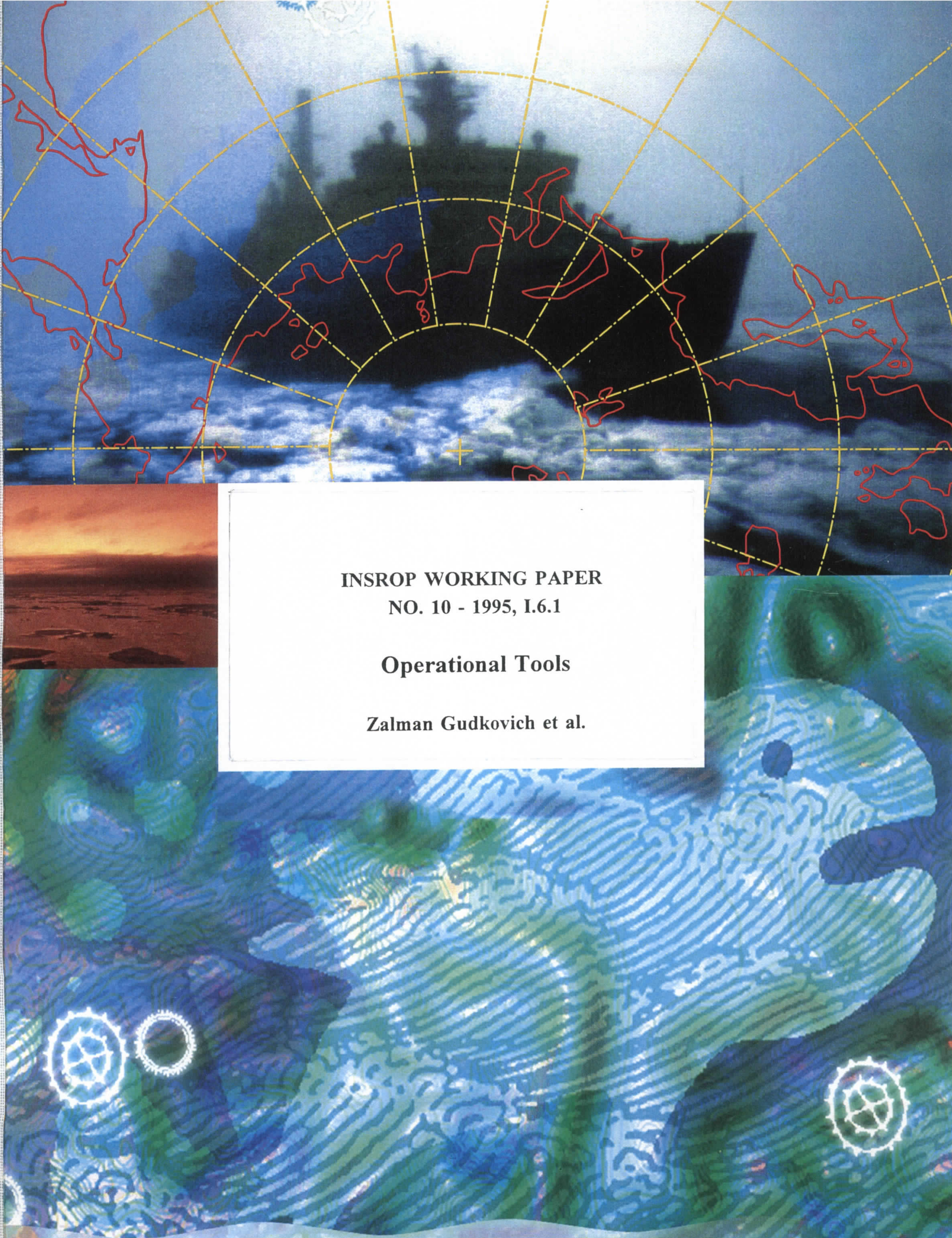

# INSROP WORKING PAPER
## NO. 10 - 1995, I.6.1

# Operational Tools

Zalman Gudkovich et al.

**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

Ship & Ocean Foundation, Japan

# INSROP WORKING PAPER NO. 10-1995

Sub-programme I: Natural Conditions and Ice Navigation

Project I.6.1: Operational Tools

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## *What is an INSROP Working Paper and how to handle it:*

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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# SUMMARY

Methods of meteorological, oceanographic and ice forecasts (of a general purpose and specialized) with different periods in advance, which are used for the scientific-operational support to navigation along the Northern Sea Route, are reviewed. Physical and statistical grounds of different methods are considered, the hydrological information they use is given, the presentation forms of the prognostic data are described, the questions of assessing the quality of the forecasting methods are covered. Main directions of further development and improvement of the methods, technologies for the preparation of forecasts and forms of their presentation to the users are formulated.

KEY WORDS: methods of meteorological, oceanographic, ice (of a general purpose and specialized) forecasts, periods in advance, scientific-operational support to navigation, grounds of methods, hydrological information, assessment of the quality of methods.

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# 1 INTRODUCTION

The Project aims to develop a comprehensive system for the meteorological, oceanographic and ice forecasts on the basis of the existing and improved methods to address the objectives of planning and operational management of transit shipping along the Northern Sea Route (NSR)

The objectives of the first stage, to which the present Report is devoted, include a review of the existing methods of meteorological, oceanographic and ice forecasts for different periods, used for the support of navigation along the NSR, as well as a description of the initial information, used in the forecasts and the forms of the prognostic information presentation to the users.

The 1991 Report covered in sufficient detail the hydrometeorological conditions of the transit navigation along the NSR and briefly characterized the current system of the scientific-operational support to shipping in this region. The present Report develops further the main statements of the previous Report.

The system of the scientific-operational support to shipping, which is considered below, allows for a sufficiently effective planning of the cargo flows, distribution of the transportation means and the icebreakers at the preliminary planning stage gradually making the information more detailed with the approach of the commencement dates of the operations.

Thus, the forecasts from 3 to 6 months in advance allow for a general estimation of the expected background of ice conditions (ice cover extent, area of close ice and its distribution type) on the main route segments. With the period up to 1 month in advance the forecast of ice distribution with a 10-day interval is given during the entire navigation period. On the basis of these forecasts the recommendations for the dates of the beginning and end of the transit navigation along the NSR are worked out and the regions with the most heavy ice conditions are identified.

Finally, the regular forecasts of the expected meteorological, oceanographic and ice conditions from 1 to 10 days in advance, reported to the icebreakers and the ships, help the navigators to select an optimal navigation variant on different segments of the route during a specific voyage.

The information, which the present Report contains, will enable one at the second stage of the Project to choose the most effective methods to achieve a necessary quality standard of the forecasts and improve them, thus allowing for the development of a common concept of the improved system of providing various forecasts for the transit navigation along the NSR.

# 2 METEOROLOGICAL FORECASTS

Navigation on the Northern Sea Route (NSR) requires a complex hydrometeorological support. Its constituent part is meteorological forecasts divided into short range (up to 3 days), medium range (up to 8-10 days) and long range (from 1 to 12 months in advance). According to the system of hydrometeorological support acting currently at NSR the task of compiling shortrange weather forecasts is the responsibility of Administrations of Arctic Hydrometeorological Services. Medium and long range meteorological forecasts are being developed at AARI from where they are sent to interested users.

Contrary to the short range forecasts, the medium and, especially, long range ones yield information about the expected fields of atmospheric pressure and air temperature averaged over different time intervals, as well as about the probability of predominating air transfers, wind directions in polar regions around stations and their average velocities. Forecasted are also the dates of stable transition of air temperature through 0°C in spring and autumn.

These forecasts allow one not only to gain an impression of the general pattern of meteorological conditions in NSR seas but also to use the available information for oceanological and ice forecasts.

Meteorological forecasting is carried out by the macro circulation method whose main principles and their realization have been made by the research staff of the Department for Long Range Meteorological Forecast at AARI.

A separate section cites the principles of quite different methodology elaborated at AARI for meteorological forecasting for 10 to 35 days. The method is based on analyzing long term series of daily geopotential and surface pressure fields presented as the expansion factors into spherical functions and subsequent field reconstructions as superposition of harmonics of certain frequencies. To agree altitudinal and surface fields, the hydrodynamic model of the atmosphere is applied.

The given method is now being tested. The above results of testing experimental forecasts during one year indicate the method to be promising for operational practice and, possibly, for forecasting climate change.

## 2.1 The principles of the macrocirculation method

One of the most difficult problems of macrometeorology of great scientific and practical importance is developing and implementing the methods of meteorological forecasting for various periods in advance.

Difficulties in solving this problem are primarily caused by an extremely large volume of factors influencing the formation and change of weather and climate, the changing role of these factors with time, and an insufficient amount of observational data, especially over oceanic regions.

In the history of macrometeorological studies, many attempts were made to build the methods for long-range forecasting with large and small lead time for different regions. They are mainly based on taking into account various relationships established statistically as well as on considering such properties of atmospheric processes as periodicity, rhythm and inertia. It was frequently so that those attempts were also based on considering a number of external factors (solar activities, tidal forces of the Moon and the Sun, etc.).

The diversity of approaches to solving the problem of long-range forecasts provided a large number of forecasting methods based on different principles and taking into account (not always principal) features of atmospheric processes in individual regions of the Northern Hemisphere. It is natural that the verification score was not high for the forecasts developed by using the above methods.

It was necessary to formulate the main principles and major ways to solve the problem that could appear to be a uniting one for different approaches. They were formulated in the beginning of the 1930s. Most of them expressed that the processes observed in the limited regions of the hemisphere had to be studied and forecasted taking into account the totality of processes, at least, on the Northern Hemisphere assuming them to be mutually related and mutually caused.

As this idea became more and more widely recognized, studying general atmospheric circulation expanded not only in terms of its mean long-term characteristics (normals) but also with the aim of discovering the features of its transformation from one state into another, i.e., features being of prognostication value.

The most extensive studies in this aspect have been carried out by G.Ya.Wangengeim who proposed a number of modern ideas and in the 1940s he created the basis for macrocirculation method for long-term meteorological forecasting that was further developed and used in practice at AARI.

In the modern shape, the principles of this method are formulated as follows (Girs A.A., 1974).

A. The processes in a limited region are to be considered as the manifestation of atmospheric general circulation under certain physiographic conditions of this region. The necessity comes from this for studying and forecasting Arctic processes taking into account all processes of the Northern Hemisphere.

B. To take into account the circulation background of the hemisphere, when analyzing processes and developing forecasts over the Arctic, in addition to average long-term characteristics (normals), it is necessary to consider features of its certain forms manifesting themselves on daily altitudinal and ground maps of the Northern Hemisphere. As these forms, it is appropriate to adopt forms W, C and E determined by Prof. G.Ya. Wangengeim (Wangengeim, 1946, 1952) for the Atlantic-Eurasian sector of the hemisphere and circulation types Z, $M_1$ and $M_2$ established by Prof. A.A Girs (1948) for its Pacific-American sector. Combination of forms and types yield nine varieties of macroscale circulation: $W_z$, $W_{m1}$, $W_{m2}$, $C_z$, $C_{m1}$, $C_{m2}$, $E_z$, $E_{m1}$, $E_{m2}$. Revealing these varieties is based on taking into account the most important features of zonal and meridional atmospheric circulation and the state of the hydrosphere: the character of long thermal baric waves observed in the troposphere and lower stratosphere, the distribution of pressure and air temperature anomalies, precipitation at the Earth's surface, the level and surface temperature in seas and oceans, etc. In this connection the indicated forms and types of circulation are the complex conceptions for building on their basis the method for long-term meteorological forecasting.

C. In developing atmospheric processes, a number of redistribution stages or periods for air masses of certain directions could be revealed. There are the stages of different duration: the elementary synoptic process (ESP) of 3-4 days in duration, periods of homogeneous circulation (PHC) of 8-12 days in duration, intrayear stages of 1 to 5 months, the epochstages of 2 to 6 years and the circulation epochs of 10 to 30 years. All of them are stages in the process of developing atmospheric circulation and, therefore, they are closely interrelated and mutually caused.

D. The processes in a forecasted time interval are naturally coming from the development of processes observed in the previous (initial) period. Therefore, taking into account the continuity of developing atmospheric processes, it is necessary to build the forecast relationships in the shape of groups of uninterrupted chains of developing homogeneous processes with different duration.

E. As far as at present the role of acting factors and especially their changes with time have been determined but insufficiently, in the forecasting work, it is therefore appropriate to use analogues. However, these should be selected by genetic indications reflecting features of developing process rather than by external indications of similarity. Thus, the selected analogues are usually called homologues.

F. When developing forecasts of any lead time, it is necessary to take into account climatic features of the forecasted region in more detail.

Being guided by the above principles, the staff of AARI Department for Extended Meteorological Forecasts have accomplished a number of studies and found certain features to be of prognostication value. They, primarily, touch features of the development and transformation of atmospheric circulation forms at different stages and in transition from one natural stage to another; features of developing macroprocesses in seasonal groups for the initial and forecasted year, some relationships between atmospheric processes and cosmic-geographical factors.

The order and the ways of using the above and other features in developing long-term meteorological forecasts of large and small lead time have been cited in more detail in a number of monographic reviews and collections of scientific proceedings (A.A.Girs, 1948, 1974, 1978; G.Ya.Wangengeim, 1946, 1952; N.D.Vinogradov, 1977, 1991; L.A.Dydina, 1954,1982; A.A.Dmitriev et al., 1989).

They are reduced to comparing the features and characteristics of current macroprocess with revealed groups of processes with long homogeneous development, which allows choosing "acting" groups in which circulation and weather characteristics are the main indicators for determining the best homologues.

In polar and subpolar regions, the macrocirculation method is the basic one when providing long-term meteorological forecasts. As for the duration of forecasted period and the set of forecasted variables, it has no alternative either in Russia or abroad.

### 2.1.1 The method for long range background meteorological forecasts and its specification by months and PHC

Developing the macrocirculation method and compiling certain forecasts require a specially formed complex of meteorological information reflecting the state and change of atmospheric processes in the extratropical zone of the Northern Hemisphere. Day-to-day collection, processing, diagnosis and archiving of this material are the necessary precondition for operating forecast service and implementing research including the preparation of different regime-reference guides. In AARI, during many years an archive of initial meteorological information has been kept. See Table 1 for contents.

The process of compiling, specifying and improving the background meteorological forecast for the polar region of the Northern Hemisphere for January-December can be presented as the following main stages:

A. Analysis of circulation background for meteorological regime, its intrayear changes in the current circulation epoch and its stage at which the initial and forecasted years are presented.

B. Determination of circulation background, meteorological regime, the character of their intrayear changes in the next year based on the consideration of the data on circulation epoch and its stages.

C. Analysis of developing hydrometeorological processes in the initial year in the Northern Hemisphere in the Arctic.

D. Selection of homologues for initial year processes and the determination of acting background and seasonal groups.

E. Analysis of selected group of homologues and the determination of variants of their combinations in each forecasted month.

F. Choice of the most probable variant of homologue combination for each month in the forecasted period.

G. Construction of anomaly diagram for circulation form recurrence and prognostication maps of the anomaly distribution for meteorological elements for each month in the forecasted period.

H. Improving forecasts for mean monthly characteristics over homogeneous circulation periods.

I. Compilation of prognostication maps and diagrams describing the background of the entire 12-month period.

J. Composing text and making background forecast for January-December for the polar region in the Northern Hemisphere.

K. Running improvements and specifying background forecast for the next 1-3 months by the dates outlined by the provision plan.

It should be mentioned that the realization of each of the above stages requires carrying out the entire complex of studies, which calls for the availability of skilled specialists in the area of macrometeorology.

The prognostication information is accessible for users in the shape of albums of diagrams and maps. As an example in Figs.1-5, there are the fragments of background meteorological forecast for December 1993.

Specifying background forecasts on the planned dates established by provision practice (5 March, 5 June, 5 August and 5 September). They touch all the elements of this forecast. In addition, along with the specification the forecast is being developed for improving intramonthly evolution for PHC for the next 1-3 months. In specification for March and August, the forecast is being composed for the dates of stable transition of air temperature through 0°C in the spring and autumn periods, respectively. The necessary condition for implementing any method of long-term forecasting into the provision practice is estimating its confidence and efficiency. All the aspects of this estimation are quite fully presented in the "Manual on formulation and estimation of verification score of long-term weather forecasts of large and small lead time for the Arctic" (Guide-book, 1961).

Table 1. Initial information used in forecasts

| List of material | Observ. period | Dates of observations or averaging period | Number of stations |
|---|---|---|---|
| **I. On magnetic media** | | | |
| Daily surface pressure | from 1935 | standard dates | 286 |
| Daily values of geopotential of surface 500 HPa | from 1949 | standard dates | 223 |
| Surface pressure for ESP* | from 1948 | ESP | 146 |
| Geopotential of surface 500 HPa for ESP | from 1949 | ESP | 159 |
| Mean monthly surface pressure | from 1900 | mean monthly | 233 |
| Mean monthly air temperature | from 1881 | mean monthly | 233 |
| Meridional and latitudinal gradients of mean monthly pressure over 8 climatically significant regions of the Arctic temperate zone | from 1990 | mean monthly | 8 |
| Mean monthly frequency of 16 different wind directions (bearing) at polar stations | from 1932 | mean monthly | 22 |
| **II. On maps (atlases)** | | | |
| Day-to-day cyclonic and anticyclonic trajectories for ESP | from 1940 | ESP | Arctic, temper. zone |
| Surface pressure for ESP | from 1940 | ESP | 146 |
| Values of geopotential of surface 500HPa over ESP | from 1949 | ESP | 159 |
| Mean 10-day maps of surface pressure | from 1945 | decade | 286 |
| 10-day mean air temperature and its anomalies | from 1945 | decade | 286 |
| Surface pressure over intramonthly periods (PHC)** | from 1937 | PHC | 286 |
| Values of geopotential H-500 for PHC | from 1949 | PHC | 159 |
| Mean monthly surface pressure and its anomalies | from 1881 | month | 286 |
| Mean monthly air temperature and its anomalies | from 1881 | month | 286 |

| List of material | Observ. period | Dates of observations or averaging period | Number of stations |
|---|---|---|---|
| Mean monthly values of H-500 and its anomalies | from 1949 | month | 159 |
| **III. Graphics** | | | |
| Annual variations of mean monthly values of forms (G.Ya. Vangengeim) and types (A. A. Girs) of atmospheric circulation | from 1891 | | |
| Integral curves of annual and long-term variations in daily air pressure anomalies for 11 representative stations in the Arctic and 10 regions of temperate zone of the Northern Hemisphere | from 1916 | | |
| **IV. Hydrometeorological bulletins** | | | |
| Daily data on air temperature and wind at Arctic stations at major terms of observations | from 1949 | | |
| Mean 10-day pressure, air temperature, wind and ice cover in the Arctic | from 1935 | | |
| Mean monthly pressure, air temperature, wind and ice cover in the Arctic | from 1935 | | |
| **V. Catalogues of macrosynoptic atmospheric processes** | | | |
| Catalogue of macrosynoptic processes by classification of G.Ya. Vangengeim (E, W, C) for the Atlantic-Eurasian sector of the Northern Hemisphere since 1891 (a version on magnetic disk is available) | | | |
| Catalogue of macrosynoptic processes by classification of A. A. Girs (Z, $M_1$, $M_2$) for the Pacific-American sector of the Northern Hemisphere since 1900 | | | |
| Catalogue of types of synoptic processes in the Arctic by elementary synoptic processes since 1939 | | | |
| Catalogue of dividing macrosynoptic processes into the periods of homogeneous circulation (PHC) since 1900 | | | |
| Catalogue of stages within a year since 1900 | | | |
| Catalogue of boundaries of changing circulation epochs and stages in each epoch. Appendices: Integral indices of the character of thermobaric fields in the Arctic and in the Northern Hemisphere for these epochs and their stages (on maps and in graphs) since 1881 | | | |

*ESP - Elementary synoptic process;

**PHC - Period of homogeneous circulation

Estimating the forecast's verification score is based on direct comparison of predicted and observed weather characteristics. Therefore, prior to checking the forecast verification score, it is necessary to compile the maps of actual distribution of forecasted elements.

Checking the pressure field forecast is conducted by comparing prognosticated and actual maps for mean monthly pressure and revealing the correctness of localizing basic baric formations. The verification score of predicted localization is estimated qualitatively.

In addition, the verification score index for pressure field forecast can serve as a verification score for airflow directions and the recurrence forecast for dominating wind directions.

To check the forecast of basic airflow directions, the maps are compiled on which prognosticated and actual directions of airflows are copied.

An admissible discrepancy between prognosticated directions and the actual ones was taken as equal to ±2 bearings (±45 degrees).

To determine a forecast verification score, the number of points is counted with the discrepancy between the prognosticated and actual directions being equal to and less than ±2 bearings. The ratio between this number of points and their total number for which the forecast was given would present the forecast verification score. It is calculated over the entire Arctic and individually for each sea.

To check the wind forecast verification score along the entire route, the forecast verification score is calculated for each station and an average value is taken from all the quantities obtained. The calculation begins with determining an actual recurrence of forecasted direction (quadrant), then determining the value of error and its weight, i.e., percentage that will compose the error relative to the forecasted wind recurrence.

The mean weighted verification score of recurrence of all the forecasted quadrants is calculated by the formula:

$$X = \frac{O_1 B_1 + O_2 B_2 + O_3 B_3}{100}$$

where X - is the unknown mean weighted verification score of the forecast;

$O_1$, $O_2$, $O_3$ - are the verification scores of the first, second and third quadrants;

$B_1$, $B_2$, $B_3$ - are the weights of the first, second and third quadrants.

An estimation of forecast verification score for air temperature anomalies is made over a certain series of stations, comparatively evenly distributed along the NSR. The sign and value of temperature anomalies are estimated separately.

The errors of temperature forecasting are calculated. The number of stations is counted at which the forecasting errors are equal to or less than an admissible one. In this case a standard deviation of the mean monthly temperature anomaly with confidence of 60 % at a given station and in a month under consideration serves as an admissible error. The forecast proved to be correct and the total number of stations would be the forecast verification score for the temperature anomaly value.

The forecast of a temperature anomaly sign is considered to be proved in case the signs of forecasted and actual temperature anomalies at a given station coincide or the temperatures were forecasted and observed to be similar to mean long-term values, i.e., the temperature normal. In this case the normal means the temperature anomalies equal to and less than ±0,5°C.

Then the ratio between the number of stations with the forecast of temperature anomaly sign being proved and the total number of stations, which would present a verification score of forecasted anomaly and temperature signs over the entire Arctic.

In conclusion, it is to be indicated that over the long period of compiling a background meteorological forecast its efficiency, is on the average, 12-15% relative to climatological forecasts.

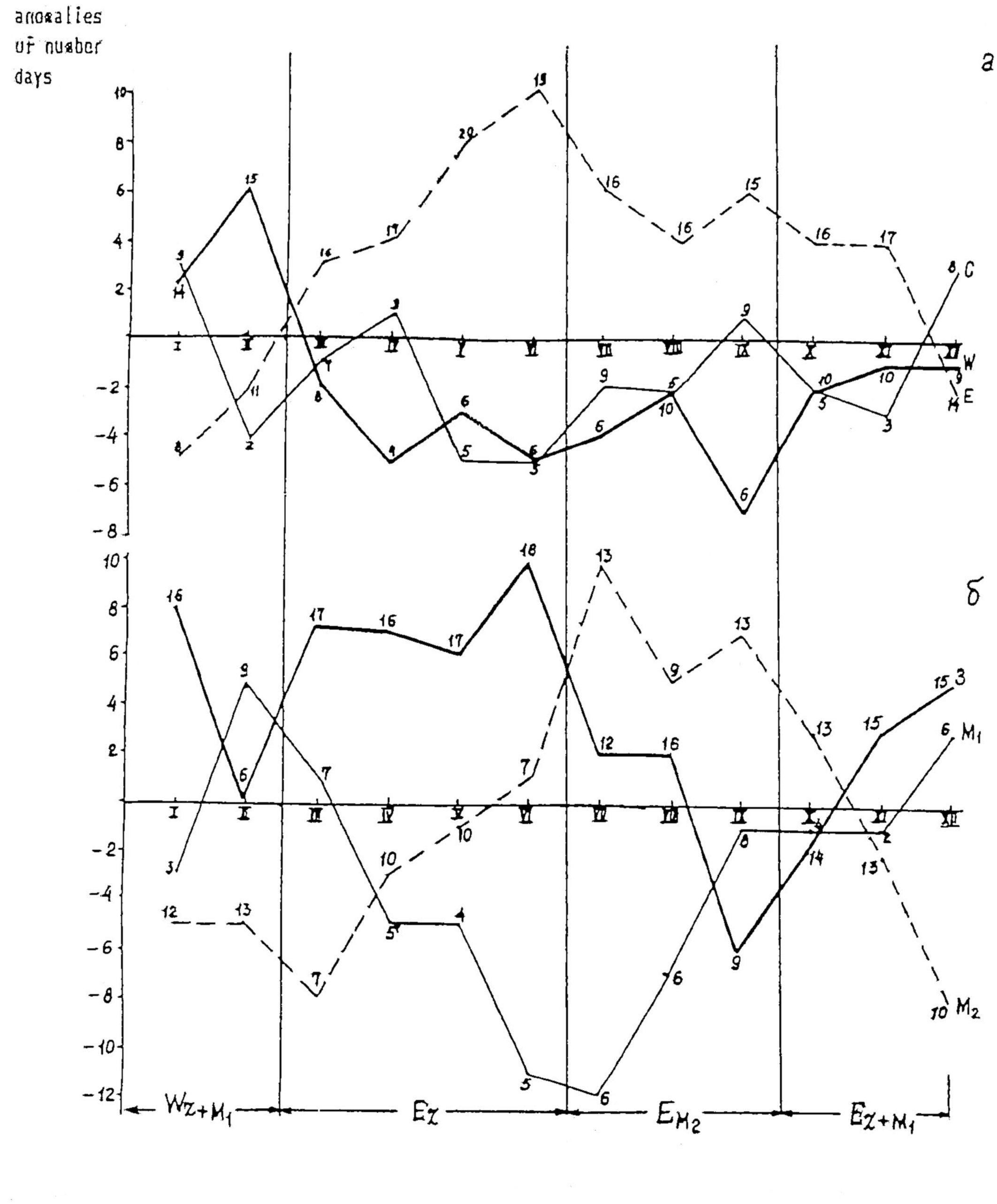


Fig. 1.Example of a forecast of the anomalies of occurrence frequencies of the main forms of atmospheric circulation W, C, E(a) and types of the processes Z, M $_1$, M$_2$ (b) for January-December 1993

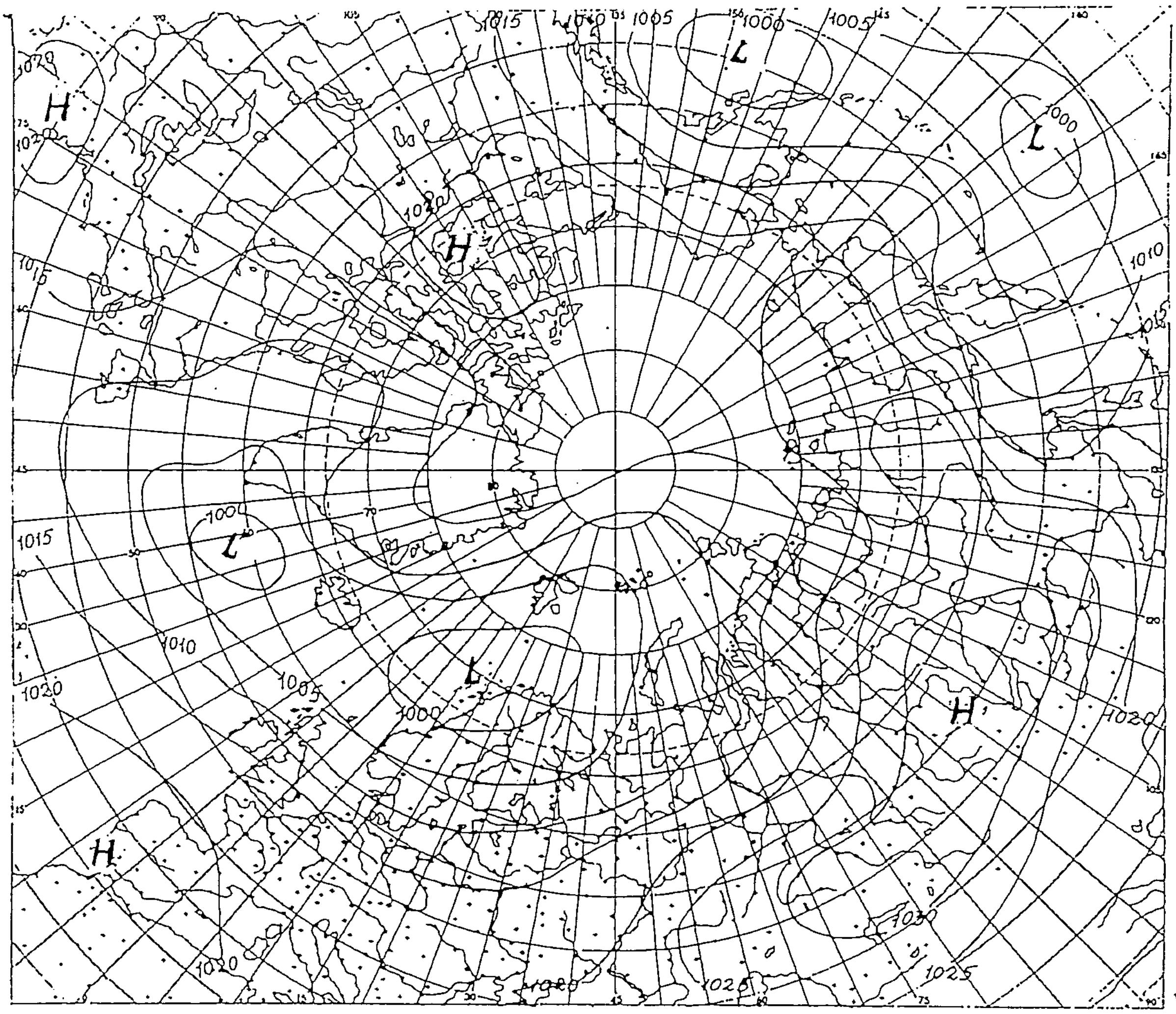


Fig. 2. Expected mean monthly air pressure distribution in December of 1993

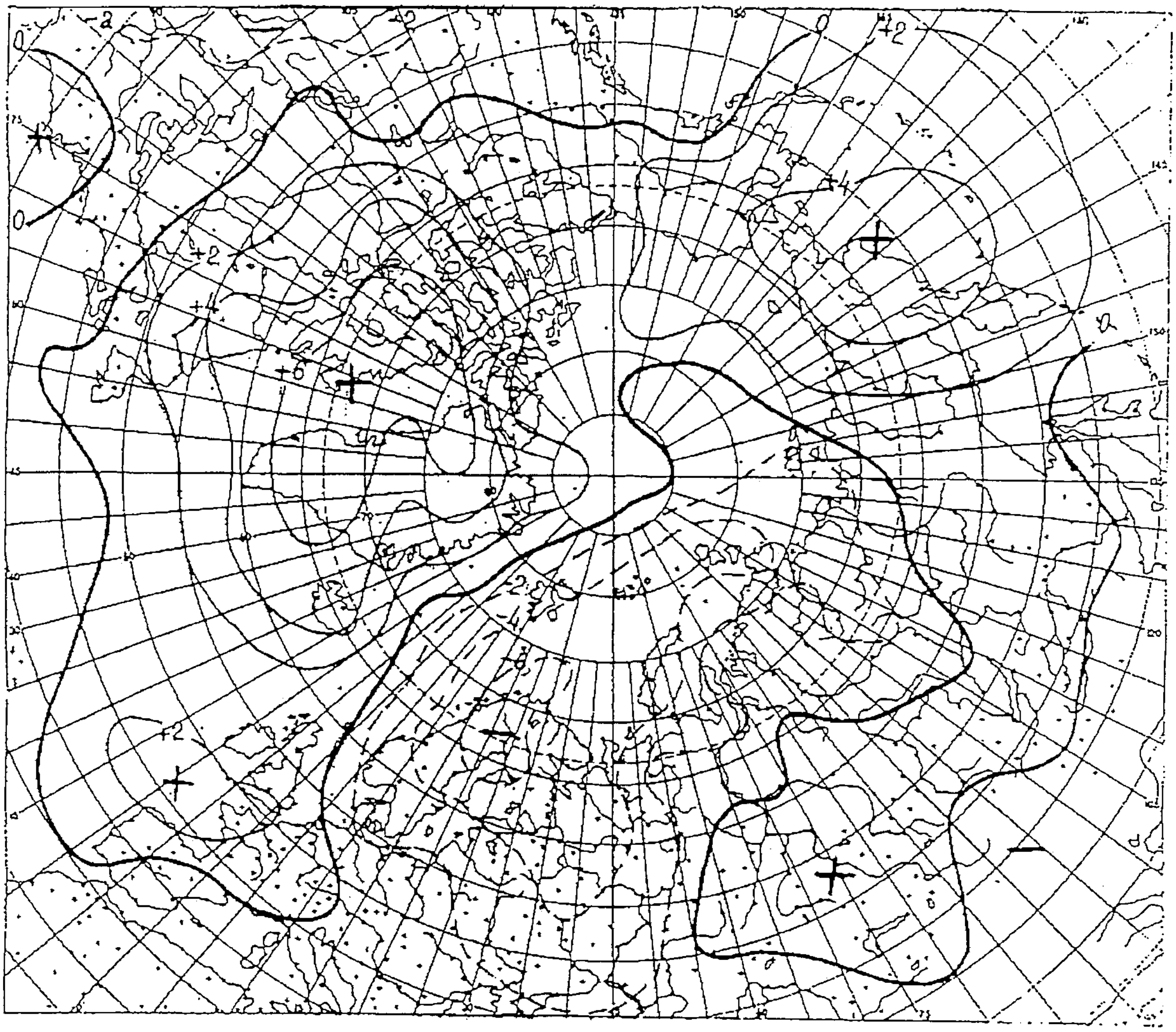


Fig.3. Expected air pressure anomalies in December of 1993

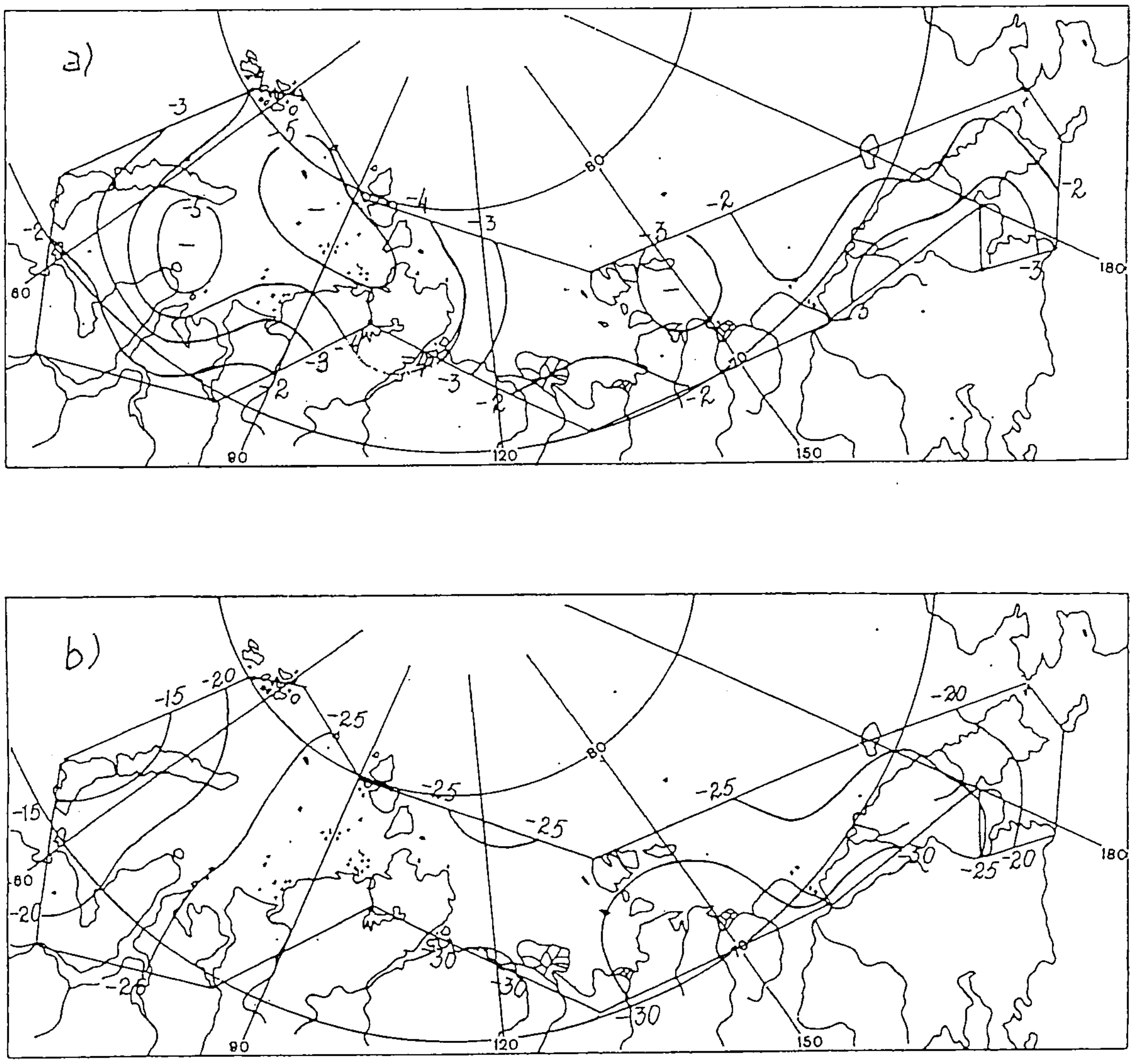


Fig. 4. Expected distribution of air temperature anomalies (relative to the norm for 1936-1965) (a) and of mean monthly air temperature (b) in December of 1993

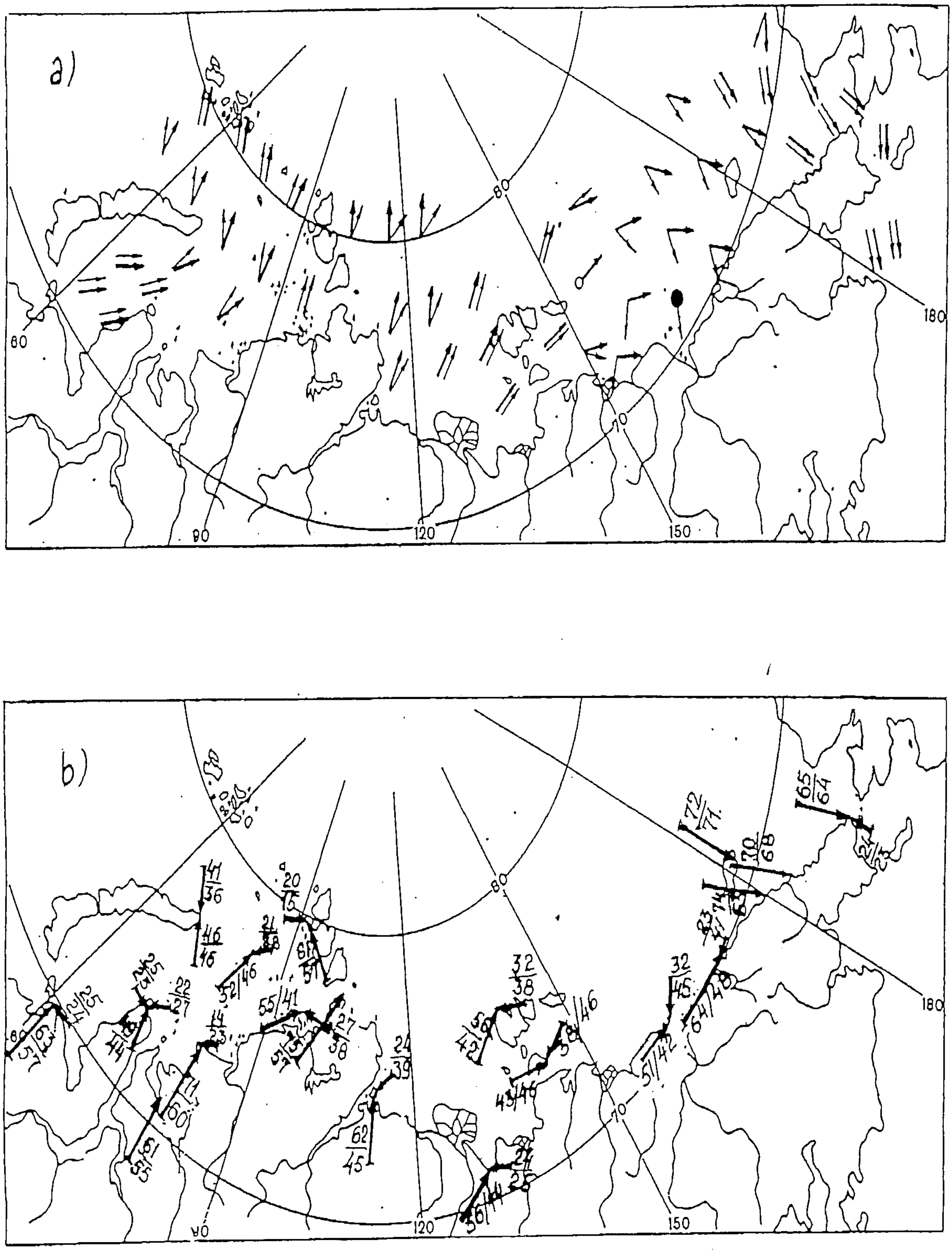


Fig. 5. a) - expected directions of air flows (forecast - thick arrows, mean multiyear - thin arrows);
b) - expected directions of prevailing winds and their occurrence frequency (%) (numerator - according to the forecast, denominator - by the norm) in December of 1993

### 2.1.2 The medium-range forecast methods

The macrocirculation method for medium-range forecasting is based on those principles that are laid down for a large-range time forecasting:

- relationships between the types of synoptic processes observed in the Arctic and the character of weather in this region;
- features of transforming elementary synoptical processes throughout 20-30-day periods (7-9 ESP) and their links with macro-transformations of forms W, E and C of atmospheric circulation of the Northern Hemisphere;
- relations between structural features of baric formations in the initial ESP and the character of developing synoptical processes in the following ESP;
- indications of the character of future development of the processes obtained from the homologues selected for the initial processes.

The essence of the aforementioned relationships and features is thoroughly described in the monograph by L.N.Dydina (1964). The information about meteorological parameters cited in Table 1 was the initial for the forecast.

The process of compiling a medium-range forecast can be presented as the following stages:

A. Analysis is given to the current synoptical processes. For this purpose the circulation forms over the last 16-20 days are determined as well as the shape of initial macrotransformation and the type of processes in the Arctic.

B. A preliminary selection of circulation homologues is performed aimed at determining the tendency of process development for the next 3-10 days.

C. A prediction scheme is constructed for process development ($AT_{500}$ and ground) for the first 3-4 days for the forecasted period by using different types of additional criteria.

D. The forecast is made for synoptical position for the next 3-10 days taking into account the homologues chosen.

E. The weather forecast is developed for individual regions of the Arctic.

F. The prediction maps are compiled, they are prepared to be transmitted to the user via phototelegraphic communication.

The contents and form of these forecasts are determined mainly by the practice requirements in the process of hydrometeorological support of navigation along the NSR. This type of forecasts is compiled at AARI for 8-10 days in advance once a week. It contains the prediction maps of average pressure for the first and second half of the forecasted period with indicating the trajectories of baric formations shift (Fig. 6)., the predominating wind directions with indicating their average velocities and possible intensifications (Fig. 7) as well as mean values of air temperature.

Estimating the forecast verification score (Guide-book, 1961) is carried out by direct comparison of forecasted and actual values of elements, since in the medium-range forecasts allowance is made for main predominance of recurrence of meteorological elements with certain values.

The success of a forecast is usually estimated by a 10-number scale (10 numbers=100%). The forecast of dominating value of meteorological element (wind and temperature) is considered to have a verification score of 10 numbers in case the recurrence of cases of a given element in the forecasted interval amounts to not less than 70-80% of all the observations. Assessing the success of the forecast of pressure field pattern is conducted by comparing prognosticated pressure differences between certain pairs of stations to their actual differences.

The forecast for each element is considered to be proved with mark "satisfactory" if its estimate is within 5.1 to 6.9 numbers, "good" within 7.0 to 7.9 numbers and "perfect" - within 8.0-10 numbers.

In addition to long- and medium-range meteorological forecasts composed at AARI by the macrocirculation method, there are the weather forecasts for 1-3 days given by the administrations of the Arctic Hydrometeorological Regional Services. The principles of compiling these forecasts, formulation and the shape of presentation, the method for obtaining estimates are similar to those for compiling the medium-range forecast. The methodological assistance of AARI in this case consists in preparing and transmitting specific information to AHRS and preparing necessary personnel. Success of these forecasts has been repeatedly confirmed by the practice of their use.

The synoptic services of the Arctic AHRS quite widely use the forecast maps of the European Center for Medium-Range Weather Forecasts (ECMRWF) of up to 10 days and the maps by Japanese macrometeorologists developing the method for complex use of hydrodynamic forecast of synoptic situation for up to 5 days with typical model situation including the polar regions of East Arctic.

The forecast by ECMRWF is built on the basis of a 15-level hydrodynamic model taking into account a number of important physically significant weather-forming processes (radiation budget, phase water transformations, precipitation, friction, soil roughness and moisture, snow cover, etc.). The correlation coefficient between actual and prognosticated high throughout 5-6 days. For the subsequent period, of importance is disagreement between forecasted and actual situation.

In this aspect, the medium-range forecast by the macrocirculation method is more successful. In it, the mechanism of reconstructing macroprocesses throughout the entire 10-day anomalies of field H on daily maps of this forecast is quite confident. Therefore, in practice of provision of navigation at temporal sections of the medium-range forecast, the successful combination is carried out of the ECMRWF forecast at the first stage of provision with the AARI forecast at the subsequent stage, i.e., beyond the 5-6-day period.

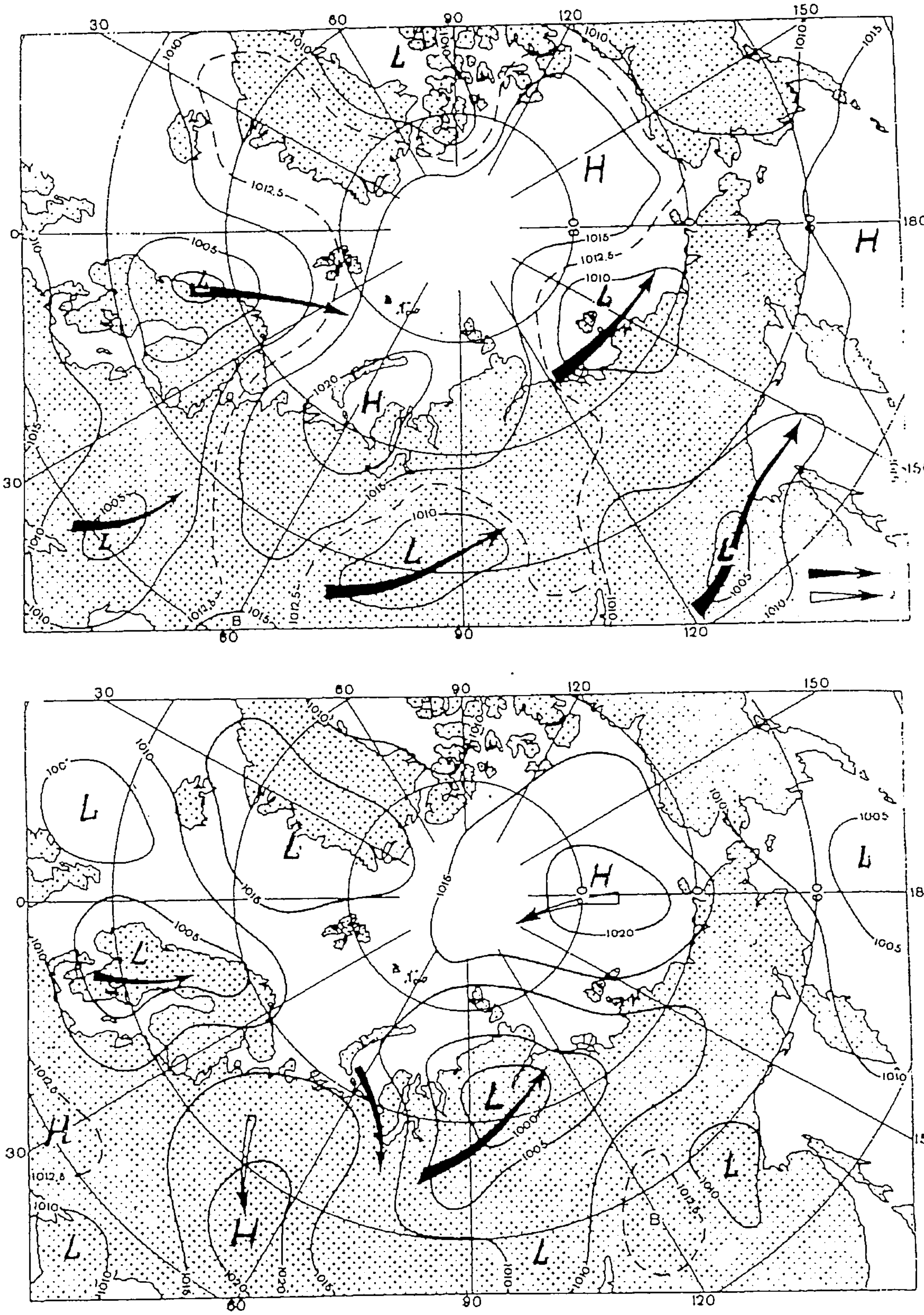

Fig. 6. Forecast of air pressure distribution for the first (at the top) and the second half of the forecasted period (at the bottom)

I - cyclone trajectories;
2 - anticyclone trajectories

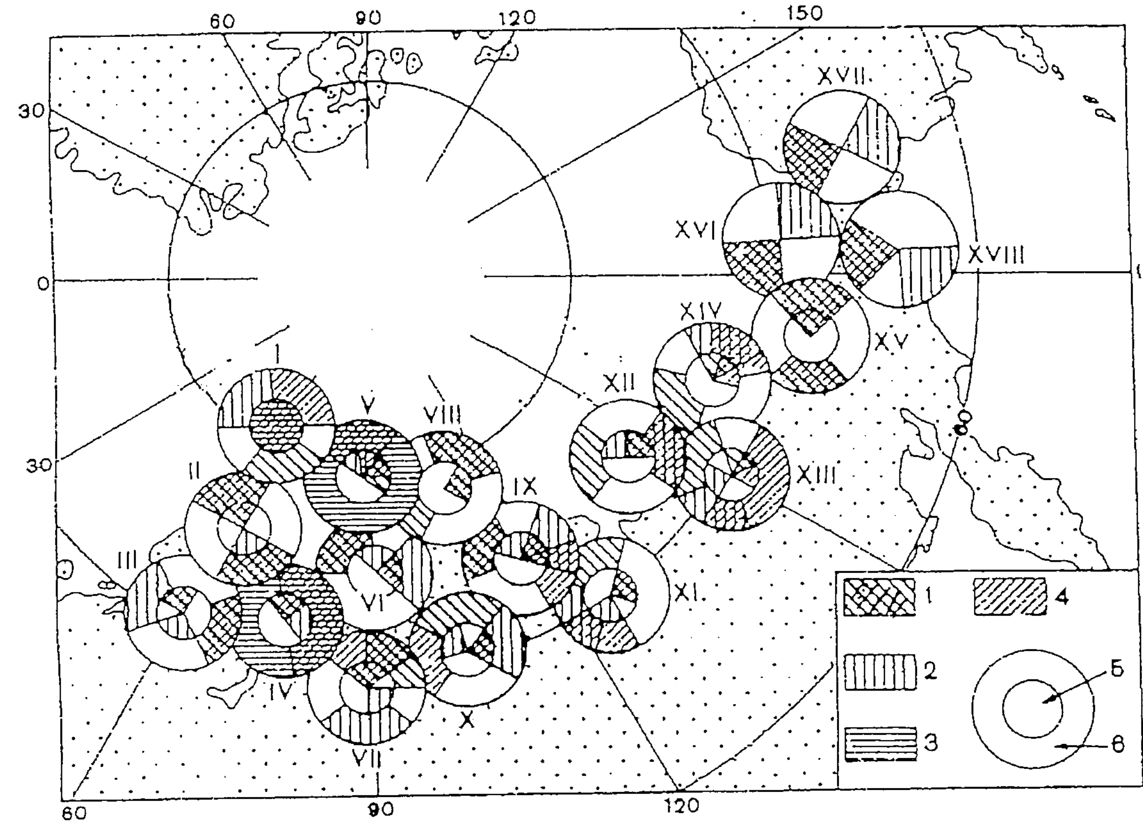


Fig. 7. A mapped wind forecast for the first and the second half of the predicted period.
I - prevailing wind direction according to the forecast;
2 - prognostic wind direction, second by occurrence;
3 - variable wind;
4 - wind direction which actually prevailed;
5 - first half of the period;
6 - second half of the period.

## 2.2 The principles of a new oscillatory-hydrodynamic model for long and medium-range forecasting

Achievements in nonequilibrium thermodynamics and developing the theory of dynamic systems (P.Glensdorf and I.Prigozhin, 1973; E.N.Lorents, 1981) allow at present studying more thoroughly the natural processes presented as long-term series of observations of the parameters of some system. Primarily this pertains to such media at the atmosphere, ocean and ice being the constituent elements of the Earth's climate system the observations of which have been conducted for a long time. According to Mr.I.Prigozhin, a Belgium scientist, the Noble Prize winner in physics, these series have the tracks of all the variables participating in the description of dynamics of a system and allow identification by the modelless way of some key features of the corresponding system (H.Nickolas and I.Prigozhin, 1990).

These fundamental principles were laid down to form the basis of a new methodology for long-term detailed forecasting of meteorological fields and of investigation of the character of climate system evolution developed at AARI by G.A.Zablotzky and M.P. Yevseyev. The main ideas of this methodology are set forth in the corresponding theory. The theoretical conclusions are corroborated by the analysis of prototype data and realized into the numerical scheme of detailed long-term forecasting of meteorological fields for 10 to 35-day periods as well as the scheme for calculating the sign of mean monthly anomaly of geopotential $H_{500}$ for the periods of up to 10-15 years ahead for high and middle latitudes of the Northern Hemisphere. The universality of the methodology developed allows its application, in principle, to other components of the climatic system: ocean and ice.

The theory formulates the principal statements of forecasting the phenomena of any physical nature on the basis of time series of prototype data. Any long-term observations could be presented in the shape of quasi-stationary and considerably non-stationary constituents of the process. Quasi-stationary constituent is described by sum of free and forced oscillations corresponding to system parameters (e.g., altitude of isobaric surface), whereas the considerably non-stationary constituent is determined by the phase portrait of the system or some invariant subset called an attractor.

The analysis of prototype data set is carried out on the basis of long-term observations of the altitude of 500 mb-surface and surface pressure recorded at regular grid points of the Northern Hemisphere. Daily fields of geopotential and surface pressure were approximated by the series expansion factors on the basis of spherical functions. At the first stage of studies, transecting spectrum was made on the wave number 9 and subsequently on the wave number 18, since the contribution of components with higher wave numbers is quite small. The harmonical analysis was made to the sets of expansion factors at time intervals of 80 and 180 days and 30 years. In the last case mean monthly values of the coefficients were calculated.

The results of analyzing short-term series allow revealing fluctuations approximated by sinusoida and having the amplitudes of tens dkm and a share of variance of 30-60% of the general spectra of variations (M.P.Yevseyev, D.A. Golyev, 1990). The periods of these variations vary from 10 to 180 days, which allows their use in the problem of forecasting. Similar quasi-periodic processes are typical of the circulation objects described by small wave numbers and which carry the major energy load in the system of circumpolar vortex of the hemisphere. For this reason the method is maximally efficient in high and middle latitudes where the kinetic vortex energy is maximum.

The results of analysis of mean monthly sets of expansion factors allow revealing a number of stable variations with small amplitude and the period of 180 days to 15 years. These periodical motions can be used to forecast the sign of pressure field anomalies for the periods of 10 to 15 years. However, in this case, of extreme importance is studying the accumulation of small disturbances and their consideration in the character of the evolution of planetary or hemispheric process.

Sinusoidal variations discovered in short-term series of observations continually change their phase and amplitude, disappear and reappear. However, their permanent availability in a certain spectrum of wave disturbances justifies concluding that at least in low-frequency areas the circulation character with an accuracy of 60-70% can be described as the superposition of several sinusoids.

The realistic existence of long-periodical variations in the Earth's atmosphere is proved by the results of a number of theoretical studies of the problem of free-running frequencies of free oscillations in the free atmosphere on the basis of analytical solution of linearized equations of hydrodynamics. In studies by M.P.Yevseyev (1976) and V.A.Yefimov (1987), the whole class of these oscillations with the periods of a few hours to 22.5 years has been revealed.

The developed numerical scheme of the forecast allows on the basis of comparatively similar algorithms revealing the most important parameters of the system responsible for the long-term evolution of the process and calculating the characteristics of its future state. This approach allows omitting conventional hydrodynamic models which equations, as many authors (Jacques Van Mieghem, 1973; G.D.Robinson, 1978) think, in their present shape, are unable to describe a real long-term and considerably non-stationary process. The method is also free from the statistics or the principle of analogy without which the existing practical methods for long-term forecasting are impossible (J.Wagner, 1989). In the first approximation, the problem is solved for quasi-stationary process. A certain element of non-stationarity is taken into account with the help of the phase-frequency method for analysing time series.

The scheme consists of two large calculational modules: oscillatory and hydrodynamic. The oscillatory module serves for processing and analysis of initial data and forecasting of large-scale circulation components (M.P.Yevseyev, 1993). In the problem of long-term detailed forecast, as initial data the sets of expansion factors for daily fields of geopotential H and surface pressure over 182 initial days with spectral limitation on the wave number 18 are used. When analyzing, each series of expansion factors is approximated by the set of working sinusoids. Sinusoids are summed up and the resulting curve represents a quasi-linear course describing with an accuracy sufficient for practice, the real atmospheric process in the low-frequency area of the spectrum. The period of 182 days is taken to consider half-year fluctuations especially distinct in high and middle latitudes (E.I.Lutsenko, 1987). The analysis of time series is carried out without considering mean annual variations. The annual variations were calculated in advance for each set of expansion factors.

A hydrodynamic module is created on the basis of the known spectral global model of atmospheric circulation (V.A.Yefimov, 1982). As compared to the initial variant, in the working module, the spectral resolution is increased, an additional spectral analoque of the equation of tendency is introduced to calculate surface pressure fields and a spectral analogue of moisture transport equation is added to calculate the areas of precipitation fall or its deficiency. In this shape the module serves only for comparing initial pressure, temperature and moisture fields balanced by external energy sources. Under the external energy sources are meant here the data on the thermal state of sea surface layer, the extent of cooling the atmosphere from continental and sea ice and heating in zones of subtropical deserts. In the first approximation, to estimate these effects, the climatic parameters averaged over months can be used; however, high grade information about the thermal state of the underlying surface prepared anew for each forecast, is to be used in future.

### 2.2.1 Forecast verification

The scheme of a long-term detailed forecast for geopotential $H_{500}$ and the surface pressure field for the terms from 10 to 35 days passed through planned tests.

To estimate the forecast quality, the fields of geopotential H and the fields of surface pressure on the 10th, 15th, 20th, 25th, 30th and 35th days of the forecast are used. Comparisons were conducted for four arbitrarily selected regions: Europe (5°W-65°E), Siberia (65°E - 135°E), East(135°E-155°W) and America (155°W - 65°W). No estimation has been performed for fields in the Atlantic because of scarce data available in the AARI efficient data bank. In each region, to calculate criteria of verification score, 50 points were used located at regular intervals at grid points between 80°N and 45°N.

As criteria of forecast verification score, there were used the values of correlation coefficient allowing one to judge whether the similarity of field geometry as well as the values of anomaly index "ρ" are testimony to the adequacy of anomaly signs. The correlation coefficients were calculated between 1) real and prognosticated fields (estimation of methodological forecasts), 2) fields on the initial day and actual fields on the day of forecast (estimation of inertia forecasts when initial fields are forecasted ) and 3) normal and actual fields (estimation of climatic forecasts). The anomaly index "ρ" is calculated in a similar way for anomalies of corresponding fields.

The estimation was performed with a 2-day shift before and after the date of forecast. The shift was caused by inaccurate approximation of extremes of corresponding disturbancies and possible incoincidence, as a consequence, by 1-2 days by-phase of prognosticated and actual fluctuations of spectral modes of the fields of geopotential $H_{500}$.

In Tables 2,3 the correlation coefficients are presented for methodical, inertia and climatological forecasts of surface pressure and $H_{500}$ fields for May-October 1992. The mean efficiency of forecasts as compared with the inertia ones was 0.20, with climatological 0.16. It should be mentioned that comparing correlation between methodical and climatological forecasts is typical only for the great variability of fields and unfit for the fields containing some constant element shading the features of circulation important from a forecaster's point of view but insignificant at this permanent background. So, this is the state-of-art estimating climatological forecasts of geopotential $H_{500}$-fields (Table 3) and surface pressure fields in the cold period of a year (Table 4). Permanent and well-defined westerlies-easterlies provide in every case a very good correlation of normal with each real field and revealing the true value of forecasts relative to climate becomes impossible. Moreover, weakening westerlies-easterlies in the prognosticated fields (which is natural because of lack of high-frequency components and impossibility of predicting for this period the actual depth of cyclones) leads to the fact that verification score of climatological forecasts is in this case above the methodological ones, even if there is full coincidence of preroutined and actual altitude troughs and ridges.

To compare methodological and climatological forecasts, the anomaly index "ρ" is applied. The value of this criterion in estimating surface pressure forecast in the period from May to October are cited in Table 5. The efficiency of these forecasts is +0.22, which along with an estimate of correlation coefficient value over the same period is testimony to its success. Fields of geopotential $H_{500}$ estimated by this criterion (Table 6) have efficiency of +0.15, which shows their certain progress. In winter time (November-December), estimating forecasts of surface pressure fields and geopotential $H_{500}$ is also above the estimate of climatological forecasts, although the efficiency of surface pressure forecasts is somewhat lower than in the warm period of a year (Table 7).

As a whole, the forecast estimation shows mean excess of 18%, on the average, for methodological forecasts, as compared to the inertia and climatological ones, for the surface pressure fields, and of 15% for the geopotential $H_{500}$-fields. The routine module for analysis of climatic variability of atmospheric processes was tested in 1993. By mean-monthly values of expansion factors for geopotential $H_{500}$-fields over the 1950-1979 period the forecast was composed for anomaly sign of mean-monthly fields of geopotential $H_{500}$ for the next 15 years. The preliminary analysis of this data justifies concluding that forecasting of large and extended geopotential field anomalies several years in advance is, in principle, possible. So, in July 1992, with a lead time of 13 years, a prediction was made of an abnormally hot and dry summer in Europe, cold weather in North America and active cyclonic activities in the Arctic. The corresponding routines are available from the authors.

Thus, common methods have been created for long-term forecasting of atmospheric circulation character for different terms from 10 days up to several years.

To complete the studies on full theoretical scheme by the theory given, a number of additional studies and calculations will be required to be accomplished. Only after that may a common routine scheme be developed for forecasting circulation characteristics and climatic parameters for high and middle latitudes for different time intervals.

Table 2. Criteria of verification score of detailed extended forecasts of surface pressure fields (correlation factors) over May-October 1992

| Month | Days of forecast | | | | | | Mean |
|---|---|---|---|---|---|---|---|
| | 10 | 15 | 20 | 25 | 30 | 35 | |
| May | 0.48 | 0.17 | 0.40 | 0.50 | 0.26 | 0.37 | 0.36 |
| June | 0.27 | 0.21 | 0.25 | 0.50 | 0.43 | 0.38 | 0.34 |
| July | 0.55 | 0.46 | 0.37 | 0.32 | 0.21 | 0.37 | 0.38 |
| August | 0.38 | 0.34 | 0.42 | 0.62 | 0.50 | 0.44 | 0.45 |
| September | 0.54 | 0.43 | 0.22 | 0.17 | 0.14 | 0.20 | 0.28 |
| October | 0.37 | 0.32 | 0.62 | 0.58 | 0.53 | 0.58 | 0.50 |
| Mean method | 0.43 | 0.32 | 0.38 | 0.45 | 0.34 | 0.39 | 0.38 |
| Mean inertia | 0.23 | 0.22 | 0.15 | 0.28 | 0.07 | 0.12 | 0.18 |
| Mean climate | 0.24 | 0.05 | 0.14 | 0.26 | 0.19 | 0.30 | 0.20 |
| Efficiency (by inertia) | 0.20 | 0.10 | 0.23 | 0.17 | 0.27 | 0.27 | +0.20 |
| Efficiency (by climate) | 0.19 | 0.27 | 0.24 | 0.19 | 0.15 | 0.09 | +0.18 |

Table 3. Criteria of verification score of detailed extended forecasts of geopotential $H_{500}$-fields (correlation factors) over May-October 1992

| Month | Days of forecast | | | | | | Mean |
|---|---|---|---|---|---|---|---|
| | 10 | 15 | 20 | 25 | 30 | 35 | |
| May | 0.58 | 0.75 | 0.58 | 0.78 | 0.71 | 0.74 | 0.69 |
| June | 0.65 | 0.74 | 0.54 | 0.72 | 0.62 | 0.50 | 0.63 |
| July | 0.50 | 0.59 | 0.60 | 0.45 | 0.46 | 0.38 | 0.50 |
| August | 0.64 | 0.51 | 0.68 | 0.55 | 0.55 | 0.41 | 0.56 |
| September | 0.59 | 0.62 | 0.34 | 0.54 | 0.64 | 0.64 | 0.56 |
| October | 0.73 | 0.79 | 0.68 | 0.76 | 0.77 | 0.80 | 0.76 |
| Mean method | 0.61 | 0.67 | 0.55 | 0.63 | 0.62 | 0.58 | 0.62 |
| Mean inertia | 0.66 | 0.63 | 0.55 | 0.62 | 0.55 | 0.52 | 0.59 |
| Mean climate | 0.79 | 0.73 | 0.71 | 0.78 | 0.73 | 0.76 | 0.75 |

Table 4. Criteria of verification score of detailed extended forecasts of geopotential $H_{500}$ and surface pressure $P_0$ (correlation factors) over November-December 1992

| Month | Fields | Days of forecast | | | | | | Mean |
|---|---|---|---|---|---|---|---|---|
| | | 10 | 15 | 20 | 25 | 30 | 35 | |
| November | $H_{500}$ | 0.68 | 0.72 | 0.83 | 0.62 | 0.70 | 0.74 | 0.72 |
| | $P_0$ | 0.64 | 0.56 | 0.63 | 0.50 | 0.51 | 0.67 | 0.58 |
| December | $H_{500}$ | 0.49 | 0.68 | 0.68 | 0.66 | 0.65 | 0.66 | 0.64 |
| | $P_0$ | 0.84 | 0.82 | 0.71 | 0.70 | 0.53 | 0.81 | 0.74 |
| Mean method | $H_{500}$ | 0.58 | 0.70 | 0.76 | 0.64 | 0.68 | 0.70 | 0.68 |
| | $P_0$ | 0.74 | 0.69 | 0.67 | 0.60 | 0.52 | 0.74 | 0.66 |
| Mean inertia | $H_{500}$ | 0.70 | 0.74 | 0.72 | 0.54 | 0.59 | 0.66 | 0.66 |
| | $P_0$ | 0.58 | 0.51 | 0.52 | 0.51 | 0.31 | 0.56 | 0.50 |
| Mean climate | $H_{500}$ | 0.81 | 0.80 | 0.84 | 0.77 | 0.76 | 0.67 | 0.78 |
| | $P_0$ | 0.70 | 0.64 | 0.68 | 0.71 | 0.60 | 0.68 | 0.67 |
| Efficiency (by inertia) | $H_{500}$ | | | | | | | 0.02 |
| | $P_0$ | | | | | | | 0.16 |
| Efficiency (by climate) | $H_{500}$ | | | | | | | -0.10 |
| | $P_0$ | | | | | | | -0.01 |

Table 5. Criteria of verification score of detailed extended forecasts of surface pressure fields (anomaly index "$\rho$") over May-October 1992

| Month | Days of forecast | | | | | | Mean |
|---|---|---|---|---|---|---|---|
| | 10 | 15 | 20 | 25 | 30 | 35 | |
| May | 0.45 | 0.31 | 0.39 | 0.37 | 0.20 | 0.34 | 0.34 |
| June | 0.22 | 0.42 | 0.26 | 0.51 | 0.23 | 0.47 | 0.35 |
| July | 0.34 | 0.56 | 0.33 | 0.25 | 0.26 | 0.37 | 0.35 |
| August | 0.27 | 0.46 | 0.24 | 0.54 | 0.39 | 0.38 | 0.38 |
| September | 0.42 | 0.18 | 0.06 | -0.06 | 0.01 | 0.36 | 0.16 |
| October | 0.09 | 0.01 | 0.29 | 0.38 | 0.37 | 0.29 | 0.24 |
| Mean method | 0.30 | 0.32 | 0.26 | 0.33 | 0.24 | 0.37 | 0.30 |
| Mean inertia | 0.10 | 0.18 | 0.09 | 0.02 | 0.06 | 0.04 | 0.08 |
| Mean climate | | | | | | | +0.22 |

Table 6. Criteria of verification score of detailed extended forecasts of geopotential $H_{500}$-fields (anomaly index "ρ") over May-October 1992

| Month | Days of forecast | | | | | | Mean |
|---|---|---|---|---|---|---|---|
| | 10 | 15 | 20 | 25 | 30 | 35 | |
| May | 0.28 | 0.18 | 0.01 | 0.51 | 0.43 | 0.43 | 0.31 |
| June | -0.08 | 0.26 | 0.07 | 0.52 | 0.40 | 0.26 | 0.25 |
| July | 0.13 | 0.35 | 0.25 | -0.18 | 0.31 | 0.42 | 0.21 |
| August | 0.22 | 0.02 | 0.43 | 0.19 | 0.12 | -0.05 | 0.16 |
| September | 0.24 | 0.45 | 0.23 | 0.22 | 0.13 | 0.32 | 0.27 |
| October | 0.12 | 0.24 | 0.15 | 0.44 | 0.16 | 0.10 | 0.23 |
| Mean method | 0.15 | 0.25 | 0.19 | 0.28 | 0.26 | 0.25 | 0.23 |
| Mean inertia | 0.17 | 0.18 | 0.08 | 0.04 | -0.05 | 0.06 | 0.08 |
| Efficiency | -0.02 | 0.07 | 0.11 | 0.24 | 0.31 | 0.19 | +0.15 |

Table 7. Criteria of verification score of detailed extended forecasts geopotential $H_{500}$-fields and surface pressure ($P_0$) (anomaly index "ρ") over November-December 1992

| Month | Fields | Days of forecast | | | | | | Mean |
|---|---|---|---|---|---|---|---|---|
| | | 10 | 15 | 20 | 25 | 30 | 35 | |
| November | $H_{500}$ | 0.38 | 0.13 | 0.44 | 0.24 | 0.23 | 0.44 | 0.31 |
| | $P_0$ | 0.49 | 0.66 | 0.32 | 0.09 | 0.42 | 0.62 | 0.43 |
| December | $H_{500}$ | 0.23 | 0.38 | 0.26 | 0.20 | 0.34 | -0.02 | 0.23 |
| | $P_0$ | 0.41 | 0.34 | -0.08 | 0.16 | 0.03 | 0.17 | 0.17 |
| Mean method | $H_{500}$ | 0.30 | 0.26 | 0.35 | 0.22 | 0.28 | 0.21 | 0.27 |
| | $P_0$ | 0.45 | 0.50 | 0.12 | 0.12 | 0.22 | 0.40 | 0.30 |
| Mean inertia | $H_{500}$ | 0.25 | 0.27 | 0.15 | -0.05 | -0.04 | -0.04 | 0.12 |
| | $P_0$ | 0.20 | 0.30 | -0.06 | 0.05 | 0.15 | 0.14 | 0.13 |
| Efficiency | $H_{500}$ | 0.05 | -0.01 | 0.20 | 0.27 | 0.32 | 0.25 | +0.15 |
| | $P_0$ | 0.15 | 0.20 | 0.18 | 0.07 | 0.07 | 0.26 | +0.17 |

## 2.3 Short-range forecasts

Short-range meteorological forecasts (up to 3 days) are considered to be one of the most important parts of marine hydrometeorological information support for safe shipping and other activities at sea. According to the Instruction of Rosgidromet for hydrometeorological information support to sea operations in the Arctic, the divisions of the Federal Service are responsible for the preparation of short-range weather forecasts, detection and warning about dangerous natural calamities by the responsibility zones of the Territorial Administrations of the Hydrometeorological Service.

On the basis of international and national regulation documents the marine hydrometeorological support is subdivided into general (main) and specialized. In order to fulfil the international obligations of Russia in respect of providing safe navigation, the marine meteorological information services on the hydrometeorological conditions of a general use are carried out by the corresponding Territorial Divisions. All navigators receive meteorological information on the sea areas, as required by the Marine Meteorological Bulletin. It includes:

A. Storm warnings which are prepared when the following phenomena are expected: (wind $V_{max}$ > 30 m/s, dense fog, icing, storm wave > 6 m, ice appearance).

B. Overviews of main elements of the surface weather chart.

C. Forecasts for general use, including: wind speed and direction, air temperature, visibility, icing conditions, wave (wind-induced, swell), ice edge position.

The bulletins are issued at least twice a day. The ice on the surface of the Arctic seas is considered to be a specific medium for shipping and presents a navigation danger for most of the ships, with the exception of the ships of a special class. Accordingly, the International Convention documents include the encounter of ships with ice into the list of dangers, requiring an obligatory warning. Due to this, as decided by the WMO, the marine meteorological services to ships navigating in the ice, were included in specialized services.

Specialized short-range weather forecasts, which aim to assist ice navigation, are prepared both on a regular basis and at single requests. These forecasts characterize in particular detail those meteorological elements, which present the largest interest for a given ship type and which affect the variability of ice conditions along the navigation route and in the unloading point (fog, precipitation, increase of wind force in unfavorable directions, etc.).

The methods of short-range forecasts of different meteorological elements, terminology, formulation and evaluation of the verification score of forecasts are regulated in Russia by special handbooks and manuals on listing short-range weather forecast services. The majority of short-range forecasts of meteorological elements are calculated using objective calculation methods and have a high verification score.

When forecasting weather conditions, all forecasting methods, adopted by the Central Commission on Methods of Rosgidromet are used in a complex. However, preference is given to those, whose verification score is best in the conditions of the different regions. The Territorial weather services widely use the prognostic charts and advice of the Rosgidrometcenter and other prognostic centers in the forecasts of the synoptic situation. In recent years the synoptic services in the Arctic have quite widely used the prognostic charts of the European and Japanese weather forecasting centers. The forecast of the synoptic situation up to 5-6 days, which also covers polar regions, is constructed on the basis of hydrodynamic models. The best verification score of such forecasts for polar regions is observed during the first three-four days. The use of prognostic charts of the synoptic situation contributes in many respects to the reliability of short-range weather forecasts in the Arctic.

# 3 OCEANOLOGICAL FORECASTS

Sea hydrological forecasts along with ice and weather ones are the necessary components of scientific-operational support to navigation on the Northern Sea Route (NSR). The most important thing for supporting navigation on NSR and satisfying the needs of national economy in the Arctic is forecasting sea level and waves.

As for the level forecasts, they are elaborated for shallow areas of Arctic seas where the depths can limit navigation. These are bars shallows on Siberian rivers flowing into Arctic seas (Turushinsky and Lipatnikov shallows on the Yenisey river, bars on rivers Yana, Indigirka, Kolyma), the port Tiksi, the Laptev and Sannikov straits and some other sites.

The wave forecasts for Arctic seas are given only in the periods of clearing from ice when a strong wave can develop and threaten navigation.

## 3.1 The principles of prediction technique

The methods for oceanological forecasts, in particular, sea level and wave forecasts, are usually subdivided into empirical and numerical hydrodynamic. The former are based on studying the nature of these phenomena and factors causing them, by the prototype data, revealing empirical dependencies of one phenomenon (in this case sea level fluctuations and wave), the so called predictants, on other phenomena, the so called predictors, as a rule, causing and accompanying the predictants. When forecasting waves, for example, it is clear that wind causes them and the greater the wind velocity, the stronger the wave. However, in case the question is not about open deep sea, it is also important to know wind direction and its acceleration, coastal line direction, sea depth, presence or absence of ice, etc.

When developing empirical-statistical methods for forecasting sea level it is also necessary to discover the quantitative dependence of level fluctuations on wind velocity over adjacent sea area or over the entire sea, on its direction (wind effect phenomena). Wind field can characterize surface pressure field or efficient gradients of atmospheric pressure. Both synoptic and prediction maps may be utilized to forecast atmospheric pressure fields.

All the initial hydrometeorological information is subjected to statistical processing. Dependencies are found by the correlation method, optimum linear extrapolation, the cluster analysis method, etc.

The forecast methods based on using numerical hydrodynamic models are the algorithms and programmes for solving the system of equations allowing, by means of computer, the determination of sea level position by prescribed boundary and initial conditions and values of external forces. When forecasting sea level and wave, the initial information is obtained, in the final analysis, from actual or prognostication synoptic maps as the fields of surface atmospheric pressure and surface wind. For the Arctic seas, it is also necessary to use information about ice conditions.

## 3.2 The numerical method for forecasting sea level at route sites limited in depths

To forecast wind effect phenomena as for level fluctuations, the two-dimension model of storm surges is used and verified for Arctic sea conditions (A.Yu.Proshutinsky, 1993):

$$\frac{\partial \vec{U}}{\partial t} + 2\vec{\omega}_z \vec{U} = -(H+\zeta)\,\nabla\zeta - \frac{(H+\zeta)}{\rho}\nabla P_a + \frac{1}{\rho}(\vec{\tau}^{\,s} - \vec{\tau}^{\,b}) \qquad (1)$$

$$\frac{\partial \zeta}{\partial} t = -div(\vec{U})\,, \qquad (2)$$

where t - is time,

$\vec{U} = \int_0^{H+\zeta} \vec{U} dz$ - the vector of full flow,

$\vec{\tau}^{\,s}$, $\vec{\tau}^{\,b}$ - tangential frictions at the surface (s) and bottom (b) of the water flow, respectively,

$P_a$ - atmospheric pressure,

$\zeta$ - level deviation from undisturbed state,

H - non-disturbed depth,

$$\vec{\tau}^{\,b} = K\rho\,\vec{U}|\vec{U}|, \quad K = \frac{K_w}{(H+\zeta)^2}, \quad K_w = 2,6\cdot 10^{-3}, \qquad (3)$$

$$\vec{\tau}^{\,s} = c_\alpha \rho_\alpha |\vec{W}|\vec{W}, \quad c_\alpha = (1,10 + 0,04|\vec{W}|)\cdot 10^{-3} \qquad (4)$$

where $\vec{W}$ - is the vector of water surface wind velocity

$c_\alpha$, $\rho_\alpha$ - the coefficient of friction and air density.

The wind velocity at the water surface is determined from geostrophic relationships taking into account correlation transition factor C and the angle of wind deviation from the direction of geostrophic $\alpha^s$ .

The influence of ice cover is not taken into account in the model. The initial information for calculating by the model serves the fields of surface atmospheric pressure computed in ECMRWF. The period in advance of the forecasts is 6 days.

Non-consideration of the influence of ice cover on sea wind effect phenomena restricts using this method by navigation period when the influence of ice cover can be neglected.

The necessity of developing the universal method for forecasting wind effect phenomena that can be used independently of available ice conditions both in navigation and internavigation periods resulted in creating a modified method (I.M. Ashik et al., 1989).

The major differences between the modified and the above methods are:

A. Taking into account ice cover by supplementing the system of equations for shallow water terms describing water friction of ice as well as corresponding system of equations of ice cover dynamics.

B. Limiting the size of the area in question by Arctic seas (from the Kara to Chukchi Sea) necessary to economize computer resources.

C. More accurate model calibration requiring the modification of calculation technique for surface wind and tangential stress on water and ice surface.

As the initial conditions, the state of rest is taken and the function of ice concentration is prescribed in accordance with the real ice distribution.

Analysis of experimental calculations shows that the modification conducted allows a 1.5-2-fold increase in the quality of calculations of sea level fluctuations because of wind effect phenomena with developed ice cover and strong winds.

The quality of forecasts for wind effect-caused sea level fluctuations depends to a considerable extent on lead time and amounts to 90-95% for the first, 80-85% for the second and about 70% for the third day having subsequently lowered up to 50-60% with an admissible error of 0.8$\sigma$.

Forecasts are being developed the year round and given to the user in the shape of radiograms with indication of the values of sea level deviations from the zero surface at polar stations on the basic synoptic dates.

## 3.3 The probability method for forecasting nonperiodic level fluctuations

Non-periodic sea-level fluctuations are a complicated process in terms of prediction because the causes forming it do not always lead to an adequate consequence. The relations of level with numerous factors influencing it is not a functional because these factors themselves are constantly interacting with each other in a very complicated manner. Their interaction being unpredictable with sufficient accuracy, therefore, the sea level fluctuation process acquires probabilistic properties.

The probabilistic forecast can be presented in the shape of arbitrary function of predictant distribution depending on predictor initial values. However, in practice the solid distribution function is almost always sufficient to be replaced by three discrete gradations ("level rise", "level drop", "average level"). Usually this form of presenting the probabilistic forecast is more suitable for the user. In some cases the probabilistic forecast can be presented in the shape of guaranteed values of the level of prescribed support.

The probabilistic forecast method (V.I.Andryushchenko, 1985) is based on the Bayes formula, as components of vector-predictor are used:

- surface field of atmospheric pressure (actual),
- initial position of the level at the forecast moment,
- calendar features of level variations at a given site.

By its nature, the probabilistic forecasts reflect an objectively existing, at each certain situation, uncertainty of the future state of a forecasted element, this uncertainty being expressed in a quantitative form characterizing itself the "extent of confidence" of a predictor in accomplishing level gradations.

To estimate the verification score of probabilistic forecasts, an expression is suggested establishing in the best way the correspondence of forecast quality in probabilistic and categorical shapes:

$$F = \left(1 + \sum_{j=1}^{n-1} \frac{P_j}{d}\right) P_0 \cdot 100\% \qquad (5)$$

where $P_0$ - is the prognostication probability of the gradation realized;

$P_j$ - the prognostication probability of the rest n-1 gradations;

d - the number of gradation beginning with the realized one (zero).

The method has been developed and used for the summer period of navigation in the East-Siberian Sea and for the winter period of navigation in the Kara Sea. The forecasts are compiled with a 3 to 5-day period in advance. Table 8 presents verification score of level forecasts developed by using actual initial data at the moment of forecasting. When the method is unavailable and the optimum strategy under the conditions of uncertainty is forecasting "average level", the verification score of these forecasts amounts on the average to 51.8%. The efficiency of the technique is thus more than 16%, which is quite enough for this period in advance. In using the prognostication initial material, the verification score and, naturally, the efficiency of probabilistic level forecasts increases on the average by 15-20%.

Table 8. Verification score of probabilistic level forecasts (%) compiled on actual initial material over the 1993 navigation period (N is the number of forecasts)

| Station | Period in advance, days | | | Average | N |
|---|---|---|---|---|---|
| | 3 | 4 | 5 | | |
| 1.Ambarchik | 68 | 68 | 64 | 67 | 297 |
| 2.Nemkov | 70 | 69 | 67 | 69 | 138 |
| 3.Shalaurov Cape | 72 | 69 | 66 | 69 | 156 |
| 4.Sopochnaya Karga | 68 | 67 | 63 | 66 | 180 |
| 5.Dixon | 69 | 68 | 66 | 68 | 213 |
| 6.Tadibyayakha | 68 | 68 | 64 | 67 | 132 |
| 7.Kharasavey Cape | 70 | 69 | 68 | 69 | 174 |
| 8.Amderma | 72 | 69 | 67 | 70 | 162 |
| Average | 70 | 68 | 66 | 68 | |
| N | 492 | 484 | 476 | - | 1452 |

### 3.4 The numerical method for wave forecasts

To forecast wind waves the spectral parametric model has been chosen, developed in St-Petersburg department of the State Oceanographic Institute (I.V.Lavrenov, 1993) and adapted to Arctic sea conditions (V.A.Stepanov). A number of features justify this choice:

- spectral models are the best to conform with modern ideas about the nature of wind wave;
- the results of running models in non-Arctic seas show good correspondence of calculation findings to observational data;
- universality of the programme allowing for the possibility of simple prescription of the design region, enables its easy adaptation to varied ice conditions;
- the model is efficient and requires a computer time to be less in order of magnitude as compared to the discrete spectral models.

The most important initial information is the prognostication fields of surface atmospheric pressure calculated at the European Center of Medium-Range Weather Forecasts (ECMRWF) and coming every day to AARI in the code GRID. This information represents the array of atmospheric pressure values of the Northern Hemisphere (from 20° to 90°N) at grid points of the spherical co-ordinate system with the same angle spacing of 5° by latitude and longitude. Maximum period in advance of the forecast is 144 hours and determines the limit period in advance for waving forecast. Discreteness of pressure fields is 24 hours. Out of the total volume of information, only a portion referring to a forecasted sea area is selected according to the programme. It is linearly interpolated in space and time into the grid points of smaller rated grid for each time step.

Wind field is routined by interpolated pressure field. To take into account ice conditions, complex ice maps are applied, composed at the Ice center of the AARI. In accordance with them the location of ice cover edge is determined and, accordingly, rated areas are changed and an array of wind acceleration values is formed.

The model is designated to calculate wave elements (average heights, directions of propagation and periods) by wind fields or surface atmospheric pressure fields over deep sea, therefore to calculate waves in shallow regions (the Ob-Yenisey region, the south-eastern region of the Laptev Sea, the western part of the East-Siberian Sea), it is supplemented with a routine block providing the correction of calculation results for wave characteristics via taking into account real depths at each grid point in rated region. In this case empirical relationships between wave characteristics and sea depths are used.

Arctic seas differ from one another by great non-uniformity of their depths. In addition, depending on synoptical situation one and the same region, as for the conditions of wave formation, can be referred alternately to abyssal and shallow.Therefore, water areas of more than 50 m in depth are arbitrarily referred to as abyssal. When the depth is less than 50 m, a routine is carried out of limitedly admissible average wave height $h_n$ at depth H with wind velocity V:

$$\overline{h}_n = 0{,}062\, V^{0,4} \cdot H^{0,8} \tag{6}$$

If the mean wave height calculated by deep water model exceeds the possible limit then its correction is made, i.e.:

$$\overline{h} = \overline{h}_n$$

Then average heights are reduced to a 5%-support based on the modified Rayleigh distribution with shallows taken into account, suggested by B.Kh.Glukhovsky. Wave height correction is made in routine algorithm without feedback, i.e., it has no influence on calculations by the deep sea scheme.

Wind wave forecasts are given to the user as maps: for the seas of the North-European basin of the Arctic Ocean the year round and for the seas of the Russian Arctic in the periods of appearance of rather large water areas free of ice (August-September).

The quality of forecasts depends on the region, season, and the period in advance. It amounts, on the average, to about 90% on the first, 80-85% on the second, about 75% on the third, 65-70% on the fourth, 60-65% on the fifth, and 50-60% on the sixth day and an admissible error is accepted here to be $0.3h_n$ (Manual, 1982).

## 3.5 The method for complex forecasting of ice-hydrological conditions in Arctic seas

The method for complex forecasting of ice-hydrological conditions (Yu.A. Vanda, 1987; B.A.Krutskikh et.al., 1985) is designated for predicting the totality of most important dynamic elements of hydrological and ice regimes in seas of the Siberian shelf the period of advance is 5-7 days. The theoretical premises for developing the method have been the findings of studies by B.A.Krutskikh (1978) who generalized and gave formulations of conceptions of elementary hydrological processes (EHP) and natural hydrological periods (NHP) in the course of changing hydrodynamic characteristics of the sea surface layer. These conceptions reflect a united organically linked complex of hydrometeorological processes in the Arctic: in the period of developing this or that elementary synoptic process (ESP), over the Arctic a certain position of baric systems is formed.

Pressure and wind fields corresponding to it create in Arctic seas a specific macrocirculation of water, ice and level surface non-levelling which retain the main features during NHP. As a result of these macroscale processes ESP develop characterized by unidirectivity of their variations within homogeneous hydrological regions. Processes inside NHP are type-designed. There are seven major types of dynamic processes developing simultaneously in all marginal seas of the Russian Arctic.

Each type has its own features of synoptic systems, water and ice dynamics. For all types of processes, the schemes of currents, topography of open surface and ice drift have been built. In their first version, typical schemes of topography of open surface and integral currents for these types are calculated by using simplified linear hydrodynamic models without considering ice cover and for seas of the Siberian shelf only and the maps of ice drift for the same regions are compiled by the empiric method. Subsequently, to specify and update missing information over uncovered and inaccessible regions, recalculations have been made for typical schemes of level non-levelling, ice cover drift, compacting and diverging by more improved two-dimensional numerical hydrodynamic large-scale model of the Arctic Ocean (A.Yu.Proshutinsky, 1993) including all the Arctic seas. The field of application, thus, on the complex method for forecasting ice-hydrological conditions has considerably expanded. At the present time these forecasts are applied, primarily, when supporting Arctic navigation on the traditional coastal routes of the Northern Sea Route (NSR) and transit navigation by high-latitudinal routes and in addition can be used, for example, in organizing and conducting non-standard research-tourist legs of icebreakers to the pole region.

The block scheme of a complex forecast for ice-hydrological conditions in Arctic seas is presented in Fig.8. In the upper part of the scheme, there is a set of initial data. By the contents all the totality of this information is subdivided into meteorological and ice-hydrological, by the type - into permanent current. In the scheme, permanent information is outlined by double lines. By means of this method important indicators of dynamic ice and hydrological processes are being forecasted, including level surface topography, predominating ice drift directions and typical zones of unidirectional tendency of changing ice cover concentration (zones of compacting and diverging). The method is designated to forecast these indicators both over the entire Arctic basin, as a whole, and over each sea of the Siberian shelf, individually. Allowance is made for mapping of these forecasts, which provides for their being clear and informative (Fig. 9).

The qualitative analysis of the results of comparing forecasted tendency in ice redistribution to the actual one shows their satisfactory agreement. A more strict assessment is accomplished to forecast sea level topography by observational data at polar stations (island and mainland). The forecast of level position is estimated by sign and value. An allowable error is chosen based on the criterion $\pm 0.674$ of root-mean-square deviation of level over the period in advance of the forecasts. The results of estimations made by the data from 39 stations indicate also about satisfactory verification score of the predicted values for sea level. So, over the western region of the Northern Sea Route (the Kara Sea and western part of the Laptev Sea) the level forecast verification score amounts by tolerance 77% and by sign 85%, and for the eastern region of NSR (the eastern part of the Laptev Sea, the East-Siberian and the Chuckchee Seas) 78% and 83% respectively. Analysis of errors shows that they introduce no principal changes into the prognostication schemes of level topography and ice drift (Yu.A.Vanda et al., 1988).

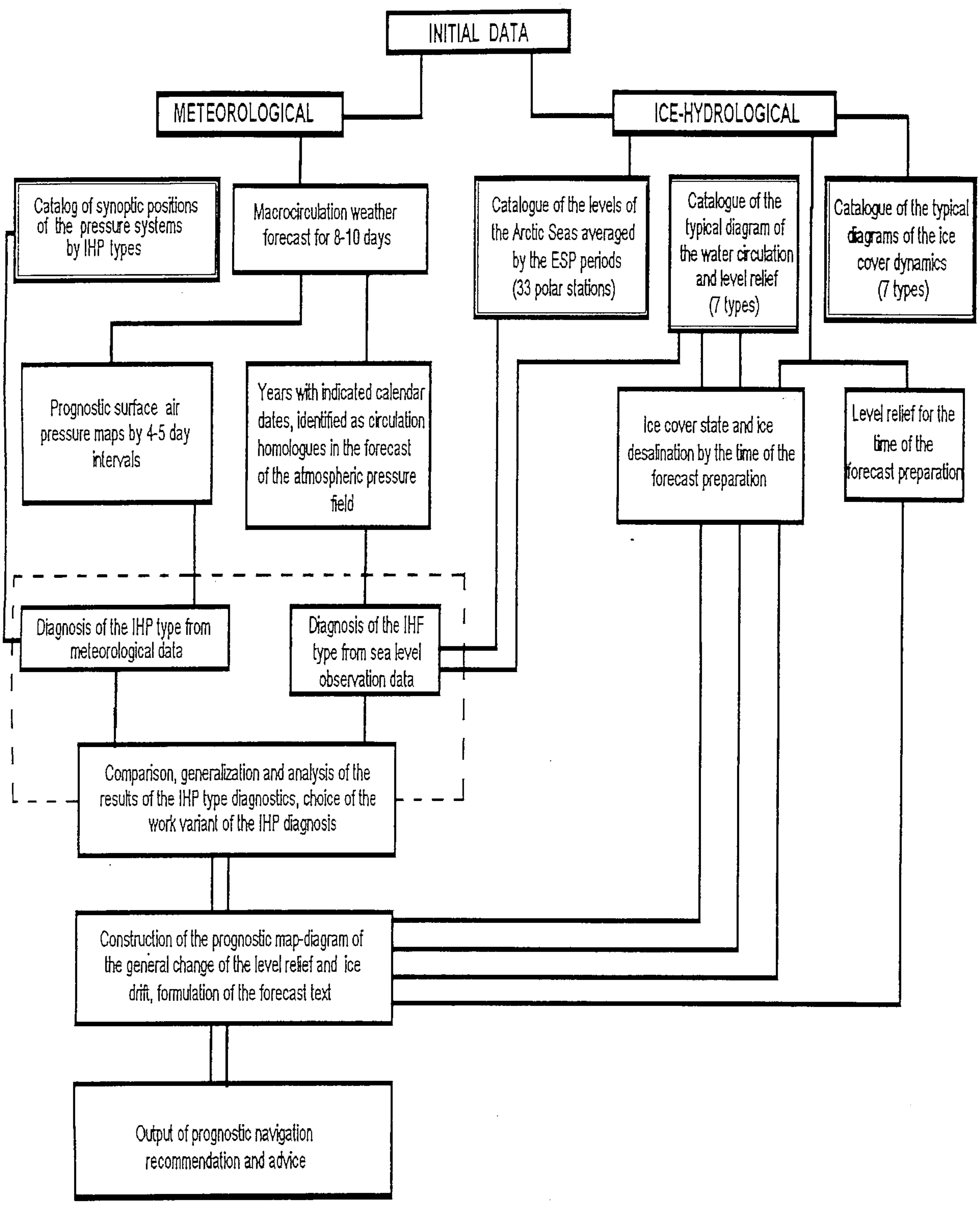


Fig. 8. A block-diagram of the technology for the preparation of a composite forecast of the ice-hydrological conditions in the Arctic Seas for 5-7 days.

IHP - Ice-Hydrologic process,

ESP - elementary synoptic process,

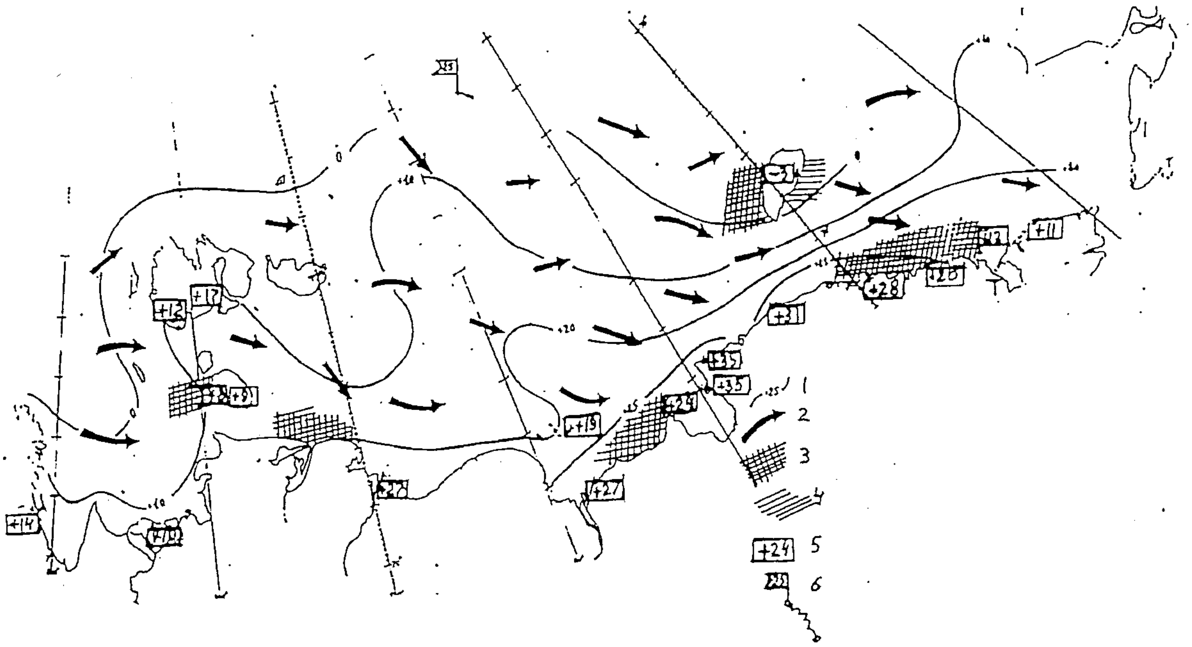


Fig. 9. An example of a prognostic map-diagram of the varying ice conditions from July 24 to 30 of 1981.

I - isolines of the prognostic anomalies of sea level;
2 - prevailing direction of the ice drift;
3 - zones of ice pressures and compacting;
4 - zones of diverging;
5 - mean value of the actual level anomalies;
6 - actual drift of the NP-25 station.

## 3.6 Short-range forecasts for sea level and wave compiled at the arctic administrations of hydrometeorological service

Short-range level forecasts with the period in advance of one day are compiled by using empirical relationships (V.I.Andrjushchenko, 1979; Y.A.Vanda, 1982; Yu.V.Zakharov, N.V.Mustafin, 1965; Ye.N.Uranov,1972, etc.) taking into account the direction and intensity of atmospheric circulation in the shape of sums of efficient atmospheric pressure gradients or wind projections on the effective water surge direction as well as the level deviation from its average value at stations located on the route of predominating direction of moving baric systems.

The ways of level forecasting are designated for possibly full consideration of physic-geographic conditions in individual regions and features of developing synoptic processes. Most equations are based on taking into account the asynchronous relationship between synoptic processes and the level fluctuations they cause. This shift in time amounts to a few hours or 2-3 days and is caused by not only inertia in level fluctuations but also predominating west-east baric systems movement (80% of all cases). The latter allows predicting the course of level at station located eastward, as well as for meteorological and level data on water areas located westward.

Along with prognostication formulae allowing pre-calculation of level independently of synoptic forecast, there are the equations designated for full or partial use of synoptic forecasts. A number of simple but convenient methods are applied to estimate the expected level position with a given wind forecast (e.g., diagrams and graphs of level correspondence to different wind direction velocities).

The verification score of these forecasts is 85-90% and even above (on average 87%). For the regions of the eastern part of NSR, the level forecast methods with the period in advance of 2-3 days have been elaborated (V.I.Andrjushchenko, 1985;Yu.A.Vanda, 1982) on the basis of taking account of asynchronous relationship between level fluctuations and antecedent atmospheric pressure distribution, using the law of leading flow to determine probable displacement of baric formations, applying optimum linear extrapolation of atmospheric pressure fields as well as applying geopotential fields in the mid-troposphere and type-design of atmospheric circulation by means of the paragroup method of cluster analysis. The verification score of these methods reaches 80% with allowable error of $0.674\sigma$.

The empirical methods for wave forecast in Arctic seas are based on type-design of wave-formation conditions and calculation of wave fields by typical fields of surface atmospheric pressure (V.Ye.Kalyazin,1986).

It is established that heavy storms arise both when cyclones pass by typical trajectories and in quasi-stationary situations when during a certain period of time the direction of isobars does not change and considerable pressure gradients are retained over the rated water area. The typical cyclonic trajectories are divided into quasi-stationary plots. For each of them, typical wave fields are calculated assuming that a certain baric field is corresponded by a certain wave field. This division allows observing the entire process of wave generation, transformation and damping under the typical process. Quasi-stationary situations are differentiated by the intensity of baric fields and isobar directions. Verifying typical fields is conducted by the efficient gradient method representing the pressure differences at bench points. Disagreement between prognostication and typical efficient gradients is eliminated by correcting typical field which is used for the forecast.A disadvantage intrinsic of all type-designs (impossibility of describing the entire diversity of natural processes by typical ones) can be eliminated by computer calculation of prognostication field wave by prognostication surface pressure field. The method for routing wind and wave fields is the development of ideas by Z.K. Abuzyarov (1981) and K.M.Sirotov (1978) concerning elaborating wave forecast methods for the North Seas (Hydrometeocenter of the USSR).

Advantages of the above approach to forecasting waves are as follows:

- under the conditions of limited initial hydrometeorological information it is possible to quite operatively make a forecast;
- possible increase of the period in advance of wave forecast up to 3 days;
- wave characteristics are obtained with quite sufficient accuracy for research-operation work as well as spatial and time resolution.

The verification score of wave forecasts is 90% with allowable error of 0.3 $h_n$.

## 3.7 Pre-calculation of tidal sea level fluctuations

Specificity of level regime of Arctic seas consists in predominating wind effect fluctuations of the tidal ones. Nevertheless tidal level fluctuations comprise, as a rule a considerable value and are to be taken into account when compiling sea level forecast.

Tidal level fluctuations are pre-calculated annually by known harmonic tide constants for the navigation period (July-October) along the entire route of NSR as well as for the autumn-winter and winter-spring periods over the western regions of the Arctic. The pre-calculated tide levels are available in the shape of reference-books disseminated to the Arctic Administrations of the Hydrometeorological Service and are considered when compiling level forecasts.

All the reference-books are composed according to the same scheme and represent a set of tables of hourly values of tide levels in deviations from an average for each month during the navigation period. Positive values mean that the tide level is above and negative - below and average. The pre-calculation of tide level is carried out by Darvin's method by harmonic constants of 11 major components of tide ($M_2$, $S_2$, $N_2$, $K_2$, $K_1$, $O_1$, $P_1$, $Q_1$, $M_4$, $MS_4$, $M_6$). Harmonic tide constants are computed as means from all values for the given months. When pre-calculating tides for a certain month, harmonic tide constants for this month are used, thus taking into account the seasonal variations of harmonic constants caused, primarily, by changing ice conditions.

Handbooks for pre-calculated tides for July-October contain tables for the following stations: Amderma, Cape Kharasaway, Se-Yaga, Antipayuta, Novy Port, Dixon, Island Golomyanny (the Kara Sea), Cape Kosisty, Tiksi (the Laptev Sea), Shalaurov Cape (the East-Siberian Sea), Shmidt Cape (the Chuckchee Sea), Provideniye Bay (the Bering Sea). Handbooks for the autumn-winter period include tables for the stations of the Kara Sea: Bolvansky Nos, Yugorsky Shar, Amderma, Cape Kharasaway, Cape Zhelanya, Dixon, Sopchnaya Karga, the Islands of Izvestia, Baikolovo, Island Golomyanny, Island of Pravda and for the winter-spring period for Bolvansky Nos, Yugorsky Shar, Amderma, Cape Kharasaway. An example of table in the handbook is Table 9.

Table 9. Mean verification scores (%) of level and wave forecasts

| Element | Period in advance (days) | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| | Physical-statistical methods | | | | |
| Level | 87 | 80 | 70 | | |
| | Probabilistic methods | | | | |
| Level | | | 70 | 68 | 66 |
| | Numerical methods | | | | |
| Level | 92 | 82 | 73 | 65 | 54 |
| | Spectral method | | | | |
| Wave | 95 | 83 | 75 | 68 | 62 |

# 4 ICE FORECASTS OF A GENERAL PURPOSE

The changes in the ice cover state as affected by various hydrometeorological factors create diverse ice conditions in the Arctic seas. The ice conditions in the sea can be characterized by a relative area, occupied by ice (ice cover extent), area of the close ice zones (ice massifs), position of the ice edges and fast ice limits, thickness distribution over the area, concentration and other characteristics of the ice cover state. To characterize ice conditions the aspects of the ice cover transition from one state into the other are also important such as dates of the beginning of melting and freezing, dates of the fast ice break-up, dates of the ice reaching some definite thickness.

The listed characteristics of ice conditions govern the conditions of practical human activities in the Arctic seas, such as shipping, shelf exploration, etc. The effectiveness of these activities depends, in the main, both on the regular observations of the ice cover and a possibility to calculate and forecast the characteristics of ice conditions.

The methods applied in the ice forecasting practice are divided into two main groups: the physical-statistical and numerical methods. The characteristics of these and other methods used in the practice of the scientific support to the operations on the Northern Sea Route are presented in the sections below.

## 4.1 The bases of the physical-statistical methods of ice forecasts

The development of the physical-statistical methods of ice forecasts is based from the very beginning on the formation of a physically non-controversial prognostic conceptual model, accounting for the dependence of ice conditions on different hydrometeorological factors, and which could provide for a sufficient reliability and the advance period advance of the method of the forecast.

The essence of the physical-statistical forecasting in the very general form can be formulated as follows: a definite anomaly of the ice conditions corresponds to the same set of the anomalies of the natural factors affecting the ice cover state. The first systematic presentation of the bases of these methods was made by Viese (1944). The subsequent studies of physical processes in the ice cover, typical features of the spatialtemporal hydrometeorological conditions allowed for a more justified approach toward revealing the factors, governing the anomalies of some or other characteristics of the ice state. The results of these studies were summarized in (Gudkovich et al., 1972) and in the series of subsequent works, aimed to improve understanding of the different aspects of the problem, a more objective finding of the information predictors, a search for the approach to automated procedure of the preparation of the ice forecasts and presentation of their results.

During the selection of the predictors it is important to understand the role of the preceding and the next processes in the total set of the factors, affecting ice conditions.

The effect of the preceding processes governs the state of the ice cover ( $I_{t_0}$ ) by the moment of the forecast preparation ($t_0$) and when necessary can be taken into account on the basis of observations or calculated by actual data. The ice cover state for the forecasted moment (t) in the future ($I_t$) depends both on its initial state ( $I_{t_0}$ ) and on those changes ($\Delta I$), which will occur under the influence of the next processes during the time interval ($\Delta t$), equal to the period in advance of the forecast ($\Delta t$ = t-$t_0$).

The effect of the initial state of the ice cover, the ocean and the atmosphere on the intensity of the subsequent hydrometeorological processes reflects the presence of the "advance mechanisms" in nature, which along with the direct contribution of the initial conditions create the possibility of the forecast with some or other period in advance, that is, govern the predictability of the hydrometeorological conditions.

The predictability depends significantly on the properties of the medium under study. It is different for the ice cover, the sea and the air. And even the different characteristics of the ice cover state can have a differing predictability. The predictability depends on the scale of the considered phenomenon. Thus, the limit of the predictability of some synoptic processes, cyclone and anticyclones does not exceed 3-4 weeks (Yudin, 1968). However, some averaged weather characteristics, such as mean monthly and mean seasonal distribution of air pressure or temperature, can be predicted with a much larger advance period.

The effect of the initial state of the ice conditions is usually noticeable over an extended which is indicated in the persistence of the sign of the anomalies of some ice state characteristics over several months and in the high self-correlation coefficients of the values of the ice cover extent and the area of close ice during summer in some Arctic seas (Gudkovich et al., 1972). That is why the allowance for the initial state of the ice cover is considered to be an important basis for the ice forecast methods.

However, with the forecast 6-8 months in advance, the influence of the initial ice conditions either weakens or disappears and the forecast of ice characteristics is fulfilled on the basis of the "advance mechanisms", inherent in the processes in the atmosphere and hydrosphere, which are evident in sufficiently close correlation relationships of the ice conditions and hydrometeorological factors of the preceding seasons (Gudkovich et al., 1979). In other cases the forecast of ice characteristics depends on the possibility of predicting the meteorological conditions, governing the ice melt and drift.

The dependency (S) of different ice phenomena (U) as affected by a set of hydrometeorological factors ($x_i$) can be presented in the formalized form:

$$S(a_{ij}\Delta x_{ij}) \rightarrow \Delta U_i \quad (7)$$

where $\Delta x_{ij}$ - anomalies of the natural factors,

$a_{ij}$ - a relative measure of their influence,

$\Delta U_i$ - anomaly of the ice phenomenon.

The forms and the ways of a practical implementation of this dependency in the physical-statistical forecasting methods are diverse. More often the dependency (7) of the forecasted ice characteristics on the factors, governing them, is expressed by the linear regression coefficients in the form:
where U - calculated or forecasted characteristics of the ice cover,

$$U=\sum_{i=1}^{n} k_i x_i + c \quad (8)$$

$k_i$ - regression coefficients,

$x_i$ - equation arguments, characterizing the indicators of different hydrometeorological processes,

c - a free term of the equation.

The dependency (7) is also fulfilled in the forecasting methods on the basis of different subdivisions into types. The application of the division into types presupposes a preliminary classification of the hydrometeorological processes into a number of the types, corresponding to some or other ice conditions. The success of the forecast using the method of the division into types depends on how successfully the classification features have been chosen and on the temporal stability of the type of ice conditions (Yegorov, Spichkin, 1990).

Another way to fulfil the dependency (7) is used in the forecast method, based on taking into account the ratio between the indices of the anomalous informative predictors and the forecasted elements of the ice regime (Kovalev, 1979), as well as in the methods, based on the principles of the discriminant analysis, presented in section 4.4 of this report.

For an effective support of Arctic navigation and other types of practical activities during a considerable interannual variability of ice conditions in the seas of the Siberian Shelf (Fig.10) a system of ice forecasting has been set up, which consists of the forecasts of three types depending on their periods in advance: long-range ice forecasts from I to 6-7 months in advance; medium-range forecasts from several days to one·month in advance and short-range forecasts with several days in advance.

The contents, dates and the presentation form of each kind of ice forecast are given in the next sections.

In order to develop and improve the physical-statistical methods of ice forecasts in the Arctic Seas a series of continuous and sufficiently long observations of the ice cover state and the characteristics of the hydrometeorological phenomena in the Arctic all year round are considered necessary.The system of such observations began to be formed at the beginning of the second decade of the present century, when in 1913-1916 the first polar stations were established in the south-western Kara Sea.

The basis of the structure of the network of polar stations, at which along with the meteorological observations also ice observations were carried out, was formed in the 30s-40s during the period of the active exploration of the Arctic, the NSR and the increase in research activities in the seas of the Siberian Shelf. The network of polar stations was completed in the early 60s.

The stationary ice observations at polar stations are important, because they are carried out at the permanent points with strict regularity during the whole year. This allows determination of the precise dates of the ice cover changes, such as: ice thickness growth, the date of freezing and the beginning of melting, the date of the establishment and break up of fast ice, etc.

It is obvious that the stationary observations, conducted mainly in the coastal regions were insufficient to provide a full understanding of the ice amount and distribution in open sea. That is why since the 30s a visual airborne ice reconnaissance has become the main tool for ice data collection.

The airborne reconnaissance in the marginal seas and in the Arctic basin was carried out with varying frequency from February to November ( and later also in December). Annually they were repeated by the standard routes at ten-day intervals in the summer-fall period, enabling tracing the spatial-temporal change of all components of the ice cover. Without exaggeration one can say that knowledge on the ice cover of the Central Polar basin and the ice regime of the Arctic Seas was largely gained by visual airborne ice reconnaissance, which for 40 years was the main source of the ice data, until the appearance of the instrumental observations means (SLAR,satellites).

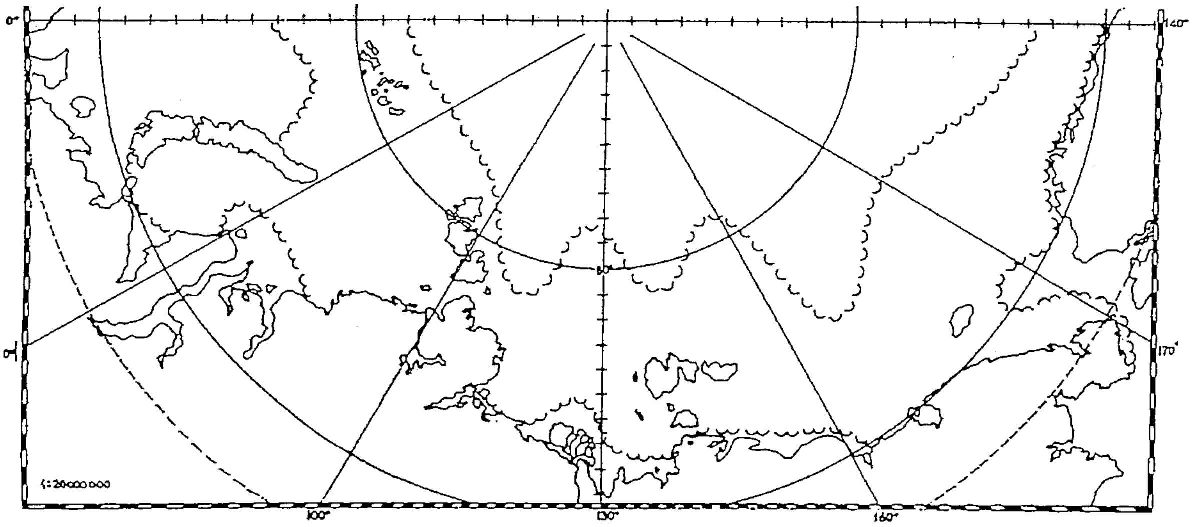

Fig. 10. Position of the ice edge at the smallest (I) and largest (2) extent in September

A considerable contribution to the study of ice cover in the central Arctic has been made by the observations at the drifting "North Pole" stations ("NP"). From 1937 to 1991 31 drifting stations were set up. The observations at the NP allowed study of the main features of the ice drift in the Arctic Ocean, due to these stations a vast amount of information on the snow and ice distribution, the rate of ice growth and melting and other ice cover characteristics was collected.

The main typical features of the ice drift in the marginal seas were obtained by means of the automated drifting radio-meteorological stations and radiomarks, set up on the ice from 1953 to 1975.

At present satellites are considered to be the main means of collecting ice information in the Arctic Seas. Airborne ice reconnaissance (visual and instrumental) is carried out occasionally, being used to test and correct satellite data. With the transition to satellite observations it became possible to obtain almost synchronous information on ice distribution simultaneously in several regions of the Arctic seas. It should, however, be noted that there was a loss of information on some ice cover characteristics, not recorded by the instruments installed aboard satellites.

In addition to the ice database to develop the methods of ice forecasts one needs the archive of meteorological data during different intervals (first of all, the air pressure and temperature fields). The data on the basis of meteorological information, used in weather, oceanographic and ice forecasts are presented in section 2.

During the development of the methods of ice forecasts the oceanographic observations and, primarily, of sea water temperature and salinity are required as initial data. In earlier years the oceanographic information was collected by the annual expeditions "Marine Patrol" in the summer-fall period in each of the Arctic Seas of the Siberian shelf. In later years the marine expeditions in the Arctic are carried out only occasionally, resulting in the loss of the continuous oceanographic data, accumulated over the decades.

The information of the initial data, necessary to develop the specific forecasts with periods in advance is presented in the corresponding sections.

## 4.2 Long-range ice forecasts on the physical-statistical basis

The methods of the long-range ice forecasts on the physical-statistical methods, developed at the AARI, allow one to predict the ice conditions in the Arctic seas practically all year round, covering all stages of the ice cover development: from the ice formation in the fall and a subsequent ice growth up to the melting and destruction in the spring-summer period. Presenting the overview of the methods of these forecasts, let us begin with the fall-winter period.

### 4.2.1 Forecasts of ice conditions for the fall-winter period

These forecasts include the forecasts of the dates of the stable ice formation and the young ice reaching a thickness of 5-10 and 20-25 cm, as well as the forecasts of the ice thickness by the beginning of melting.

*A. Forecast of the dates of the stable ice formation and the ice reaching a thickness of 5-10 and 20-25 cm.*

As has been found out by numerous studies (Gudkovich et al, 1972) the beginning of ice formation and the intensity of the ice cover growth in the Arctic Seas depend, on the one hand on the heat content of the sea at the time of its maximum heating and, on the other hand - on the intensity of the heat exchange with the atmosphere during the period of the fall-winter cooling and for some regions also on the intensity of the advective heat input with sea currents.

The maximum heat content of the sea is formed under the influence of a number of the factors, and the main one among them appears to be the date of the sea becoming ice free. In turn the ice disappearance in the sea is closely connected with the direction of air transports, with which, as a rule, the air temperature anomalies are also related.

The intensity of the sea cooling due to the heat exchange with the atmosphere is known to be governed by a temperature difference between the water and the air. And the major role here belongs to air temperature (Doronin, Smetanikova, 1967).

Evidently, the methods of the long-range forecasting of the ice phenomena in the fall in the Arctic seas should be based on taking into account on the one hand the factors forming the sea heat content, and on the other hand, the factors governing the intensity of its cooling. However, to obtain the direct characteristics of the heat content of the sea active layer and its cooling is not always possible. That is why during the development of the methods to forecast the beginning of freezing, the effect of these factors has to be represented by various indirect parameters.

Thus, the ice cover extent of the sea is closely related to the dates of ice disappearance, explaining why the ice cover extent of the sea or its region can serve as an indicator of the sea heat content.

In some regions of the Arctic seas a good indicator of the maximum heat accumulation appears to be the sum of the air temperatures (at several polar stations) for June-August, and the indicator of the cooling - the air temperature in September or the sum of the temperatures of September and October.

On the basis of these physical representations the multiple regression equations are constructed for the specific points of the coast and the islands, located along the NSR, by which the forecasts of the dates of the stable ice formation are calculated.

Usually, the forecast of freezing is prepared in early August, that is why the need arises to use the long-range forecast of the air temperature. At the same time in many studies (a review of which is given by Gudkovich et al.(1972) it was found that the dates of a stable ice formation are connected with the sea ice cover extent or its region during the period of cooling. A physical explanation of this phenomenon was found in another study (Teitelbaum, 1977). During the fall period the air temperature over the Arctic Seas is formed not only by the heat advection with the air masses, but also by the state of the underlying sea surface, primarily, by the ratio of the open water area and the ice cover. That is why the ice cover extent of the sea in August is often used as a predictor during the development of the forecasts of the ice phenomena in the fall.

Also the dates of the ice reaching the thickness of 5-10 and 20-25 cm ($D_{5-10}$, $D_{20-25}$) are closely connected with the dates of a stable ice formation. That is why for their forecast the regression equations are nore often used, connecting the indicated characteristics.

The forecasts of freezing are from 1.5 to 2.5 months in advance (depending on the early or late date of the beginning of ice formation).

In addition to the methods, which use the regression equations, there are methods, based on the division into types of ice conditions in the fall by the preceding characteristic features, which allow one to forecast the freezing in the open sea regions.

*B. Forecast of the maximum ice thickness*

The ice thickness at the moment melting commences is considered to be an important component of the ice regime and in some regions of the Arctic

Seas it serves as an indicator of the anomaly of ice conditions in summertime.

The possibility of a long-range forecast of the thickness of level (fast) ice, formed in the fall follows from the analysis of the heat balance equation (Gudkovich et al, 1972) and the method itself is based on numerous empirical studies of the dependence of the ice growth on various hydrometeorological factors. The air temperature, or more correctly the sum of the air temperatures for all months, beginning with the freezing moment and to the beginning of melting appears to be the decisive factor. It has been observed that the ice thickness anomalies are sufficiently stable, so the ice thickness correlation for March 1 and May 1 is characterized for many points by the coefficient 0.8-0.9.

A significant effect on the ice growth is produced by the heat insulation properties of the snow cover. That is why taking the effect of these factors into account is necessary both for the calculation and for the forecast of the maximum ice thickness.

Usually the forecast of the ice thickness is prepared in early March. To do this the information on the ice thickness per the date of the forecast issuance and the air temperature forecast is needed. The snow depth on the ice, or more precisely a complex of characteristics, indicating the heat insulation properties of the snow cover is determined during the comparison of the actual and calculated ice thickness for the date of the forecast issuance. The forecast is compiled for more than 30 points and the forecasted anomalies of the ice thickness anomalies are generalized by the relatively uniform segments of the NSR.

### 4.2.2 Forecasts of ice conditions for the spring-summer period

This group of the forecasts includes the forecasts of the dates of the fast ice destruction, mean ice cover extent of the Arctic Seas for the first half of the navigation and the areas of the ice massifs in each month from July to September.

*A. Forecast of the dates of fast ice destruction*

The methods of the long-range forecast of fast ice destruction are developed for those segments of the NSR, where fast ice limits the navigation of the vessels, both the transit one and at the approaches to the ports.

A natural fast ice break-up occurs under the influence of thermal and dynamic processes. The date of fast ice destruction depends on the ice thickness, formed by the beginning of melting, the date of the beginning of melting and melting intensity. It is understandable that for the forecasting of this phenomenon with a large period in advance it is necessary to take into account the winter processes, governing the ice growth and the spring processes, responsible for the ice melt. Depending on the regional features of the route segments in the regression equations, which are developed for the prognostic calculations, different indicators of the hydrometeorological processes are used: air temperature for different periods from October of the last year to May of the current year, the differences of atmospheric pressure at the representative sections, generalized characteristics of atmospheric circulation.

The air temperature from March to June is taken from the long-range meteorological forecast.

*B. Forecasts of ice extent and areas of ice massifs*

With the onset of melting a gradual ice disappearance in the Arctic Seas and the formation of summer conditions take place, governing in turn, the navigation conditions and other types of activity in the Arctic seas. The ice conditions vary from year to year. The efforts of many scientists resulted in finding out that the interannual variability of ice conditions in the Arctic seas is governed by the variability of both the large-scale and local hydrometeorological processes of the periods of ice accumulation and destruction. The role of the processes of various seasons in the variability of ice conditions was estimated using the statistical methods.

Most important characteristics of seasonal and multiyear variability of ice conditions in the Arctic Seas appear to be ice cover extent, as well as the area of close ice, which most often is centered in the specific regions and which is called the ice massifs. There are nine massifs in the Arctic Seas of the Siberian Shelf and it is they which present the largest hindrance to the navigation of the ships along the NSR (Fig.11).

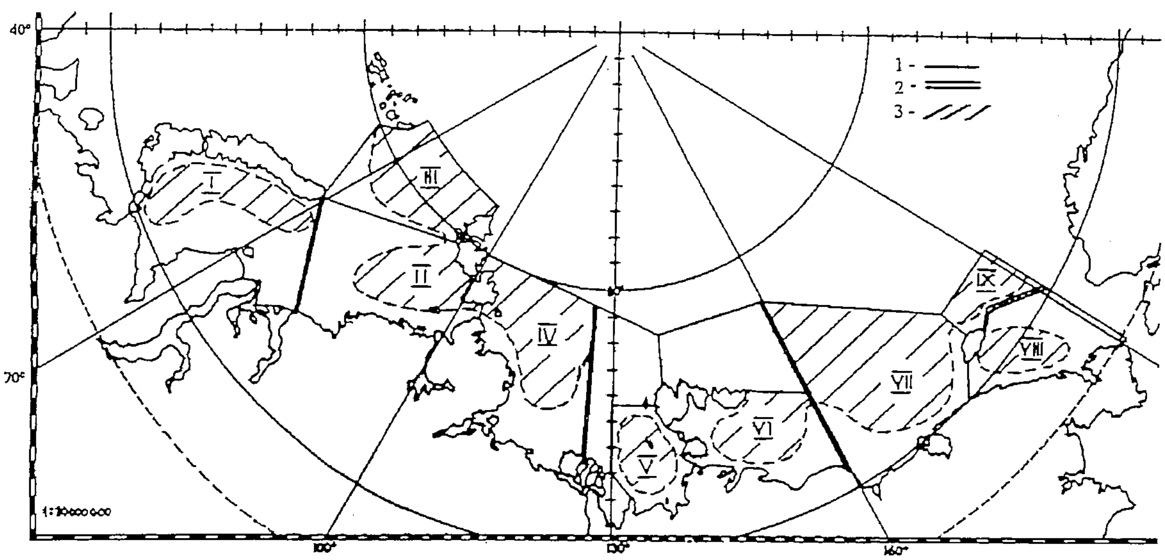


Fig. 11. The boundaries of the Arctic Seas (1) and their regions (2);
3 - a schematic position of ice massifs:
I - Novaya Zemlya; II - Northern Land; III - Northern Kara; IV - Taimyr, V -Yana; VI - New Siberian; VII - Aion; VIII - Wrangel; IX - NortherChukchi

The main methods of the empirical forecasts of the ice cover extent and the ice massifs appear to be the methods, based on the multiple correlation and the selection of the regression equations, in which the characteristics of the hydrometeorological processes of a different scale are the predictors. Depending on the differentiating features of the regime of the Arctic Seas preference is given to the characteristics of the thermal or dynamic processes or to the both. A similar approach is to the choice of the characteristics of the local and large-scale predictors, providing for a large period in advance and the verification score of the forecast, and to those, which allow one, where it is possible to avoid the use of the long-range meteorological forecast.

The regression equations for the forecast of the ice cover extent and the areas of the ice massifs have the form, given in Section 4.1, formula (8).

For the western regions of the Arctic Seas, where the role of the thermal factors of the period preceding winter and during winter is higher, one uses as predictors for the forecasts of ice cover extent and areas of ice massifs the sums of air temperatures for different time intervals, the characteristics of the general atmospheric circulation for the period preceding the forecast (a number of the days with a definite circulation type), as well as the calculated ice drift during the summer months (by a prognostic atmospheric pressure field).

As methods for the long-range forecasts in the eastern regions of the Arctic Seas one uses the results of the effect of air transports of the preceding seasons on the ice cover extent and the ice massifs in the summer-fall period, as well as the area of multiyear ice. The pressure differences at the representative sections are used as the characteristics of air transports over the central Arctic. Only the actual data are used for the forecast.

The forecast is represented by a numerical value of the expected ice cover extent and the area of the ice massifs (in %) as well as by the value and the anomaly sign, which characterizes the deviation from the mean multiyear value.

In addition to the area of the ice massifs, their position is indicated in the forecast: mean, western or eastern.

In addition to the integral characteristics of the ice conditions, that is, to the ice cover extent and the area of the ice massifs, the empirical long-range methods permit forecasting the ice distribution in the sea on the basis of its division into types. This method presupposes a preliminary classification of the hydrometeorological processes into a number of the types, corresponding to some or other ice distribution in the sea. More often the identification of three types is enough, of which one characterizes the norm, and the other two - the deviations from it in the opposite directions. The method of local-genetic division into types for the Kara Sea can serve as an example of the application of these methods in the long-range forecasts (Yegorov, Spichkin, 1990). The method provides for each region, uniform by the ice regime, the identification of the type of ice conditions, steadily persistent during the entire summer season. The division into the types is based on a combination of the characteristics of the initial ice state and partially - of the types of the expected atmospheric pressure fields.

The development of long-range ice forecasts at the AARI was historically related to the planning of cargo transportation and the support to navigation along the NSR. That is why the forecasts were always prepared on definite dates and with necessary periods in advance. Usually by these dates the actual ice and meteorological information, necessary for the forecast, had been accumulated. The forecasts are from 1 to 6-8 months in advance. In addition to general purpose forecasts, long-range special purpose ice forecasts are being developed for the support of special transit or tourist cruises as well as research expeditions.

Generalized information on the dates of the forecast issuance, their content and purpose is presented in Table 10.

Table 10. Data of the physical-statistical long-range ice forecasts for the Arctic Seas

<table>
<tr><th>Dates of the forecast development</th><th>Forecasted period</th><th>Forecasted characteristics of ice conditions</th><th>Sea reg.</th><th>Initial inform. type for the forecast</th><th>Forecast method</th><th>Prognostic information type</th><th>Purpose of prognostic information</th></tr>
<tr><td rowspan="6">15.1 "January" forecast</td><td rowspan="6">VII-VIII(2)</td><td rowspan="6">Mean ice cover extent for the first half of navigation</td><td>SWK</td><td>Actual progn.</td><td rowspan="6">Regress. equation</td><td rowspan="6">Ice cover extent values (%) for each region</td><td rowspan="6">"Baseline" approximate forecast</td></tr>
<tr><td>NEK</td><td>Actual</td></tr>
<tr><td>WLS</td><td>Actual</td></tr>
<tr><td>ELB</td><td>Actual progn.</td></tr>
<tr><td>ESS</td><td>Actual</td></tr>
<tr><td>SWCH</td><td>Actual</td></tr>
<tr><td rowspan="11">15.III "March" forecast</td><td>V</td><td>Maximum thickness for 1.V.</td><td>All sea</td><td>Actual</td><td rowspan="11">Regress. equation</td><td rowspan="11">Anomalous ice thicknesses (cm) on the NSR segments<br><br>Dates of natural fast ice break up on the limiting NSR segments<br><br>Values (%) of the areas of ice massifs</td><td rowspan="11">For planning cargo transport. for the first half of navigat. on the NSR</td></tr>
<tr><td rowspan="4">VI-VII</td><td rowspan="4">Fast ice destruction dates</td><td>KS</td><td>Actual progn.</td></tr>
<tr><td>ESS</td><td>Actual progn.</td></tr>
<tr><td>SWCH</td><td>Actual progn.</td></tr>
<tr><td>ELS</td><td>Actual</td></tr>
<tr><td rowspan="6">VII-VIII</td><td rowspan="6">Mean monthly areas of ice massife</td><td>SWK</td><td>Actual progn.</td></tr>
<tr><td>NEK</td><td>Actual</td></tr>
<tr><td>WLS</td><td>Actual</td></tr>
<tr><td>ELS</td><td>Actual progn.</td></tr>
<tr><td>EEB</td><td>Actual</td></tr>
<tr><td>SWCH</td><td>Actual</td></tr>
<tr><td rowspan="5">15.VI</td><td rowspan="4">VII-VIII</td><td rowspan="4">Mean monthly areas of ice massife</td><td>KS</td><td>Actual progn.</td><td rowspan="4">Regress. equation</td><td rowspan="4">Updated values (%) of the areas of ice massifs</td><td rowspan="4">Correction of the "March forecast"</td></tr>
<tr><td>LS</td><td>Actual progn.</td></tr>
<tr><td>ESS</td><td>Actual</td></tr>
<tr><td>SWCH</td><td>Actual</td></tr>
<tr><td>VIII(3)</td><td>Ice distribution</td><td>All sea</td><td>Actual progn.</td><td>Division into types</td><td>Maps of ice distribut. for each 10-day period</td><td>For operational support to marine operations</td></tr>
</table>

| Dates of the forecast development | Forecasted period | Forecasted characteristics of ice conditions | Sea reg. | Initial inform. type for the forecast | Forecast method | Prognostic information type | Purpose of prognostic information |
|---|---|---|---|---|---|---|---|
| 15.VII | VIII | Mean monthly areas of ice massif | KS | Actual progn. | Regress. equation | Updated values (%) of the areas of ice massifs | Correction of the "March forecast" |
| | | | LS | Actual progn. | | | |
| | | | ESS | Actual | | | |
| | | | SWCH | Actual | | | |
| | VIII(1-3) | Ice distribution | All sea | Actual progn. | Division into types | Maps of ice distribut. for each 10-day period | For operational support to marine operations |
| 15.VIII "August" forecast | IX-X | Areas of ice massifs in IX(1) and IX(3) | All sea | Actual | Division into types | Values (%) of mean 10-day areas of ice massifs Ice distribut. maps | For planning cargo transport. for the second half of navigation on the NSR |
| | | Ice distribution IX(1-3) | All sea | Actual progn. | | | |
| | | Dates of stable ice formation and ice reaching 5-10, 20-25 cm thickness | KS | Actual progn. | Regress. equation | Dates of ice formation beginning and ice reaching 5-10, 20-25 cm thickness | |
| | | | LS | Actual progn. | | | |
| | | | ESS | Actual | | | |
| | | | SWCH | Actual | | | |
| 15.IX | IX(3)-X | Dates of stable ice formation and ice reaching 5-10, 20-25 cm thickness | All sea | Actual | Regress. equation | Same | Correction of the "August forecast" |

Designations:

KM - the Kara Sea,
NEK and SWK - north-eastern and south-western Kara Sea;
LS - the Laptev Sea,
WLP and ELS - western and eastern Laptev Sea,
ESS - the East-Siberian Sea,
SWCH - south-western Chukchi Sea.
I, II, III ... - months of the year,
VIII(3) - third 10-day period of the corresponding months.

## 4.3 Medium-range and short-range ice forecasts on the physical-statistical basis

In order to collect comprehensive information about the expected ice conditions on the shipping routes and in specific points the ice forecasts from 1 to 30 days in advance are made regularly in an operational regime. On the basis of these forecasts the navigation recommendations for the management of sea operations are developed.

The physical-statistical forecasts 1-30 days in advance are based on the same physical understanding and hypotheses of the causes and formation mechanisms of ice processes as during the long-range forecasting. However, the statistical typical features, used in these forecasts are found in the data of corresponding observations, which are usually more restricted in time and space (Skriptunova, 1984).

The scientific-operational groups, which are organized by the Rosgidromet Administrations in Pevek, Tiksi, Dikson and Amderma for the navigation period, prepare the forecasts 1-3 days in advance - 2-6 times a week, 8-10 days in advance - 3-4 times a week, and 15-30 days in advance - twice a month. As requested by the users, forecasts with other periods in advance are issued too.

The main features of the methods of the most important types of ice forecasts for shipping are considered below: ice formation and growth of young ice, ice melt and fast ice destruction, drift and appearance of pressures, shift of the edges and boundaries of close ice (massifs), ice distribution in the limited regions (Abuzyarov, 1974, Kudryavaya et al, 1974).

During the development of all types of short- and medium-range ice forecasts one uses the maps of ice distribution for the time of the forecast preparation, as well as the data of meteorological forecasts with 1-3 days, 4-8 days, a month (up to 30 days) in advance with their updating for some circulation periods: prognostic maps of atmospheric pressure, air temperature, wind speed and direction, expected dates of the air temperature transition across 0°C.

The main information on the features of short- and medium-range ice forecasts of different characteristics of the ice cover are given below.

*A. Forecasts of the dates of the onset of a stable ice formation and the thickness growth of young ice*

Forecasts of ice formation and growth of young ice are compiled in the fall to determine the time of the end of the unescorted navigation and the beginning of the icebreaking escort on the route at specific points. The results of the forecasts are presented in the form of the map of the freezing isochrones and in the tables of the dates of freezing and ice reaching a thickness of 5-10, 20-25 and 50 cm.

The ways to forecast the time of the beginning of a stable ice formation are based on taking into account the intensity of the loss of the sea heat, accumulated in summer, during the fall period.

In the shallow Arctic seas the intensity of this process can be expressed by the date of the air temperature transition to below 0° in the fall and the air temperature in September. The mean date of the air temperature transition across 0° precedes the date of the beginning of a stable ice formation in different regions by 9-57 days. The least time interval in the Laptev Sea and in the western part of the East-Siberian Sea is 10-17 days, in the Kara Sea - 16-38 days, and in the eastern part of the East-Siberian and the Chukchi Sea - 13-35 days.

For some points the forecast of the dates of the onset of ice formation can be made by the regression equations, which take into account the prognostic air temperature in September or in the third ten-day period of September, as well as the water temperature in the first ten-day period of September.

The verification score of such forecasts with the allowance for +- $\pm 0.674\sigma$ is 70-85%.

During the forecasting of the dates of ice formation for the coastal regions the equations are used, which take into account the date of the air temperature transition across $0^\circ$, concentration of the previous ice in the region, the water temperature anomaly for the ten-day period prior to the air temperature transition across $0^\circ$ and the air temperature anomaly for the ten-day period after the air temperature transition across $0^\circ$.

The verification score of such forecasts is 75-85%.

To forecast the dates of ice formation in open sea the methods of Krutskikh (1970) are used, who calculated the standard regression equations for 61 points, covering all Arctic seas (Fig.12).

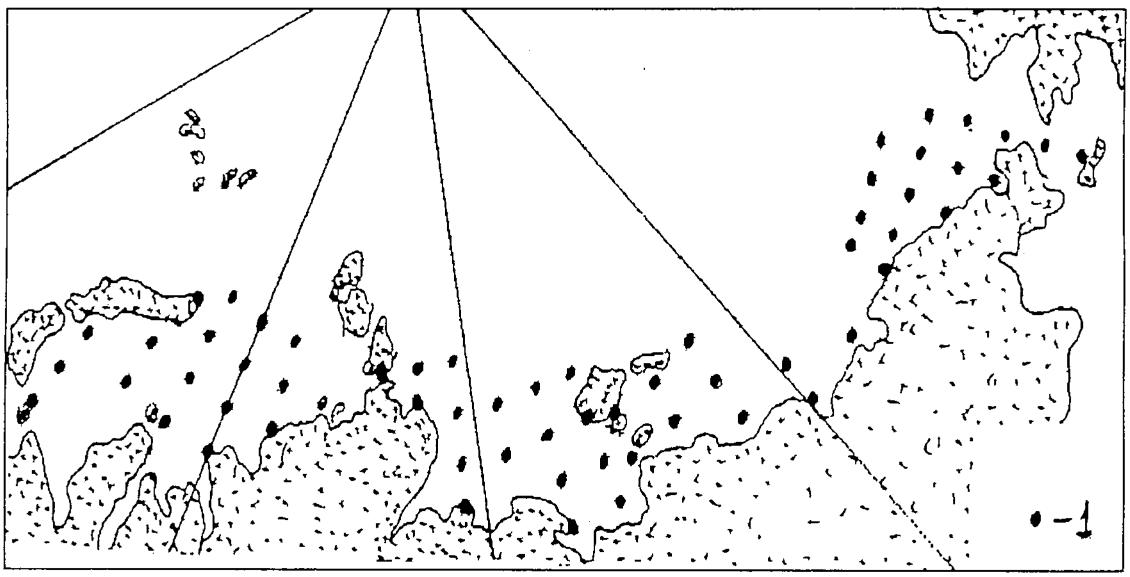


Fig. 12. A diagram of the points (1) for which the dates of the beginning of a stable ice formation are calculated

The main predictors in them are the mean thickness of the active sea layer, which in the ice presence is assumed to be equal to 0, ice concentration at the point, the distance from the point to the edge of the previous ice, air temperature in the third ten-day period of September in the given region.

The verification score of the forecasts, presented in the form of the chart of ice formation isochrones (Fig.13) is 70-80%. It should be noted that neither of the forecasting methods (this concerns the forecasts of all other characteristics too) yields good results in all regions at different initial ice conditions and therefore it is necessary to have a set of several forecasting methods and to select the best one for the given conditions.

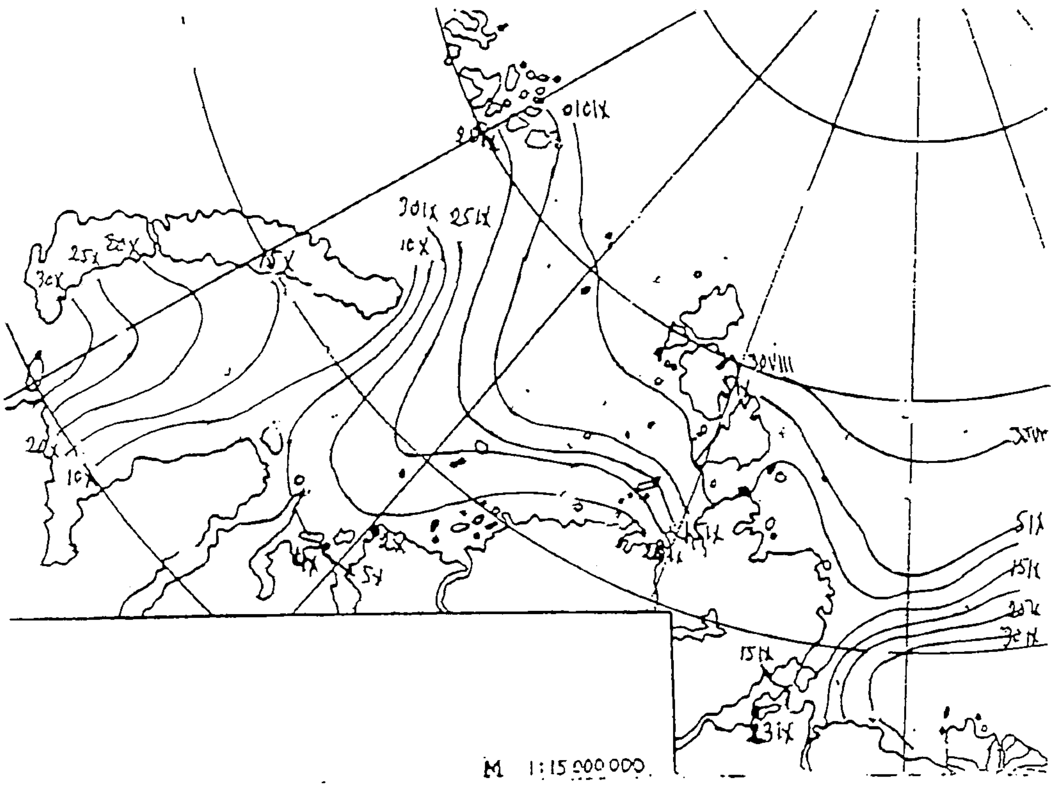


Fig. 13. An example of the forecast of the ice formation dates in the Kara Sea in 1983

I - ice formation isochrones

Further ice growth after the beginning of ice formation, the young ice reaching a thickness of 5-10, 20-25 and 50 cm, limiting the navigation, are forecasted in most cases by means of statistical dependences between the dates of the ice formation beginning and the dates of the ice reaching these thicknesses.

During the forecasting of the young ice thickness in the regions of open sea of large significance can be the air temperature, snow depth on the ice and the young ice thickness for the time of the preparation of the forecast.

To increase the timeliness and facilitate the work, tables (Table 11) and diagrams (Fig.14) have been compiled.

Table 11. Ice thickness growth (cm) depending on the initial thickness ($h_0$) and the expected sum of degree-days of frost $\Sigma$-$t_a$.

| $h_0$ cm | $\Sigma$-$t_a$ | | | | | |
|---|---|---|---|---|---|---|
| | -5° | -10° | -15° | -20° | -25° | -30° |
| 0 | 0.8 | 1.6 | 2.4 | 3.2 | 3.8 | 4.7 |
| 10 | 0.6 | 1.1 | 1.7 | 2.3 | 2.9 | 3.4 |
| 20 | 0.4 | 0.9 | 1.3 | 1.8 | 2.2 | 2.5 |
| 30 | 0.4 | 0.7 | 1.1 | 1.5 | 1.8 | 2.2 |
| 40 | 0.3 | 0.6 | 0.9 | 1.2 | 1.5 | 2.0 |
| 50 | 0.2 | 0.5 | 0.8 | 1.1 | 1.3 | 1.8 |

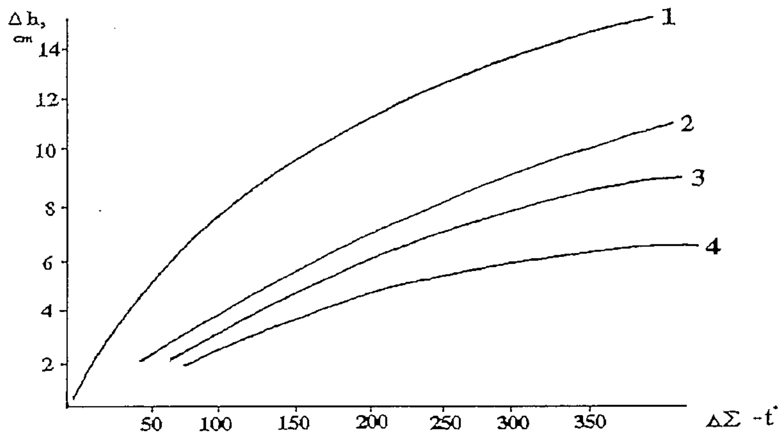


Fig. 14. Growth of ice thickness $\Delta h$ cm, depending on the increase of the sum of degrees-days of frost $\Delta\Sigma$-$t^{\circ}$ at a different snow depth $h_s$ on the ice and different ice initial thickness $h_0$:

1 - $h_s > 10$ cm, $h_0 < 60$ cm;
2 - $h_s = 11$-$20$ cm, $h_0 > 60$ cm;
3 - $h_s > 20$ cm, $h_0 < 60$ cm;
4 - $h_s > 20$ cm, $h_0 > 60$ cm.

*B. Forecasts of the ice melt in spring.*

Forecasts of the ice melt and the days of fast ice destruction are prepared in spring to determine the dates of the beginning of marine operations in the vicinity of the ports and the unloading points, the dates of the beginning of the icebreaking navigation along the routes. The dates of fast ice destruction are also required to develop the forecasts of close ice disappearance in the region.

The methods of forecasting the ice melt are based on taking into account the amount of heat incoming to the ice cover due to solar radiation, heat advection by air flows and the heat of the active sea layer.

The dates of the beginning of melting are quite accurately determined by the time of the air temperature transition across a definite value (from -0,5° to - 1,4°C. This time in most of the regions along the Arctic coast falls on the third ten-day period of May - second ten-day period of June.

For short-range and medium-range forecasts there is no need for the calculation of the radiation heat and a complete calculation of the heat balance of the ice cover, as there is a close relationship between the heat amount, incoming to the ice and the air temperature. That is why to calculate the ice melt the one-parametric linear equations of the type:

$$\Delta h_i = k\sum t_a + c$$

where $\Delta h_i$ - ice thickness decrease,

$\Sigma t_a$ - sum of the degrees-days of the heat,

K and C - are found empirically.

The forecasting practice has shown that good results are obtained using the methods of analogues and inertial dependences, when initial state is predicted.

The correlation coefficient in such dependences for the 10-day intervals can vary from 0.60 to 0.99.

Thus, in order to prepare the forecasts of the ice melt it is necessary to know the maximum ice thickness, to find out the date of the onset of melt, to take the air temperature for the forecasted period from the weather forecast and, using the methods mentioned above, to calculate the melting.

The effectiveness of the methods mentioned as compared with the climatic ones with the allowance $\pm 0.674\sigma$ is 35-55%.

*C. Forecasts of the dates of fast ice destruction.*

The decrease of the thickness of fast ice results ultimately in strength failure followed by fast ice destruction. The fast ice break-up occurs, as a rule, under the effect of the dynamic factors - wind, surge fluctuations of the sea level and tidal currents. Only in closed bays and inlets due to intensive melting can fast ice be completely destroyed at place as a result of melting.

The preceding thermal processes prepare fast ice for break-up. Most of the methods of the short- and medium-range forecasts of the dates of fast ice destruction are based on this. Taking into account the thermal factors allows assessment of the melting rate and the time of the ice thickness decrease to the critical one at which fast ice can be broken up by some dynamic factor. The value of the critical ice thickness for each point is found empirically.

For some points there is a widely used method, by which the destruction dates are forecasted by air temperature in May, June or July - actual and prognostic - depending on the time of the forecast preparation.

For some points in which forecasts of the wind speed for several days have quite a good verification score, the regression equations are used which take into account in addition to ice melting also the forecast of the wind speed.

Of great help during forecasting are the diagrams of the relationship of fast ice critical thickness with the speed of the destructive wind (Fig.15).

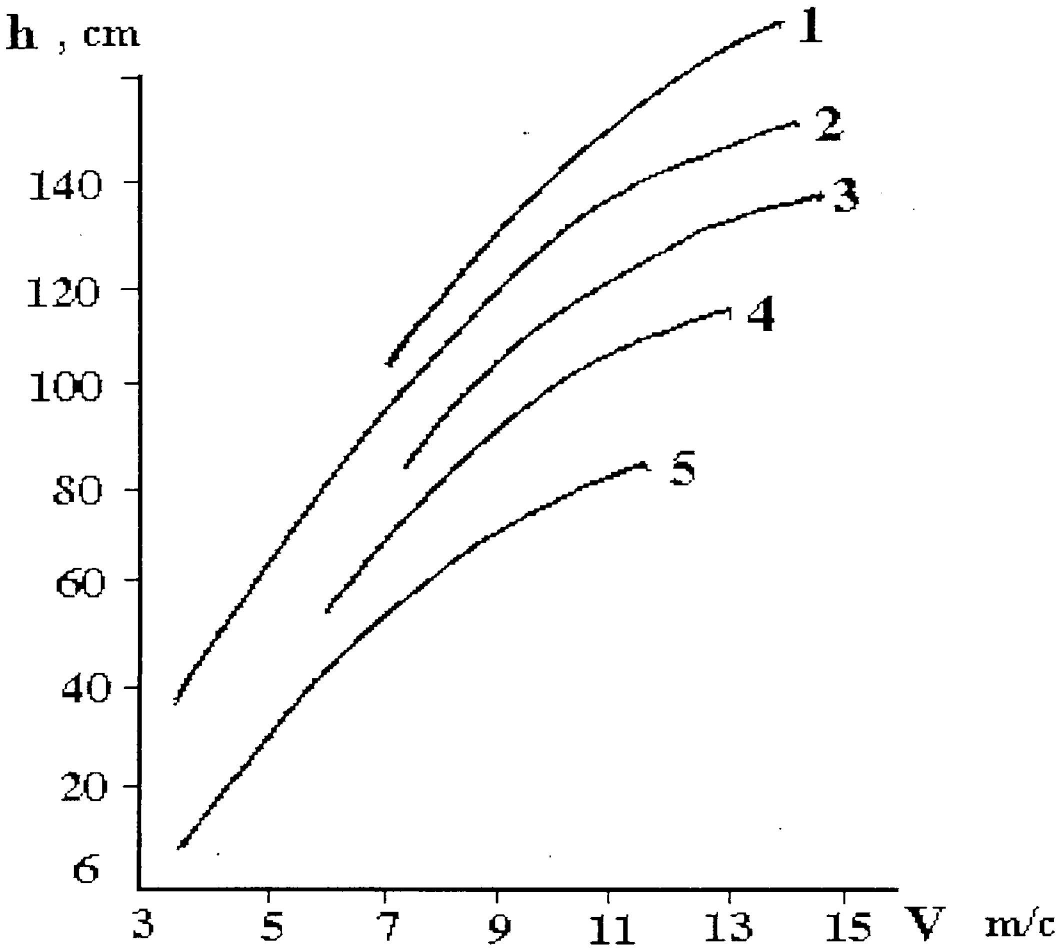


Fig. 15. Relation of ice thickness to wind speed, destroying fast ice in different geographical points of the Arctic (1-5)

The periods in advance of such forecasts depend to a great extent on the possibility of forecasting the wind speed, being 5-8 days.

There is a widely employed method which uses the date of the ice melt up to some specific thickness (for example, 130-150 cm) as a predictor in the forecasts of the time of fast ice destruction.

Such forecasts are prepared 10-20 days in advance. For some remote regions where the data on ice thickness are absent and the forecast of the air temperature is not quite accurate, one can use the regression equations which take into account the area of close ice in this region during the preceding period.

For open parts of the seas and the straits the equations of multiple regressions were derived, in which the following characteristics are used as the predictors: the anomaly of the date of the air temperature transition across 0°, the anomaly of ice thickness at the time of the air temperature transition across 0°, the anomaly of the sum of the degrees-days of frost in September-May, the anomaly of the air temperature in May, June or July. The equation allows prediction of the destruction dates for a large number of the points at the coast, for the straits and natural fast ice regions in open sea parts (Fig.16).

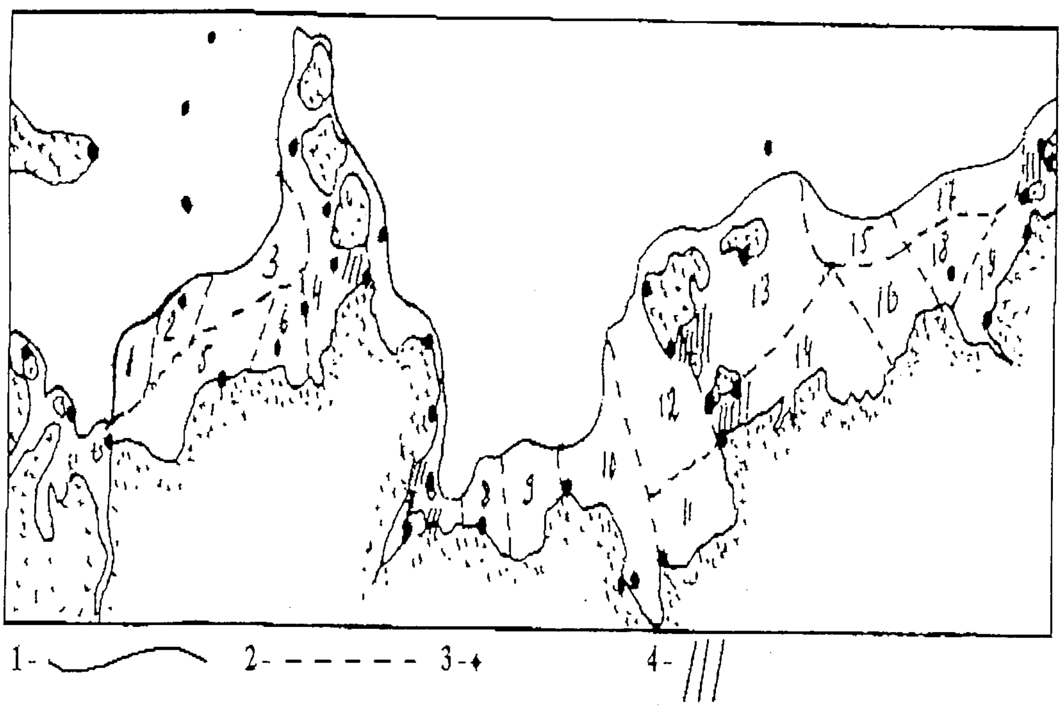


Fig. 16. A layout of the regions, straits and points for which forecasts of fast ice destruction are issued.
I - fast ice limit,
2 - boundaries of the regions 1 - 19,
3 - points,
4 - straits.

The forecasts are 5 - 30 days in advance, and their effectiveness, relative to the climatic forecasts is 20-35%.

*D. Forecasts of the ice drift and pressures.*

The main factors governing short-range - from 1 to 10 days - changes of ice conditions in the seas are considered to be the dynamic factors, and in particular, the ice drift.

Forecasts of the ice drift are prepared during the whole navigation period. They are used to estimate the direction and intensity of the dynamic processes in the ice. The data on the drift are necessary to forecast the pressures in the regions where heavy ice conditions are preserved. These forecasts are most important during the spring and late-fall period and for navigation in the ice up to 8-10/10 concentration.

Practically all forecasts of the drift 1-10 days in advance are based on "Zubov's rule", which relates the drift direction and velocity to the direction of isobars, atmospheric pressure gradients or with the wind direction and speed:

$$W_{dr}=A\frac{\partial P}{\partial x}; \qquad W_{dr}=KW \tag{10}$$

where $W_{dr}$ - drift velocity,
$\partial P/\partial x$ - atmospheric pressure gradient,
W - wind speed,
A and K - empirically calculated isobaric and wind drift coefficients.

The method of the drift forecasting develops towards a more specific value of the isobaric and wind coefficients and the drift deviation angles from isobars or wind direction in various regions and under different conditions.

Also the morphological ice characteristics, coastline, distance from the shore, sea depth, sea currents and other characteristics are taken into account. The tidal currents are taken into account in short-range forecasts in those areas where they can induce pressures in close ice.

A general drift character, its direction, formation of the compacting and diverging zones can be determined from the ice drift charts, plotted for 8 wind directions, and which are contained in special Handbooks (an example is given in Fig.17).

The calculations of the drift direction and velocity can be fulfilled by the standard values of isobaric or wind coefficients and deviation angles, and then corrected by local adjustment coefficients, calculated for the specific regions, or directly by the drift coefficient values and the deviation angle, obtained from the observations in the given sea region (Table 12,13).

The calculated ice drift vectors for several days indicate the shift of the close and open ice zones, as well as the position of the compacting and diverging zones, which are shown at the standard charts, presented in the Handbooks, mentioned earlier for different wind directions. The fields of the ice drift velocity allow one to identify the divergence and convergence zones, which govern the places of possible diverging and compacting in open sea regions.

Due to the fact that in the general case the non-uniformity of the drift velocity field depends on the wind speed the degree (force) of compacting, measured in arbitrary units (from 1 to 3) can be estimated according to Table 14.

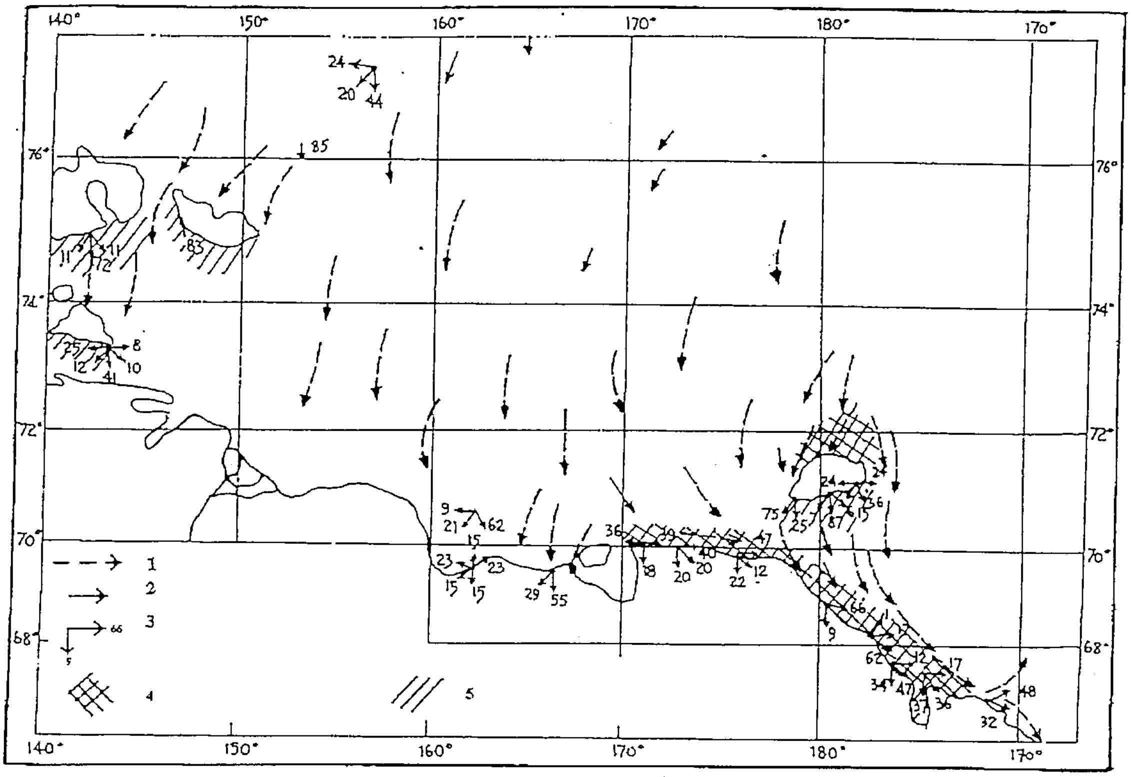

Fig. 17. Diagram of the ice drift in the East-Siberian and Chukchi Seas at the north wind (1), 2 - observed drift; 3 occurrence of the drift directions (in %), 4 - pressure zones, 5 - diverging zones.

Table 12 Mean ice drift velocity depending on the pressure gradients and ice thickness

| Pressure gradients, (mb/km) $\cdot 10^3$ | 3 | 6 | 10 | 13 | 16 | 19 | 22 | 25 | 32 |
|---|---|---|---|---|---|---|---|---|---|
| Wind speed, (m/c) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 10 |
| Ice drift velocity, h=150 cm (km/day) | 1.6 | 3.3 | 6.7 | 8.0 | 10.0 | 12.0 | 15.0 | 17.0 | 21.0 |
| Ice drift velocity, h=250 cm (km/day) | 0.6 | 2.4 | 4.8 | 7.3 | 9.5 | 12.0 | 14.0 | 17.0 | 21.0 |

Table 13 Mean wind (K) and isobaric (A) coefficients and the drift deviation angles from the wind direction (α) and isobars (β) in summer for close ice of the East-Siberian Sea

| Direction of wind and isobar (where to) | K | α° | A km²/mb·day | β° |
|---|---|---|---|---|
| N | 0.030 | 9 | 840 | -13 |
| NE | 0.022 | 1 | 620 | -21 |
| E | 0.032 | 20 | 900 | -2 |
| SE | 0.033 | 0 | 950 | -22 |
| S | 0.016 | -3 | 460 | -25 |
| SW | 0.032 | 16 | 920 | -6 |
| W | 0.029 | 21 | 830 | -1 |
| NW | 0.029 | 0 | 830 | -22 |

Table 14. The degree of compacting in close ice depending on the wind speed

| Wind speed, m/s | 4-6 | 7-12 | > 12 |
|---|---|---|---|
| Compacting force, in arbitrary units | 0-1 | 1-2 | 2-3 |

From experience it is known that the extent of the compacting zones in winter is larger than in summer and that the force of compacting is stronger in the coastal regions than in the open sea.

The shallow character of the seas, where the NSR passes, a rugged configuration of the coastline, the presence of the tides, the existence of grounded ice during the spring and the late fall periods significantly complicate the forecasting of the drift and the pressures. Of considerable help here appears to be knowledge of the ice regime features of the specific sea regions in different seasons.

Forecasts of pressures have a sufficient verification score with 1-3 day periods in advance. For longer periods they are of an assessment character.

The forecasting of tidal pressures is advisable only in some regions where the tidal effects are clearly pronounced during calm and weak wind conditions. These forecasts are compiled with the help of the Handbook on tidal currents and the table of advance calculation of the tidal level oscillations.

*E. Forecasts of the shift of the edges and limits of close ice.*

Forecasts of the shift of the edges and limits of close ice can be prepared as independent ones. But more often they are an integral part of the forecasting of ice distribution in a specific region. The results are presented in the form of the map of the edge position and close ice limits, or as a plain language text with the data on the direction and value of the shift of the edge and the limits of the massif.

The prognostic calculations of the shift of the edges and the limits of close ice are made by means of the empirical isobaric or wind coefficients.

The pressure gradients and wind characteristics are taken from the prognostic map. During the calculations with 1 - 5 days in advance the empirical coefficients are close to the corresponding values of the ice drift coefficients, and more than 5 days - may considerably differ from them due to the effect of thermal processes.

Also the adjustment coefficients to the calculated drift directions are used which are obtained for different drift directions. Practice shows that during the edge drift to open water drift speed decreases by 40-60%, as compared with the drift in the opposite direction.

The forecast of the shift of the limits and edges is considered to be rather difficult when there is a small gradient atmospheric pressure field over the region. In this case the calculation of the ice melt is necessary and is made by the relations of the melting value with air temperature. At the thickness of 20-30 cm the remaining ice usually disintegrates and large areas become ice free over a short time period.

For the forecast of the shift of the close ice limits the standard diagrams of the change in the position of the limits at different drift directions for 5 - 30 days are constructed (Fig.18). The forecasts based on them with 5 - 15 days in advance have a large verification score at sufficiently stable drift directions.

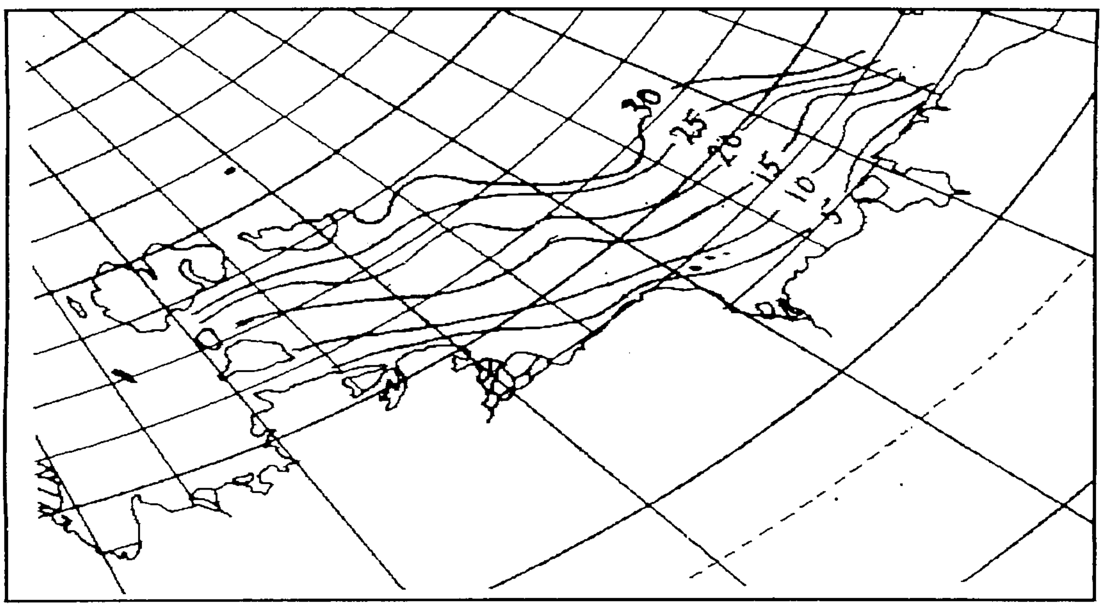


Fig. 18. Scheme of the shift of the southern limits of close ice for 5-30 days with the prevailing eastern and south-eastern winds in the East-Siberian Sea

There is a good verification score of such charactersitics important for navigation as the position of the isthmus of close ice, compacting zones, state of polynyas and regions of large break-ups in the ice cover.

Forecasts of the ice edge position at the specific sections up to 30 days in advance are based on multiple regression equations which take into account the preceding and forecasted differences of atmospheric pressure, areas of old ice and ice massifs in the given sea and other factors. According to these relations the forecasts of the position of the edges for the end of June, July, August and September are made.

*F. Forecasts of ice distribution in local regions.*

Forecasts of ice distribution are most important for the assessment of the navigation conditions. The specific marine operations in particular sea regions are planned on their basis. The forecasts are being developed during the navigation period from 10 to 30 days in advance. They are prepared in the form of the charts of ice distribution, where the forecasted drift vectors are plotted and the regions of possible ice compacting and divérging and other ice characteristics are indicated.

In the practice of the scientific-operation support to the navigation in the Arctic there is widely used a comprehensive forecasting of ice conditions in the specific local regions, taking into account all regional features of the ice regime important for navigation. Such forecasts combine all calculated-forecasted information, obtained during the development of the forecasts for some components of the ice cover.

During the forecasting of ice distribution for 5 - 30 days the forecasts, made for natural ice regions have the largest verification score.The main point of this forecasting method is to determine the future type of the development of ice processes in the local natural ice region (Fig.19) based on the actual state of the ice cover and the expected types of the development of atmospheric and hydrological processes. For the initial and the expected types of ice conditions in this or that region there are special handbooks.

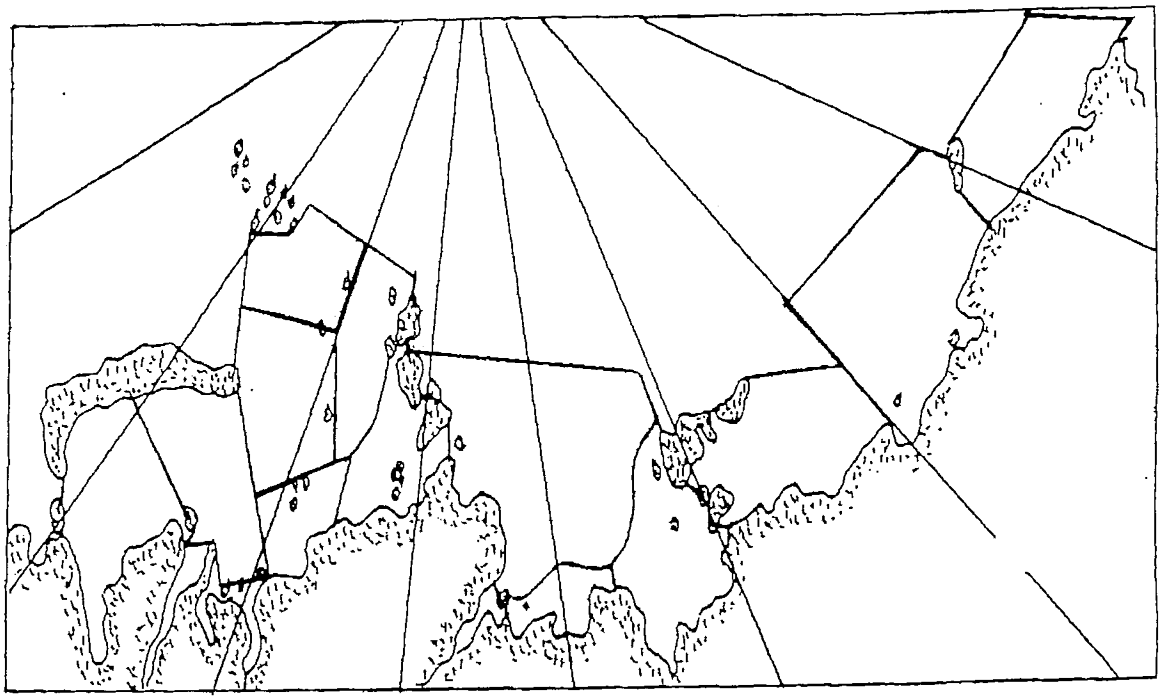

Fig. 19. Layout of natural ice regions

The diagram for the development of such forecasts is presented in Fig. 20. It is quite universal and, depending on the knowledge of the role of some or other factors in the formation of ice conditions, can include the most successful methods.

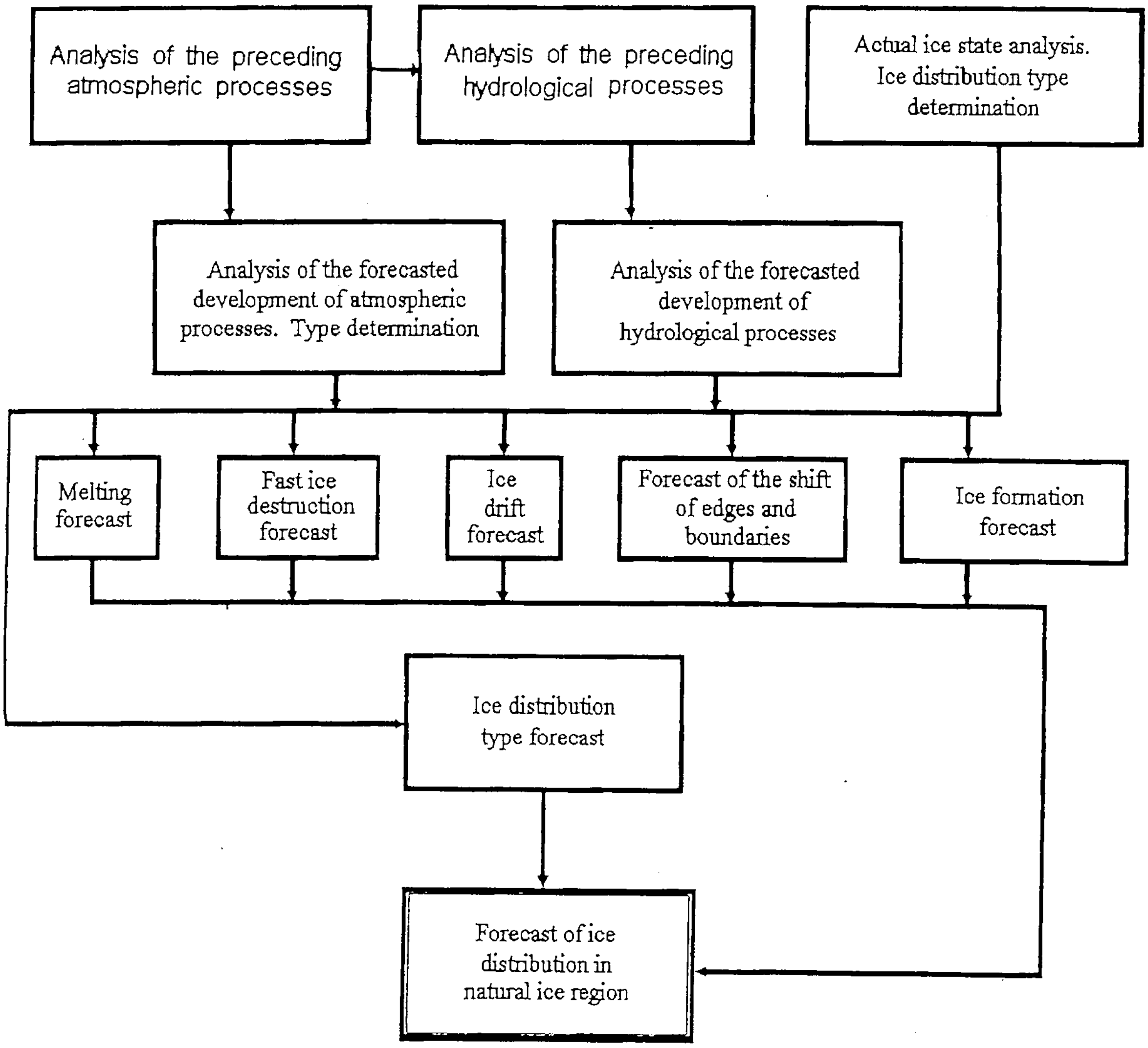


Fig. 20. Block-diagram of the technology for the preparation of ice distribution forecasts in natural ice regions

## 4.4 Research on the probability of the automated preparation of physical-statistical forecast with different periods in advance

The formation of ice conditions in the Arctic Seas is governed to a large extent by the character of atmospheric processes, on which the intensity of ice growth and melting and also its drift depend. That is why further development of long-range ice forecasts is closely connected with the solution of one of the most acute problems of present-day meteorology, that is: to find out physical causes for the occurrence of long-period anomalies of atmospheric circulation.

Another, equally important, way of improving the quality of long-range ice forecasts is to improve the methods of forecasting.

To resolve this problem on the basis of constructing the correlation dependencies results in a contradiction of some kind. On the one hand, the complexity of the investigated processes requires the inclusion of a large number of the arguments into the regression coefficients. On the other hand, at small observations series this leads to the instability of the calculated statistical parameters.

Removal of this contradiction is possible by means of the methods which allow one to identify highly informative characteristics from initial data. This task is resolved by the information transformation.

Let us call a set of data on the state of the atmosphere and the ocean the information system A. Then under the system of the predictors (X) one should understand the results of the transformation (F) of the system A, that is X = F(A).

The information system (A) and the respective system of the predictors (X) is not something absolute and constant. They can vary depending on the task set. And the variation can be both due to the choice of system A, and due to the transformer F.

If the forecasted ice conditions are designated as L, then the ratio between A, X and L can be represented in the form of the following scheme:

$$A \rightarrow X \rightarrow L$$

This scheme illustrates the fact that the data on the state of the atmosphere and the ocean, collected in A, are used in the ice forecasts not directly, but through the system of the predictors X.

And the case is possible, when X, being comprehensive characteristics of the system A is not of large value for L forecasting. 0 And vice versa, characterizing the system in rather a limiting way, the system X can turn out to be informative relative to the future ice conditions.

As has already been mentioned above the transition from the system A to the predictors X is connected with the F transformation. Such transformation usually results in a decrease of the volume of the initial information, its reduction.

The latter circumstance is of major importance since the total information volume in A is usually quite large and cannot be fully used during L forecasting.

One should distinguish between the structural and the relative compression methods.

The goal of the structural compression methods consists in finding out the transformation which leads to such a system of X predictors, on the basis of which one can reconstruct the initial information system A with a prescribed degree of accuracy. The relative methods of compression are aimed at delineating such part of the information which is directly relevant to the future ice conditions. Here, from a prognostic view point the method of relative compression appears to be more effective. A general feature of the relative compression methods is the fact that the X = F(A) transformation is based on taking into account the properties of L. This gives a possibility to extract from system A the required information, screened by the processes which do not have any relation to the forecast.

A multi-dimensional discriminant analysis can serve as an example of a relative compression. The study made which is aimed to estimate the effectiveness of discriminant analysis during the forecasting of the ice cover extent of the Arctic Seas (Kovalev, Nikolaev,1971, 1976) has shown that the predictors, identified by means of a discriminant analysis are sufficiently informative.

Quite important appears to be the fact that the relative methods of compression can be constructed in such a way that the information thus identified would be maximum relative to the criterion chosen. This allows one to make optimal the decisions, connected with the search and selection of the informative predictors. Since the entire procedure for the development of the forecasting method consists of the solutions of such kind, it appears to be possible to make this process automatic on the basis of a wide use of the relative compression methods. The problems of searching and selecting the optimal informative predictors can be addressed in the framework of creating the Automated Forecasting System (AFS) on the basis of the linear combinations using the computer (Kovalev et al.,1980). The principal diagram of such system is shown in Fig. 21. The information system, which includes the archives of ice and hydrometeorological information is considered to be its obligatory component.

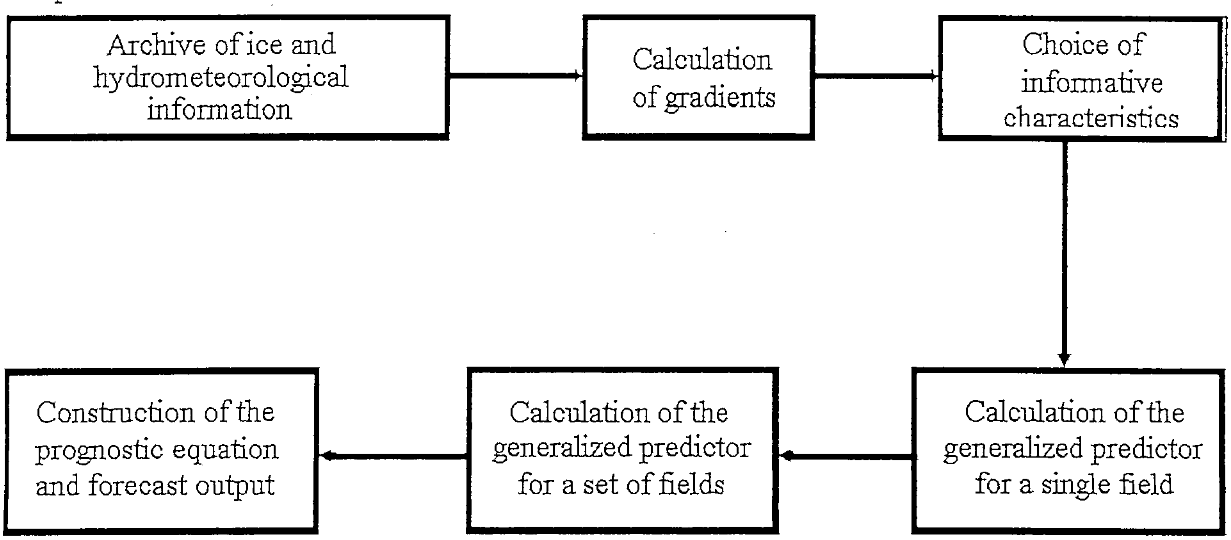


Fig. 21. Block-diagram of the automated search system for the optimum predictors and the construction of prognostic equations on the basis of linear combinations.

The most suitable form of presentation of the latter appears to be the fields of geopotentials, atmospheric pressure, water, air temperatures, etc., prescribed in the points of the grid overlapping the region under study (for example, part of the hemisphere to the north of the parallel 50° N).

The next block of the AFS is the program for calculating the differences in the characteristic values between all grid points. Particularly informative appear to be the atmospheric pressure differences, characterizing the geostrophic flows in the atmosphere. For air temperature its direct values can turn out to be more informative in some regions.

The number $N_\Delta$ of possible pressure differences rapidly increases with an increase in the number n of the grid points:

$$N_\Delta = n(n-1)/2$$

Thus, at n=20 $N_\Delta$ = 190, and at n=100 $N_\Delta$ = 4950.

From the large number of the obtained characteristics it is necessary to choose a restricted number of the most informative predictors, containing that part of the information, which has a direct relevance to the future ice conditions. For this the threshold values of quotient correlation coefficient for the given volume of sampling at a prescribed probability are used as a criterion during the selection of the predictors in the corresponding AFS block. The reduction of the volume of initial information is achieved by a more strict component at the selection of significant coefficients.

Taking into account that some anomaly or other of the ice characteristics is formed under the effect of non-uniform factors for a prolonged time interval, and the volume of the available samplings (the length of the observation series is usually small), the total number of the selected informative characteristics on all fields and time intervals, as a rule, exceeds the permissible number of the predictors to construct the regression equation. That is why for each group of the informative characteristics referring to a single field, there is one generalized predictor P, representing a sum of the effect coefficients ($K_i$):

$$P = \Sigma K_i ,$$

where the $K_i$ values are calculated by the formula:

$$K_i = U \cdot r^2,$$

here U - calculated value of the function by the regression equation;
r - square of the quotient correlation coefficient.

Similarly the generalized predictors for several fields are obtained. In this case the coefficient of the effect of the characteristics of all fields analyzed are summed up. The final prognostic equation has form:

$$U = a\sum_{1}^{n} P + b$$

where n - number of the information fields taken into account.

The suggested automated system envisages a possibility to conduct the analysis at any calculation stage, which is very important to account for the physical nature of the identified predictors, to prescribe different criteria to select the informative characteristics, to determine the errors of calculation (forecast) for the entire series of the forecasted phenomenon.

The program envisages the possibility to choose from the archive of multiyear data the length of the series,equal for all characteristics used in the calculation, as not all characteristics, entered into the archive can have the same observation series.

One more feature of this system is the possibility of its constant adjustment with the increase of the observation series and input of new hydrometeorological characteristics. The software of this system has been developed for the computer "Minsk-32".

The automated system was preliminarily tested relative to the forecasts of the ice cover extent of the Arctic Seas and their regions. As initial data the fields of mean monthly atmospheric pressure,expressed by its values in 189 grid points covering the Arctic region, were taken. Preliminarily, in order to reduce the information volume, these data were averaged over 21 regions. Also the series of mean monthly air temperature values over the Arctic Seas were used.

The analysis of the results has confirmed the typical features known earlier (Gudkovich et al.,1972), which characterize spatial and temporal dependencies of the ice cover extent of different regions on weather conditions.

The use of the above mentioned archived data on air pressure and temperature has allowed for the construction of the prognostic schemes for the ice cover extent of the Arctic Seas 6-8 months in advance (Kovalev, 1981).

The testing of the verification score of the forecasts was made on independent data. For the analysis the ice cover extent series of the Barents, Kara, Laptev, East-Siberian and the Chukchi Seas for July-September was used.

The assessment of the verification score of the January and March forecasts has shown their sufficiently high effectiveness (see section 4.8), being 8-19% (with permissible error $\sigma$ - for the January forecasts) and 16-33% (with permissible error 0.8 $\sigma$ - for the March forecasts).

In the final form the automated system yields the following characteristics:

- informative predictors, selected from the pressure fields and other hydrometeorological characteristics;
- regression equations between each informative characteristics and the forecasted characteristics;
- a generalized predictor for the entire series,used in the calculation;
- final regression equation between the generalized predictor and the forecasted characteristics;
- final result, containing the actual and prognostic series and the forecast error for each year which allows for the determination of the verification score of the forecast for the entire series used.

Thus, the results of the operation of the automated system demonstrates its wide possibilities for research purposes and preparation of the prognostic schemes with different periods in advance.

To introduce this system further into the research and prognostic activities it is necessary:

- To convert the software, developed for the "Minsk-32" computer for the modern computer means;
- To make the choice of hydrometeorological characteristics to extend the archive and to use different characteristics on the ice regime for the forecast;
- To establish a complete database for different meteorological and ice regime characteristics, which need to be forecasted.

## 4.5 Mathematical models as the basis for numerical methods of ice forecasts with different periods in advance

The numerical methods are based on physical-mathematical models of the ice cover evolution, which include the systems of differential equations in quotient derivatives with boundary conditions and methods of their numerical solution.

The construction of mathematical models of the ice cover has quite a long history, the presentation of which lies beyond the scope of the present report. More or less detailed reviews referring to this problem of the studies can be found in the monographs of Doronin (1969), Doronin and Kheisin (1975), Timokhov and Kheisin (1987), Appel and Gudkovich (1992). In spite of a large number of the ice cover models, developed both in Russia and abroad, only some of them have found application in the practice of providing ice forecasts of different kinds.

Of the foreign models most known appears to be the dynamic-thermodynamic model of Hibler III (1979, 1980), where the results of Semtner (1976) are used as a thermal block. In 1987 this model served as a basis for the Polar Ice Predicting System (PIPS), the aim of which was to issue regularly daily ice forecasts with up to 6 days in advance for the entire Arctic Ocean (Preller, 1985).

The PIPS is an integral part of the Automated Environmental Prediction System (AEPS), used by the US Navy. Similar regional systems (RPIPS) are being developed, for instance, for the Barents Sea. The methods of numerical forecasts for the Gulf of Bothnia (Lepparanta, 1980) can also serve as an example of the regional use of the ice cover model.

A brief description of the ice cover models developed at the AARI and which are used in the ice forecasting system for the Arctic Seas is given below.

For scientific support to navigation along the Northern Sea Route there are usually used both the dynamic models, aimed to simulate the shift of ice, its concentration, diverging and deformation under the wind effect, and the dynamic-thermodynamic models, which along with the dynamic processes also take into account the thermal processes of the ice melt and growth. The dynamic models are used during short-range forecasting, while the dynamic-thermodynamic ones - in long-range and medium-range calculations and forecasts.

A description of the basic dynamic-thermodynamic model is given in detail by Appel and Gudkovich (1992). It is based on the postulates of the mechanics on the mass and momentum conservation, expressed by the differential equations (11) and (12). (These equations refer to the one-dimensional case; however, a two-dimensional description does not change the principal diagram, although it has some features complicating the calculation formulas):

$$\frac{\partial m}{\partial t}+\frac{\partial mW_x}{\partial x}=D_m \qquad (11)$$

$$\frac{dmW_x}{dt}=F_m+F_r \qquad (12)$$

Here: m - ice mass;
$W_x$ - drift velocity component by x-axis;
$D_m$ - mass change rate under the effect of thermal processes;
$F_m$, $F_r$ - external and internal forces, respectively;
t - time.

All forces and the mass are referred to the sea surface unit.

Taking into account that the time for the establishment of the ice drift velocity is equal to several hours, in order to find the drift velocity field to model the change of the ice cover state for the time intervals, exceeding a day, one can use the stationary motion equation, however, the determination of local mass changes is obligatory. With the quasistationary formulation ( m has a small influence on $\vec{W}$) the integration by time can be fulfilled without a strict combined solution of the equations (11) and (12). At each time step the Δt equation (12) is used to find $\vec{W}$, and the equation (11) - to find m.

The m value can be expressed through the function of the probability density of ice thickness φ(H) and the ice cover concentration N:

$$m=\rho N\int_0^{H_{max}} H\varphi\ (H)\ dH=\rho N\overline{H} \qquad (13)$$

In the moving cell the change of mean thickness ( $\overline{H}$) and φ(H) is governed by the effect of thermal processes

$$\frac{\partial H}{\partial t}+W_x\frac{\partial H}{\partial x}=D_H \qquad (14)$$

where $D_H$ - rate of the ice mean thickness change as affected by thermal processes, which is related with the corresponding rate of the mass change by the ratio:

$$D_H=\rho ND_H+\rho\ \overline{H}D_N \qquad (15)$$

where $D_N$ - rate of the concentration change under the effect of thermal processes.

From the equations (11), (12), (14) and (15) we obtain the equation for the determination of concentration

$$\frac{\partial N}{\partial t}+\frac{\partial N W_x}{\partial x}=D_N \tag{16}$$

For the integration of the equations (14) and (16) one uses their splitting into two systems, which are being resolved successively at each time step. First, the change of N, $\overline{H}$ (φ) is determined as affected by the thermal processes, then their redistribution due to the drift is found.

Under the effect of the thermal processes in the Arctic Seas the change of ice thickness and concentration, as well as the heat content of the upper water layer occurs. Their intensity is determined on the basis of the equation of heat balance of ice or water surface:

$$q_s = q_\Sigma (1-\alpha) + E_a + q_T + q_d$$

where $q_s$ - resulting heat flux through the surface;
$q_\Sigma$ - total short-wave solar radiation;
$\alpha$ - albedo of the underlying surface;
$E_s$, $E_a$ - long-wave radiation of the surface and counterradiation of the atmosphere;
$q_T$, $q_d$ - sensible and latent turbulent heat exchange of the surface with the atmosphere.

The study of the semi-empirical expressions $E_s$, $E_a$ and $q_s$ taking into account the conditions characteristic of the Arctic allowed one to derive an approximate equation for $q_s$:

$$q_s = q_\Sigma (1-\alpha) + A + B T_a - C T_s \tag{18}$$

where $T_a$, $T_s$ - air and underlying surface temperature;
A, B, C - coefficients, the value of which depends on the value of some physical constants and other parameters.

Taking into account that the values $q_\Sigma$ and $\alpha$ in each moment are known, the value turns out to be connected with two parameters -air temperatures in the boundary layer and at the surface. Resolving equation (18) together with the heat conductivity equation for the ice-snow cover at the condition of a linear temperature change by thickness in each layer

$$q_s = \frac{T_s - \Theta}{\dfrac{h}{\lambda_{sn}} + \dfrac{H}{\lambda_i}} \tag{19}$$

where θ - ice bottom temperature (freezing temperature of water of a prescribed salinity);
h - snow depth;
$\lambda_{sn}$, $\lambda_i$ - snow and ice heat conductivity,

we find $T_s$, and at a prescribed $T_a$ we get a possibility to calculate the value $q_s$. At $T_s \geq 0^\circ$C melting occurs; in these conditions the value $q_s$ is determined at $T_s = 0^\circ$C taking into account the value $\alpha$, characteristic of one and the same surface (snow, "dry" ice, puddle, thaw hole or fracture).

The value $T_a$ in formula (18) is found taking into account the transformation of temperature above an inhomogeneous underlying surface, sea ice cover extent and heat advection in the atmosphere on the basis of the empirical dependencies. The process of the formation of puddles and their transformation into thaw holes , which is taken into account in the model, is connected with the non-uniform snow depth.

The snow depth change at level parts due to the melt or growth is determined by the equation:

$$\frac{dH}{dt} = -\frac{q_s}{\rho L} \tag{20}$$

Also the heating or the cooling of the upper uniform water layer at the ice free sea surface is calculated. In the presence of ice cover (N<1) the heat, absorbed by fractures ( proportional to their relative area, I-N) is partially lost to the lateral ice melt, resulting in the concentration decrease:

$$\frac{dN}{dt} = \frac{q_1}{\rho LH} \tag{21}$$

The portion of this heat is assumed to be proportional to N. In the variant of the model which in addition to the evolution of mean ice thickness takes into account the change of the probability density function $\partial\varphi/\partial t$, this is achieved by a separate calculation of the melting of "dry" ice parts and those, covered by puddles. For this the change of the area and depth of the puddles in time is taken into account.

The dynamic block of the model is based on the force balance equation (motion equation) for the ice surface unit:

$$\frac{m\,d\vec{W}}{dt} = \vec{\tau}_a + \vec{\tau}_w + \vec{F}_c + \vec{F}_\rho + \vec{F}_f + \vec{F}_R \tag{22}$$

where $\vec{\tau}_a$, $\vec{\tau}_w$ - tangential stress at the upper and lower ice surfaces;

$\vec{F}_c$ - Coriolis force;

$\vec{F}_\rho$ - projection of the gravity force on sea surface;

$\vec{F}_f$ - form resistance;

$\vec{F}_R$ - internal resistance, governed by the interaction of the floes with each other.

Since the stationary motion is being considered, the left part of the equation (22) is assumed to be equal to 0.

To calculate $\tau_a$ one uses 10-day averaged fields of atmospheric pressure at sea level. In these conditions the tangential stress is proportional to the first degree of the wind speed, and the expression $\tau_a$ takes the form:

$$\vec{\tau}_a = K_a\,(\cos\gamma_a \vec{K} \nabla P_a + \sin\gamma_a \nabla P_a) \tag{23}$$

where $\gamma_a$ - angle of the surface wind deviation from isobar;

$\nabla P_a$ - atmospheric pressure gradient;

$\vec{K}$ - single vector, perpendicular to the horizontal plane;

$K_a$ - coefficient of proportionality.

The expression for the tangential stress at lower surface is similar to (23):

$$\vec{\tau}_w = K_w [\cos\gamma_w (\vec{W} - \vec{U}_g) + \sin\gamma_w \vec{K} (\vec{W} - \vec{U}_g)] \quad (24)$$

where $\gamma_w$ - angle between the relative drift vectors and the tangential stress;

$\vec{U}_g$ - vector of the gradient current velocity at the lower boundary of the friction layer;

$K_w$ - coefficient of proportionality.

In the expressions (23) and (24) the following values of the parameters are assumed:

| | |
|---|---|
| $K_a$ = 23.5 (m) | $\gamma_a$ = -23° |
| $K_w$ = 0.3 (kg/s·m²) | $\gamma_w$ = 174° |

If the calculations are made by instantaneous (at fixed hours) pressure fields, then instead of the expressions (23) and (24) the quadratic dependencies are used.

For the forces $\vec{F}_c$ and $\vec{F}_\rho$ the traditional expressions are used:

$$\vec{F}_c = -\rho H 2\omega_z \times \vec{W} \quad (25)$$

$$\vec{F}_\rho = -\rho g H \vec{K} \times \nabla\delta \quad (26)$$

where $2\omega_z$ - Coriolis parameter;

$\nabla\delta$ - slope of the level sea surface.

The force $\vec{F}_f$ is taken into account during the calculation of the velocity of open and very open ice (N<0.7). In this case $F_R$ = 0, and the drift velocity depends on the thickness and horizontal dimensions of the floes, i.e. the degree of fracturing of the ice cover. The latter can be determined on the basis of the empirical dependencies on ice concentration and degree of destruction.

Since the effect of the internal interaction forces is evident mainly in the energy dissipation as a result of ice break- up and hummocking and the description of the dissipation processes for the ice cover formally coincides with the expression for stresses in viscous liquid, the force $\vec{F}_B$ is related with the deformation rate. And the normal pressure stresses in the main axes ($\xi$ and $\chi$) of the deformation rate tensor are determined:

$$\left.\begin{aligned} F_{B_\xi} &= K_1 H \frac{\partial^2 W_\xi}{\partial \xi^2} \\ F_{B_\chi} &= K_1 H \frac{\partial^2 W_\chi}{\partial \chi^2} \end{aligned}\right\} \tag{27}$$

The coefficient value in these expressions is determined from the conditions:

$$K_1 = \begin{cases} K_1' H(3N-2) & at \ N>0.67, \ div\vec{W}<0, \ \dot{\varepsilon}<0 \\ 0 & at \ N\leq 0.67, \ div\vec{W}\geq 0, \ \dot{\varepsilon}>0 \end{cases} \tag{28}$$

Here $\dot{\varepsilon}$ - deformation rate,

$K_1' = 10^{10}$ kg/s·m² .

The calculation of the drift velocities for the grid points is carried out by means of iteration, and the free drift ($F_B$ = 0) is assumed to be the initial approximation, and the direction of the main ellipse deformation is taken from the results of the preceding iteration.

As a boundary condition for the drift velocity at solid boundaries the velocity component normal to the shore is assumed to be equal to 0 (at the on-shore drift).The tangent component is found from the conditions of the presence of a narrow boundary layer in which the shear deformation is large. The values of the viscosity coefficient within this layer are assumed to be dependent on the stress normal to the shore. At a liquid boundary and at the ice edge during the drift from the calculation area the velocity of the free drift is assumed.

The model uses a principally new method of calculating the advective changes of the ice cover parameters, based on the allowance for the subgrid changes of these parameters (C). The inconstancy of C within the cell is taken into account by means of determining not only the average value

$$C_m = \int_{-0,5}^{0,5} C(\zeta)\, d\zeta \tag{29}$$

but also the first moment of its spatial distribution ($J_m$).

$$J_m = \frac{1}{C_m} \int_{-0,5}^{0,5} C(\zeta)\, \zeta\, d\zeta \tag{30}$$

This allows one to reduce the calculation errors by two orders of magnitude, as compared with the use of an explicitly directional finite-difference approximation, with the preservation of the simplicity of realization (Appel, Speransky, 1990).

The model, the main features of which are presented above, is used to develop long-range and medium-range forecasts of ice distribution in the summertime, as well as for calculations in winter (mainly multiyear ice distribution).

The software envisages a possibility of the calculations for an arbitrary configuration of sea area, located within a rectangular contour, which is divided into square cells.The spacing of the grid used is from 50 to 75 km. The introduction of the grid with a 25 km interval is planned. The matrices of the differentiating indications for the cells: "land", "fast ice", "sea" and the corresponding boundaries between them are identified at the grids. After the break-up of fast ice a new matrix of the differentiating indications is formed and automatically the directions of coastal boundaries, necessary for the calculations are determined.

The application of the equation (20) for the calculation of ice growth in winter does not allow for the calculation of heat influx to the bottom ice surface from the lower water layers. The effect of such flux is particularly large in the areas where an advection of relatively warm and saline waters is noted. Mean values of the indicated heat flux, determined by different ways from the field experimental data can be prescribed for each cell as an external parameter. However, more strictly they are calculated in the model of Frolov (1981), which takes into account the initial distribution of water temperature and salinity at standard levels in the regular grid points, as well as the process of the upper sea layer salination at ice formation. Developing the results of the preceding studies (Doronin, Smetannikova, 1963) the model mentioned above enables one to calculate the vertical deep heat fluxes, governed both by the convection and the turbulent heat exchange taking into account the horizontal heat and salt advection by wind-driven currents. Using the method, based on this model, the distribution by sea areas of the dates of a stable ice formation, thickness and concentration of young and multiyear ice, the edge location at the end of each ten-day period with up to 4 months in advance are forecasted.

The model of the long-term ice cover evolution in the fall-winter period was later modified (Petrov, Frolov, 1990). The calculation of the inhomogeneity of the ice cover thickness, connected with the formation of break-ups and hummocking was introduced into the model. In order to take these effects into account the method of the "particles in the cells"was used, which was first applied in ice models (Ovsiyenko, 1976). The ice thickness distribution and concentration in each cell are determined by a set of the markers which have an individual thickness and the amount of hummocking. Three types of the hummocks, introduced into the model have morphometric features, depending on the initial thickness of level ice. The hummocking starts among ice with a minimum thickness and is restricted by a limited amount of hummocking, depending on ice thickness. The advantage of this model is not only in the possibility to obtain the information on such important for the navigation characteristics of ice as the amount of hummocking, but also in the large accuracy in the calculations of the heat exchange through ice, volume of the ice formed, as well as the convection intensity in the subice water layer.

Of quite obvious interest appears to be a short-range dynamic model of ice redistribution in the fall-winter period, developed in the Murmansk branch of the AARI, which is used for the support of the transport operations and the activities of the fishing fleet in the Barents Sea and the south-western Kara Sea (Zuyev, 1983).

The tangential stress at the upper surface in the equation of motion is in agreement with the parametric model of the atmospheric boundary layer (Romanov, 1974), and at the lower surface - by means of integrating the turbulent energy balance equation within the boundary ocean layer. The ice cover is represented by a continuous two-dimensional elastic medium, the pressure change in which depends on ice thickness, being related with the change of its concentration.

To solve the equation system the method of particles in the cells is used. Approximately also the effect of the thermal processes on the change of the ice thickness, concentration and the edge position is taken into account.

The method provides a possibility to forecast up to 3 days in advance the ice edge position, concentration field, formation and disappearance of flaw polynyas, position of the compacting and diverging zones of the ice cover.

A comparatively simple short-range dynamic model of the ice cover (Kolesov, 1990), adapted to the conditions of the Arctic basin, the Barents and the Kara Seas allows for the calculations of the drift velocity field, concentration and diverging zone of the ice cover and some characteristics of its stresses and deformation. Here the ice cover has the properties of a viscous non-compressible film and the pressure is expressed by the equation of the Poisson's type (Nikiforov, Timokhov, 1974). A particular feature of this model appears to be the introduction of the notion "concentration threshold" (N = 0.9) on reaching which the internal interaction forces begin to act, and in the drift velocity field the divergence is equal to 0. The non-uniformity of the ice thickness, obtained either from the observation data or from the climatic calculations, for example(Hibler, 1979) is taken into account. For the Arctic basin a grid with a 200 km spacing is used, in the seas - from 10 to 50 km. For the model verification the data of observations of the drift of automated buoys "ARGOS" are used.

In conclusion of the review let us mention the model of the cover dynamics of the synoptic scale, developed at the AARI, a particular feature of which appears to be a more accurate description of the external forcing impact on the ice, as well as of the dynamic processes directly in the ice (Pozdnyshev, 1990).

The model takes into account the ageostrophic component, inherent to the real wind, related with the non-stationary pressure field and constituting on an average 20% of the geostrophic wind speed. The non-stationary pressure field is one of the reasons for the ice drift divergence, appearance of the pressure zones in the ice cover. The scale of this phenomenon is comparable with the characteristic dimensions of the pressure formations, and the divergence value, governed by the ageostrophic component, is comparable with the mean value of the velocity divergence of the stationary ice drift.

To calculate the wind transformation near the Earth the parameterization of the stratified boundary layer is introduced into the model. The calculations of the annual variations of the tangential wind stress and its turning angle in the surface layer, made for the average conditions of the central Arctic indicate that the allowance for the stratification can change the tangential stress by 2.25 times, and the turning angle - by 10°.

The model uses the non-stationary equations of sea ice motion, which take into account the Coriolis force, the tangential stresses from the side of air and water, the internal interaction force. The friction force at the ice cover bottom is prescribed by the quadratic resistance law. To describe the internal interaction forces the ice representation as a hard-plastic medium is used.

The model was used to investigate the conditions for the occurrence of inertial variations of the ice drift velocity, as well as for the calculation of the occurrence of pressures in the Arctic basin, recorded by specialized observations at the drifting "North Pole" stations.

## 4.6 The information used in numerical ice forecasts and calculations

To fulfil numerical calculations and forecasts it is necessary to prescribe the initial conditions and current information. Considering that the existing system for the acquisition and reporting of the hydrometeorological data (including ice data) does not always allow one to obtain the required characteristics of the state of the ice cover and water masses at the time of the forecast preparation ($t_0$), there is a need to use the data for the earlier period t (let us call it the initial moment, to which the initial information corresponds) and to derive the change of the conditions for the period $t_0$ - $t_1$ by means of numerical calculations.

In this connection the current hydrometeorological information, on which the changes of the forecasted ice characteristics depend from the initial momemt $t_1$ up to t - the time moment for which the forecast is given, should be arbitrarily divided into the current actual and the current prognostic information: the latter refers to the time interval t - $t_0$, which expresses the period of the forecast in advance. Let us note that the difference of the notions "calculation" and "forecast" is in the fact that in the first case all current information is considered to be actual and in the second case, at least partially - prognostic.

The initial data for all numerical methods of the ice forecasts are, first of all, considered to be the ice observation data (visual and instrumental airborne reconnaissance, satellite images in the visible, IR and radio ranges). These data are presented in the form of the composite charts, which combine all available ice data, collected over a limited time interval (usually 3-7 days). The data on ice concentration are entered into the computer with the help of the display in the format "Contour", being automatically averaged by each cell and then they are entered in the matrix form (in grid points) onto a technical medium. The ice thickness data are entered separately in the matrix form.

The ice information, reported by the time of the calculation of the forecasts is used for the correction of the corresponding calculated data and as a result the initial information for numerical forecasts is formed.

The initial ice information for the long-range numerical forecasts for the fall-winter period is formed in the third ten-day period of August. And the data on ice thickness can be taken from the calculations for the summer period, or derived from empirical concentration dependences. The initial information on water temperature and salinity is important for these forecasts. These data are obtained as a result of mapping of the observations of the oceanographic expeditions and coastal stations, as well as of the airborne IR-surveys - taking into account the character of mean multiyear or standard fields. The matrices of temperature and salinity values at 11 standard levels (0, 5, 10, 15, 25, 35, 50, 75, 100, 150, 200 m) are formed by the points of the coarse grid with a double spacing relative to the main grid.

Special matrices contain information on sea depth, coastline, mean position of fast ice boundaries in each month.

The initial information for numerical long-range and medium-range forecasts for the summertime includes the data on ice concentration and thickness in late May (in the Barents Sea -in late April). The information on ice thickness is obtained from the estimates of the ice age, observations of coastal stations, being updated from the results of numerical forecasts for the preceding winter period.

The short-range numerical forecasts use similar data as initial information, at the moments, most close to the time of the preparation of the forecasts.

The numerical methods use three types of initial information:

A. Air temperature and atmospheric pressure fields at sea level (actual or prognostic) presented either in the form of charts at fixed hours or charts, averaged over the definite periods (several days, ten-day, elementary synoptic period), or in the form of the table of the atmospheric pressure fields in the points of a 5 degree geographical grid, disseminated by the European Center of the Weather Forecasts. Considering that the fields of meteorological elements have quite a smooth structure, during the use of the weather charts in long-range and medium-range forecasts the values of meteorological elements are taken in the coarse grid points (200-400 km spacing), and then they are reconstructed into the points of the main grid by means of parabolic interpolation. Interpolation is also used in the numerical short-range forecasts to reconstruct the atmospheric pressure in the points of the square grid from the data referring to the geographical grid.

B. Climatic information, obtained on the basis of the processing of the observation data for a more or less long preceding period. It includes the information on total short-wave radiation, cloudiness, humidity, thickness of the mixed surface water layer, diagram of the "constant" surface currents, position of the fast ice boundaries in each month, thermal-physical properties of snow and ice, etc. In the conditions of the Arctic, where due to a small interannual variability of cloudiness and other factors it can be sufficient to take into account only the annual variations of the intensity of short-wave radiation, its values being prescribed in the form of the matrices of mean multiyear ten-day fields in the coarse grid points. Instead of the prognostic air temperature and atmospheric pressure fields due to their low verification score the long-range forecasts also use mean multiyear maps. The mean diagrams of the surface currents are constructed on the basis of the existing understanding on water circulation, model calculations and the analysis of the errors of the preliminary calculations, in which the currents were not taken into account.

C. Empirical (statistical) dependencies, which allow deriving the required parameters from the calculations. The examples of the use of such information in the numerical methods of ice calculations and forecasts are the dependences of the snow depth on mean ice thickness, dependence of the surface albedo on the snow cover and a relative snow melting, empirical typical features of the air temperature transformations over a different underlying surface, etc.

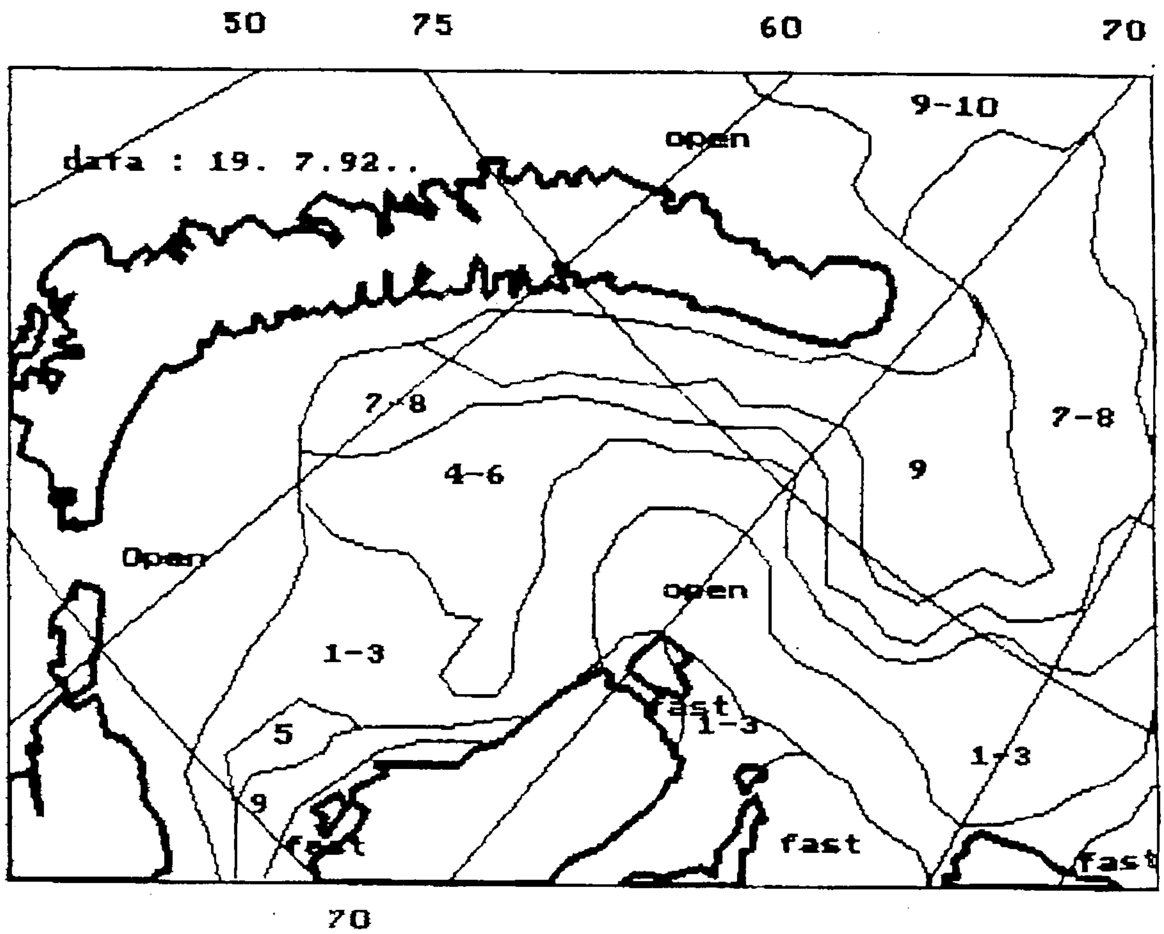


Fig. 23. An example of the forecast of ice concentration 7 days in advance

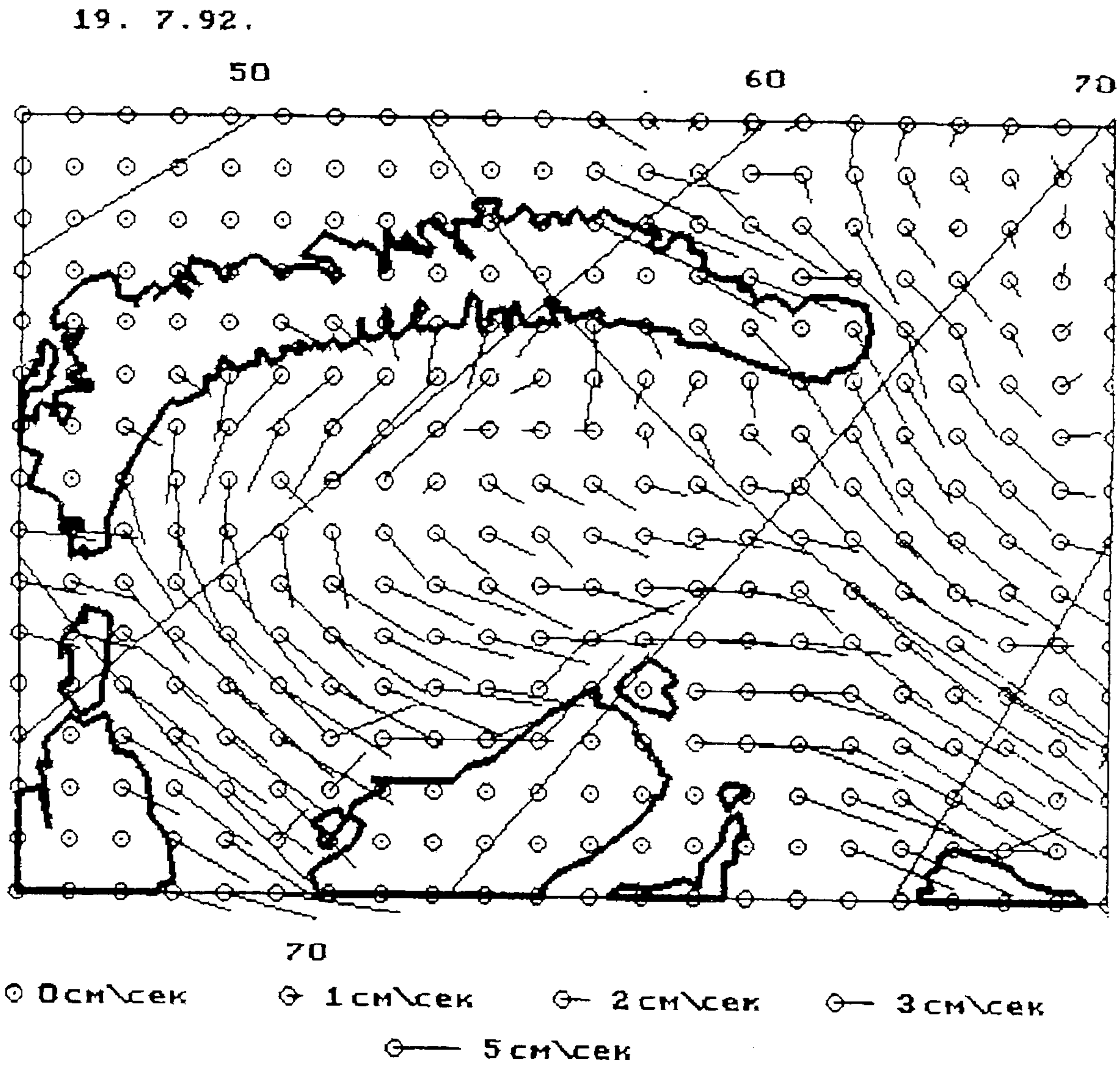


Fig. 24. An example of the forecast of the ice drift velocity field for the 7th day

methods of ice calculations and forecasts.

The subsystem has the following aims:

- calculations of distribution in space for each day of the most important ice cover characteristics;
- thickness, concentration, degree of destruction, degree of fracturing, amount of hummocking, compacting, deformation parameters, etc.;
- correction of the results of the calculations by the ice observation data from different sources;
- computation of ice forecasts with different periods in advance, their presentation in the form, suitable for the user and entry of the calculated and prognostic fields into the corresponding information bases;
- estimation of the forecast quality.

The solution of the first two objectives will provide a possibility to combine the advantages of the actual and calculated information on the ice cover state and eliminate the shortcomings of each of them. As a result, a system of continuous tracking will be created, which will provide a reliable ice information to different users and which will allow one to obtain the reliable data on the initial conditions for the forecasts and calculations.

The application of numerical methods in the ALISA system suggests the information exchange both between some subsystem components and with the other subsystems, including the bases of meteorological, oceanographic and ice information. This exchange should be carried out automatically with the help of the service softwares.

At present the work on the automatization of the technology of ice calculations and forecasts has not yet been completed. The input of the meteorological and ice information reported to the AARI,to the computer as well as the output of the calculated and prognostic ice information in the form suitable for the user are automated. The automatization of the connection of the computer with the communication block where the information is received from the corresponding regional centers, has to be improved.

The created automated system does not appear to be something unchangeable. With the improving methods of observations, calculations and communication means as a result of the replacement of some blocks and the development of the new ones, the automated system will be modernized.

## 4.8 Estimation of the quality of the methods of ice forecasts

The objective to estimate the quality of the methods of ice forecasts and their verification score is not strictly solved. The estimation criteria and the methods differ with the different methods of forecasting (empirical or numerical), depending on the periods in advance and being in all cases adequate to the level of the knowledge of natural typical features of the variability of hydrometeorological phenomena and processes of various scales.

As the physical-statistical methods of ice forecasts mainly use the method of multiple correlation, the practice of ice forecasting uses as an estimation method a general correlation coefficient (R) between the forecasted and observed value. Due to the distribution of anomalous ice characteristics and errors of their forecast being close to a normal one, the ratio of mean quadratic error (S) to the root-mean square deviation ($\sigma_u$) of the forecasted ice characteristics: $S/\sigma_u$ is assumed to be the criterion of the accuracy and reliability of the forecasts.

Mean quadratic error of the forecast (S) is determined by formula:

$$S=\sqrt{\frac{\sum_{1}^{n}\delta^2}{n-p}} \tag{31}$$

where $\delta = u-u_p$ (u - observed value of the ice characteristics,
$u_p$ - its prognostic value);
n - number of the terms of a multiyear series,
p - number of the degrees of freedom, equal to the number of the constant values, included into the regression equation (that is the regression coefficient and the free equation term).

The values S, $\sigma_u$ and R are related with each other by the ratio:

$$S=\sigma_u\sqrt{1-R^2} \tag{32}$$

The ratio $S/\sigma_u$ shows the gain in the error distribution, which is due to the forecast method as compared with the error distribution in the case of assuming the expected value according to the norm. The lower the ratio $S/\sigma_u$ ($R \to 1$), the more reliable the prognostic method; at $S/\sigma_u = 1$ the method does not have any advantages as compared with the forecast "according to the norm" (climatic forecast).

The ratio $S/\sigma_u$ is also related with the most important quality criteria of the method - its cumulative probability and effectivenes. Under **the cumulative probability of the method** ($P_m$) one understands the ratio of the number of the successful forecasts (m) to the total number of the forecasts for the considered series of observations (n) at a prescribed permissible error ($\Delta$):

$$P_m=\frac{m}{n}\cdot 100\% \tag{33}$$

The value of **the permissible error** is determined as the fraction of the root-mean -square deviation depending on the period in advance of the forecast. For short- and medium-range forecasts the value of the permissible forecast error is usually assumed to be equal to $0.674\sigma$, for long-range - $0.8\sigma$, for super long-range - $\sigma$.

It can be seen from Fig. 25 how the cumulative probability of the method ($P_m$) changes with the change of the ratio $S/\sigma$ (or R). At the values of $S/\sigma < 0.25$ and $R > 0.96$ the cumulative probability of the method will be equal to 100%. This means that the dependency of the forecasted value on the factors governing it, approaches the functional one. At established permissible errors the 80% cumulative probability can be reached for the short-and medium-range forecasts at $R \sim 0.85$, for long-range - $R \sim 0.75$ and super long-range - $R \sim 0.6$.

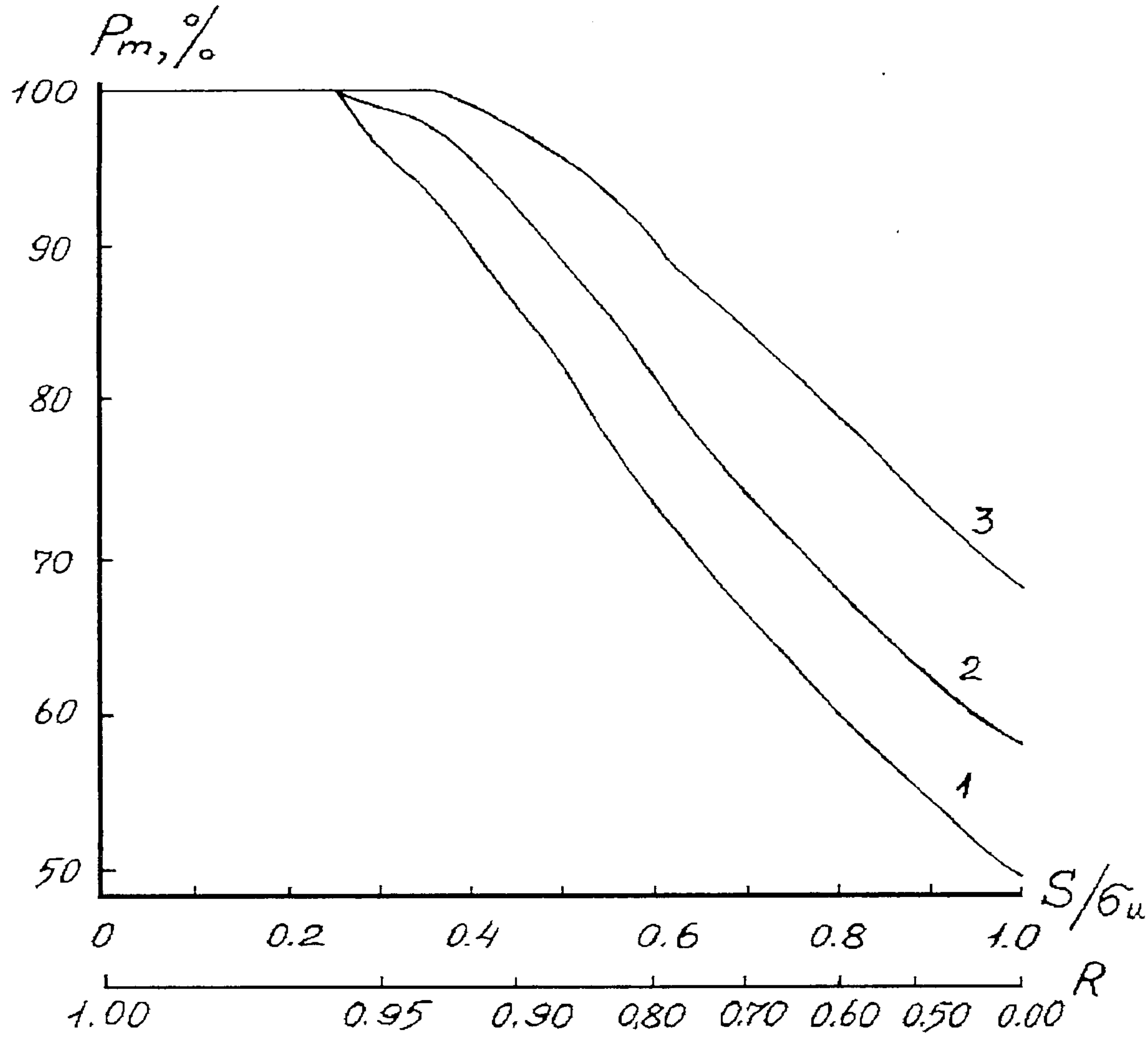


Fig. 25. Dependency of the cumulative probability of the methods of forecasts on the quality criteria ($S/\sigma_u$, R) with a different permissible error: 1 - $\Delta = 0.674\ \sigma_u$; 2 - $\Delta = 0.8\ \sigma_u$; 3 - $\Delta = \sigma_u$

A theoretical cumulative probability of the climatic forecasts with the indicated permissible errors is equal, respectively, to 50, 58 and 68%.

Under **the effectiveness of the forecast method** ($\gamma$) one understands the gain of the method ($P_m$) as compared with the cumulative probability of the climatic forecast ($P_N$):

$$\gamma = P_m - P_N \tag{34}$$

where $P_N = m_N/n \cdot 100\%$,

here $m_N$ - the number of the cases when the difference of the climatic value (norm) from the actual one does not exceed the permissible error,

n - total number of the terms of the series.

A theoretical forecast method can be considered to be effective already when its cumulative probability at prescribed permissible errors will be a little higher than that of the forecast according to the norm at the same permissible errors allowances, that is, when it will exceed 50, 58 and 60% for the methods of the forecasts with corresponding periods in advance.

In practice the application of the method of the forecast is considered to be advisable when the cumulative probability of the method ($P_m$) at a permissible error $\Delta = \pm 0.674\sigma_u$ exceeds that of the permissible deviation not less than by 18%, and at $\Delta = \pm 0.8\sigma_u$ - not less than by 10% (Manual, 1982).

The effectivenes of long-range ice forecasts, which are developed at the AARI, varies within 15-30% at an average verification score of the forecasts being 80%.

The permissible error ($\Delta$) is used also for the quantitative estimation of the verification score of the specific forecast: if the forecast error $\delta < \Delta$, then the forecast was successful (100%), in the opposite case - it failed (0%). In addition to the quantitative estimation the verification score of the forecast is estimated by the sign of the anomaly: the forecast was successful with the coincidence of the signs of the prognostic and observed anomaly and vice versa with no coincidence the forecast failed (if only the absolute value of the forecast error does not exceed the permissible error).

If the aim of the long-range ice forecasts is to predict the anomalies of some or other characteristics of the ice conditions in a specific year, that is their deviations from the norm, then the aim of the short- and medium-range forecasts is, as a rule, to predict the changes of these characteristics for the period in advance of the forecast. And the error of the forecasts of ice characteristics is precisely equal to the error of the forecasted change of these characteristics $\delta(u) = \delta(\Delta u)$. During the determination of the permissible error, however, one is based on the value of the mean-root-square deviation of the ice characteristics changes for the period in advance $\sigma(\Delta u)$ and $\sigma(\Delta u) \neq \sigma(u)$. This value depends not only on the period, but can change in space and from season to season, that is why to determine it, special statistical studies are required.

The mean verififcation score of short- and medium-range ice forecasts for the last 15 years is 90%. The verififcation scores of the specific forecasts are presented in section 4.3.

When estimating the quality of the long-range numerical ice forecasts of the generalized characteristics (ice cover extent, area of close ice, etc.), the same criteria are used as for the statistical methods of the long-range forecasts of these characteristics.

The estimation of the verification score of the long-range forecasts for the fall-winter period is given for three characteristics.

The forecasts of the position of the ice edge in the Barents Sea at some meridian and parallels were assessed with the 100 km allowance. Mean 10-year verification score of these forecasts was 70%. Mean verification score of the forecasts of the dates of a stable ice formation in the area of 15 polar stations in the Kara sea was 72% at 6-10 days allowance. The forecasts of ice thickness in fast ice at 10 stations of this sea were on an average 74% successful with the allowance 8 - 17 cm. The verification score of similar forecasts for the fall-winter period for the eastern Arctic seas differs insignificantly from these results.

The cumulative probability of the calculations of the indicated characteristics is distinctly higher (by 10% on an average), as well as of the calculations of the position of the boundaries of the inclusion and prevalence of old (multiyear, second-year) ice in February-May.

The estimation of the verification score of numerical calculations and forecasts of the ice concentration fields was made by comparison of the actual and calculated concentration values in the grid cells. And it was assumed that the verification score is 100%, if the actual and the calculated concentrations in the cell fall into one gradation, and 50% if these values belong to the adjacent gradations; in other cases -0%. The total verification score is determined by means of averaging the estimates in the cells.

As shown by the results of the test, mean 5 year cumulative probability of calculating the concentration fields in the seas indicated above, exceeds 80% at the 20% effectiveness, and the mean value of the modulus of the concentration errors is equal to $0.4\sigma$ ($\sigma$ - standard deviation value averaged over the area). Mean success of the forecasts of the concentration fields was 78%.

The verification score of the medium-range forecasts of the concentration fields in the summertime is close to this value, which turned out to be 77% for 10 years (on an average 10 forecasts for the year).

Mean verification score of the short-range forecasts of the characteristics of the ice cover deformations in the Arctic basin is 70-75%.

# 5 SPECIALIZED ICE FORECASTS FOR SHIPPING ALONG THE NORTHERN SEA ROUTE

## 5.1 Main directions of the development of specialized ice forecasts for shipping along the NSR

As a result of the development of the Arctic marine transportation system, that is of the Northern Sea Route, a new direction in the ice research has been formed - the study of the ice cover as the shipping medium. Numerous studies by the specialists of the Laboratory for ice navigation studies of the AARI have allowed one to find out and assess the effect of ice conditions on the possibility of the ship motion in the ice and express it through the operating characteristics of navigation (Buzuyev, 1973, Buzuyev et al., 1981, 1982, Gordienko et al., 1967).

Specialized ice and operation characteristics of the ship motion in the ice are considered in more detail in Project I.5, Section 2.

The increase of the volumes and intensity of transportations along the Northern Sea Route has required setting up the system for the planning of sea operations. The prognostic information on the ice cover state and its characteristics has become the basis for planning shipping in the ice. But the general level of forecasting far from always allowed one to determine ice conditions on the route of the ship's motion with a necessary period in advance and in sufficient detail.

These circumstances - the demands of practical activities to arrange and plan shipping, on the one hand, and insufficient information content of the ice forecasts of a general use on the other hand, required looking for the new forms and methods of forecasting ice conditions directly on the way of the ship navigation.

There were several important stages in the establishment of specialized ice forecasts. A specialized form of the presentation of the prognostic ice information appeared practically simultaneously with the first ice forecasts in the 20s-30s. The first navigation recommendations presented a qualitative interpretation of the ice forecasts of a general use and referred to the navigation of some vessels. With the beginning of a regular navigation along the entire NSR (mid 30s) the character of the navigation recommendations has not significantly changed. They continued to have a qualitative, descriptive character, containing the recommendations for the choice of the easiest way for the navigation, assessment of the navigation possibility in various ice zones.

The next stage is related with the development and evolvement of the general principles of forecasting the ice state characteristics, accumulation of data on the ice cover effect on the motion of the ships. It refers to the early 60s. The navigation recommendations began to include more quantitative characteristics. The ice navigation experience not only confirmed the need of the navigation recommendations, but also showed their prognostic independence (Buzuyev et al., 1967, Volkov, 1964, Gordienko, 1977, Gudkovich et al., 1972). They began to include:

- dates of the possible beginning and end of navigation in the ice with the support of icebreakers and without them;
- the recommended routes of the ships;
- possible dates of fast ice destruction by icebreakers;
- most favourable periods for bringing the cargos to the remote areas of the Arctic;
- guaranteed dates of the end of mass escort of ships at the limiting segments of the NSR;
- dates of removing the last ships from the Arctic;
- dates of the navigation end.

The transition to the study of the ice cover as the shipping medium has provided a possibility to develop common methods to investigate the features of ice navigation conditions in different Arctic regions. It has allowed one to find out the main typical features of the distribution of the ice cover characteristics on the way of the ships, depending on total ice distribution in the sea, to understand anew a vast amount of accumulated data.

As a result of a purposeful study of the ice navigation conditions by mid 70s the number of types of navigation recommendations increased (Handbook-1974)(in addition to those listed above):

- preparation of the schedules of the length of the route in fast ice and drifting ice of different concentration during navigation on the main segments of the NSR;
- estimation of ice thickness at each segment of the route from the observation results and using the calculations;
- a comparison of the navigation conditions according to different variants at each segment of the route to find out the optimum routing variant;
- calculation of time consumption to pass the segments of the route by the convoys and single vessels, participating in a particular sea operaion.

The creation of the method of a quantitative estimation of the navigation difficulty for icebreakers and ships during any distribution of ice characteristics contributed to the transfer to specialized ice forecasts (Buzuyev et al., 1976, 1987). The developed method enabled one to express all diversity of ice conditions, which affect actively and in a different way the movement of the ship, by a small number of the ice-operating characteristics of navigation conditions. The quantitative characteristics of the navigation difficulty are considered to be: velocities of the movement of icebreakers and ships in uniform ice zones (V), total navigation time ($T_{ice}$) in uniform ice zones and along the NSR segments, coefficient of the navigation difficulty ($K_d$) - a non-dimensional indicator, allowing one to compare objectively the effect of ice conditions of navigation on the movement of different icebreakers and ships, to determine the criteria of the possibility of different types of navigation.

The method of a quantitative estimation of the navigation difficulty extended the possibilities of both the applied and the research objectives.

Further studies showed the existence of a principal and objective possibility to forecast specialized ice-operating characteristics for the standard navigation routes in the Arctic Seas with a different period in advance (Buzuyev et al., 1983, Xaika et al., 1987, Report, 1985).

The formation of the new forecasting direction - specialized ice forecasts, on the one hand is the result of multiyear studies by the AARI specialists to investigate the ice cover characteristics directly on the navigation route and assess their influence on the navigation possibility of the ships, and on the other hand, an alternative to the existing methods of the ice forecasts of a general use, which are not sufficiently informative to address the objectives of the organization and planning the shipping. At present there is a clear understanding that specialized ice forecasts and ice forecasts of a general use are interrelated and supplement each other, rather than being alternative.

The development of specialized ice forecasts envisages a complex use of all available hydrometeorological information -regime data, actual hydrometeorological data, the results of numerical and physical-statistical forecasts. And the composition and content of the prognostic specialized data are governed, on the one hand by the need for a practical use of this information for the organization and planning of shipping, and on the other hand, by the existence of physical grounds to forecast the required characteristics with a required period in advance and the interval.

At the present stage of its development the specilized ice information for shipping in the Arctic contains in addition to those listed above, the following ice and operating characteristics of the navigation conditions:

A. Ice characteristics:

- total extent of the way in the ice on the route segments;
- extent of the way in different ice zones and the ice massif;

B. Operating characteristics:

- velocities of the motion of the icebreakers, ships and convoys of different types on the route segments and separately by the ice zones;
- total time consumption for the navigation of the icebreakers, ships and convoys on the NSR segments;

C. Ice-operating characteristic:

- location of the optimum navigation variant;
- type of the ice navigation conditions on average for a ten-day period and for a month on different navigation segments;
- type of navigation on the whole (and its periods).

The advance period of the developed methods of the forecasts is governed by the time scale of the shipping objectives. To solve the operational objectives of the fleet, the time scale of which does not exceed 10 days, the short-range forecasts (up to 3 days in advance) and medium-range (up to 8-10 days in advance) are required. The tactical goals of the fleet with a time scale up to 30 days require medium-range forecasts (from 10 days to 1 month in advance). The solution of the strategic goals of a general planning, the time scales of which are from 3 to 6 months, is based on the long-range forecasts (up to 6 months in advance, taking into account a detailed description and updating - from 1 to 4 months in advance).

At the present time a method of the forecast of the type of the navigation conditions for the route segments in the western region of the Arctic in summer up to 1 month in advance has been developed and is widely used for the goals of the operational-tactical management and planning of the fleet activities. Using this method it is possible to forecast the type of the navigation conditions (easy, medium, heavy), ice and operating characteristics of the navigation conditions on an average for a 10-day period, from 1 to 3 ten-day periods in advance. The forecast is compiled at the AARI and the Dikson regional administration of the Hydrometeorological Service.

To resolve the strategic goals and the objectives of a general planning the method of forecasting mean monthly ice and operational navigation characteristics from 1 to 3 months in advance and the method of forecasting the navigation type 4-5 months in advance for the winter navigation period for the route segments of the western Arctic were developed. The forecast is prepared at the AARI.

The development of specialized ice forecasts at the present stage is motivated by the need to constantly improve the management and operation system of the fleet in the ice (Zaika et al., 1987). There are all conditions for a further progress in this direction. The methodical bases of specialized forecasts for the summer and winter navigation periods in the western Arctic are developed, the main principles of forecasting are formulated, the effective approaches to the establishment of the forecasting methods are suggested, the large actual and calculated data bases on the navigation conditions and other hydrometeorological information are accumulated (Buzuyev et al, 1987, Report, 1985).

The further advance in the direction of the ice specialized forecasts for the near future should be a practical implementation of the concept of the multilevel system of specialized ice forecasts developed at the Laboratory for ice navigation studies of the AARI for shipping in the western zone of the NSR (Report, 1991).

Then, the multilevel system of specialized ice forecasts should be expanded and extended to the eastern NSR zone. Thus, the system for the specialized ice information services to the users should provide the prognostic data for the entire Arctic marine transportation system - the Northern Sea Route.

## 5.2 Methods for forecasting ice-operating characteristics of mean 10-day navigation conditions in the summertime with up to 30 days in advance

Medium-range specialized ice forecasts are to address the objectives of the tactical planning of marine operations along the NSR: to correct the plan-schedule of marine operations for the navigation, update the plans of special sea operations, plan specific sea operation of a wide range,etc. Taking into account the area of their application, the requirements to them govern the need to forecast the sufficiently informative ice-operating indicators of the navigation conditions, referring to the NSR segment and generalized for not more than 10 days. And these forecasts should be not less than 1 month in advance.

At present there are developed two methods of forecasting ice-operating characteristics of mean 10-day navigation conditions along the segments of the NSR western region in summer with 1 month in advance.

The first method was developed in 1984 by Brovin. The second method - by a group of the authors - Brovin, Dubovtsev, Yulin in 1993. It further develops and improves the direction of forecasting ice navigation conditions of the operational-tactical time scale.

*A. Forecast of a 10-day type of ice navigation conditions on the western NSR segments during summer navigation up to 1 month in advance.*

This method allows one to forecast the type of the ice navigation conditions (easy, medium, heavy) for the first, second and third 10 day periods of the months. In accordance with the type forecasted the ice and operating characteristics of the navigation conditions by the optimal variant are determined.

The method uses physical-statistical dependencies on the basis of the division into types. The prognostic dependencies with up to 1 month in advance are based on the inertia of the generalized characteristics of ice navigation conditions. Additionally the forecasts of the ice cover extent and the areas of the ice massif over the navigation region are used.

The method has been developed for three segments of the NSR western region:

- western ice edge - Dikson island,
- Dikson island - Cheluskin Cape,
- Cheluskin Cape - Tiksi Inlet.

The forecast is prepared for the summer navigation period - June-September. The forecast is 1 month in advance with a detailed presentation by 10-day periods.

The forecasting of the 10-day type of ice navigation conditions with 1 month in advance is based on the following:

- the division of ice conditions into types by an optimal variant on the specific NSR segment for each 10-day summer period; as a criterion of this division the value of total time consumption of the self-contained progress of the nuclear-powered icebreaker of the "Arktika" type in the ice on the specific NSR segment ($t_{ice}$) was taken, the critical values of the coefficient of the navigation difficulty ($K_d$), governing the safety of the specific ice navigation types were used as an additional criterion;
- typical features of the transformation of the types of navigation conditions during summer for each route segment from one 10-day period to another;
- generalizations used to determine the probability of the formation of the corresponding types of ice navigation conditions;
- statistical dependencies between the ice-operating characteristics of the navigation conditions and generalized characteristics of ice conditions - ice cover extent and the ice massif area of the navigation region.

Thus, the forecasted type of ice navigation conditions is governed by the dependency of the form

$$T_{NC_{i+n}} = f\left[\left(\sum_{i-3}^{i-1} T_{NC}\right),\ T_{NC_i} S\right] \tag{35}$$

where: $T_{NC_{i+n}}$ - forecasted type of navigation conditions,

$\sum_{i-3}^{i-1} T_{NC}$ - combination of the types for the preceding three 10 day periods,

$T_{NC_i}$ - type of navigation conditions during the 10 day period of the forecast preparation,

S - forecast data on ice cover extent and ice massif area,

n - advance period of the forecast (10 day periods).

The types of ice navigation conditions for the three preceding 10 day periods and during the 10 day period when the forecast is being developed for each of the route segments are considered to be the main initial data for the forecast. Additionally, the prognostic data on the ice massif area and the ice cover extent of the region are used.

The preparation of the main data is carried out as follows:

- from the maps of actual ice situation the ice conditions by the optimal variant for the given route segment for four 10 day periods are taken;
- by means of the model of a quantitative estimation of the ice navigation difficulty the operating navigation characteristics ($t_{\kappa\epsilon}$, $K_d$) are calculated;
- the types of ice navigation conditions for three 10 day periods preceding the forecast are determined according to the established criteria ($t_{\kappa\epsilon}$, $K_d$) and from the analysis of the types obtained a generalized type of the ice navigation conditions for these three 10 day periods is found;
- the type of ice navigation conditions during the 10 day period when the forecast is being developed is determined.

The method employs special probability tables of the transitions of the combinations of the initial types into a specific prognostic type of the ice navigation conditions. Such tables are calculated for each of the route segments of the western NSR region. The initial data for the forecast, listed above serve as input data into the table. The result of the use of the tables appears to be the determination of the most probable types of ice navigation conditions for the next three 10 day periods (1 month in advance).

The determination of the mean 10 day period type of navigation conditions makes it possible to proceed to the ice and operating indicators, characteristic of this type:

a. Ice characteristics:

- total length of the way in the ice ($L_{total}$);
- length of the way in the specific ice zones, for example in the ice massif and the ice massif core ($L_i$);

b. Operating characteristics:

- time consumption for progress in the ice ($t_{ice}$);
- mean motion velocities on the route segment (V);
- difficulty coefficient ($K_d$).

These mean 10 day indicators of the navigation conditions refer to the optimal variant of the navigation segment, describing mean conditions directly on the sailing route for the self-contained motion of an icebreaker or convoys of different ships.

The forecast of a mean 10 day type of the navigation conditions on the route segments of the western NSR is prepared in summer (VI-IX) with the possibility to update the forecast in one or two 10 day periods.

The results of the independent tests of the method by the authors and in practice have shown the mean verification score of the forecasts for the entire summertime over all segments of the western NSR region to be 87%.

*B. Specialized ice forecast of quantitative characteristics of the navigation conditions and the position of an optimal variant in the western Arctic region from 10 to 30 days in advance.*

The presented method of the ice forecast, as the one considered earlier, aims to address the objectives of the tactical planning of the fleet activities in the western NSR region in the summer navigation period. It was necessitated by the need to forecast the additional characteristics of the navigation conditions, in particular, the position of the optimum navigation variant, and by the possibility to improve the methods of the division into types and forecasting the ice navigation conditions. To improve the division of ice navigation conditions into types the new parameter of the division into types - $\Sigma\ \Delta t_{ice}$ - the total increase of the calculated time consumption due to the navigation in specific ice zones for the nuclear-powered icebreaker of the "Arktika" type was used.

$\Sigma\ \Delta t_{ice}$ is determined as the difference between the calculated total transit time for the NSR segment of the "Arktika" in real ice situation by an optimal variant and the transit time of the "Arktika" on the same way in open water. The criterion $\Sigma\ \Delta t_{ice}$ has allowed one to obtain a more objective estimation of the ice navigation difficulty, as compared with the $\Sigma t_{ice}$ earlier , which makes the new division of ice conditions into types more universal.

The considered method of a specialized ice forecast for shipping allows one to forecast generalized characteristics of the navigation conditions ($\Sigma\ \Delta t_{ice}$), type of ice navigation conditions, the position of the optimal navigation variant.

The method is developed for the segment Dikson island -Cheluskin cape of the western NSR region. The forecast is prepared in summer (June-September) with a 10-day interval and one month in advance.

The method of forecasting the value $\Sigma \Delta t_{ice}$ is based on physical-statistical dependencies, expressed by the regression equations. The forecasting of the 10-day type of ice navigation conditions (easy, medium, heavy) on the basis of $\Sigma \Delta t_{ice}$ allows one to pass to the types of ice and operating characteristics of the navigation conditions. The forecast of the position of the optimal variant is based on empirical-statistical inertial dependencies.

The method uses:

- the division of ice navigation conditions into types for each 10-day period of the summer navigation period, the value serving as the criterion of the division into types;
- typical features of the transformation of the optimal variant position during summer from one 10-day period to another;
- statistical dependencies between the characteristics of the navigation conditions and the information predictors from the actual fields of the hydrometeorological characteristics and the characteristics of the preceding navigation conditions.

The value $\Sigma \Delta t_{ice}$ is a function of the ice cover state and does itself simultaneously reflect this state in a complex way. The value $\Sigma \Delta t_{ice}$ is found as follows:

$$\sum \Delta t_{ice_{i+n}} = f\left(\sum T_{ice_i}, \Delta t^*_{i,i+n}\right) \qquad (36)$$

where $\sum \Delta t_{ice_{i+n}}$ - future value $\Sigma \Delta t_{ice}$ during the 10 day period,

$\sum \Delta t_{ice_i}$ - actual value $\Sigma \Delta t_{ice}$ during the preparation of the forecast i,

$\Delta t^*_{i,i+n}$ - value of the change of $\Sigma \Delta t_{ice}$ between the 10-day periods i and i+n,

n - period in advance of the forecast (10-day period).

In this calculating scheme there is one actual indicator $\sum \Delta t_{ice_i}$ and one prognostic ($\Delta t^*_{i,i+n}$). The value of $\Sigma \Delta t_{ice}$ characterizes the current state of the ice cover and the navigation conditions. The value $\Delta t^*_{i,i+n}$ characterizes in a complex way the value of the changes of the navigation conditions with the change of the ice cover state.

The value of the change of the indicator of the navigation conditions ($\Delta t^*_{i,i+n}$) depends on a large number of factors. To search for the most informative predictors the prognostic system was used (Kovalev, 1981; Kovalev et al., 1981, Yulin, 1990). This system has been considered in more detail in section 4.4.

The most informative predictors to forecast the value $\Delta t^*_{i,i+n}$ are:

- pressure differences at some sections, which characterize the ice cover drift;
- mean monthly air temperature at polar stations, characterizing the melting processes;
- the preceding indicators of the navigation conditions $\Sigma\Delta t_{ice}$, these characteristics indicate the current state of ice conditions.

The system mentioned allows one on the basis of a discriminant analysis to choose the most informative predictors, combine them into a generalized non-dimensional predictor. On its basis a linear regression equation for the 10-day period i+n is constructed

$$\Delta t^*_{i,i+n} = kQ + A \tag{37}$$

where: k - regression equation coefficient,
Q - generalized predictor,
A - free equation term.

The value $\Delta t^*_{i,i+n}$ is forecasted for the first, second and third 10-day periods. Then according to the calculation scheme given above, the values $\Sigma\Delta t_{ice_{i+n}}$ for these periods are calculated. The obtained prognostic values $\Sigma\Delta t_{ice_{i+n}}$ allow one to determine the type of the navigation conditions for the respective 10-day period. The final forecast is formulated in the form of the type of the ice navigation conditions and the typical ice and operating characteristics of the navigation conditions for the respective 10-day period. They are enumerated in detail in the description of the first method.

The forecast envisages the possibility of updating in one and two 10-day periods during the entire period of the forecast preparation (June-September).

The results of the method tests by the authors have shown the mean verification score of the forecast to be 82%.

The forecast of the position of the optimum navigation variant for one-three 10 day periods is made at the same time. It is based on the probability of the preservation of the optimal variants due to the inertia of ice processes. The initial data for the forecast are:

- the position of an optimal variant in the preceding 10-day period;
- the forecasted type of ice navigation conditions.

Here also the special tables of the probability of the preservation of an optimum variant are used. The forecast is made for the route segment Dikson island- Cheluskin cape for one-three 10-day periods with the possibility of updating each 10-day period. The results of the authors' test of the method of the optimum variant position have shown the mean verification score of the forecasts to be 85%.

The description of the method, the rules for the preparation of the initial data and the tables are contained in the "Instructions for the use of the forecast method". The method is sufficiently formalized and can be used by any trained oceanographer. The use of this method requires special databases on surface pressure, temperature and quantitative characteristics of the navigation conditions, stored at the Department of Ice Regime and Forecasting of the AARI.

The forecasting methods are used in the scientific- operational work. The forecasts are made at the Laboratory for ice navigation studies of the AARI or by the scientific-operational group at Dikson. The forecasting results are used for the operational activities on the route and the operational planning of sea operations up to 10 days, as well as for the tactical planning of the fleet activities with a time scale up to 30 days.

## 5.3 Method of long-range ice forecasting of the navigation type and mean monthly conditions of winter navigation on the western NSR segment

Long-range specialized ice forecasts aim to address the most general objectives of the support to shipping: to make and update the transportation plans for the navigation on the whole and its stages, to develop the plans for the specific special voyages, to identify the general directions of marine cargo transportations in the Arctic, to plan the use of different types of icebreakers, etc. Depending on the application area, the requirements to them govern the necessity to forecast sufficiently generalized ice-operating characteristics both in space (the Arctic region, the NSR segment) and in time (navigation and its periods) with the possibility of their detailed presentation later. Usually - this is the type of ice conditions of the seasonal navigation period for a specific NSR segment, and at its detailed presentation - the type of navigation conditions for each month of the considered period, which has ice and operating characteristics of the navigation conditions.

The method of long-range ice forecasting of the navigation type and mean monthly conditions of the winter navigation was developed by A.Brovin in 1987-1991 for the westernmost NSR segment (western ice edge in the Barents Sea - Dikson island), on which at present regular winter voyages are made. The method covers the winter navigation period from February to May.

The method has a physical-statistical basis and uses the technique of generalizations by types. The background ice-operating characteristics - type of the winter navigation 3-6 months in advance - are being forecasted as well as mean monthly ice-operating characterisitics and the corresponding ice and operating characteristics of the navigation conditions up to 3 months in advance. All ice and operating characteristics refer to the optimal navigation variant.

The forecasting is of a composite character, being subdivided into three stages:

- development of the background ice forecast of the winter navigation type ($T_{NCw}$), represented by five possible gradations: easy, medium with a tendency to easy, medium, medium with a tendency to heavy,

heavy; the gradations are expressed by whole numbers from 1 to 5, respectively;

- updating of the navigation type and preparation of a detailed forecast of the type of ice navigation conditions by months (February-May) for the entire winter navigation ($T_{NCi}$);
- updating of the forecast of mean monthly types of ice navigation conditions.

The background determination of the winter navigation type is necessary in the middle of November, which is connected with the dates of a preliminary planning of the operation of the fleet for the winter period.When identifying the predictors to forecast the winter navigation type high correlation coefficients were obtained for the generalized atmospheric circulation indicator -the stage of the atmospheric circulation epoch for December-May (C ) (Girs, 1971, Girs, 1984), as well as for the indicator which takes into account the interannual variability of ice conditions and their regional features - the type of the preceding summer navigation on the NSR segment considered ($T_{NCs}$). The indicators mentioned are included in the regression equation.

The next forecasting stage - the updating of T and the transition to mean monthly ice-operating indicators of the sailing conditions ($T_{NCi}$) is at the end of January. At this time it becomes possible to use the background meteorological and the numerical ice forecasts , as well as the sufficiently inertial characteristics of ice conditions, forming its background at the beginning of a "colder" period of the year.The updating of the navigation type ( $T'_{NC}$) is based on a combined qualitative analysis of $T_{NCw}$, forecasted in November and on the type of ice navigation conditions, observed in the second 10-day period of January.

Then the transition to the mean monthly types of ice navigation conditions ($T_{NCi}$) is made. Its prognostic basis appears to be the occurrence frequency of ice navigation conditions in specific winter months, depending on the updated navigation type ( $T'_{NC}$) and the background of ice navigation conditions, formed in January. The forecast is from 1 to 4 months in advance.

This dependency for practical use is expressed by the tables of the formation probability of the specific $T_{NCi}$, depending on the given parameters.

At the third, final forecasting stage mean monthly types of ice navigation conditions are updated. This is carried out at the end of each month, after receiving the information on the real navigation conditions for the past month. The prognostic dependencies are based on the probability of the development of $T_{NC}$ taking into account the actual ice navigation conditions. And the Byers's theorem was used, which allows for a reestimation of the probability of $T_{NC}$ development hypotheses taking into account the information newly received. These dependencies are also presented in the Table form.

The forecasted mean monthly types of ice navigation conditions - easy, medium, heavy - have ice and operating characteristics of the navigation conditions, indicating their distribution with an optimal variant. The ice characteristics include: the probability of the formation of a specific ice zone with the optimal variant and the length of the way in the ice on the whole, in polynyas and young ice zones, in the ice massif, as well as at the periphery and the core of the ice massif. Also the statistical indicators, showing the distribution of these characteristics are given. The operating characteristics are represented by the velocity of motion and the time spent for the nuclear-powered icebreakers of the "Arktika" type and a standard convoy of the "Arktika" + the M/V SA-15 in the indicated ice zones and on the whole on the navigation route under consideration.

The practical trials of the forecasting method considered were carried out by the scientific-operational group of the Headquarters of Marine Operations of the western region of the NSR (Dikson island) during 1987-1990. The verification score of the forecasts of the winter navigation types was 75% and of the mean monthly type of ice navigation conditions - 89-69% depending on the period in advance of the forecast.

The creation of this forecasting method of generalized ice-operating indicators of the winter navigation conditions was governed by the need to address the objectives of a preliminary and general shipping planning at the sea part of the route Murmansk port-Dudinka port during the winter navigation period most difficult in terms of ice. The application of the indicated forecasting method in the operational practice allows one to resolve such goals of the general planning as the assessment of the requirement and the dates of the necessary icebreaking support, particularly the need to use powerful icebreakers (nuclear-powered icebreakers), forecasting of the changes in the velocity of the routing of convoys and planning of the work of the ports to handle transportation ships, as well as other practical goals.

The presented method is considered to be part of the general system of specialized ice forecasts for the planning of shipping along the NSR. The development of similar methods for the forecast of generalized ice-operating indicators of the navigation conditions for the NSR segments and the entire route on the whole for summer navigation will allow for a timely solution of many problems of the preliminary and general planning of transit shipping (see section 5.4).

## 5.4 Estimation of the possibility to set up a multi-level system of specialized ice forecasts for shipping

The hydrometeorological information, ice forecasts of a general use and specialized ice forecasts are to be used for the organization, planning and management of sea operations along the Northern Sea Route. Their aim is to contribute to the maximum effectiveness and safety of shipping through ice.

In recent years the development of the marine transportation system has reached a qualitatively new level. A need has arisen to organize and plan regular all-year-round navigation in the western Arctic and regular transit shipping along the whole NSR in summertime.

To plan and to address such objectives is possible only on condition reliable, regular and sufficiently complete prognostic information is provided.

The entire complex of the objectives to organize the shipping in the Arctic region can be divided into 5 directions.

In each direction there is a number of the main goals of the fleet, the analysis of which allows one to formulate the requirements to the hydrometeorological information.

Fig.26 shows the directions and the main associated goals of the organization of shipping on the NSR, as well as their temporal and spatial scales.

A. A prospective planning of the navigation in the Arctic region is made for the period from 3 to 25-30 years. Within its framework the following main objectives are to be addressed:

- design and construction of the icebreaking and transportation fleet;
- design and equipment of the ports, places of stay and unloading;
- identification of the prospective directions of cargo transportation in the Arctic region, taking into account the economic development.

It can be based on the expert assessments, climatic data, superlong-range specialized forecasts, which should contain:

- the conclusion about the expected character of the climatic changes of the ice cover in the next years (from 3 to 25-30 years);
- climatic estimates of the ice conditions of navigation on the existing and prospective routes and the possible limits of their changes;
- periods of a possible and a guaranteed navigation of the icebreakers and the ships of a specific type on the segments of the NSR and according to the possible transportation directions.

B. A preliminary planning of sea operations is made 3-6 months before their start. In March the summer navigation (VI-X) is planned (in more detail for its first half). In August - for the period of the end of the summer navigation (X-XI) and the beginning of the fall-winter operations (XI-XII). In November-December the work for the winter navigation period (I-V) is planned.

This envisages the fulfilment of the following tasks:

- determination of the general directions and the order of sea cargo transportations in the Arctic (western, eastern or a mixed scheme);
- preparation of the transportation plan for the navigation and its stages;
- updating of the plan of sea operations according to the navigation stages;
- development of the preliminary plans of the specific special (not standard) voyages;
- determination of the possible dates of single transit voyages and of the period of a mass transit navigation.

The objectives of the preliminary planning of sea operations require the following prognostic specialized information:

- navigation type (type of navigation period) by regions and on the whole along the NSR;
- mean monthly types of ice conditions of navigation by the NSR regions with the ice-operating characteristics;

- dates of the beginning of navigation (by the NSR regions);
- dates of the beginning and end of the navigation without icebreaking support (by the NSR regions);
- dates of the end of the navigation by the regions and on the whole along the NSR.

C. The strategic planning of sea operations is made from 1 to 3 months in advance, including the following main objectives:

- preparation and updating of the plan-schedule of sea operations, including the supply of the polar stations;
- development of the plans of the specific special sea operations;
- determination of the specific dates of the transit navigation along the NSR.

The plans of these sea operations can be developed on the basis of the following specialized ice information:

- updating of mean monthly types of ice conditions of navigation with spatial detailed characteristics by the NSR segments;
- dates of the beginning-end (period) of the specific navigation types (with the icebreaker, without the icebreaker, for the ships of a specific ice class, etc.);
- dates of the possible start of the supply operations for different places in the Arctic;
- dates of the beginning and end of the navigation, related with the ice reaching the thickness, restricting navigation;
- ice-operating characteristics by types (length of the way in different ice - L, time consumption - $t_{ice}$, motion velocities -V) according to the optimum navigation variant on the NSR segments for the icebreaker and the standard convoys.

D. Tactical planning of sea operations is made from 10 to 30 days in advance, envisaging the fulfilment of the following objectives:

- correction of the plan-schedule of sea operations;
- updating of the plan of special sea operations;
- planning of the ice fleet distribution on the route;
- updating of the dates and periods of the transit navigation;
- planning of the specific sea operations of a wide range (transportation, supply, special routing,etc.).

The objectives of the tactical planning are based on obtaining the following types of specialized ice information:

- ice-operating characteristics by types (L, $t_{ice}$, V) at the NSR segments, segments of the specific navigation variants with details by 10-day periods;
- extent of the way in various ice by possible navigation variants with details by 10-day periods;
- position of the optimum navigation variant, by 10-day periods for the NSR segments;

- updated dates of the beginning-end (period) of the specific navigation types for icebreakers, some vessels and convoys of different ships;
- dates of the possible (most economical) use of the specific types of icebreakers;
- updated dates of the ice conditions, at which sea operations in remote areas of the Arctic are advisable;
- updated dates of the appearance on the NSR of ice conditions, limiting the specific navigation types;
- dates of possible special voyages (routing of ships and structures of a limited shipping capacity).

E. The operational management of sea operations is carried out in the time interval from 1 to 10 days, including the objectives for operational activities of the fleet and management decisions, which are practically at once introduced into practice. It includes:

- updating of the plan of specific sea operations (5-10 days in advance), designation of the icebreakers and the ships of the convoys;
- stationing of icebreakers, formation of the convoys; - management of specific sea operations (including special sea operations) 1-5 days in advance;
- selection of the places of a possible stay of the ships and the convoys for the specific NSR segments with a deterioration of the ice situation.

The indicated objectives govern the need to obtain the following types of specialized ice information:

- position of the optimum navigation variant on the NSR segments;
- position of the edge and limits of ice of different concentration in the region of the optimum navigation variant (to select the places of the formation of convoys, of a safe stay of the vessels);
- the length of the way in various ice; - time consumption, motion velocity on the NSR segments and in the specific ice zones;
- navigation variants in the narrow places (straits), their preservation or change;
- periods of the improvement or deterioration of ice situation (ice compacting, concentration or diverging, ice drift character).

The present work does not consider the direction of the prospective planning, which is not directly related with the practical activities of the fleet. Its analysis appears to be the aim of the studies of the specialists-analysts on the long-range planning of the economy. Let us dwell on the planning of the fleet activities, beginning with the level of a preliminary planning.

One of the features of all planning directions in the activity of the fleet is considered to be their interrelation and succession. First of all, independently on the time scale they have a common purpose - a reliable, regular and safe shipping along the NSR. Secondly, all directions are united by a common organization principle. The planning aims of a higher time level

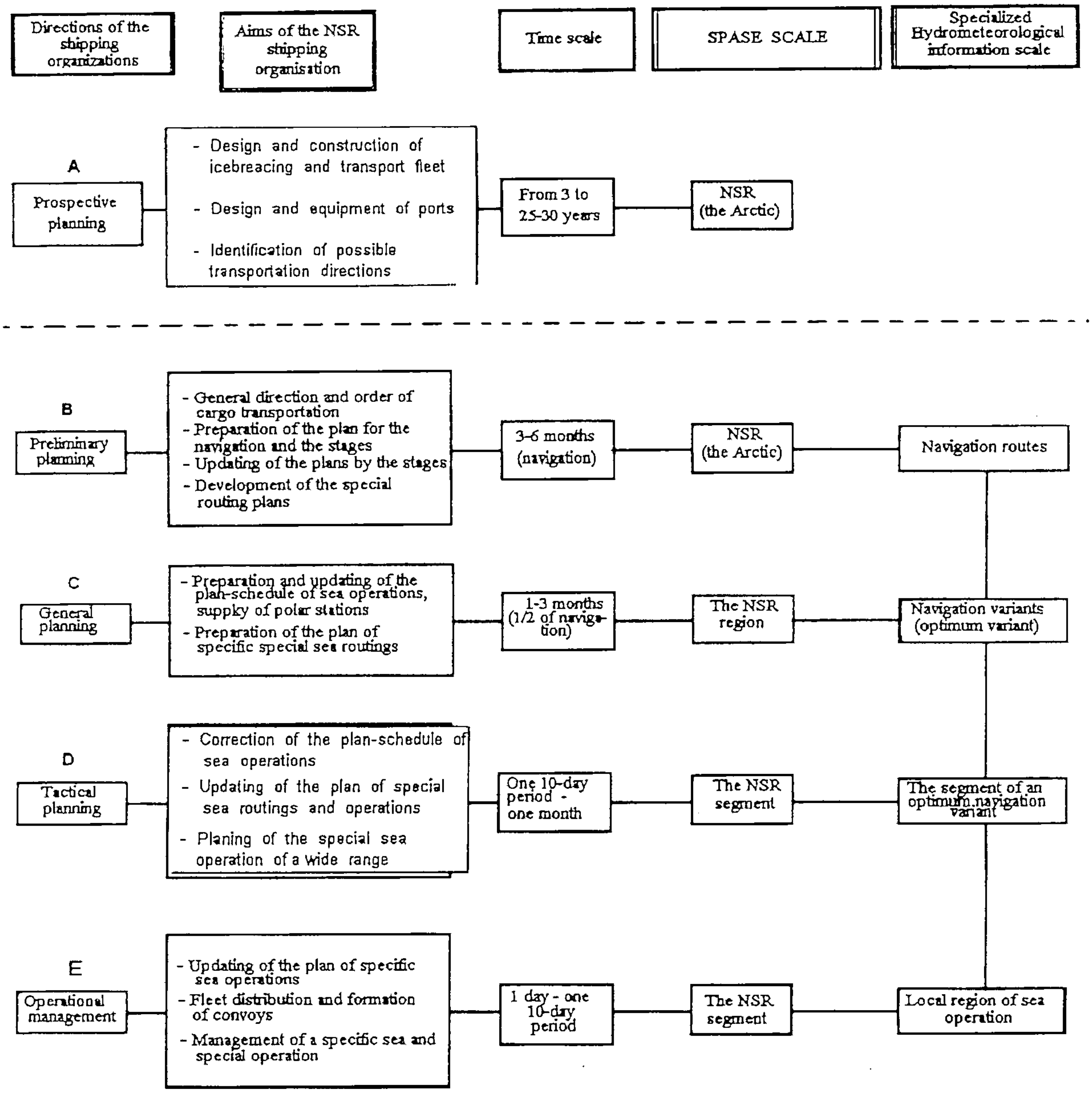


Fig. 26. The directions and objectives of the organization of shipping along the NSR, scale of the specialized hydrometeorological information

A, B, C, D, E - text reference.

appear, in turn, to be a preliminary plan of the objectives of a lower time level.

In this system of the shipping planning and organization the principle from a larger time scale to a smaller one is implemented. All organization of the planning and management of the fleet activities is made from the preliminary planning through the updating of a strategic time scale to the specific implementation of operational-tactical aims. The objectives of the operational management appear to be an integral part of the aims of the tactical planning.

It is natural that the functioning of such a complicated planning and management system of the fleet activities, including tens of icebreakers, hundreds of transportation vessels, tens of ports and supply points, is impossible without a smoothly functioning system of prognostic information: ice, hydrometeorological, and specialized ice information.

The Laboratory for ice navigation studies of the AARI has developed a concept of the multilevel system of specialized ice forecasts for the shipping (Report, 1991). A general layout of the multilevel system is presented in Fig. 27. The system is based on the principle: from the forecast with a large period in advance to the forecast of a smaller period in advance but more detailed. A specialized ice forecast is the main structural component of the system. Each component of the system meets the requirements of its level of the organization and planning of the shipping.

The forecast 6 months in advance and with details for the first 3 months, referring to the entire route and its regions corresponds to the objectives of the preliminary planning. The forecast 3 months in advance and with details for the first month, referring to the route segments and the NSR regions corresponds to the objectives of the strategic planning. The forecast 1 month in advance and with details for one 10-day period, referring to the segments of the NSR corresponds to the objectives of the tactical planning. And finally, the forecast 10 days in advance and details for the first 2-3 days, referring to the segments of the NSR and some parts of these segments, corresponds to the operational management objectives.

The content of specialized ice information for each level of the organization and planning of shipping is considered in more detail above and presented in Fig. 27. A multilevel system provides for a common cycle of the specialized prognostic ice information for shipping. A preliminary forecast for the entire navigation period (it is detailed for the first half of navigation) includes specialized prognostic information for 1 month of the navigation and a specific prognostic information for one 10-day period. In a 10-day period the forecast for the second 10-day period is made and when necessary it is updated for the first month. After the second 10-day period a specialized ice forecast for the second month with details for the first 10-day period is prepared. And the forecast for the first half of navigation can be updated. Thus, a continuous cycle of specialized ice information appears, which is capable of providing support to the implementation of the shipping aims at all time levels of the planning of the fleet activities.

To develop a multilevel system of specialized ice forecasts for shipping appears to be reasonable, as it meets the objectives of the main directions of the organization and planning of shipping, is based on the existing and successfully tested specialized ice information and does not require the evolvement of principally new approaches.

Also a number of the structural components of the system -specialized ice forecasts with different periods in advance and time averaging intervals are already worked out and introduced into practice (Table 15).

This allows one to consider it to be possible to set up a multilevel system of specialized ice forecasts for shipping along the NSR.

At the first stage the multilevel system of specialized ice forecasts can be developed and introduced for the western NSR region. At the second stage the system should be expanded and extended to the eastern NSR region and thus, to provide a continuous cycle of the prognostic specialized ice information services to all users of the NSR.

At present one can state that 20-25% of the volume of the studies, referring mainly to the western NSR, are fulfilled for the establishment of the multilevel system. To set up a complete system of specialized ice forecasts for the western NSR region requires the development of the new, and improvement of the existing, forecasting methods (Table 15). For the winter period the forecasts for all levels of the tactical planning and operational

Table 15. Methods of specialized ice forecasts, used for the shipping support in the western NSR region

| Time scale of shipping organization | Methods of specialized ice forecasts developed and used in practice | |
|---|---|---|
| | Winter | Summer |
| Preliminary planning 3-6 months | Navigation type forecast 4-5 months in advance | - |
| General (strategic) planning 1-3 months | Forecast of mean monthly types and ice-operating characteristics of navigation conditions 3 months in advance and 1 month averaging interval | - |
| Tactical planning on 10-day period - 1 month | - | Detailed specialized ice forecast 1 month in advance and 1 month averaging interval. Forecast of the optimum variant position and of the types of navigation conditions for one-three 10-day periods |
| Operational management 1-day - one 10-day period | - | Numerical specialized forecast for 7-8 day and details for 1st and 2d halves of the periods for all route segments |

management are necessary. For the summertime - for the levels of a preliminary and strategic planning. For the level of operational management it is necessary to forecast specialized characteristics not only for the segments of the routes, but also on a smaller space scale: in some local parts, in some parts of the route segments. Specialized ice forecasts up to 30 days in advance (for the level of tactical planning) by all means should envisage the forecasting of the position of the optimum navigation variant. At present the ice-operating characteristics for the optimum navigation variant are predicted without the indication of its position.

In addition to the need to develop new forecasting methods the already existing methods (Table 15) cannot be considered to be perfect and fully satisfying the users. With the formation and the addition of new data to the initial data bases, search for new typical features and approaches to forecasting, with the appearance of new ideas, these methods should be also improved, updated and supplemented.

It seems that the activities in this area in the framework of the II stage of INSROP should be directed to the assessment of the spatial-temporal variability of the generalized ice-operating characteristics of the navigation conditions in the western NSR region during summer navigation. The goal of this study is to find out the typical features of their formation and the possibility of long-range forecasting. This will allow one to create the entire cycle of the prognostic specialized ice information for the support of the shipping planning in the western NSR region during summer navigation.

# 6 CONCLUSION

The information presented in the Report under Project 1.6 characterizes the system of the scientific-operational hydrometeorological forecast services to the navigation along the Northern Sea Route, formed historically in Russia. All three links of this system, including the meteorological, oceanographic and ice forecasts with different periods in advance are considered separately. The system is concluded by specialized forecasts, which allow one to transform the notions, related with the characteristics of natural conditions, into the parameters, which govern directly the navigation conditions.

The Report considers both the basis of the forecasting methods used and the content of the information bases used during the preparation of the forecasts, and the form of the presentation of the latter and assessment of their quality.

Obviously, the current state of each of the links of the prognostic system requires to be further improved.

The objectives of the successive studies to develop and improve the macrocirculation method of long-range weather forecasts are as follows:

- to make the analysis more objective and separate the atmospheric processes at the stage of a different time scale;
- to study the causes for the formation of large anomalies of the main meteorological components in the Arctic, including particularly dangerous phenomena and their forecast;
- to study the intensity of the development of long thermal pressure waves;
- to further investigate the effect of the circulation epochs and their stages on macrosynoptical processes of the specific years.

Further investigation and improvement of the oscillating- hydrodynamical model can be quite promising both for the development of the methods of meteorological forecasts and for the oceanographic and ice forecasts. The forthcoming studies in this direction should include:

- continuation of the tests of the method of forecasting the geopotential $H_{500}$ and surface pressure fields 10-35 days in advance;
- development of the method of finding out and taking into account a significantly non-stationary circulation component, in particular, the atmospheric relaxation parameter, which can permit extension of the period in advance of the forecasts up to a season and a year;
- expansion of the capabilities of a prognostic scheme by taking into account the external energy sources, related with the distribution of the surface ocean layer temperature, cloudiness, ice cover area;
- increase in the number of the forecasted parameters due to air temperature and cloud cover precipitation.

In the area of oceanographic forecasts it is necessary to use new, more advanced models, which will improve the quality of the numerical forecasts of the level, waves and currents. It is also required to make the existing regional physical-statistical methods universal, objective and automated on a computer basis.

Also the studies in the field of the methods of ice forecasts of a general purpose have similar goals. It is necessary to extend to the other regions the methods of long-range ice forecasts, based on the division into types and objective identification of natural ice-oceanographical regions. The studies of the variability of the flaw polynyas and the systems of discontinuities in the ice cover, important for navigation in winter should be continued and the methods of forecasting these components created on this basis.

It appears to be quite promising to introduce the automated prognostic system, based on the objective search for the information predictors using the bases of meteorological, oceanographic and ice data.

Further development of the methods of numerical ice forecasts will be in two directions:

- to improve mathematical models on the basis of investigating the dynamical and thermodynamical processes in the ice cover, ocean and the atmospheric boundary layer;
- to improve the technology of ice calculations and forecasts.

The first direction envisages a more accurate description of the effect of the wind and the currents on the ice cover by means of a combined solution of the problem of the interaction of sea-air stratified layers, as well as a more justified approach to the determination of the internal interaction forces and ice cover rheology.

The second direction envisages a maximum automated preparation of the initial and current information, a rapid and easy-to-handle access means to hydrometeorological archives, development of a continuous tracking (monitoring) system for the ice state with the combination of numerical calculations with the observation data assimilation.

For the support of the transit navigation on the NSR, of major importance will be a multilevel system of specialized ice forecasts, outlined in the Report, which provides data important for the navigator, which are used for the navigation planning at various levels: from the prospective to the operational one.

The goal for the near future is to provide specialized ice forecasts of different levels for the all-year-round cycle of the change of the navigation conditions in the western sector of the Arctic and then to extend this system to the entire NSR.

Also, a closer interaction of the methods of specialized ice, oceanographic and meteorological forecasts of a general purpose will be required.

It seems that the provision of hydrometeorological forecasts for the support to the navigation along the NSR should be based on the system currently used in Russia, some components of which will be improved as indicated above taking into account the achievements in other countries.

The success of this work will largely depend on its financing.

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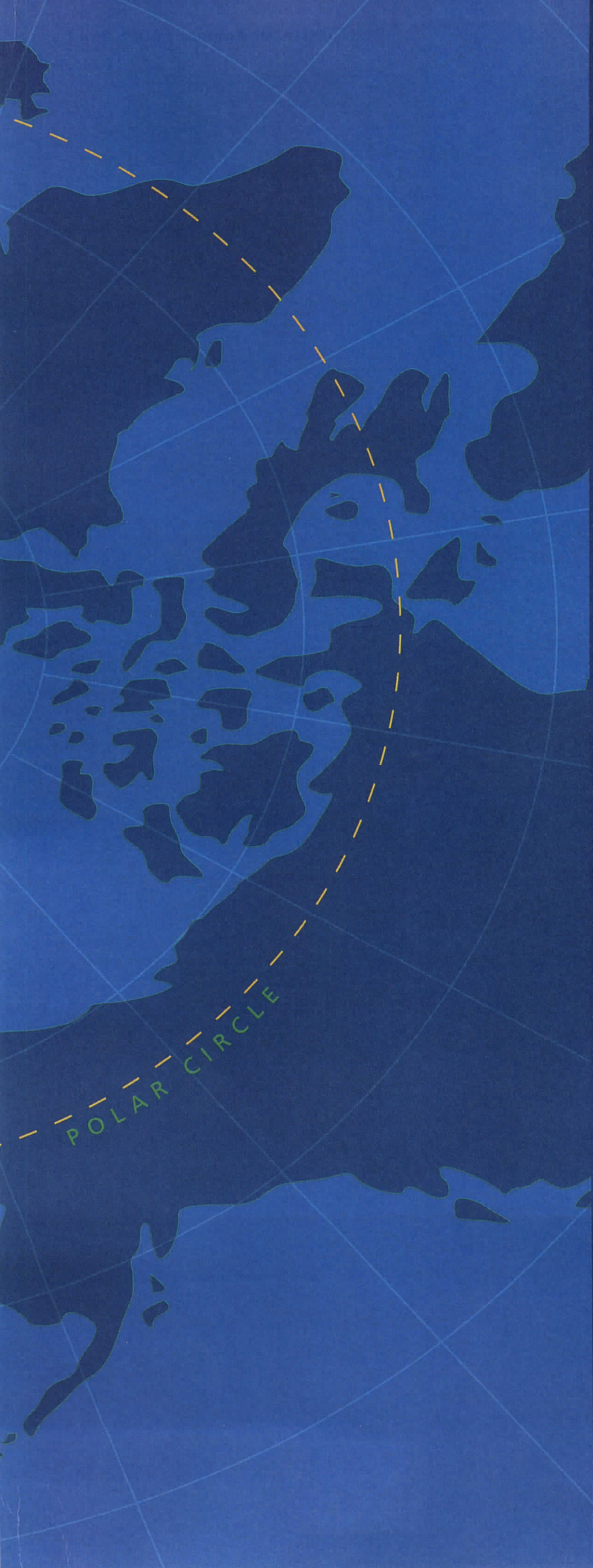


**The three main cooperating institutions of INSROP**

**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.