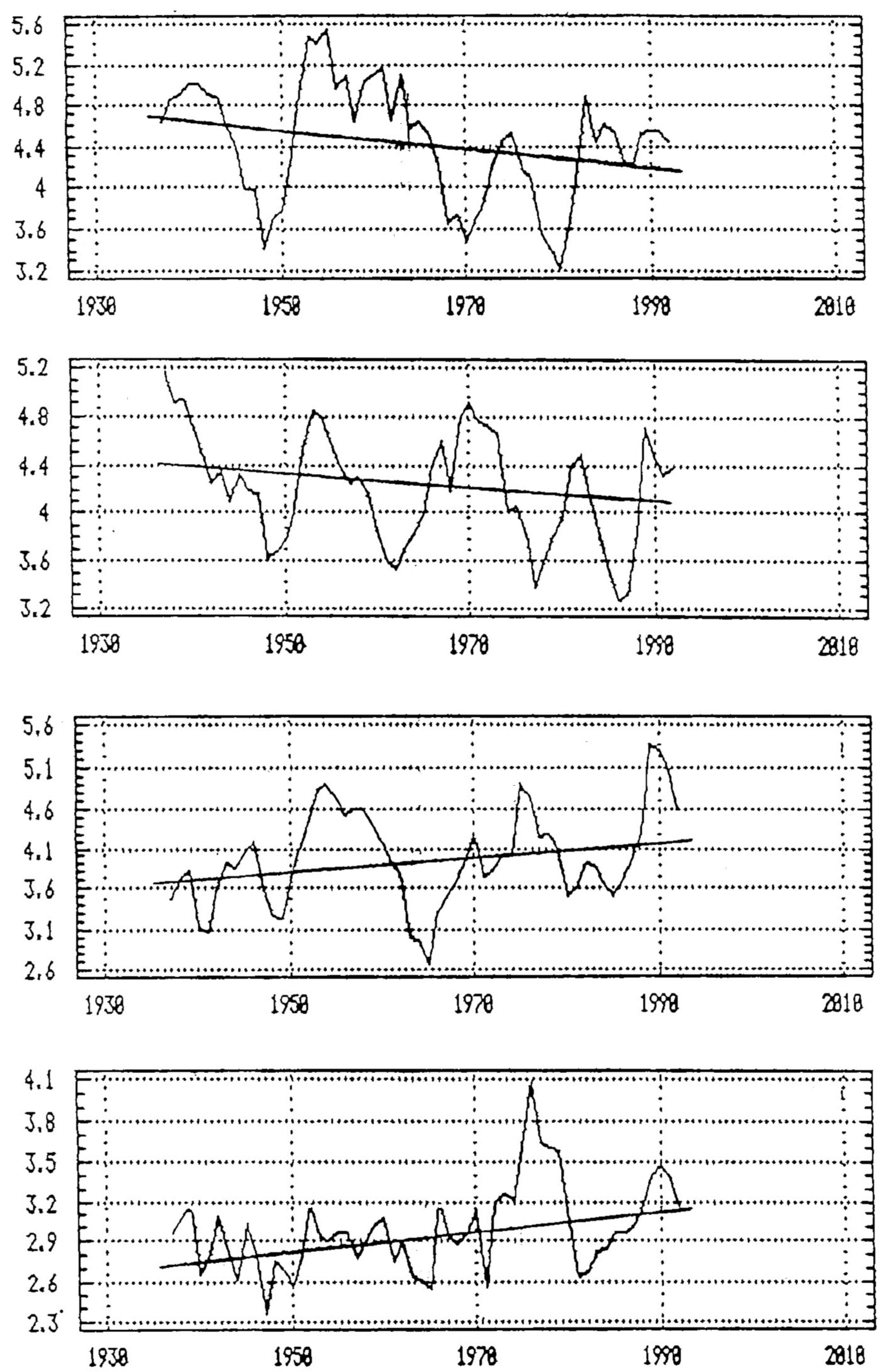


Fig. 1.2. Mean monthly air temperature near the Earth's surface averaged by 5-year periods for summertime (July-August)

Climate changes over the area of the Siberian arctic seas for the period of reliable instrumental meteorological observations in the Arctic are expressed first of all, in appreciable air temperature fluctuations. Fig. 1.3 illustrates interannual changes in mean air temperature for 2 navigation months (July, August). They are calculated on the basis of mean monthly temperatures at 4-5 coastal and island meteorological stations in each of the seas. There are well pronounced interannual fluctuations of mean temperature with an amplitude of 1.5-2°C and temporal scale from 7 to 16 years. Also, linear trends are evident that indicate an air temperature increase over the seas in the eastern Arctic with a rate of 0.005-0.007 deg/year and a weak temperature increase over the western seas with a rate of less than 0.001 deg/year. The air temperature trends opposite in sign over the eastern and western seas of the NSR confirm the existence of a climatic opposition between these regions (Climatic regime, 1991; Zakharov, 1981). This opposition is related to the prevailing influence of the Icelandic and Aleutian Lows on atmospheric transfers.
Fig. 1.4 presents charts of the spatial distribution of summer temperature differences during the period 1981-1991 and preceding periods beginning from the period 1937-1947. An analysis of the charts of differences has shown the following. The main sources of air temperature changes during the last period are in the mainland regions of Eurasia. The air temperature over the region of the north-east of Eurasia (partly Eastern Siberia and Chukotka) significantly decreased during the last period with regard to the period 1950-1980, while it increased over the region of West Siberia. That is why, temperature differences between the last and previous periods are not great, not exceeding 0.5-0.8°C. The highest temperatures observed in some seas fall on different periods. Thus, regarding the last period higher air temperatures are traced in the area of the Kara and Laptev Seas in 1937-1947, the East-Siberian Sea in 1959-1969 and the Chukchi Sea in 1970-1980.

The charts of differences also show opposite phases in the character of air temperature changes over the Kara and Laptev Seas on the one hand, and the East-Siberian and the Chukchi Seas on the other hand. This opposition is especially well-defined during the period 1937-1947 and 1948-1958.



a)

b)

c)

d)

Fig. 1.3. Interannual air temperature changes by 5 year periods for summertime (July-August)

a) Kara Sea; b) Laptev Sea; c) East-Siberian Sea; d) Chukchi Sea.

A comparison of the changes in the western and eastern Arctic of such parameter as air temperature dispersion within a month calculated for the period from 1948 to 1992 and which characterises stability of weather conditions, has shown an absence of significant tendencies in all navigation months.

The wind regime from 1966 to 1985 has a tendency to decrease in occurrence of storm winds in all the seas under consideration.

In the Kara Sea during the period 1966-1985 the wind speed tended to a decrease. Mean number of days with a wind speed more than 25 m/s in May-October decreased from 4 to 1 during this period.

In the seas of the eastern Arctic there is a tendency for a decrease in the number of cases with storm wind speeds. Thus, in the East-Siberian Sea the number of days with storms during the period 1966-1955 decreased by 1-2 days on the average during summer. In the Chukchi Sea winds with a speed of 25 m/s and more were more frequent during the period 1966-1976 than during the next period 1979-1986.

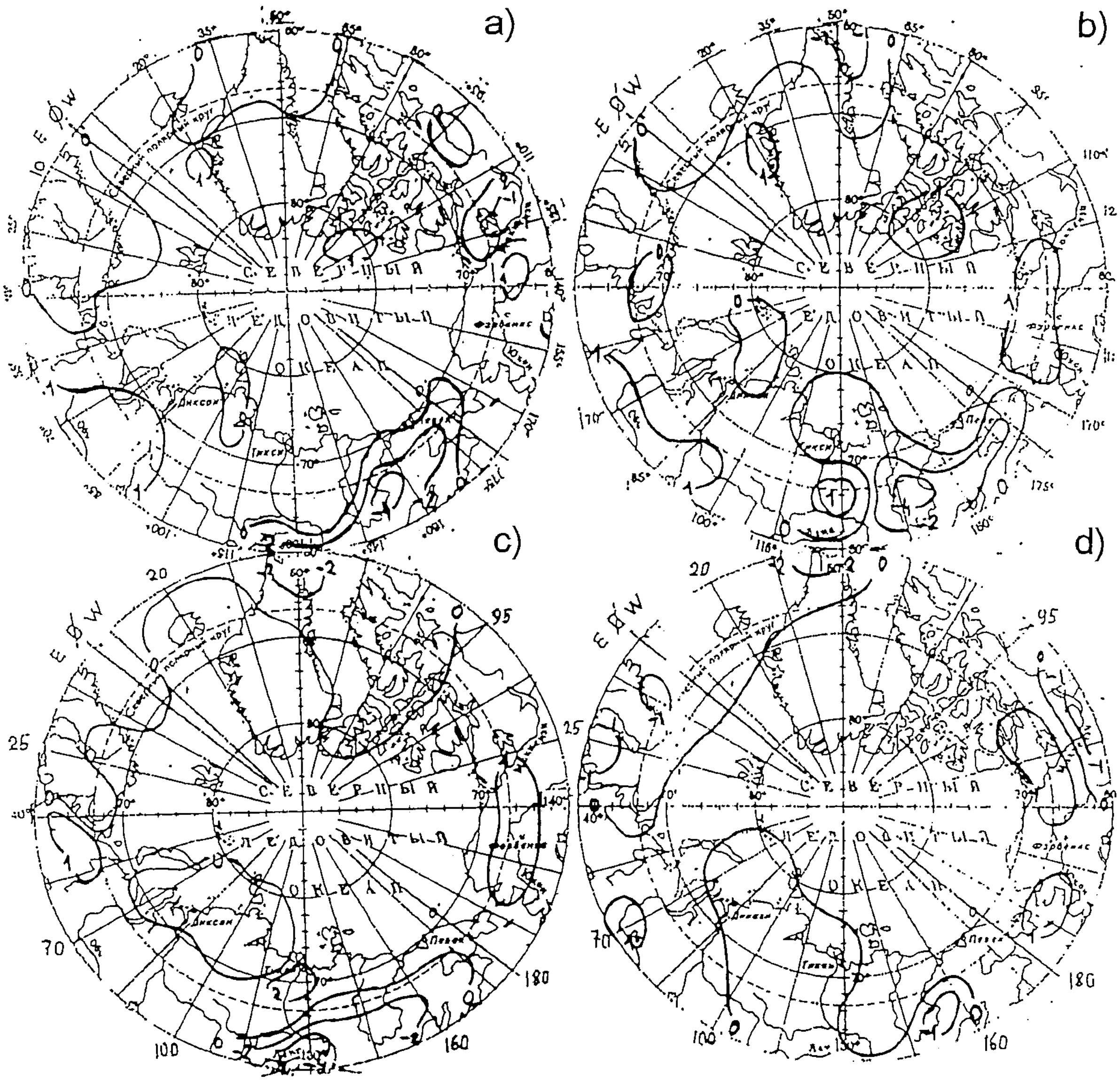


Fig. 1.4. Difference in mean June-August air temperature between separate periods

a) 1981-1991 and 1970-1980, c) 1981-1991 and 1959-1969,
b) 1981-1991 and 1948-1958, d) 1981-1991 and 1937-1947.

2 ICE CONDITIONS

2.1 Ice situation prior to ice cover decay

By late May - early June ice cover in the NSR region (Fig.2.1) reaches its largest development. Continuous thick ice actually covers the whole of the region from its northern limits to the shores of the Asian mainland and from Novaya Zemlya to the Bering strait. Open water is observed at this time only behind the fast ice edge in the form of comparatively narrow strips of flaw polynyas that are formed in the regions of stable off-shore winds and occupy up to 2% of the area $2.3x10^6$ km^2. Fast ice is significantly developed on the NSR. By June it comprises 28% of this area. West of the Severnaya Zemlya Archipelago and in the vicinity of the New-Siberian Islands fast ice is especially developed; its edge here is a hundred kilometres offshore. The ice thickness in fast ice of the Laptev and East-Siberian Seas reaches approximately 2 m. West and east of these seas it decreases to 1.5-1.0 m. Outside the fast ice limits in the region of drifting ice its thickness can be more or less than in fast ice depending on the character of the winter off-shore or on-shore drift. In the Kara and Laptev Seas where winds of the southern half of the horizon prevail in winter, the thickness of drifting ice is generally less than that of fast ice. In the East-Siberian Sea where winds of an opposite direction dominate, vice versa, the thickness of fast ice is less than that drifting ice. This feature is confirmed by the difference in age categories of ice in these seas. Mean multiyear area of multiyear and second-year ice in the Kara Sea is only 1-2%, while in the eastern East-Siberian Sea this area reaches almost 30%. The differences in drift conditions on the western and eastern segments of the NSR also govern the prevailing western location of flaw polynyas along the NSR. Hummocked ice cover occupies 20-40% of the area. In some regions, as for example, at a junction of fast ice and drifting ice zones of enhanced hummocking up to 60-80% are formed.

The prevailing ice form is large breccia fields (500-2000 m in diameter).

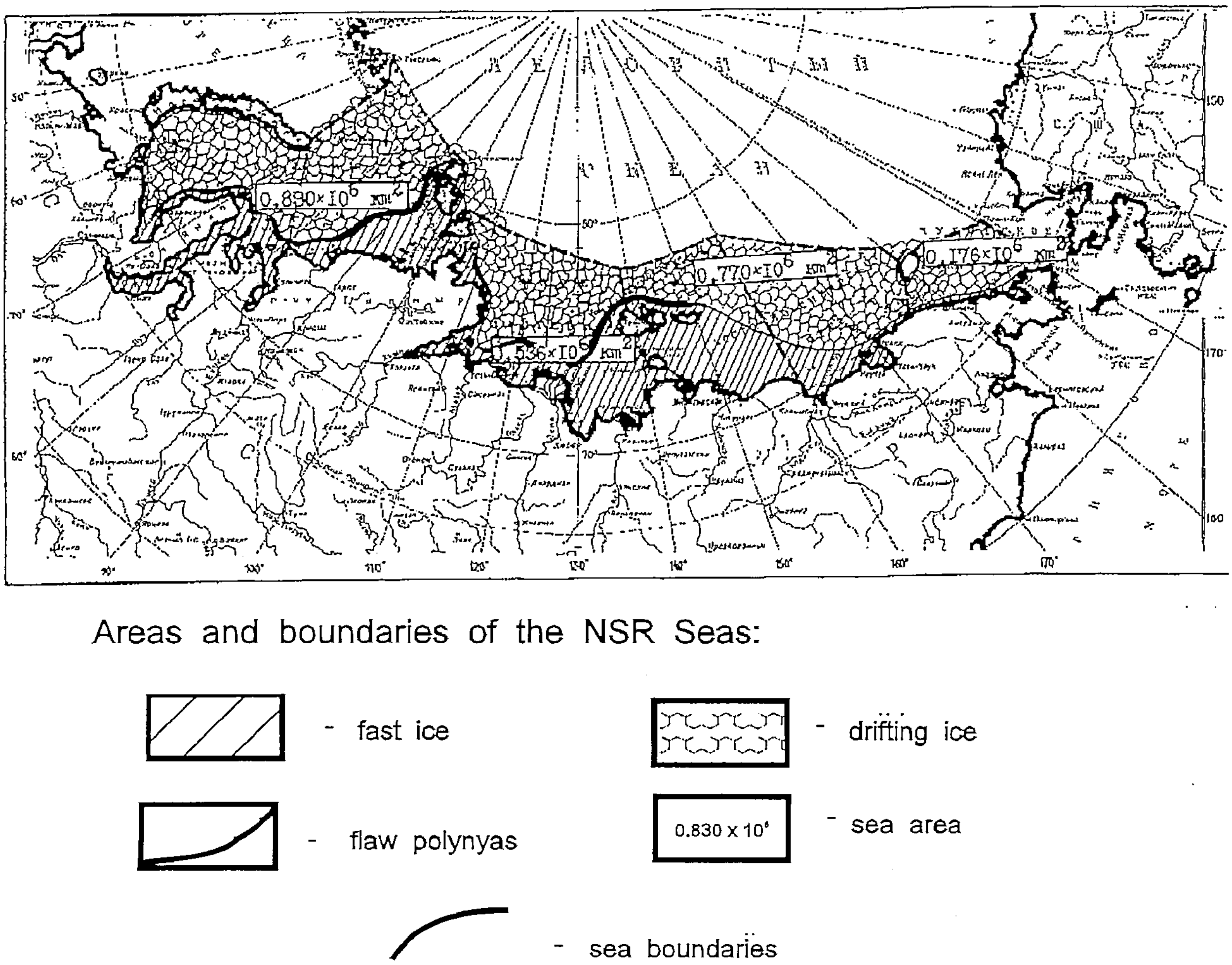


Fig. 2.1. Extent of fast ice, drifting ice and flaw polynyas along the coast of Siberia at the beginning of the Arctic summer

2.2 Ice conditions along the NSR during the Arctic summer (June-September

The term "ice conditions" denotes a set of parameters (area, thickness, concentration, hummocking, decay, fracturing, etc.) that characterise the ice cover state. An improvement in ice conditions is a process of ice area reduction and a decrease in its thickness and concentration accompanied by improved shipping conditions. A deterioration in ice conditions is a reverse process.

Summertime, especially its second half, is the most favourable period for shipping north of the coast of Siberia. The first visual indications of its onset (snow darkening and occurrence of first puddles) in the southern region of the Arctic Seas appear in late May-early June, and in the northern region 10-20 days later. From this time the process of ice cover decay (melting and disintegration) is increasingly intensive up to September when in the north of the seas the formation of young ice among remaining ice begins. In a general form the process of the change in ice area, concentration and age categories in Siberian waters in summer is presented in Fig. 2.2, 2.3.

The ice distribution by concentration and age categories is given in percent of the area 2.3×10^6 km^2 within the boundaries shown in Fig.2.1. The features of this distribution during summer allow a division of this season into two periods different in duration: June-August and September. The first of these periods is characterised by improved ice situation expressed in fast ice decay, increased area of open water, increased fraction of very open (1-3/10) and open (4-6/10) ice in the ice covered regions. The second period is characterised by expanded ice cover, reduced open water area, increased ice concentration in the process of the commencement of ice formation. September is the beginning of a progressively developing ice cover lasting more than 9 months.

It should be remembered that the picture given in Fig.2.2 and 2.3 reflects the ice cover development along the NSR in summer in its multiyear expression. Although general features of this development are of a universal character, their expression in each specific year and on each NSR segment is significantly different. Statistical characteristics of ice area obtained for each of the Arctic Seas separately provide a description of seasonal dynamics of ice conditions in the Siberian Arctic waters in much detail (Table 2.1-2.4).

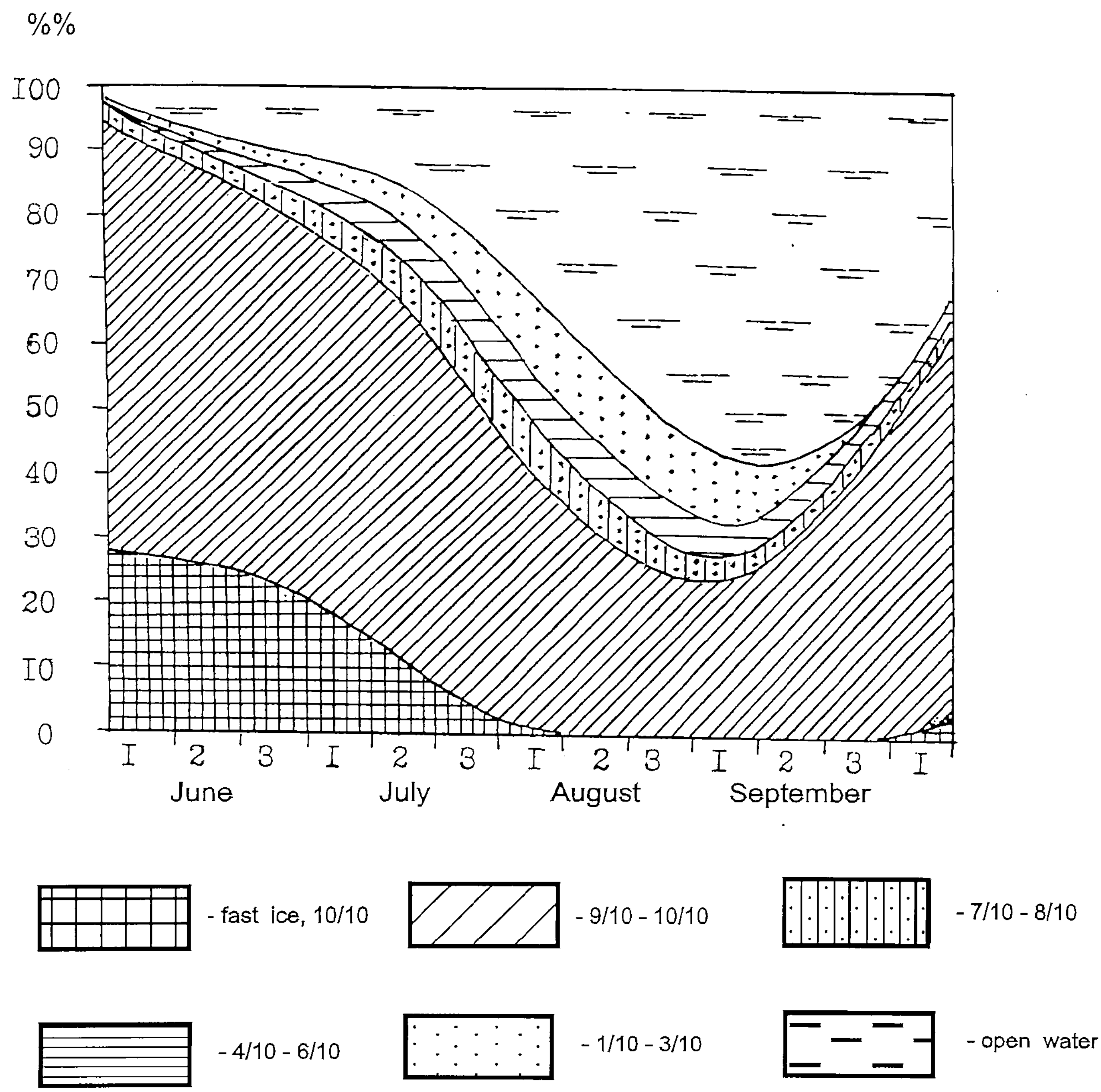


Fig. 2.2. Ice distribution by concentration during summer in Siberian arctic water

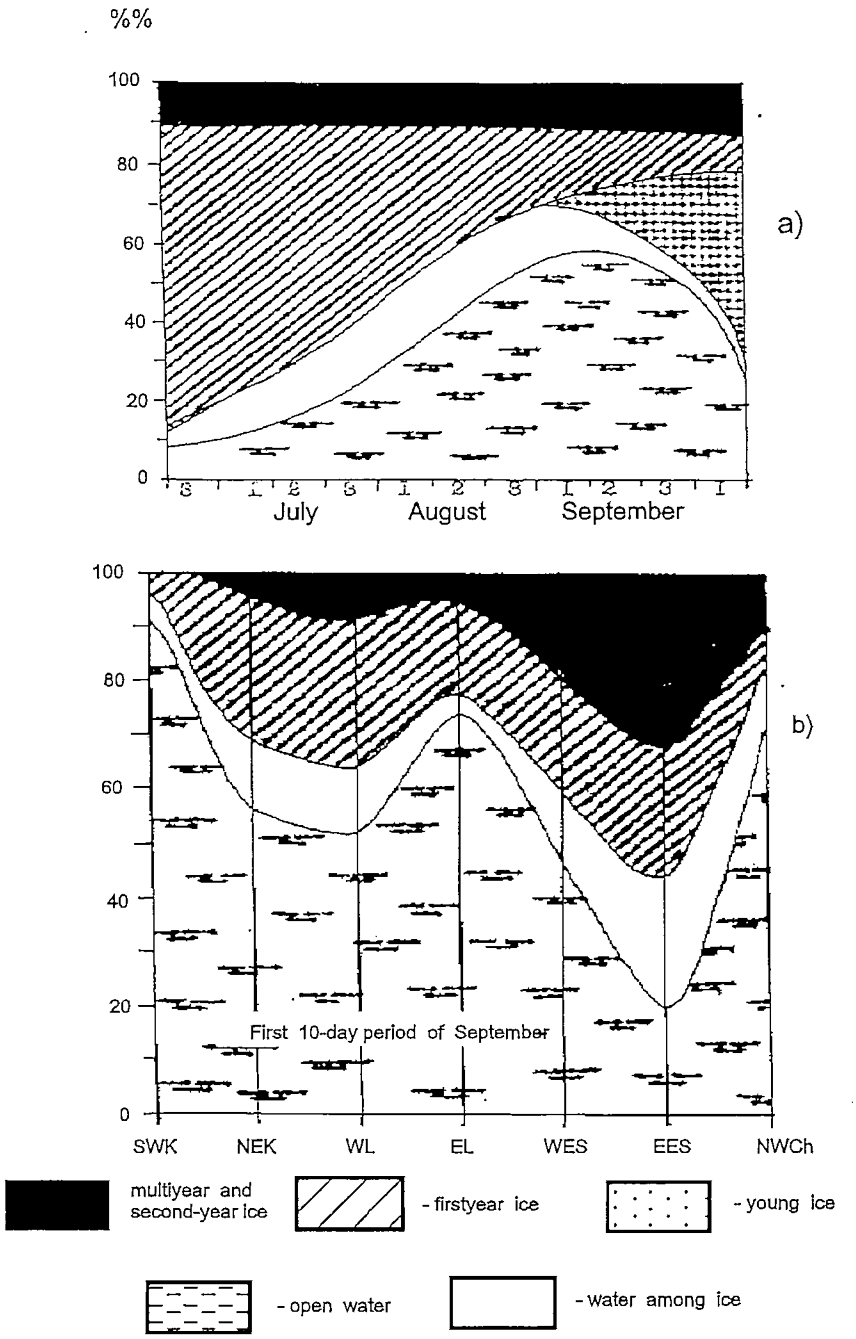


Fig. 2.3. Mean multiyear ice distribution by age categories in Siberian arctic water (a) and from west to east (b)

SWK,NEK - south-west and north-east of the Kara Sea;

WL,EL - west and east of the Laptev Sea;

WES, EES - west and east of the East-Siberian Sea;

SWCh - south-west of the Chukchi Sea.

Table 2.1. Statistical characteristics of ice area in the Kara Sea, % (series for 1940-1991)

Characteristics	Months, 10-day period								
	July			August			September		
	1	2	3	1	2	3	1	2	3
Mean	85	79	71	58	48	41	33	30	28
Maximum	99	97	98	96	92	85	74	64	67
Minimum	56	38	30	17	10	4	4	4	4
Amplitude	43	59	68	79	82	81	70	60	63
Root-mean -	9.8	12.7	14.4	17.5	17.6	17.0	17.3	16.0	16.0

Ice area is given in percent of the sea area equal to 0.830 x 10^6 km^2.

Young ice formed in September is not taken into account.

Table 2.2. Statistical characteristics of ice area in the Laptev Sea, % (series for 1940-1991)

Characteristics	Months, 10-day period								
	July			August			September		
	1	2	3	1	2	3	1	2	3
Mean	85	81	73	63	52	43	38	36	34
Maximum	99	96	96	92	95	85	83	83	83
Minimum	55	51	32	30	12	6	2	2	0
Amplitude	44	45	64	62	83	79	81	81	83
Root-mean-	10.0	11.7	15.3	18.9	20.9	20.9	20.7	20.3	20.7

Ice area is given in percent of the sea area equal to 0.536 x 10^6 km^2.

Young ice formed in September is not taken into account.

Table 2.3. Statistical characteristics of ice area in the East-Siberian Sea, % (series for 1940-1991)

Characteristics	Months, 10-day period								
	July			August			September		
	1	2	3	1	2	3	1	2	3
Mean	96	95	92	87	81	74	69	66	63
Maximum	100	99	99	99	99	97	97	93	94
Minimum	72	63	46	16	12	3	2	5	12
Amplitude	28	36	53	83	87	94	95	88	82
Root-mean -	4.5	5.7	8.6	12.7	15.0	18.2	18.9	18.9	19.7

Ice area is given in percent of the sea area equal to 0.770 x $10^6 km^2$.

Young ice formed in September is not taken into account.

Table 2.4. Statistical characteristics of ice area in the Chukchi Sea, % (series for 1940-1994)

Characteristics	Months, 10-day period								
	July			August			September		
	1	2	3	1	2	3	1	2	3
Mean	63	53	43	35	30	24	20	18	17
Maximum	95	89	85	74	67	59	60	59	69
Minimum	22	16	11	7	0	0	0	0	0
Amplitude	73	73	74	67	67	59	60	59	69
Root-mean -	17.1	14.8	15.7	15.0¤	16.0	14.4	15.9	17.5	19.1

Ice area is given in percent of the south-western Chukchi Sea area equal to 0.176 x 10^6 km^2.

Young ice formed in September is not taken into account.

The ice covered area is the most informative component of ice conditions. This and the fact that most complete, reliable and long series are available for ice area, governed its use as an indicator of these conditions.

In addition to mean 10-day values in each sea during July-September the tables contain minimum and maximum ice areas from 1940 to 1991, as well as root-mean-square deviations. They provide understanding of the variability of ice conditions on separate NSR segments for the last 50 years and more and serve as a first rough indication of the conditions that navigators should expect along the NSR. Let us mention here the most significant features of the regime of ice cover extent in the Siberian Arctic waters:

- The East-Siberian Sea, especially its eastern part, is the most complicated NSR segment in respect of ice. Mean ice area for July-September in this sea is 80%. In the Kara Sea it is equal to 53%, in the Laptev Sea -56% and in the south-western Chukchi Sea- 34%. In the East-Siberian Sea even at the end of September ice preserved after summer melt comprises 63% of its area. The situation is also aggravated by the fact that quite a considerable ice portion in this sea is composed of multiyear and second year ice

(Fig.2.3).

- At the end of the Arctic summer open water (water zones among ice are not taken into account) covers 72% of the Kara Sea area. 66% of the Laptev Sea, 87% of the East-Siberian Sea and 83% of the south-western Chukchi Sea.
- The amplitudes and root-mean-square deviations given in the tables as a measure of variability indicate the presence of strong interannual changes in ice conditions in all Arctic Seas. This means that estimates of the conditions on the basis of mean values (climatic normal values) are rather unreliable for different kinds of economic activities in the Arctic waters.
- By variability in ice conditions the first place belongs to the south-western Chukchi Sea (the variation coefficients in July, August and September are respectively equal to 27, 43 and 80%), the second place to the Laptev Sea (coefficients: 12, 30 and 54%), the third to the Kara Sea (coefficients: 5, 15 and 27%).
- Statistical characteristics of the ice cover extent of the Kara and Laptev Seas (including the variation coefficients) and particularly their changes within the season are quite uniform. One can assume that the factors controlling changes in ice conditions of a climatic scale are the same for the entire western NSR segment.

Mean value is insufficient for the complete characteristics of such variable as ice area. Although the use of an amplitude and root-mean-square deviation allows its expansion, it still remains to be incomplete. It is important to know not only the values that the ice area may reach but also the probability of the ice area reaching these values.

Fig. 2.4-2.7 present histograms, empirical distribution curves and normal distribution curves of ice area anomalies for each of the NSR seas for the navigation period. Mean 10-day values of ice areas in July-September for each of the seas served as an actual basis for diagrams. After excluding a seasonal component, a series of anomalies was obtained containing 462 terms. And they were used for describing the distribution of anomaly probabilities of ice area.

- The empirical distribution of ice area anomalies is governed by the normal distribution law on the westernmost NSR segment that is, in the Kara Sea. In the Laptev, East-Siberian and in the south-western Chukchi Seas this distribution does not meet the existing normal criteria. Taking into account that the probability distribution in these seas seems to be outwardly like a normal one, the normal distribution curves satisfying to a great extent the initial variation series were calculated for each empirical curve. The normal distribution curves are most valuable for estimating the probability of rare events, such as large ice area anomalies of any sign. In all other cases an empirical distribution curve should be used.

- The empirical distribution curves of ice area anomalies in the Kara, Laptev and south-western Chukchi Seas are characterised by a very close similarity in the area of positive values (enhanced as compared with the mean multiyear ice area). It can be said that these curve branches correspond to the normal distribution law. This, however, cannot be said with regard to negative values. No satisfactory explanation of this phenomenon has yet been found.
- An empirical distribution curve for the East-Siberian Sea differs by a large positive excess. An enhanced occurrence of small ice area anomalies is governed in this case by its slow clearance from ice during the Arctic summer, as compared with other seas.

The probability distributions presented in Fig. 2.4-2.7 refer on the whole to the period July-September. Each of them is sufficiently reliable (as mentioned above, the areas of large anomalies are exceptional), as they were plotted on the basis of the series consisting of more than 460 terms. However, their disadvantage is temporal generalisation covering the whole summer period. When planning or navigating along the NSR it is important to gain understanding about possible ice conditions in a more narrow time interval, for example, in the first 10 days of August, second 10 day-period of September, etc. For providing data of this kind calculations of probabilities by ice cover extent gradations were made for each of the nine 10-day periods from July to September (Table 2.5-2.8). It should be considered that data on the probability distribution in these tables should, obviously, be specified due to limited series (slightly more than 50 terms in each 10-day period). This is seen from the probability distribution character itself. Unfortunately, only TIME can eliminate this shortcoming.

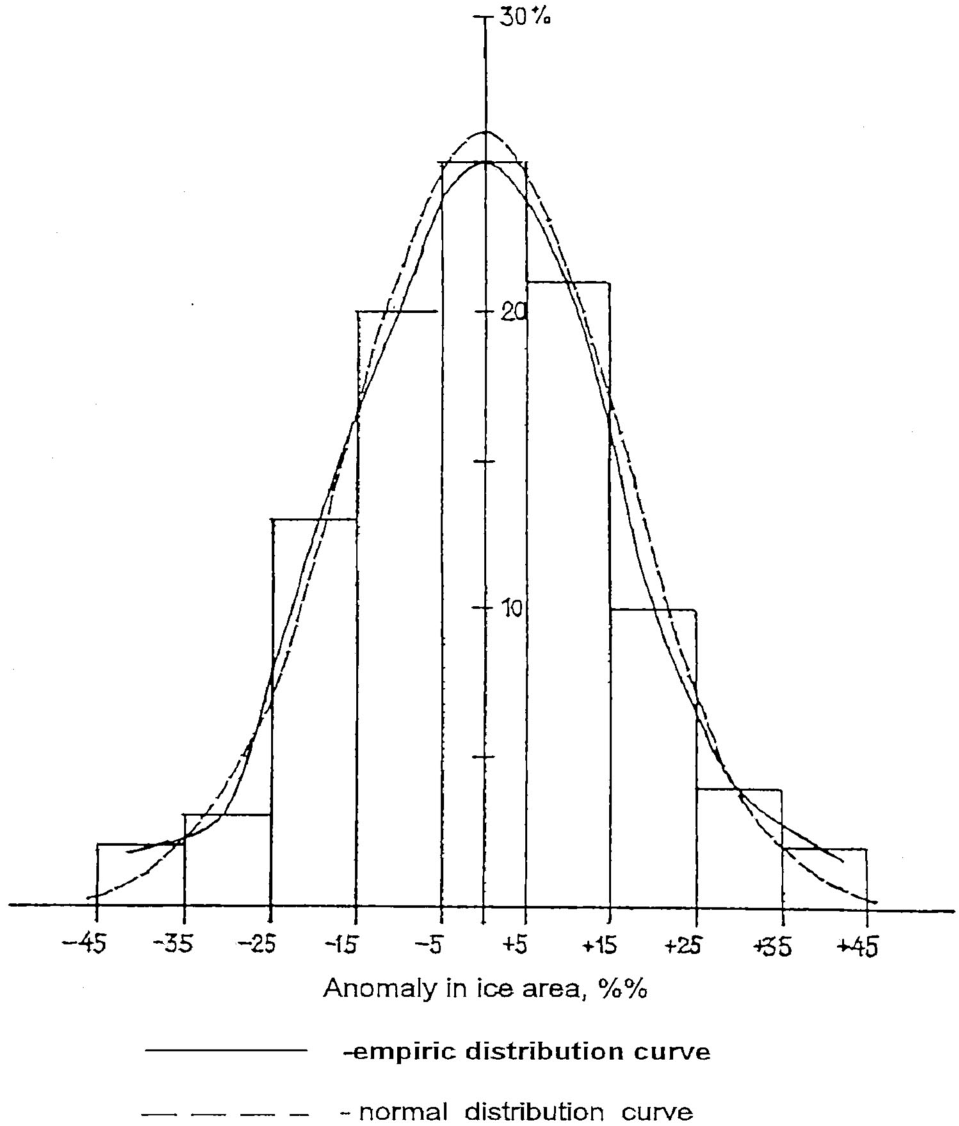


Fig. 2.4. Histogram, empirical distribution curve and normal distribution curve of anomalies in ice area in the Kara Sea in July-September (ice area anomaly is given in % of the Kara Sea area - 830.000 km^2)

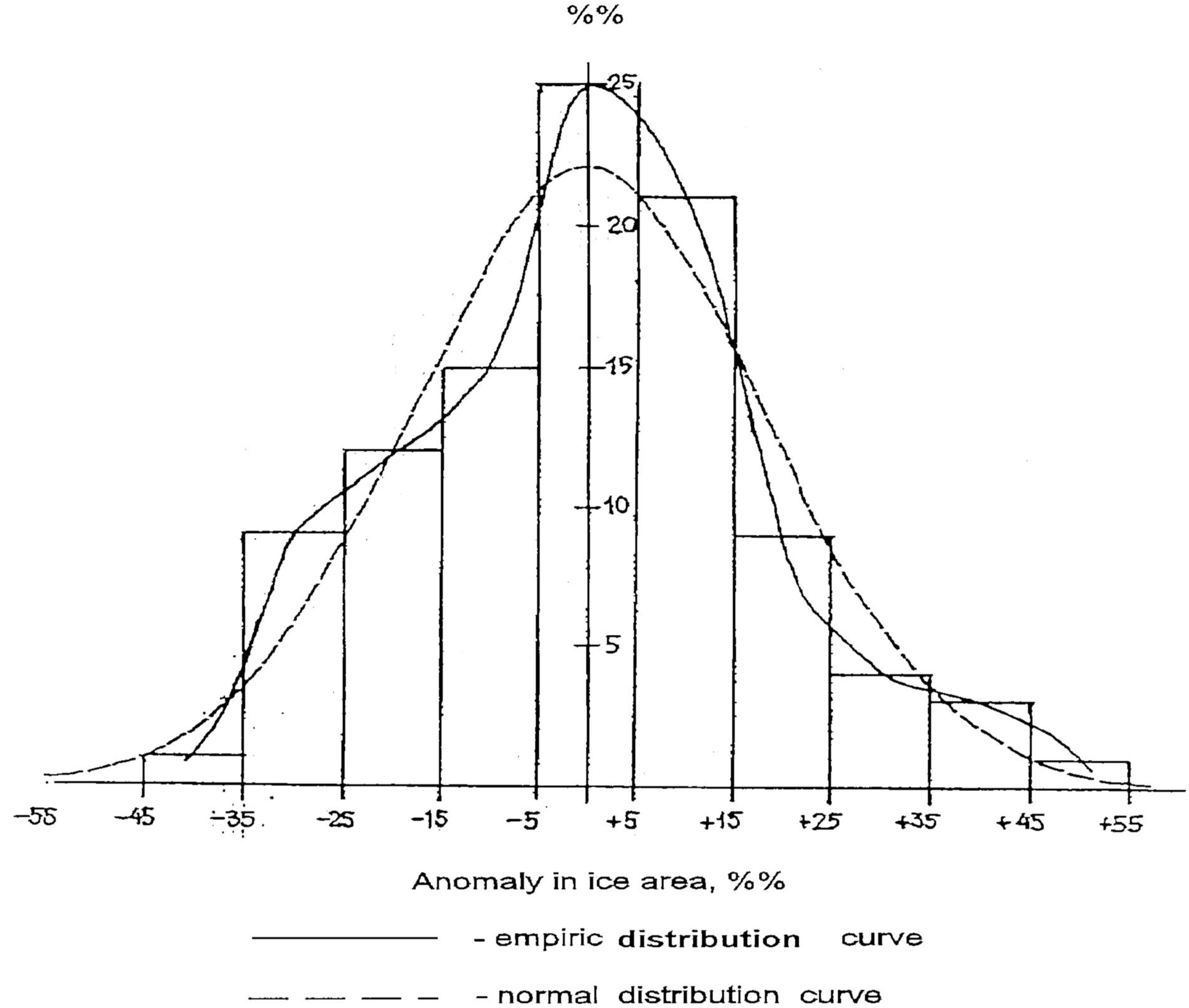


Fig. 2.5. Histogram, empirical distribution curve and normal distribution curve of anomalies in ice area in the Laptev Sea in July-September (ice area anomaly is given in % of the Laptev Sea area - 536.000 km^2)

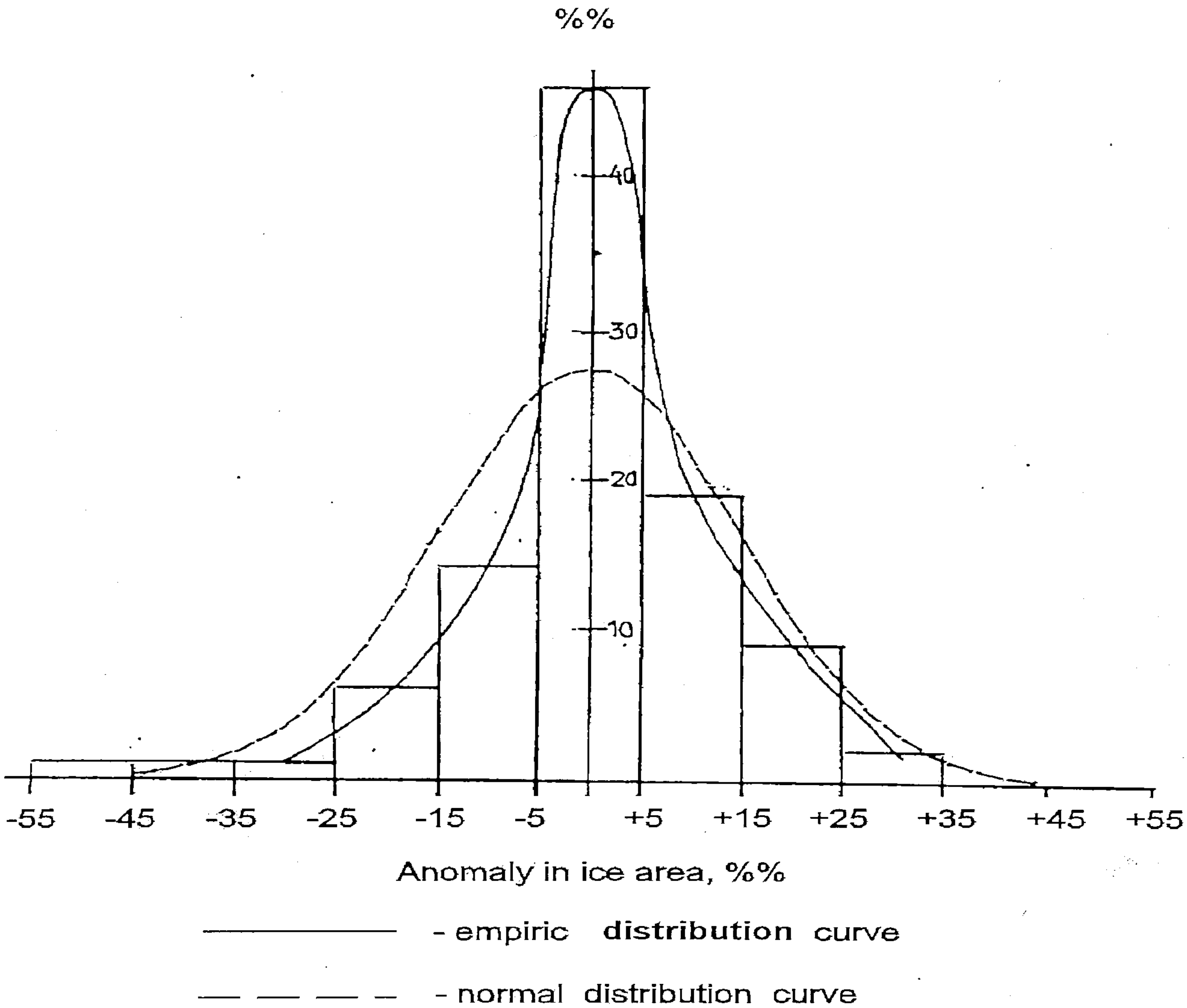


Fig. 2.6. Histogram, empirical distribution curve and normal distribution curve of anomalies in ice area in the East-Siberian Sea in July-September (ice area anomaly is given in % of the East-Siberian Sea area - 770.000 km^2)

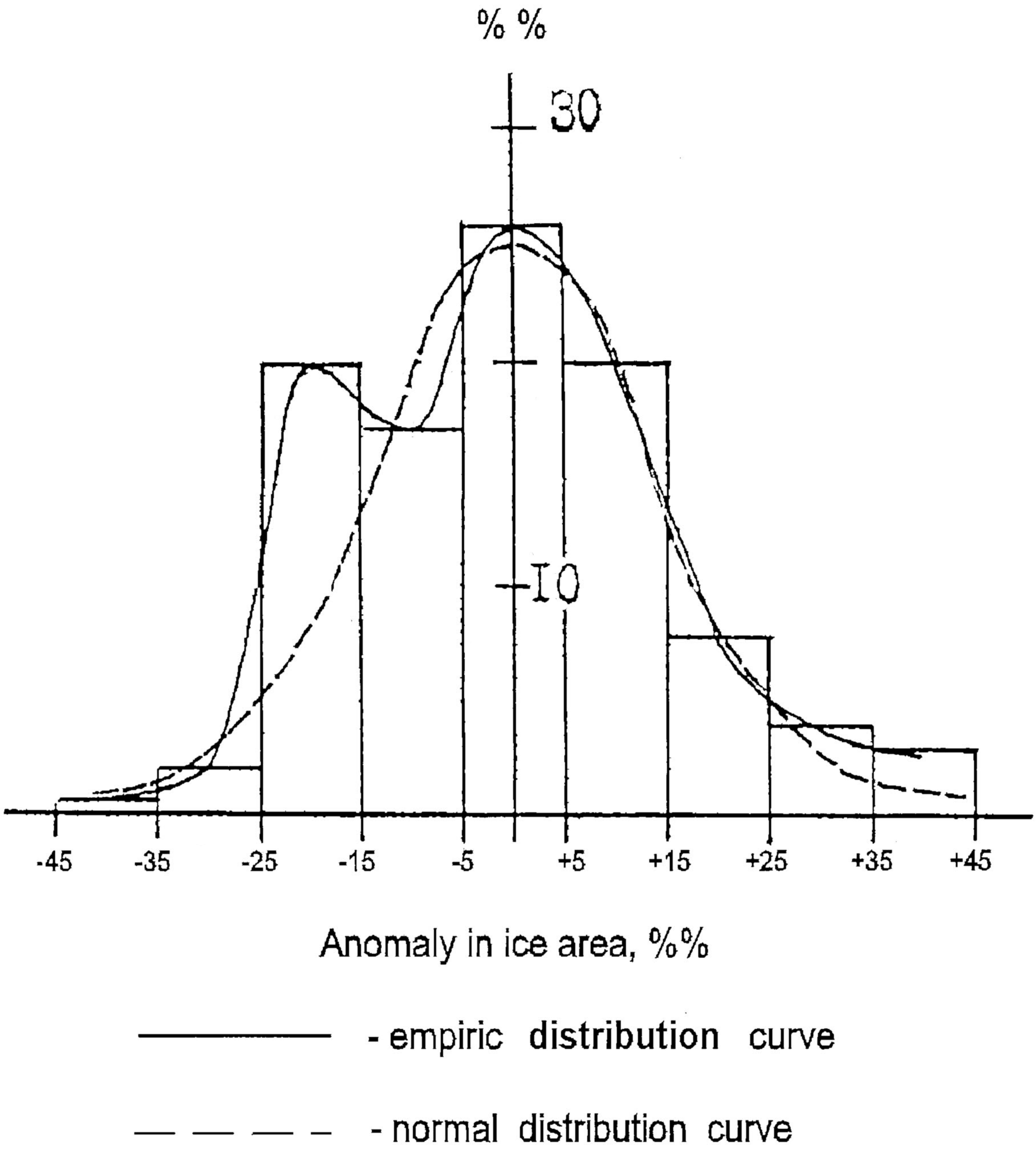


Fig. 2.7. Histogram, empirical distribution curve and normal distribution curve of anomalies in ice area in the south-western Chukchi Sea in July-September (ice area anomaly is given in % of the south-western Chukchi Sea area - 176.000 km^2)

Table 2.5. Relative occurrence frequency of ice area values within the prescribed intervals in the Kara Sea

Prescribed	Month, 10-day period								
	July			August			September		
	1	2	3	1	2	3	1	2	3
0-9	-	-	-	-	-	4	4	14	20
10-19	-	-	-	2	4	2	17	17	16
20-29	-	-	-	5	10	20	24	20	20
30-39	-	2	2	4	18	28	18	24	18
40-49	-	2	6	21	20	14	15	13	17
50-59	2	4	15	21	27	18	14	8	6
60-69	7	13	23	21	8	10	6	4	3
70-79	14	23	21	13	9	2	2	-	-
80-89	33	34	21	11	2	2	-	-	-
90-100	44	22	12	2	2	-	-	-	-

Table 2.6. Relative occurrence frequency of ice area values within the prescribed intervals in the Laptev Sea

Prescribed	Month, 10-day period								
	July			August			September		
	1	2	3	1	2	3	1	2	3
0-9	-	-	-	-	-	8	8	6	10
10-19	-	-	-	-	4	8	12	20	21
20-29	-	-	-	-	10	6	18	18	15
30-39	-	-	2	12	16	22	14	20	17
40-49	-	-	8	16	16	18	18	12	15
50-59	4	10	12	18	18	16	16	8	8
60-69	6	4	12	14	14	10	4	8	8
70-79	12	28	26	12	8	6	8	4	4
80-89	38	24	28	24	12	6	2	4	2
90-100	40	34	12	4	2	-	-	-	-

Table 2.7. Relative occurrence frequency of ice area values within the prescribed intervals in the East-Siberian Sea

Prescribed	Month, 10-day period								
	July			August			September		
	1	2	3	1	2	3	1	2	3
0-9	-	-	-	-	-	2	2	2	-
10-19	-	-	-	2	2	-	-	-	4
20-29	-	-	-	-	-	-	2	4	2
30-39	-	-	-	-	-	4	2	2	4
40-49	-	-	2	-	2	-	6	8	13
50-59	-	-	-	-	-	10	18	23	19
60-69	-	2	-	4	12	19	19	21	19
70-79	2	-	6	10	21	20	19	8	16
80-89	2	8	10	29	31	29	19	19	15
90-100	96	90	82	55	32	16	13	13	8

Table 2.8. Relative occurrence frequency of ice area values within the prescribed intervals in the south-western Chukchi Sea

Prescribed	Month, 10-day period								
	July			August			September		
	1	2	3	1	2	3	1	2	3
10-19	-	2	5	11	15	7	25	12	9
20-29	2	1	15	18	11	28	19	17	13
30-39	4	16	20	22	28	30	13	10	8
40-49	20	20	29	26	26	6	8	10	13
50-59	13	33	20	11	2	5	3	5	2
60-69	23	16	5	4	3	-	2	-	4
70-79	24	5	2	2	-	-	-	-	-
80-89	5	7	4	-	-	-	-	-	-
90-100	9	-	-	-	-	-	-	-	-

2.3 Intrasecular dynamics of ice conditions from the beginning of regular observations

The fact that ice conditions along the NSR experience not only seasonal, interannual, but also significant multiyear changes has been known since the first regular voyages along this route in the 30s. Already at that time it was suggested that the success of these voyages was governed in many respects by the improved ice situation in the Siberian Arctic waters. The improvement itself was directly related to the climate warming of the Arctic that reached its culmination at the border of the 30-40s. Since ice observations were commenced simultaneously with the first through voyages along the NSR and attained a systematic character with time, there is a possibility for tracing the changes of ice conditions on a climatic scale over the last 7 decades of the present century.

Fig. 2.8 presents the curves of ice areas in the Siberian Arctic waters (the Kara, Laptev, East-Siberian and western Chukchi Seas) in July, August and September, beginning from 1932. The following conclusions can be drawn with regard to the character of changes in ice conditions.

- Ice area experiences quite strong changes from year-to-year. For the last 6 decades its changes in July were ranging from 2.33 to 1.36 mln. km^2, in August from 1.87 to 0.69 mln. km^2 and in September from 1.47 to 0.50 mln. km^2.

- A group of years with heavy ice conditions is clearly defined: the periods of enhanced ice cover extent several years in duration are replaced by the periods of decreased ice extent. This group is most evident in September, that is, it becomes more pronounced from early to late summer.

- Variations in ice cover extent remain mainly the same during the season. This is indicated by a significant similarity of the curves referring to July, August and September. An anomaly in ice cover extent formed by July is preserved all summer in 78% of cases and that formed by August in 91% of the cases.

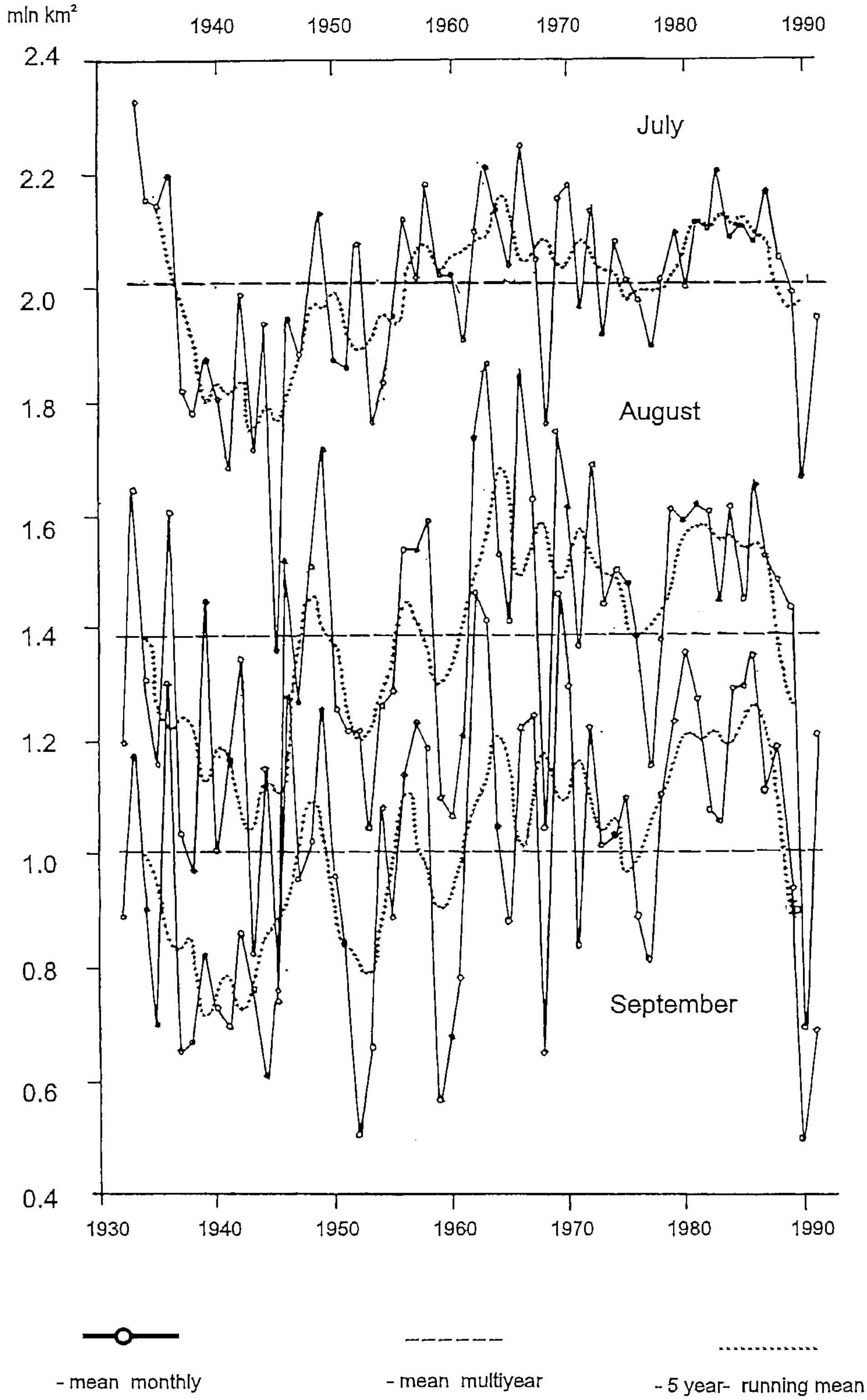


Fig. 2.8. Sea ice area in Siberian arctic water of the Kara, Laptev, East-Siberian and Chukchi Seas

- A multiyear ice cover extent minimum during the time interval 1932-1991 was observed in the late 30s - early 40s. Since that time a deterioration of ice conditions commenced along the NSR with some temporal breaks. It lasted in July and August up to the mid 60s and in September up to the mid 80s. In July this increase in ice cover extent was $0.3 \cdot 10^6$ km^2 , in August $0.5 \cdot 10^6$ km^2 and in September $0.5 \cdot 10^6$ km^2.

- During the second half of the 80s a tendency to a reduction in ice area was observed. Whether it is stable or not is impossible to predict now.

- The ice area curves along the NSR given in Fig. 2.8 do not allow an assessment of the scale of the change in ice conditions as affected by the warming of the Arctic climate. They only simulate a final phase in the warming process that began at the end of the last century.

With regard to these comments it is important to use the available capabilities to extend a time series on the ice state using even less reliable data referring to the first three decades of this century. The use of such data was possible only for the second half of August (Fig. 2.9) and only from 1924. Rare voyages along the Siberian coast during the period 1924-1931 allow a rough quantitative estimate of ice conditions for this period. An estimate of the ice state in the interval 1900-1923 that will be made at the end of this section is possible only at a qualitative level.

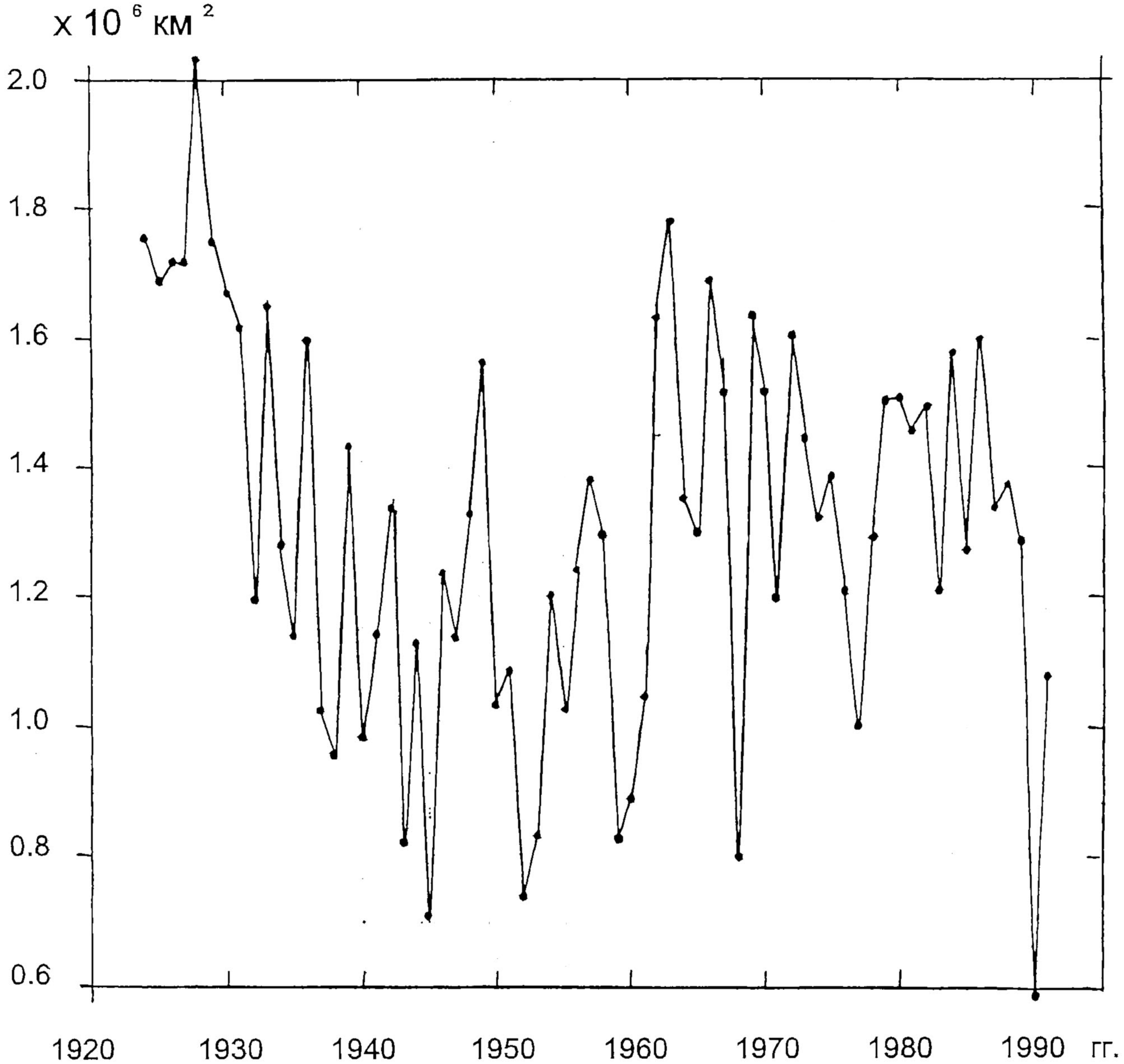


Fig. 2.9 Change in sea ice area in Siberian arctic water in the second half of August

The data on ice conditions during the period 1924-1931 indicate a rather difficult situation along the NSR. In all the years of this period the ice area was quite large reaching in 1928 the largest values for the whole period.

The area occupied by sea ice is a quite satisfactory generalised indicator of ice conditions. However, it should be taken into account that with regard to each specific NSR segment this indicator is not quite representative. Moreover, the events in some region or other can develop in the direction directly opposite to the expected one according to the generalised indicator. In order to know what to expect with an increase or decrease in this indicator on each NSR segment it is necessary to know the typical features of the changes in ice conditions in space. For this purpose the charts of ice concentration change in the Siberian Arctic waters at the phase of the cooling development in the atmosphere and an increase in generalised indicator were constructed. These charts are presented in Fig. 2.10 and 2.11.

Gridded ice concentration values in the first 10-days of September for the period 1946-1974 served as a basis for diagrams. These values were then grouped and averaged by decades 1946-1955, 1956-1965 and 1956-974. Mean value for 1946-1955 was assumed to be the reference point, although for our purpose the decade 1936-1945 is more suitable. Regretfully, there are no reliable data on ice concentration during this decade. The ice area on the NSR equal to $1.118{\cdot}10^6$ km^2 corresponds to the assumed reference point. During the next two decades this area was equal, respectively, to $1.272{\cdot}10^6$ km^2 and $1.414{\cdot}10^6$ km^2. Thus, the situations shown by the diagrams reflect the ice concentration changes at the stage of a progressively expanding ice cover. A whole amount of data referring to the warming epoch of the Arctic suggests that climatic fluctuations of such kind are accompanied by changes in concentration in a directly opposite direction.

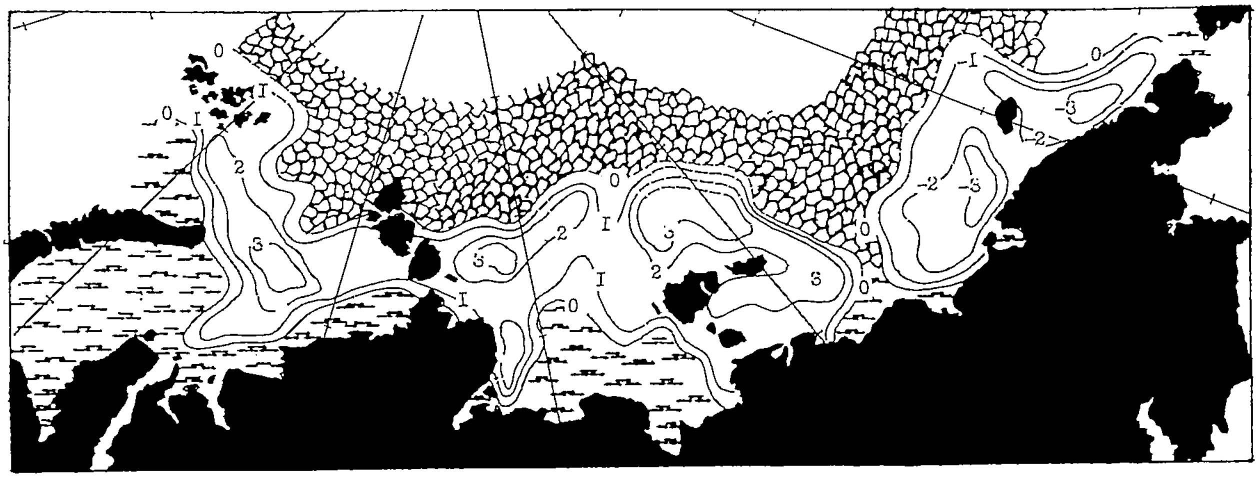


Fig. 2.10. Change in ice concentration from the decade 1946-1955 to 1956-1965 in the first 10-day period of September

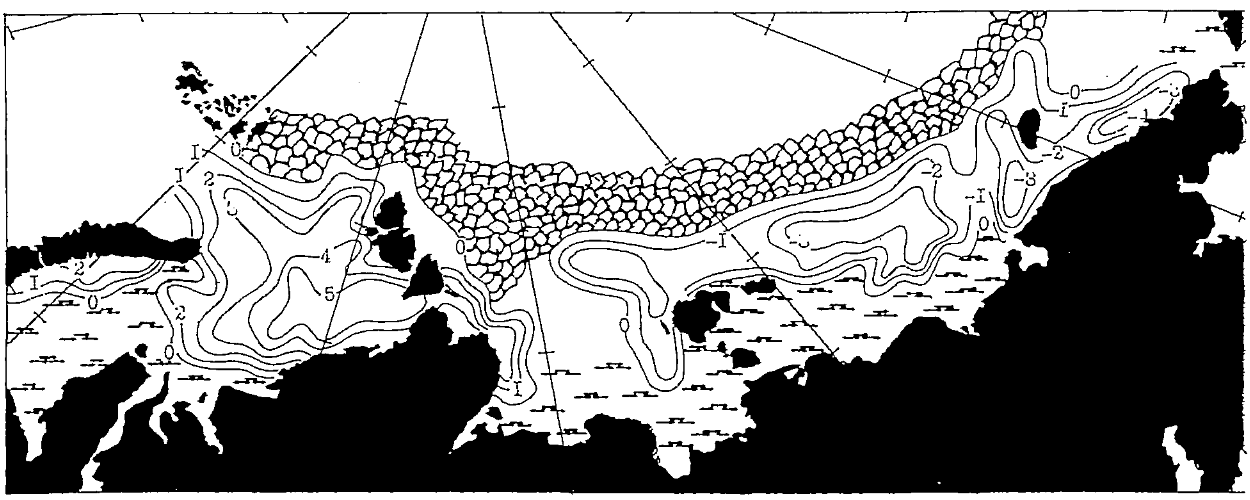


Fig. 2.11. Change in ice concentration from 1946-1955 to 1966-1974 in the first 10-day period of September

The conclusions that can be drawn on the basis of Fig. 2.10 and 2.11 are as follows:

- Deterioration of ice conditions along the NSR expressed in increased total ice area is not observed everywhere. An increase in ice concentration occurred on the western NSR segment. It was decreasing on the eastern segment (mainly east of the New-Siberian Islands). This phenomenon known as "ice opposition" was discovered already in the 30s..

- An increase in ice concentration on the western NSR segment and its decrease on the eastern one do not compensate each other. The events in the west are the governing ones for the characteristics of the general ice state along the NSR.

- The boundary dividing the NSR into western and eastern segments passes along the high pressure ridge connecting the Siberian and Canadian Highs. West of it the ice situation is formed under conditions typical of the frontal part of the Icelandic centre of the atmospheric action and east of it under conditions typical of the rear part of the Aleutian Low. The boundary dividing the NSR into two segments is mobile. Depending on the development of the main centres of atmospheric action it can be located to the east or to the west of the New-Siberian Islands. The development of cooling in the atmosphere is accompanied by a reduction in the Icelandic Low trough and a westward shift of this boundary.

- The largest changes in ice conditions of a climatic scale occur in the Kara Sea.

A strong spatial inhomogeneity of multiyear changes in ice conditions along the NSR, well-pronounced in Fig.2.10 and 2.11, indicates a need for a more detailed picture. Such detailed picture is possible if the study of variability is carried out for separate NSR segments. For this purpose Fig.2.12-2.15 were prepared disclosing the dynamics of summer ice conditions in the Siberian Arctic seas over the last 5 decades. Tables 2.9-2.12 also provide additional information of a quantitative character where the data on the number of years with ice cover extent exceeding mean multiyear one for each decade are presented.

There are just a few remarks with regard to the character of these dynamics:

- The ice state in all seas of the NSR is subjected to sharp changes from year-to-year. As a result, there is a strong temporal variability in ice navigation conditions north of the coast of Siberia.

- There is no consistency in ice area variations in these seas. In each sea these variations are quite individual and unlike each other.

- Intrasecular ice area changes are most pronounced on the westernmost NSR segment in the Kara Sea. From the early 40s and up to the late 60s this area increased by about $0.4 \cdot 10^6$ km^2, as compared with its level in the early 40s. During the period 1970-1991 ice cover extent remained quite large, although it decreased relative to its value of the late 60s.

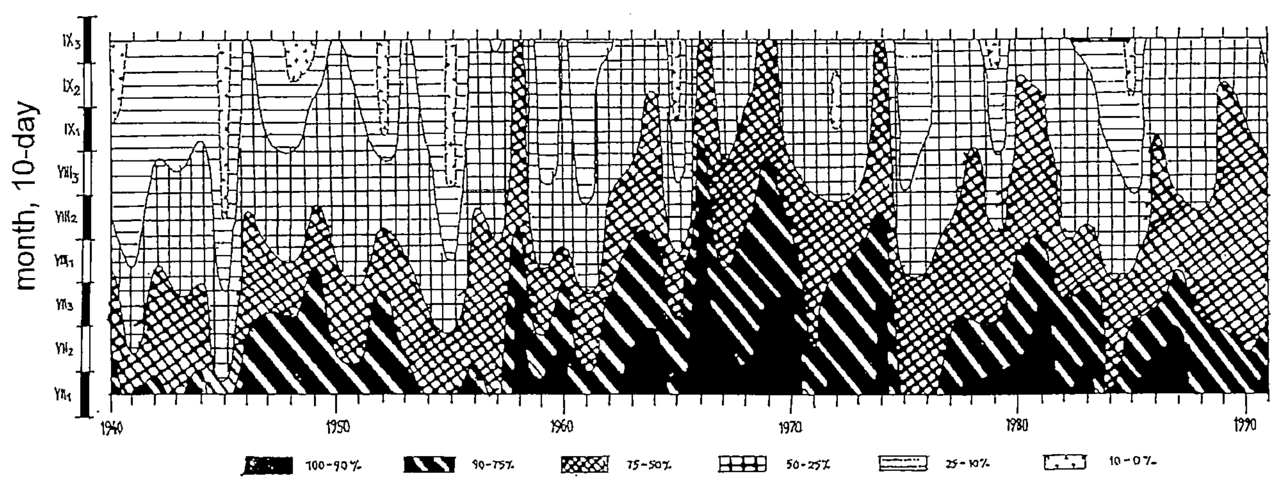


Fig. 2.12. Change in ice area in the Kara Sea in summertime during the period 1940-1991 (ice area in %% of the area $0.830 \cdot 10^6$ km^2)

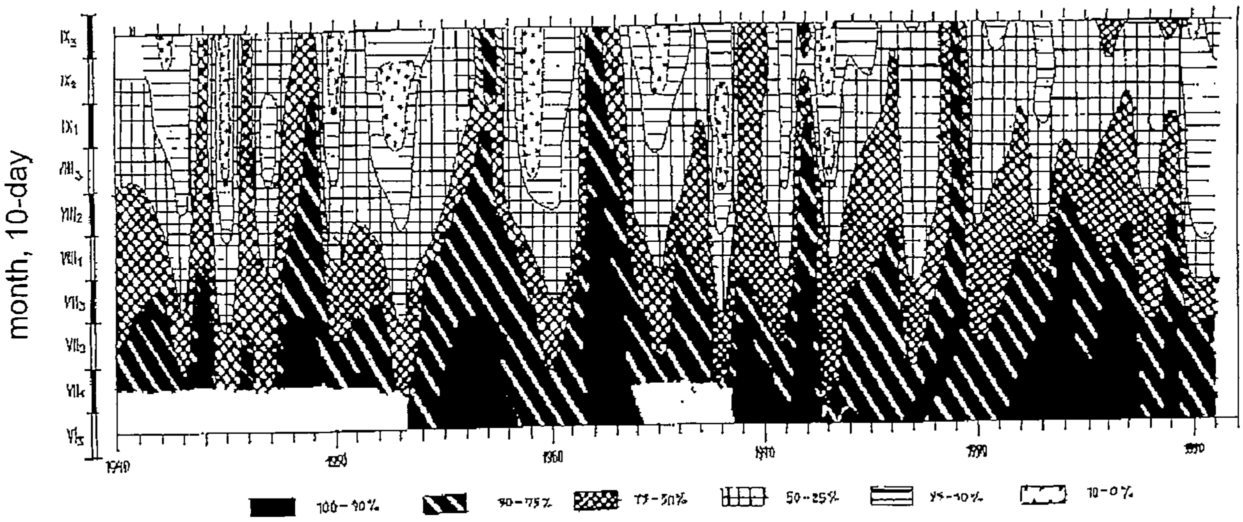


Fig. 2.13. Change in ice area in the Laptev Sea in summertime during the period 1940-1991 (ice area in %% of the area $0.536 \cdot 10^6$ km^2)

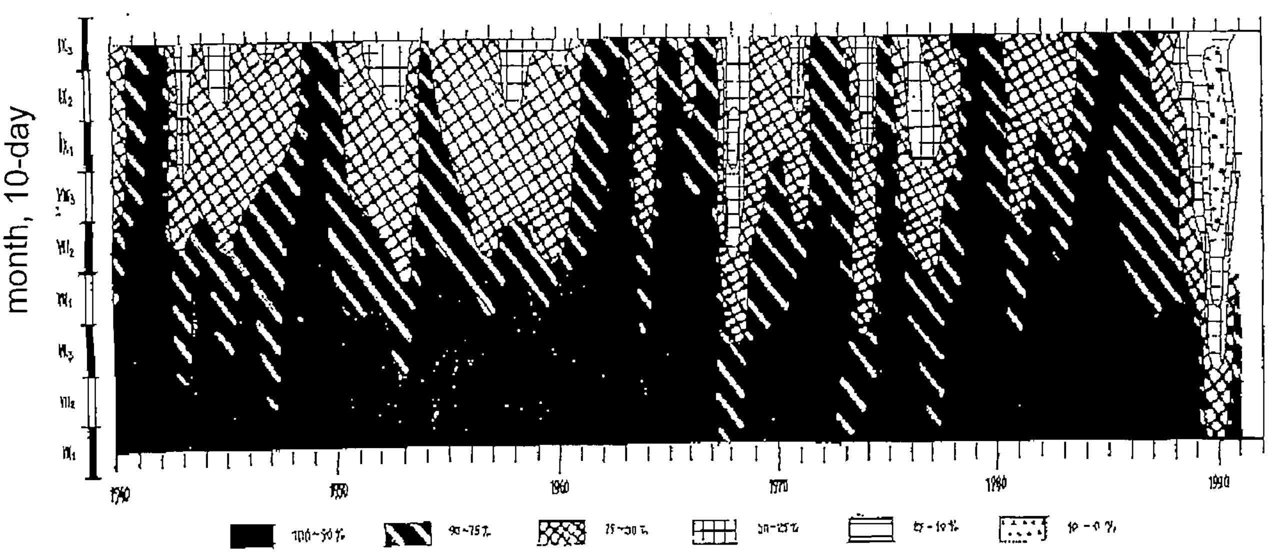


Fig. 2.14. Change in ice area in the East-Siberian Sea in summertime during the period 1940-1991 (ice area in %% of the area $0.770 \cdot 10^6$ km^2)

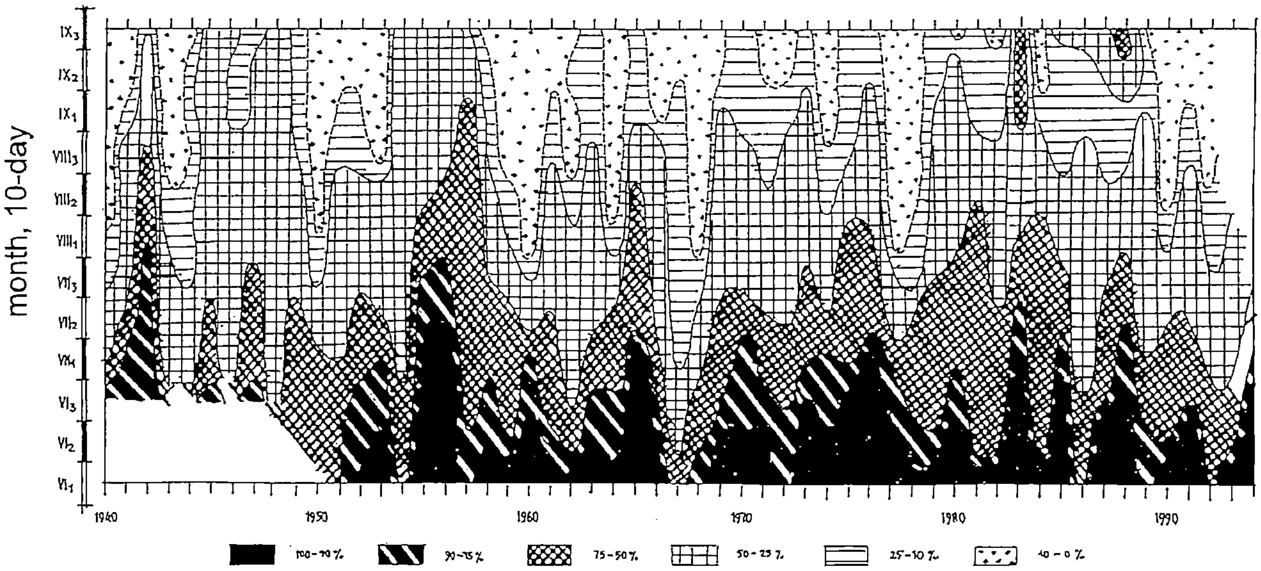


Fig. 2.15. Change in ice area in the south-western Chukchi Sea in summertime during the period 1940-1991 (ice area in %% of the area $0.176 \cdot 10^6$ km^2)

Table 2.9. Number of years with ice area exceeding multiyear normal by decades in the Kara Sea

Decade	July			August			September			Mean
	1	2	3	1	2	3	1	2	3	
1940-1949	3	3	3	2	2	1	2	1	0	1.9
1950-1959	6	3	2	3	2	1	3	4	4	3.1
1960-1969	9	9	9	8	7	7	7	7	6	7.7
1970-1979	6	6	5	8	7	7	5	5	6	6.1
1980-1989	8	9	7	6	7	5	7	6	6	6.9

Table 2.10. Number of years with ice area exceeding multiyear normal by decades in the Laptev Sea

Decade	July			August			September			Mean
	1	2	3	1	2	3	1	2	3	
1940-1949	4	4	5	4	5	6	5	6	5	4.9
1950-1959	7	5	6	4	2	4	4	3	4	4.3
1960-1969	6	5	6	5	4	4	4	4	3	4.6
1970-1979	4	5	5	3	5	4	5	5	4	4.4
1980-1989	8	7	7	6	7	5	6	6	6	6.4

Table 2.11. Number of years with ice area exceeding multiyear normal by decades in the East-Siberian Sea

Decade	July			August			September			Mean
	1	2	3	1	2	3	1	2	3	
1940-1949	7	5	7	8	7	5	5	4	4	5.8
1950-1959	6	8	8	6	6	3	3	2	3	5.0
1960-1969	7	7	8	8	6	6	6	6	6	6.7
1970-1979	5	5	6	8	6	5	6	6	6	5.9
1980-1989	9	8	6	7	8	8	7	5	6	7.1

Table 2.12. Number of years with ice area exceeding multiyear normal by decades in the south-western Chukchi Sea

Decade	July			August			September			Mean
	1	2	3	1	2	3	1	2	3	
1940-1949	4	5	3	6	7	6	5	6	6	5.3
1950-1959	6	6	6	5	7	4	5	4	4	5.2
1960-1969	5	2	4	4	4	4	3	1	1	3.1
1970-1979	6	4	6	6	5	4	6	5	4	5.1
1980-1989	5	7	7	6	8	9	5	8	6	6.8

2.4. Ice conditions along the NSR in the first quarter of the XXth century

A review of the ice state during the first 25 years of the present century can be made at present only at a qualitative level and with regard to the Kara Sea alone or to be more specific to its south-western region. Since 1869 this sea region (south of the line Zhelaniya cape at Novaya Zemlya - Dikson Island) has been regularly visited by ships (fishing, transportation and expedition vessels). The information on ice situation during these voyages was collected, studied and summarised by E. Lesgaft in 1913 (Lesgaft, 1913).

According to Lesgaft all diverse features in ice distribution in this sea for the period 1869-1911 can be subdivided into 5 types. Three of these types are of particular interest since each of them is related to ice persistence near the eastern coast of Novaya Zemlya from Matochkin Shar to Yugorsky Shar during much of navigation or even during the whole navigation period. A total occurrence of these three types during the period 1869-1911 was 43% and during the period 1899-1911 - 38%. Thus, every 4 years out of 10 an access to the Kara Sea through the Novozemel'skiye straits was either difficult or impossible because of ice . The year 1899 can serve as an example of such situation: A large amount of ice persisted all summer south of the line connecting the northern tip of the Vaigach island and Yamal peninsula in the north-eastern direction. The most southern of Novozemel'sky straits - the Yugorsky Shar was cleared from ice in early October (20 September according to the old style - Julian calendar). In 1904 the Kara Gate strait was blocked by ice in July-September. The Yugorsky Shar was ice-free that summer for only half a month in the first half of September. The main ice mass was in the south-western sea.

For comparison, let us note that during the decade 1956-1965 (not the most favourable decade of the present period) ice presence in September in the Yugorsky Shar was not observed and in the Kara Gate strait and near the Matochkin Shar strait from the Kara Sea side ice was observed only once. It should be said that these data on ice occurrence can on the whole refer to the sea region south of the Matochkin Shar latitude.

A comparison of the data on ice conditions in the vicinity of the Zhelaniya cape also indicates quite obviously more complicated navigation conditions at the beginning of this century.

According to Lesgaft sailing round the Zhelaniya cape from 1895 to 1910 was possible only in 6 cases out of 10. In our day the probability of encountering ice off the Zhelaniya cape and adjacent regions is only 10%. An example of 1901 shows the complexity of the ice situation at the approaches to the Zhelaniya cape from the Barents Sea side when the "Yermak" icebreaker was not able to approach the Zhelaniya cape. Three attempts made during the summer failed due to heavy ice.

Similar situations were quite usual at the beginning of the century. Such conclusion is confirmed by the ice state in the Barents Sea during the first decades of the XXth century as illustrated by the ice distribution charts prepared by the Danish Meteorological Institute. Summer ice boundary during these years was located southward of its modern position. The ice area in the period 1950-1969 was less than in May by $0.166 \cdot 10^6$ km^2, and in August by $0.204 \cdot 10^6$ km^2. Generally speaking, the first years of the present century had the largest ice cover extent in the whole of the Atlantic sector of the Arctic. A secular ice extent maximum in the Barents Sea (and not only in it) was in 1917. The ice area exceeded multiyear normal value in May by $0.423 \cdot 10^6$, in June by $0.528 \cdot 10^6$, in July by $0.531 \cdot 10^6$ and in August by $0.399 \cdot 10^6$ km^2. Since that time the ice area in this sea began to reduce and shipping conditions to improve. From 1927 voyages in the northern latitudes were made annually. In 1931 the expedition vessel "N.Knippvich" reached 82°N westward of the Franz-Josef Land in free navigation and the next year it circumnavigated the whole Franz-Josef Land from the north for the first time in the history of navigation.

A special emphasis on the Barents Sea in caused by the fact that there is a relation between the ice state in the Barents and the Kara Seas. Lesgaft was the first to notice it. "Between the ice state in the Barents and Kara Seas there is an obvious relationship. It is expressed by the fact that at a relatively favourable ice state in the Barents Sea (in the north and north-east) there are also favourable conditions in the northern Kara Sea, in the passage round the northern tip of Novaya Zemlya and in the Matochkin Shar. At a relatively unfavourable ice state in the Barents Sea in the north and south-east and in the northern Kara Sea there are unfavourable conditions near the northern tip of Novaya Zemlya and in the Matochkin Shar" (Lesgaft, 1913, p.151).

The facts mentioned above suggest the dominance of more severe ice conditions during the first quarter of the present century than during the whole of the next period. It means that during this quarter there was increased occurrence of years with a complicated ice situation, as compared with the modern one.

Section 2 has shown the Kara Sea to be opposed to the East-Siberian Sea by ice conditions. That is why it can be suggested that shipping conditions along the eastern NSR segment in the first quarter of this century were more favourable than the present ones. However, further actual evidence should be provided to confirm this suggestion.

3 SHIPPING CONDITIONS

3.1 A brief description of initial data on ice conditions for shipping and features of their analysis

Ice conditions of the Siberian shelf generally reflect ice cover extent (and massif areas), as well as ice distribution type. Usually these characteristics are used for analysing seasonal and interannual changes in ice conditions and for developing forecasts of different periods in advance, including climatic forecasts (Climatic regime, 1991; Gudkovich et al., 1972). In the event one speaks about shipping, it is also necessary along with the indicated characteristics to take into account ice navigation features of different types of ships (Gordiyenko et al., 1967; Kashtelyan et al., 1968).

The motion of ships in ice is selective with the use of local zones of the most favourable combination of ice cover characteristics (reduced concentration and hummocking, higher fracturing, presence of cracks, leads, etc.). The dimensions of these zones are often comparable with ship's particulars and are not always recorded by the existing methods of remote sensing diagnostics of ice cover. In this connection generalised shipborne observation data for a multiyear period are of particular importance. An analysis of these data allows us to relate the generalised characteristics of ice conditions at sea to the ice cover characteristics on the route of ships and in addition to track changes in ice navigation conditions for quite a long period. Evidence on the voyages of ships was repeatedly systematised (Kashtelyan et al., 1968; Sibirtsev and Itin, 1936). Probably, we should agree with a viewpoint of many investigators (Sibirtsev and Itin, 1936) that all data on unescorted navigation should preferably be considered by periods: 1553-1900 when reliable data are absent; 1900-1934 - there are occasional voyages; data on navigation conditions are presented in reports, logs, etc; 1934-1946 - voyages are regular, however, ice reconnaissance that allows determining the possibility of unescorted navigation at the time of sea operations is occasional; 1946 - up to present -regular data on ice distribution in the seas of the Siberian shelf allow an objective estimate of the duration of unescorted navigation.

Thus, shipping in the ice of the Siberian shelf took place from time immemorial, before ice reconnaissance shipborne data were the main source of data on the ice distribution at sea. In recent years satellite data have become the main type of remote sensing ice cover diagnostics as a result of the end of visual ice reconnaissance and a sharp reduction in the volume of instrumental reconnaissance using SLAR. Thus, the importance of shipborne ice observations again considerably increases, in particular, by using the results of these observations the thickness distribution features of old ice in the near-pole area and in fast ice of the north-eastern Kara Sea (Tunik, 1993; Busuyev et al., 1990), etc. can be determined.

In accordance with the aims of the present project the generalised characteristics of ice navigation conditions and, in particular, the duration of unescorted navigation, as well as total length of the route in ice of different concentration are considered below.

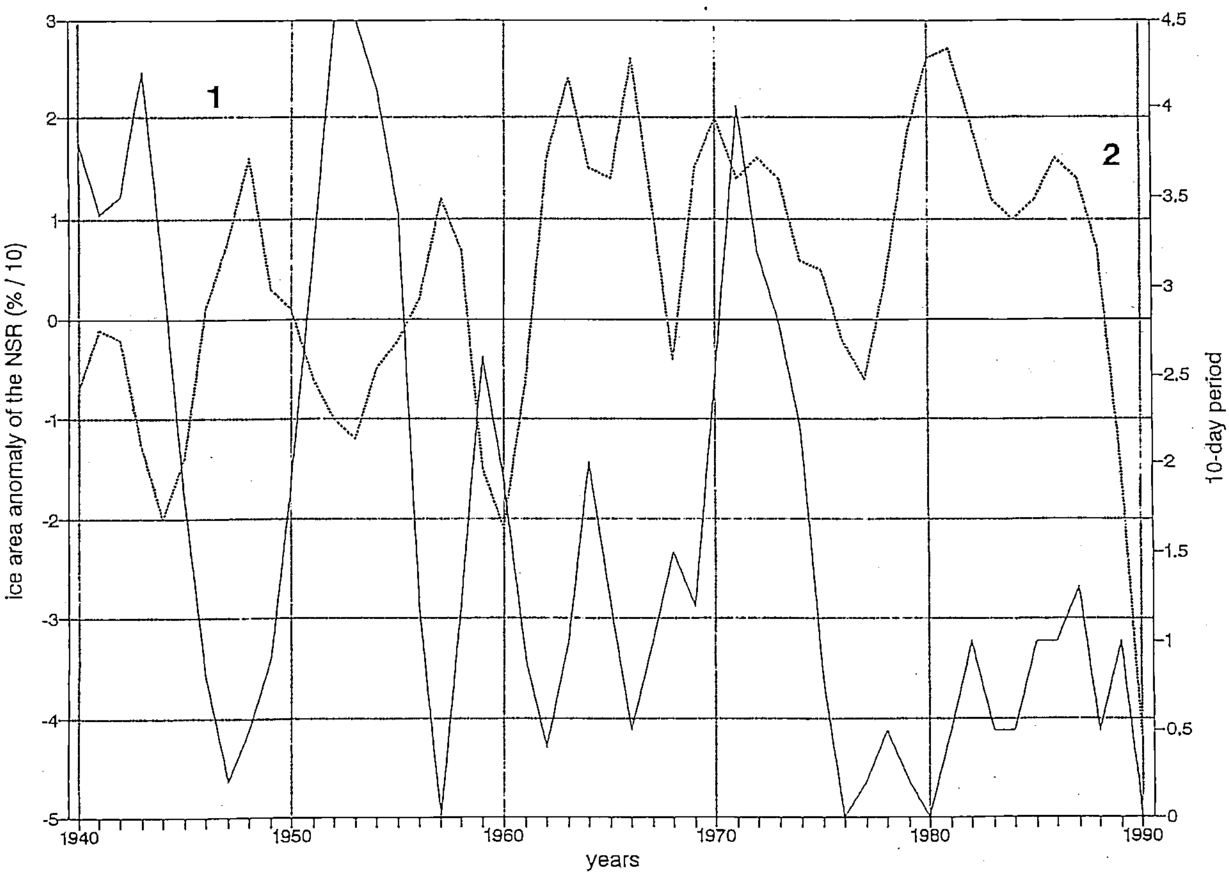
It should be stressed that ice conditions in the seas of the Siberian shelf and navigation features on shipping routes are formed as affected by the same factors.

An analysis of multiyear changes in ice cover extent, formation of different types and substantiation of the viewpoints of a possible development of ice conditions for the next 5-10 years is beyond the scope of this study (see sections 1.2, above). Our aim is to show a possible interpretation of the expected ice conditions in the interests of shipping along the NSR.

3.2 Climatic changes in navigation conditions and their relationship to ice cover extent of the seas

Let us, first of all, note that ice cover of the Arctic Seas is mainly represented by close ice; that is why there is a good relationship between their area and ice cover extent. Hence, it is of no principal importance which of these characteristics is used for analysing navigation conditions.

In the framework of the INSROP Program one speaks about transit navigation along the NSR. In this connection let us consider how the duration of unescorted navigation possible by natural conditions was changing for a long-term period (Fig.3.1).



———— - 10-day period — — — — — — - ice area anomaly (% . 10^{-1})

Fig. 3.1. Duration of unescorted transit navigation and ice area anomaly along the NSR in August smoothed by 2-year periods

The most favourable conditions for transit shipping were observed in 1940-45, 1950-55 and 1970-74 when close ice was absent on the route for 20-40 days and more. However, also periods rather unfavourable for transit shipping were observed (1965-69, 1975-89) when the possibility of unescorted navigation did not exceed 10 days.

Chronological variations in the navigation conditions are consistent with variations in total ice cover extent of the Siberian shelf seas in the most general form (see Fig. 3.1). A correlation analysis of the dependence of the unescorted navigation period along the whole NSR on total ice cover extent of these seas in August indicates that a correlation coefficient between these values is only 0.33. This is also indicated by the fact that during the years with large anomalies in ice cover extent the duration of unescorted navigation changes on a wide range. This range is also quite wide at a total ice cover extent of these seas close to the norm (Table 3.1).

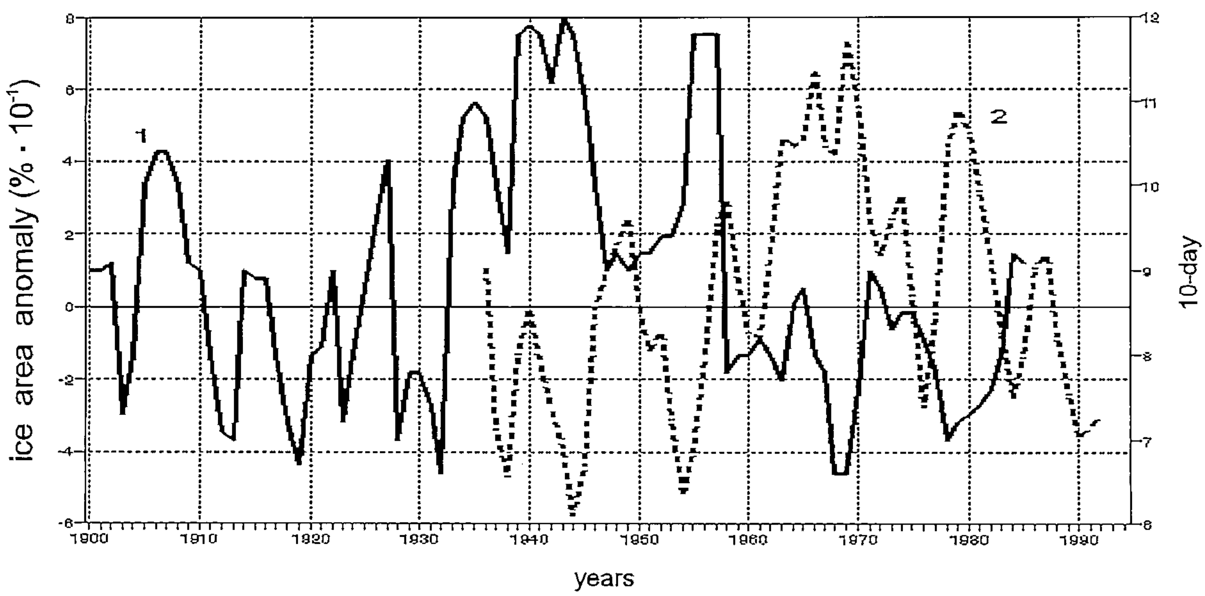
Table 3.1. Duration of transit unescorted navigation (τ, Dec.) at a different background of total ice cover extent anomalies ($\Sigma\,\Delta L$, %) in August (1940-1992)

Characteristics of the ice extent background $\Sigma\,\Delta L$, %		Changes in duration of unescorted navigation, (τ,Dec)			Number of cases	Notes
		τ_{min}	τ_{max}	τ		
normal ± 5% $\Sigma\,\Delta L$, %		0	4.1	0.9	17	
above normal	ΔL,% = 6-10			0.2	1	only one year with such combination ΔL % and is observed τ
	ΔL,% = 11-20	0	4.0	1.4	13	
	ΔL,% = 21-30	0	2.5	0.9	5	
below normal	ΔL,% = 6-10	3.8	4.5	4.1	2	
	ΔL,% = 11-20	1.1	4.5	3.3	5	
	ΔL,% = 21-30	0	1.9	0.8	2	

Unfortunately, the length of the observation series that are used, is insufficient for reliable climatic generalisations. In particular, this concerns considerable anomalies in natural phenomena and processes that occur rather seldom. In order to fill the data gap a reconstruction of the duration of unescorted navigation in marginal NSR zones from 1900 was performed on the basis of the analysis of available data (Climatic regime, 1991). A comparison of this indicator with total ice cover extent of the regions where ships sail suggests a relationship between them. However, this relationship is specific for each region (Fig.3.2, 3.3). At a maximum of total ice cover extent the duration of unescorted navigation in the south-western Kara Sea in July-September (end of the 60s, Fig. 3.2) is more than six 10-day periods. At the same time on the eastern NSR segment in the years with a significant total ice extent the duration of the period of unescorted navigation is reduced to one-two 10-day periods (Fig. 3.3). Also, the amplitude of fluctuations in the duration of this period most favourable for shipping on the eastern and western NSR segments differs almost by two orders of magnitude. After quite a favourable period in the 40s there is a tendency to a deterioration in navigation conditions on both segments. But the most significant conclusion is that even during an earlier period (1900-1940) the character of changes in the navigation duration was generally preserved. This fact suggests a principal conclusion that interannual changes of the period most favourable for shipping from 1946 up to present are quite significant (Fig. 3.1-3.3) however, the range of these changes has been preserved for quite a long time since 1900. Thus, it can be expected that in the near future the range of changes in the duration of the period of unescorted navigation will not experience considerable changes. The conclusions of possible ice cover extent changes at the border of the XXth-XXIst century (Climatic regime, 1991) and the results of the present study (sections 1, 2) support this statement.

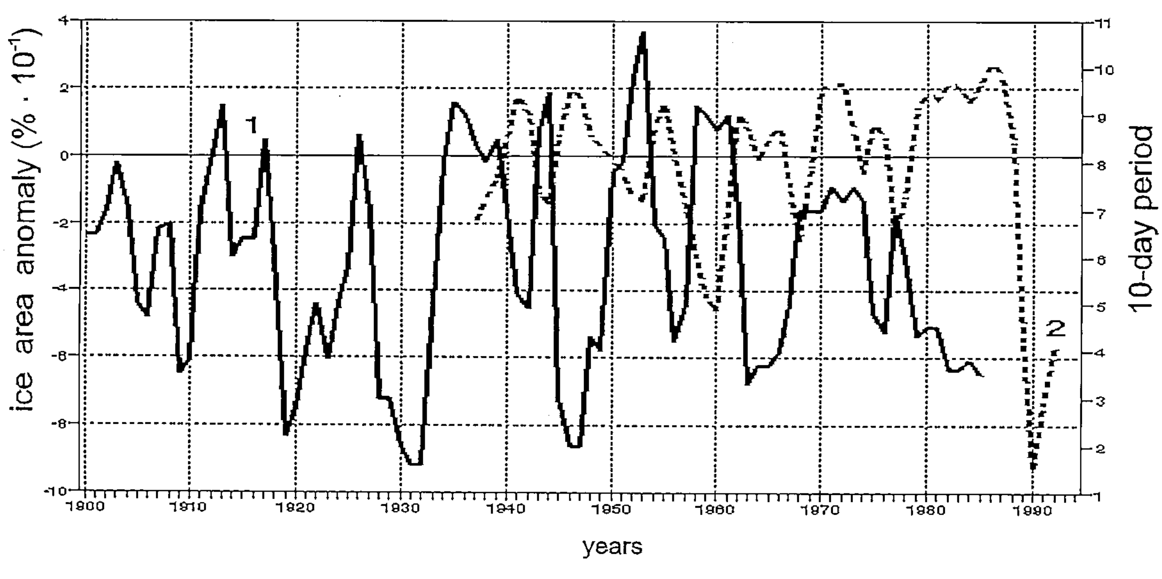
As follows from the above mentioned, the possibilities for unescorted transit navigation (at any case of the UL ships and of ships of a lower category) are rather limited. There is high probability (60%) that such navigation will be rendered impossible by ice conditions. In this connection an assessment of ice navigation conditions escorted by icebreakers is quite important.

Quite informative characteristics of these conditions may be the length of the route in ice of different concentration, and, first of all, in close ice and fast ice. As to the other characteristics of the ice cover state, they are presented in the databases on all most important components (amount of hummocking, degree of destruction, size of ice formations, etc.)



———— - 10-day period - - - - - - - ice area anomaly (% · 10^{-1})

Fig. 3.2. Duration of unescorted navigation and ice area anomaly in July-September in the south-western Kara Sea smoothed by 2-year periods



———— 10-day period - - - - - - - ice area anomaly (% · 10^{-1})

Fig. 3.3. Duration of unescorted navigation from the Bering strait to the Kolyma river mouth and ice areas in July-September in the eastern East-Siberian Sea smoothed by 2-year periods

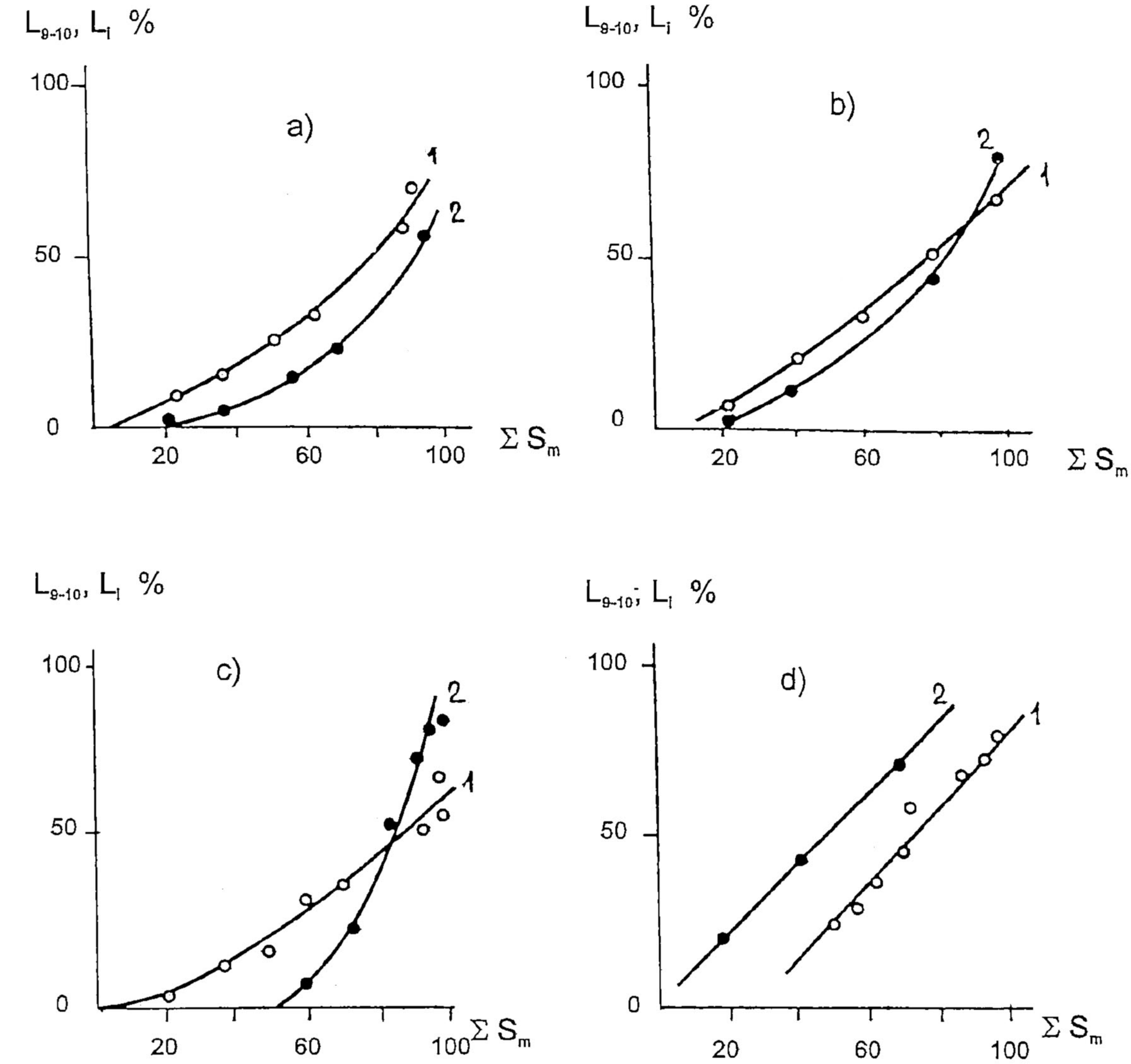


Fig. 3.4. Dependency of the length of the route in ice L_i (1) and the route in close ice $L_{9\text{-}10}$ (2) on the area of ice massifs in the navigation region (ΣS_m) along the routes:

a - Barents Sea - Dikson island (ΣS_m for Novozemel'sky massive);

b - Dikson island - Tiksi (ΣS_m mean for Severo-Zemel'sky and Taimyr massifs);

c - Tiksi - Kolyma mouth (ΣS_m mean for Yana and Aion massifs);

d - Kolyma mouth - Bering strait (ΣS_m mean for Vrangel massif and south-west of the Chukchi Sea)

As has been mentioned above, reliable data on ice amount and its distribution character were accumulated with the commencement of regular ice reconnaissance flights (1946). By using these observation data a dependency between the length of the route in ice (when travelling along the most favourable variant (Busuyev et al., 1982) and ice massif area in the navigation region has been found. As expected, the dependency under consideration shows significant differences for each of the Siberian shelf seas (fig. 3.4). These differences are governed not only by specific features of the formation and location of each of the massifs (Gudkovich et al., 1972), but also by specific features of ice navigation, primarily, depth restrictions, typical of the Arctic Seas and also by the location of the exit and destination points (ports) and other factors. Nevertheless the presented proportions (Fig. 3.4, 3.5) allow an estimate of the total length in close ice (and fast ice) for transit navigation during the years with a somewhat different state of ice massifs in the seas of the Siberian shelf.

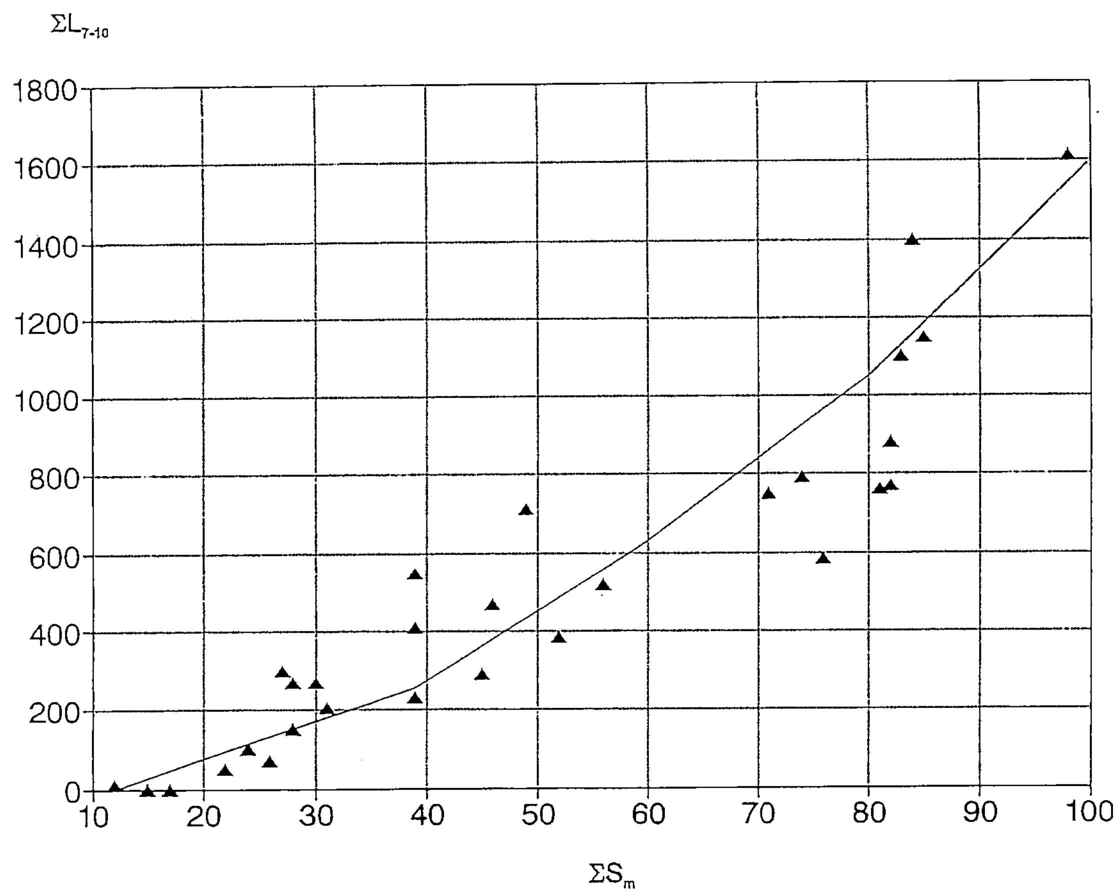


Fig. 3.5. Dependence of the length of navigation in close ice along the whole NSR on total area of ice massifs

3.3 Preliminary considerations of possible shipping conditions at the threshold of the XXI century

In 1991 the scientists of the AARI prepared a monograph that presents their viewpoints on possible changes in natural conditions of the Siberian Sea shelf up to 2005 (Climatic regime, 1991). The main portion of initial observation data and results of the studies were completed by 1988. Six years have passed and it is quite reasonable to ask to what extent the data of later observations confirm the ideas presented in the monograph. First of all, the statement that at present it is impossible to make any definite conclusion about natural conditions in the future is still in force. On the other hand, the idea that the ice cover extent regime prevailing this century will be preserved at the threshold of the XXI century, has been confirmed. Moreover, with preservation of naturally governed limits of ice extent changes, the number of scientists supporting the prevalence of enhanced background of ice cover extent in the future increases (Climatic regime, 1991; Busuyev, 1980).

It should be noted that a tendency to a deterioration in transit navigation conditions is quite evident. In the past, following a widely employed approach to an analysis of long-period fluctuations of ice cover extent, in particular of 5-7 cycles (Zakharov, 1981; Gudkovich, 1972), such statistical processing was performed for the data on the duration of transit unescorted navigation (Busuyev, 1980). The use of new data allows us to compile a summarised table of changes in transit navigation conditions for the whole available observation series (Table 3.2). As is evident from the Table, one can speak about the preservation of unfavourable background for transit navigation from a 5 year period 1975-1979. In order to predict the future of unescorted navigation, let us consider the results of the studies of other authors. In particular, the AARI specialists on long-range weather forecasts (Dmitrieyv, 1994) are quite definite in stating that atmospheric processes of 1940-1980 are opposite to the present atmospheric processes. In this connection the analogues should be looked for among the years of the beginning of the XXth century. In our case these are the data on unescorted navigation conditions on the NSR marginal zones during the period from 1900 (Fig.3.2). General typical features (range of changes, interannual variability) in navigation conditions at the beginning of the century are consistent with natural background of the end of the XXth century. Then in (Dmitrieyv, 1994) the transition to active atmospheric processes of the W form and as a result, a decrease in the temperature background are substantiated. This statement is in agreement with a tendency of changes of total ice cover extent of the Arctic Seas and systematic data on navigation conditions.

Thus, it is not groundless to say that an unfavourable background for transit unescorted navigation will be retained on the threshold of the XXI century.

Table 3.2. Occurrence (P, %) and duration of unescorted transit navigation along the NSR (τ, days) by 5-year periods

5-year periods		P% in the given 5-year period	τ, days		
Favourable	Unfavourable		minimum	maximum	mean
1940-1944		80	14	74	42
	1945-1949	40	30	31	31
1950-1954		100	27	65	41
	1955-1959	40	53	54	54
1960-1964		60	7	38	21
	1965-1969	20			20 [1)]
1970-1974		100	10	41	21
	1975-1979	20			10 [1)]
1980-1984		60	5	15	10
	1985-1989	40	20	25	22
1990-1994		40	10	25	18
	1995-1999 (?)	(20-40)			(10-20)

Note: [1)] - during this 5-year period only one year is observed when unescorted navigation was possible.

4 RECOMMENDATIONS FOR A STRATEGY OF DEVELOPING INTERNATIONAL SHIPPING ALONG THE NSR TAKING INTO ACCOUNT POSSIBLE ENVIRONMENTAL CHANGES

Shipping in the Arctic waters is related to increased risk and difficulties. Sea ice is the most significant factor governing these conditions. Not only safety but also commercial profit of transportation along the NSR depend on the state of sea ice. Generalised data on ice regime along the NSR and its separate segments are considered to be an important information source at the stage of planning and transportation. On their basis a conclusion about the dates of the beginning and end of navigation, most probable ice conditions, a possible range of changes in these conditions, etc. is being made. Forecasting with different advance periods, including climate forecasting, is based on typical features found in the process of studying the regime of forecasted phenomena.

According to the results of the second and partly of the first stages of Project 1.7.1, one can formulate a number of statements and recommendations concerning ice navigation conditions along the NSR for today and for the near future.

- The most favourable time for navigating the NSR is the second half of August and September.

- The most complicated ice navigation conditions are typical of the two NSR segments Severozemel'sky (western and eastern approaches to the Vil'kitsky strait) and Vrangel (from the Aion island to the Shmidt cape). These conditions are formed here under the influence of stationary branches of the oceanic ice massif.

- The ice state along the NSR experiences sharp changes from year-to-year, thus, causing a large uncertainty with regard to possible navigation conditions. Hence, the need of forecasting ice conditions with a large advance period.

- Along with strong seasonal and interannual changes ice conditions along the NSR also experience significant intrasecular changes. A direct result of these intrasecular changes is an alternation of long (tens of years) periods of relatively easy and heavy ice navigation periods.

- An important feature of intrasecular changes in ice conditions is their spatial non-uniformity. An extreme expression of this non-uniformity is ice opposition between the eastern and western NSR segments.

- No evident traces of the effect of anthropogenic factors on the ice state along the NSR have so far been found. That is why, generally speaking there are no sufficient causes for expecting a sharp improvement in ice and shipping conditions due to an increase in carbon dioxide concentration in the atmosphere.

- An estimate of sea ice state for the period up to 2005-2010 in these conditions should be based primarily on the factors of natural origin that controlled environmental development up to the present. The forecasts of climatic and ice conditions in the Arctic for the near future developed on this basis indicate a slight deterioration of these conditions, as compared with their current state (Climatic regime, 1991).

- For feasibility studies of perspective shipping along the NSR the main indications of ice conditions can be statistical characteristics, distribution of probabilities and other regime information obtained from retrospective data.

- For provision of safe and effective shipping in the Arctic a tendency for constructing powerful icebreakers and ships of the Arctic class is quite justified; in particular, if there is a need for a regular all-year-round navigation the flagman icebreaker with a power of about 150000 hp will be required (Busuyev, 1980).

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PART II

ACCURATE POSITIONING IN THE ARCTIC

International Northern Sea Route Programme (INSROP)

Central Marine Research & Design Institute, Russia
The Fridtjof Nansen Institute, Norway
Ship & Ocean Foundation, Japan

NATURAL CONDITIONS AND ICE NAVIGATION

SUB-PROGRAMME I

Project 1.7.1

ACCURATE POSITIONING IN THE ARCTIC

PERSPECTIVE RESEARCH
1994 Working paper

A. Baskin, S. Samonenko, CNIIMF

ST.PETERBURG

1995

1.7.1. POSITIONING ACCURACY IN THE ARCTIC

The international requirements to navigation accuracy are regulated by IMO Resolution A.529(13), accepted by IMO Assembly in 1983. According to the Resolution, the voyages of ships can be divided into:

- harbor entrances and approaches and waters, in which the manoeuvre space is limited;
- other waters.

Accuracy requirements for the first phase depend upon local circumstances and are not standardized.

For second phase the minimum positioning accuracy is established as 4% of distance from nearest navigational danger (with probability 0.95).

A navigational danger is considered any recognized feature or charted feature or boundary that might present or encompass a hazard to the ship or prescribe a limit to navigation.

In the Arctic, where the floating aids of navigation do not have high reliability because of possible ice damages, and approaches to river entries are difficult, the high accuracy of ship positioning is an urgent necessity.

Ice navigation has its specific features, requiring increased accuracy of positioning and speed definition. A high degree of accuracy is required when deciding of such tasks of ice navigation, as:

- positioning of ice patrol and of ice cover data;
- definition of vessel position relatively to ice;
- forecasting of ice conditions;
- choosing of optimum routes of ice navigation, including routes near to coast and navigational dangers;
- continuous and exact determination of vessel speed vector at fast course changes and engine reversing while navigating in the ice;
- development of perspective systems of ice exploration.

For effective use of information on ice conditions, accuracy of ice patrol positioning should be not less than half of the accuracy of methods of ice cover survey. As far as the existing systems of air radar-tracking of ice cover provide an order of accuracy ofabout 30 m, error of navigational system of ice patrol positioning should not exceed 15 m for regions of traditional seaways.

The global positioning satellite systems (GPS) "NAVSTAR" and "GLONASS", ensuring completion of mentioned tasks, are considered as promising for use in Arctic sailing.

The advantages of GPS positioning may best be achieved together with ECDIS. Some ECDIS of Russian manufacturers suit the special needs Arctic navigation. These systems provide the realization of specific tasks of ice sailing (e.g. movement in ice convoys, displaying of combined image of chart data with radar tracks and ice cover borders etc.).

THE DIFFERENTIAL MODE OF GPS

The increase of GPS accuracy is reached by use of differential operating mode (DGPS).

The differential mode of GPS NAVSTAR is based on knowledge of exact geographical position of reference station (RS), coordinates of which are used for calculation of corrections to measured pseudo-distances from all satellites in radio visibility range of RS.

The corrections, as differences of calculated and measured pseudo-distance values, are transmitted to consumer in RS operative range. The measured pseudo-ranges are exacted in satnav receiver by corrections, with subsequent computing of coordinates of user position. The advantage of this method is the independence from RS while choosing the optimum satellite constellation in receiver due to availability of corrections for any satellite, located in RS radio visibility range.

The use of DGPS, as part of general complex of navigational hydrographic support to safety of navigation on the NSR, allows to supply precision positioning at:

- river entries;
- pilotage;
- hydrographic survey;

- geodetic work;
- geological exploration on the shelf and in high sea;
- air ice patrol and at landings of planes on non-equipped stripes;
- scientific marine researches (hydrological, gravimetrical, etc.);

It is possible to suggest the following provisional division on zone of use of differential mode in dependence on radius of action and soluble tasks:

- Zone I, radius to 100 km, with positioning accuracy order 5-10 m (with probability P=95%). In this zone DGPS can be used as a means of ship position check in operative range of vessel traffic control systems (VTS), on approaches to ports and in narrowness, at pilotage, hydrographic and dredging works, navigation on rivers.

- Zone II, radius to 300 km and positioning accuracy about 10 m. In this zone DGPS can be used for increase of safety of navigation in coastal waters and in regions of high danger to navigation for reduction of probability of divergence from recommended ways and infringement of borders of prohibited regions and regions with specific mode of navigation.

- Zone III, radius to 1000 km and positioning accuracy 10 - 15 ¼ (P=95%). In this zone DGPS can be used for general navigation tasks, shelf exploitation and rescue operations.

The structure of DGPS RS equipment is regulated by RTCM special committee Standard. This Standard determines the performances, parameters of interfaces and environments conditions of reference and monitoring stations work.

RS includes the multichannel receiver of signals. RS is designed for definition of corrections to pseudo-distances from satellite, whose angle of elevation doesn't exceed the established limit of 7.5°. The values of corrections can be broadcasted to consumers through transmitters of marine radio beacons. The integrated monitoring station, as a part of DGPS subsystem, is intended for quality surveillance of RS signals. The monitoring station is usually established at small distance from RS and permits to execute the check of its work. When the correction value exceeds the established limit, the warning signal, broadcasting to RS, is formed. The joint work of reference and monitoring stations allowed to exclude errors, defined by multi-beam reception and by failures in satellite work between the consecutive almanac updating.

THE DIFFERENTIAL MODE ACCURACY

The positioning accuracy depends, mainly, on accuracy of navigational parameters measurement (pseudo-distances from satellites) and configuration of satellite constellation. The positioning accuracy valuation is produced in view of geometrical factor (HDOP). In practice of accuracy valuation and pursuant to requirements of IEC Standard 1108 on GPS receiver performances, norms and methods of tests, the acceptable value of HDOP is considered as 1 - 4. In differential mode it is important to the consider the errors of various elements of the system.

Factors influencing the DGPS accuracy:

- Noise of receiver and interchannel calibration.

  The error of measurement of navigating parameter, caused by noise of receiver has the character of white noise and depends on the duration of transmitted code elements, width of passbands of contours of tracking and signal/noise ratio. The use of multichannel receivers with effective methods of interchannel calibration, ensures the accuracy of measurements 2 - 2,5 higher in comparison with consecutive or multiplex ones and permits to achieve error level about 0,15 m - minimum possible hardware error.

  The signal/noise ratio in the point of signal reception is within the limit of 32 - 40 dB, which is caused by satellite transmitters parameters difference and different degree of signal disturbances on particular lines of satellite/vessel signal distribution.

- Multi-beam distribution.

  The errors caused by multi-beam distribution of signals depend on the quality of antenna, efficiency of considering the influence of antenna installation location. On RS, the antenna installation place should be free from structures, overshadowing satellites within the limits of elevation angles 8-10°. The influence of reflections from local objects should be reduced with the help of special screens. The suppression of signals of return polarization in top hemisphere should make about 20 dB. On vessels, this suppression is 3-5 times less. The completion of optimum antenna placing conditions on RS permits to reduce the multi-beam distribution error tc 0.2 m.

- Refraction error.
One of the sources of DGPS errors is the non-uniformity of atmosphere radio waves' distribution in the troposphere and ionosphere. Thus, the ionospheric and tropospheric refraction can be distinguished.

Residual ionospheric error depends on many factors, including:

- distance between RS and consumer;
- conditions of radio waves' distribution on line RS - consumer (underlying surface character, weather conditions, time of day etc.);
- used methods of differential corrections manufacture; - solar activity, daily variations and seasonal flares on sun.

Ionospheric refraction error depends on the radiosignals' frequencies. Therefore, method of reception on two frequencies with subsequent joint processing allows to calculate and to exclude the error of measurements. For one-frequency receivers errors can be adjusted by the method of simulation.

The influence of the troposphere is connected with local conditions and their change in atmospheric layer from the place of installation of receiver antenna to the height of 70 km. The tropospheric effect causes distortion of the way of radio waves' distribution and reduction of their speed. The tropospheric refraction factor depends on the atmospheric pressure, temperature, humidity and changes considerably with height. The tropospheric irregular error of differential measurements reaches 0.4 m for small satellite elevation angles and distance from RS not exceeding 500 km.

DGPS positioning error for distances of 300 km and less does not exceed 10 m, and for distances to 1000 km - 15 m. These figures reflect the potential accuracy of DGPS NAVSTAR.

DIFFERENTIAL MODE TRIALS IN THE ARCTIC.

The testing of GPS NAVSTAR differential subsystem in the Arctic were carried out by experts of Hydrographic Department of DMT in September - October, 1994.

The purposes of testing were the validation of DGPS accuracy on the different distances from RS, checking of shore and ship DGPS equipment reliability and definition of zones of reliable receiving of corrections.

RS of differential subsystem was mounted on the base of radio beacon "ALMAZ" on the Bolshoy Medvezhy Island. RS broadcasted differential corrections on 300 kHz frequency. As reference station equipment the complete set 4000 DGPS/MSK by TRIMBLE NAVIGATION was used.

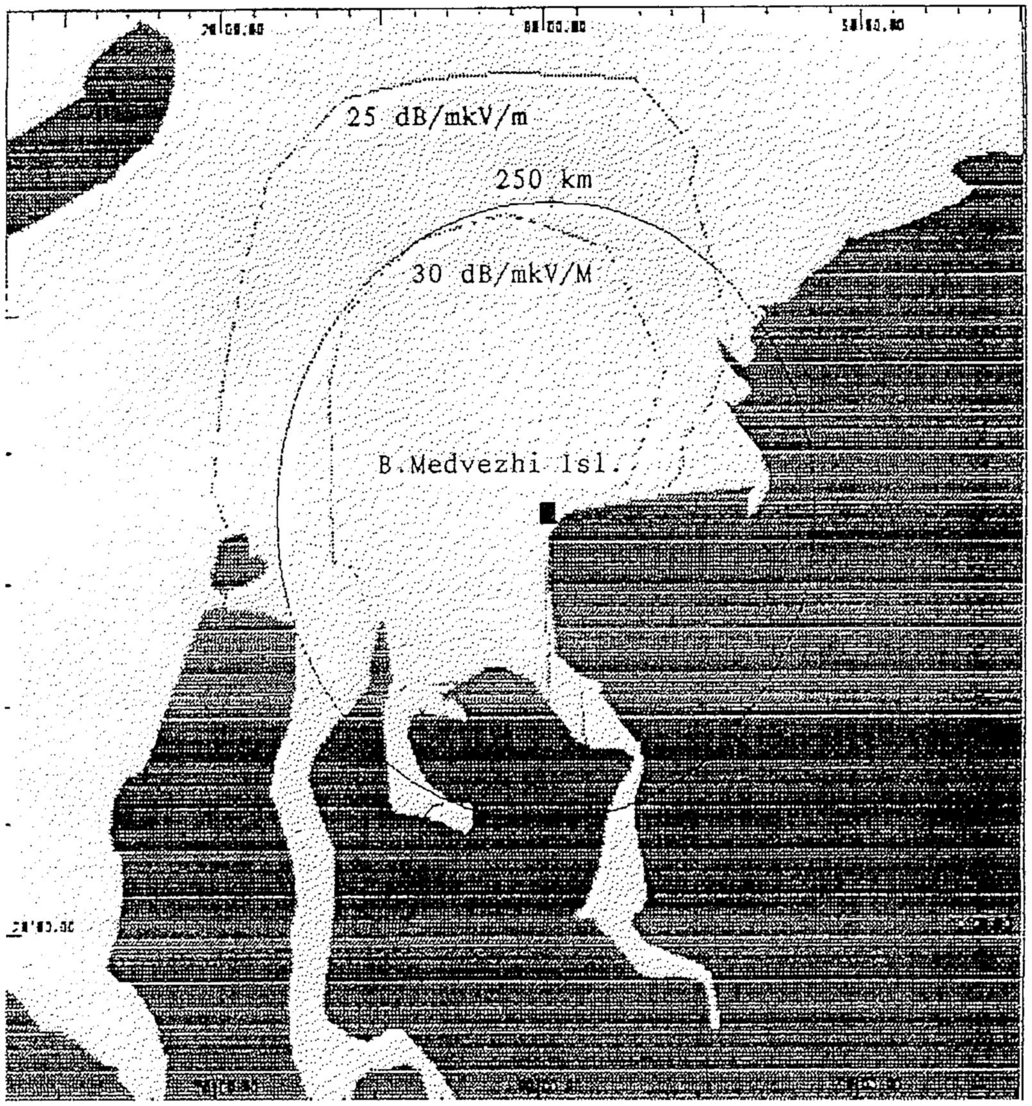


Fig.1 shows the calculated values of corrections signals field intensity of RS. Effective isotropic emitted power makes 2 Wt.

The RS antenna positioning in WGS-84 coordinate system was executed 6.09.94. The coordinates obtained by the 4000 DGPS/MSK receiver and NavTrac receiver, whose antennas were concurrent, were simultaneously recorded. After processing of 1643 records with HDOP<1.5, the following RS antenna mean position was obtained:

Latitude - 73° 31.04217'N   Longitude - 80° 09.83567'E

These coordinates were entered in RS 4000 DGPS/MSK receiver as basic ones.

Irregular measurements error is reflected by its average square value, as well as by latitude and longitude components, which have made respectively 1.483 m, 1.285 m and 1.962 m.

The RS and receivers accuracy characteristics valuation was made by the positioning data of stationary points recorded with the step of 1 minute. The results of data processing - mean coordinates, average square errors («1), latitudinal («2) and longitudinal («3) components, number of measurements in series - are given in the following table:

Place of measurements	Date	Mean coordinates		«1 (m)	«2 (m)	«3 (m)	Records number
		latitude	longitude				
Radio beacon on B.Medvezhy Isl.	06.09	73°31'.04217N	80°09'.83567E	1.483	1.285	1.962	1643
Landmark on B.Medvezhy Isl.	14.09	73°30'.970N	80°11'.132E	7.4	14.9	16.6	60
Pier,p. N 1	14.09	73°30'.3312N	80°30'.1990E	4.648	16.359	17.006	123
Pier,p. N 2	04.10	73°30'.34815N	80°30'.20664E	1.983	1.355	2.402	90

The marine measurements were made on board the hydrographic vessel *N.Kolomeytzev* from 15 September to 4 October, 1994 in the Gulf of Yenisey. On various distances from RS the value of signal level (S), the signal/noise (S/N) ratio and age of correction were fixed.

The maximum distance from basic station was 257 km. In dependence on daytime and distances from RS, the significance of signal level, signal/noise ratio and age of corrections were:

Value	S, dB/mkV/m	S/N, dB	Age, seconds
Maximal	48	25	44
Minimal	9	6	4

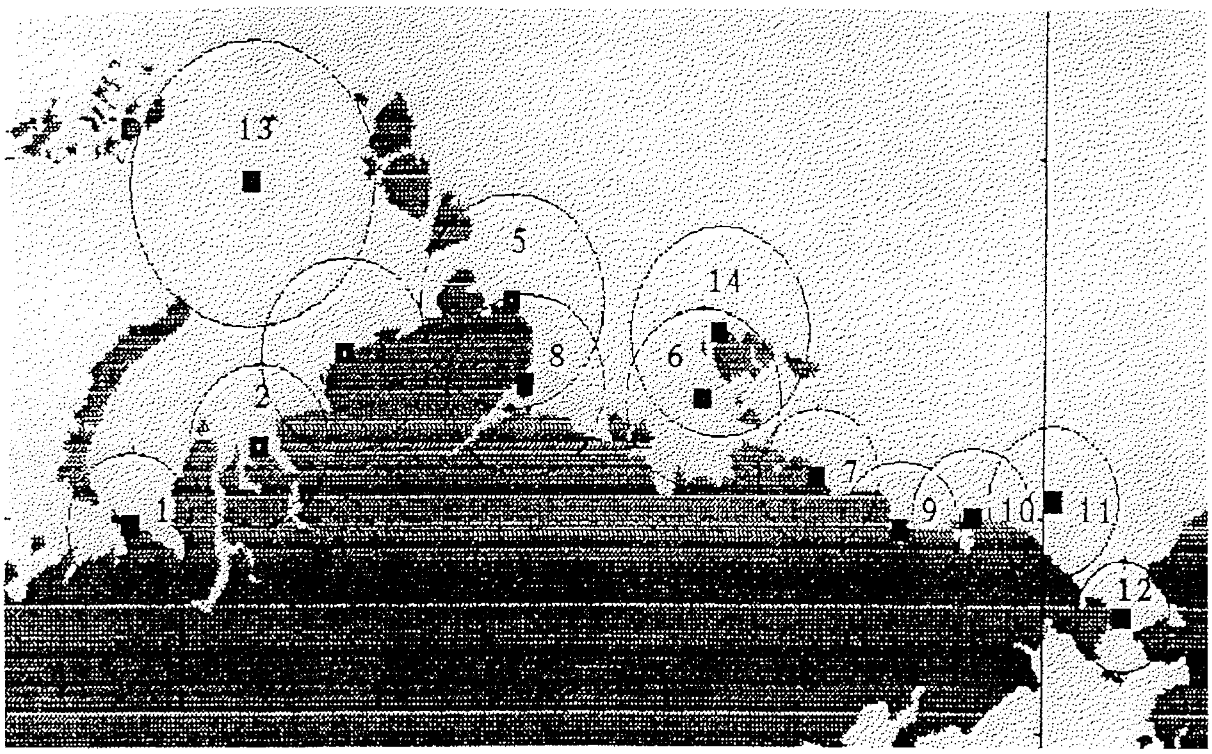
The measurements showed, that in evening and over-night periods, on distances from RS 200 km, the level of noise increases and becomes comparable with the signal level. 80 Wt power radio beacon can ensure the S/N ratio of order 15-20 dB on distances to 300 km. The tests have shown that steady corrections reception by NavBeaconXL receiver is provided at S/N = 5-7 dB. At the time of noise level increase and, hence, reduction of S/N ratio, the corrections reception ceased, or the age increased.

Tests revealed some RS instruments and receiver failures. So, 6.09.94 receiver 4000 DGPS/MSK failed. On 17 September, the receiver NavBeacon XL failure was fixed. This receiver was replaced by 4000 DGPS/IM monitoring station receiver. During a severe storm on 6 October, the radio beacon antenna was damaged and tests were terminated. This circumstance has prevented the carrying out of the valuations of DGPS working zones, as far as the terms of execution of tests were finished. The continuation of tests is scheduled for 1995.

The results of DGPS tests in the Arctic permit to generalize, that for increase of corrections reception reliability in Arctic conditions, the power of radio beacon transmitter should be increased, thereby permitting compensation of the sharp changes of reception conditions on distances from basic station to 250 km.

THE PLANS OF DGPS DEVELOPMENT IN THE ARCTIC.

Russia plans the creation of DGPS NAVSTAR/GLONASS RS network in the Arctic region. The RS installation on the base of acting radio beacons with use of present infrastructure, will allow to lower the expanses and to shorten the terms of input into operation.



The planned RS installation locations in the Arctic, agreed with the Hydrographic Department are shown on Fig.2.

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Dear Ms Dragland

I am pleased to offer the following commentary about INSROP Discussion Paper, Sub-Programme I, Project I.7.1 by V.F.Zakharov et al.

My comments do not pertain to the section on "Accurate Positioning in the Arctic", because this lies outside my area of expertise. It is my understanding, however, that the Global Positioning System -GPS- has solved virtually all problems of earth location normally encountered in navigation, with the exception of extreme accuracy required in salvage and similar sea-floor operations.

The essay on Climate and Shipping Conditions by Zakharov and co-workers is an interesting and useful summary of the vast amount of information assemble over many decades. The Tables and Figures are well chosen and informative. Assuming that this essay is written primarily for the practitioners and planners of shipping along the NSR, I find it particularly useful that the essay is not burdened with explanations and scientific conjectures but that it represents the facts as they were recorded. The comments concerning the absence of significant manifestations of human activities (anthropogenic greenhouse warming) in the polar climate and ice conditions are noteworthy, and they coincide with the findings of other researchers.

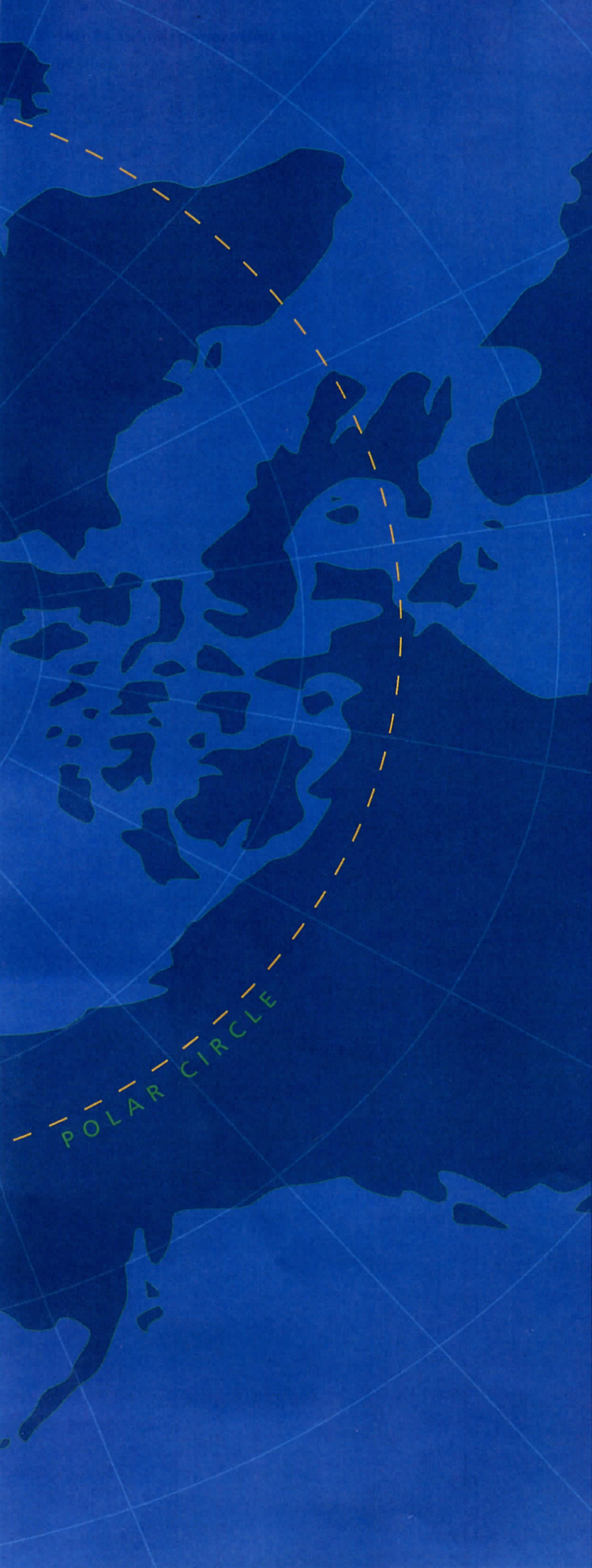
I suggest that this paper not only needs but also **warrants** a significant effort of editorial improvement. The choice of words is frequently unusual and sometimes confusing. Figure captions and Table headings are generally too sparse and should be expanded, even if this means the repetition of certain items mentioned in the text. For instance, many tables and plots do not indicate over what period of time the observations were taken. Fig.2.1.a has no caption, and the text does not explain to which geographical region the plotted curve applies. The signatures in Figs 2.10 and 2.11 are not explained. The signatures in Figs. 2.12 -0 2.15 are not legible. In some cases, the units plotted require more explanation (e.g. Fig.3.4).

But on the whole, the salient points of the record are clearly summarized and useful recommendations are made. After a thorough editorial "clean-up" this paper will, in the opinion of this reviewer, be a valuable assessment of the ice conditions along the NSR.

Yours sincerely,

N. Untersteiner

Norbert Untersteiner
Professor and Chairman



The three main cooperating institutions of INSROP

Ship & Ocean Foundation (SOF), Tokyo, Japan.
SOF was established in 1975 as a non-profit organization to advance modernization and rationalization of Japan's shipbuilding and related industries, and to give assistance to non-profit organizations associated with these industries. SOF is provided with operation funds by the Sasakawa Foundation, the world's largest foundation operated with revenue from motorboat racing. An integral part of SOF, the Tsukuba Institute, carries out experimental research into ocean environment protection and ocean development.

Central Marine Research & Design Institute (CNIIMF), St. Petersburg, Russia.
CNIIMF was founded in 1929. The institute's research focus is applied and technological with four main goals: the improvment of merchant fleet efficiency; shipping safety; technical development of the merchant fleet; and design support for future fleet development. CNIIMF was a Russian state institution up to 1993, when it was converted into a stock-holding company.

The Fridtjof Nansen Institute (FNI), Lysaker, Norway.
FNI was founded in 1958 and is based at Polhøgda, the home of Fridtjof Nansen, famous Norwegian polar explorer, scientist, humanist and statesman. The institute spesializes in applied social science research, with special focus on international resource and environmental management. In addition to INSROP, the research is organized in six integrated programmes. Typical of FNI research is a multi-disciplinary approach, entailing extensive cooperation with other research institutions both at home and abroad. The INSROP Secretariat is located at FNI.