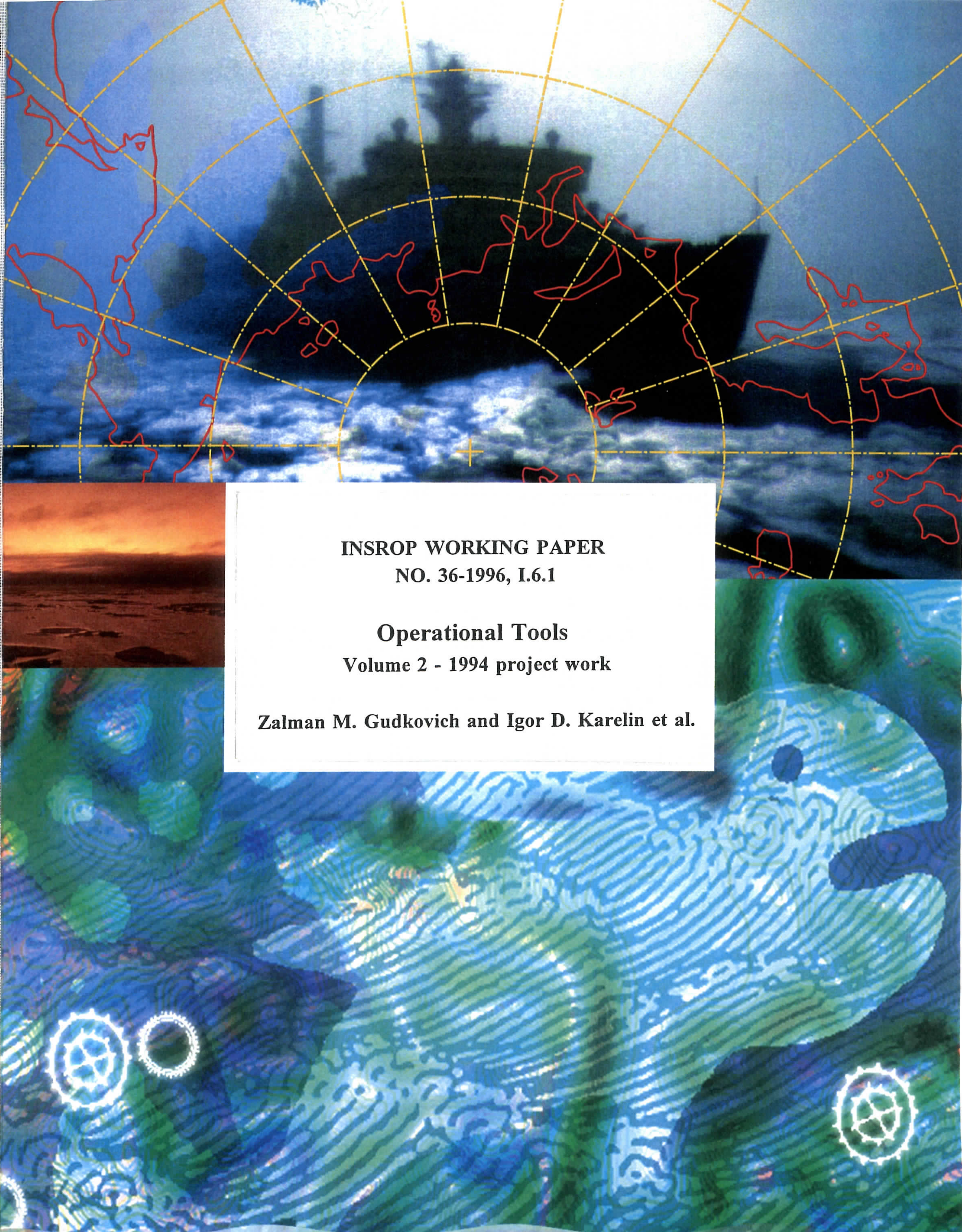

INSROP WORKING PAPER
NO. 36-1996, I.6.1

Operational Tools

Volume 2 - 1994 project work

Zalman M. Gudkovich and Igor D. Karelin 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)

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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

Improved methods for meteorological, oceanographic and ice forecasts with different advance periods that are perspective for providing scientific-operational support to shipping along the Northern Sea Route are presented. The technology for developing the suggested forecasting methods and the form for presenting initial and prognostic information are given. Effectivenes of the methods is assessed. The directions of the future development of forecasting methods in an automated system for hydrometeorological support to shipping are considered.

KEY WORDS: methods for meteorological, oceanographic and ice forecasts, advance periods of forecasting, effectiveness, stages of the development of macroprocesses, an oscillation-hydrodynamic model, a probabilistic-statistical scheme of level forecasting, automated preparation of ice data, ice-operating parameters, the Northern Sea Route.

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1 INTRODUCTION

The project aims at developing a comprehensive system of meteorological, oceanographic and ice forecasts on the basis of existing and updated methods for addressing objectives of planning of operational management of transit shipping along the Northern Sea Route (NSR).

The Report of 1994 presents a sufficiently complete overview of the existing methods for hydrometeorological forecasting with different periods in advance. It also considers hydrometeorological information that is used for forecasting and operational support to navigation and the problems of assessing the quality of forecasts and calculations. The main directions in the development of forecasting methods and forms for presenting hydrometeorological information are formulated.

The present Report develops further the problems of improving forecasting methods that are promising in terms of their use in present-day management system of transit navigation along the NSR.

In the area of long-range meteorological forecasts a macrocirculation method has been improved with regard to taking into account the influence of circulation epochs on the character of natural processes in specific years. For forecasts up to I month in advance an oscillation-hydrodynamic model of detailed forecasting of pressure fields taking into account stationary and non-stationary components of atmospheric processes was succesfully used.

Additional studies of the processes influencing sea level were carried out and an algorithm for a single probabilistic-statistical scheme of forecasting dangerous sea level changes in the regions limiting shipping was obtained.

Computer software for searching informative predictors for an automated forecasting system was constructed for ice physical-statistical general purpose forecasts 2-4 months in advance. In the course of improving a local-genetic method of ice distribution with a 10-day interval an automated ice information visualization block for the Kara Sea was developed. For the same region a numerical method for forecasting distribution of concentration, thickness, drift velocity fields 1-8 days in advance with a spatial resolution of 25 km has been improved.

A positive result has been gained in developing a system of specialized ice forecasts due to improved estimates of spatial-temporal variability of ice-operating characteristics of navigation conditions in the western region of the NSR.

2 METEOROLOGICAL FORECASTS

It is known that diverse and seemingly random meteorological processes and phenomena are governed by general objective laws of natural development of the Earth. According to one of them at this phase of the globe existence the atmosphere has a specific stability of its internal properties (structural form and character of structural relations).

However, it experiences a constant effect of internal and external forces acting in different directions and partly loses this stability, i.e. a phenomenon of the transformation of inherent properties occurs. The latter results in occurrence of meteorological processes on different spatial-temporal scales. And the transformed properties are expressed in a successive change of various specific synoptic processes and phenomena. Their frequency is governed by the total effect of the circulation factors of one direction. That is why one of the primary objectives of investigator trying to take into account the influence of the general atmospheric circulation (GAC) on synoptic processes of this region or other is a detailed study ; first of all, of internal GAC properties and then of the character of the changes that these properties undergo at a given stage of the environmental development.

2.1 Forms W, E, C - main structural components of the general atmospheric circulation

A macrocirculation method for forecasting wuth large and small periods in advance for the Arctic have been developed in the direction of taking into account the specific features of macroprocesses in the Northern Polar Region. However, up to present these studies are based on taking into account generalized large-scale features of this regime (W, E and C forms), rather than on a detailed study of the regime of the GAC mechanism components. And recent studies have shown the character of synoptic processes to be very much dependent not only on the indicated large-scale wave motion, but also on its types that are governed by differences in the wave dynamics. As a rule, the latter results in the formation of two groups of synoptic processes for each of the three circulation forms. The first group is characterized by more active components of interlatitudinal air exchange and the second -of zonal transport.

Considering the above mentioned fact, an analysis of the interannual and intraannual development of atmospheric processes was performed for the entire available observation series of the GAC state (from 1891). It showed that for the periods from a month to a year the character of mean thermal pressure field over significant regions of the Hemisphere and, especially in the polar zone was governed by occurrence frequency of the first and second groups of the circulation forms in these time intervals.

As an example, .let us consider the influence of the types of processes of one of the circulation forms (E form) on the weather regime of the Arctic.

The main feature of the processes of this form is disturbance of the prevailing western tropospheric flow in the zone of temperate latitudes. It is related to the development of the waves of a large amplitude. As a result of cold advection along the western periphery of the troughs and diverging current, their deepening and spreading to the south takes place. Also, simultaneously there is a heat ouflux along the eastern periphery of the troughs from southern latitudes, strengthening of an altitudinal ridge and its development northward in meridional direction. Further, depending on the interaction character of the troughs and ridges and their geographical position, two variants of synoptic situations occur. At the first variant the top of the blocking altitudinal ridge is above the Arctic regions. The center of the circumpolar eddy is shifted toward the Canadian sector. During this situation there is an anticyclogenesis over the seas of the western Arctic region (Fig. 1a). During the processes of the second group the altitudinal ridge develops much weaker. The circumpolar eddy is more intensive and its center is above the near-pole region. Over the western Arctic a cyclonic area is developed (Fig. 1b).

Hence, during the processes of the first group there is an intensive interlatitudinal air exchange. During the processes of the second group an increase in zonal transport components is observed.

Thus, for diagnosing and forecasting of current macroprocesses it is important to determine accurately not only the form of the GAC state but also the development stage of this state.

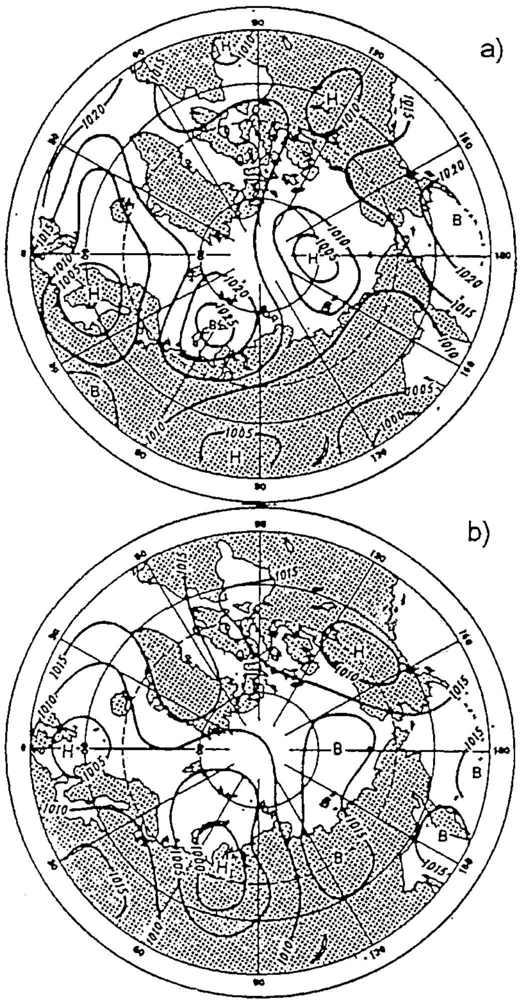

Fig. 1. Mean pressure chart for the first (a) and second(b) groups of the E circulation form processes

2.2 Uniform periods in the formation and transformation of the atmospheric circulation forms

One of the main principles of a macrocirculation method requires investigating atmospheric processes in their constant development. Such approach has shown that atmospheric circulation as one whole, consists of different in time but interelated formation stages and changes of its characteristics.

Thus, as a result of studying continous variations of atmospheric processes on the basis of daily synoptic charts of the Northern Hemisphere and identifying elementary synoptic processes in this development, it was found that along with the existing differences there are some general features in the redistribution of air masses. This fact allowed combining them into a larger development stage - a uniform circulation period (UCP) 8-12 days in duration. The study of a longer period has shown a frequent occurrence of similar UCPs or close to each other by the character of weather regime conditions. This allowed an identification of the stages within a year (1-5 months). An analysis of interannual variability of the GAC components and of the character of thermal pressure fields over the Hemisphere has revealed some similarity in their behaviour over a number of successive years (2-6 years). Thus, a notion of interannual stages of development of macroprocesses has been introduced. And, finally, by studying a multiyear occurrence of the circulation forms and a corresponding thermal pressure background, the longest stage - the circulation epoch was identified.

Temporal boundaries of all stages are recorded in catalogues. Thus, the stages of circulation epochs, their interannual stages and stages within a year (intraannual) are given in Table I.

For each of the enumerated stages the charts of the probability of the sign of anomalies of air pressure and temperature, as well as their mean values, are plotted. The use of these charts in diagnosing current processes has a definite prognostic importance.

Let us consider one more important typical feature in the development of the GAC structure that has been recently found.

Vangengeim (1952) showed that any of the three main states of atmospheric circulation (W, E and C forms) undergoes three stages in its development: progressive, regenerating and degenerating. The first is related to an increase of the circulation characteristics typical of this form. The second stage is a period of instability in the formation of typical characteristics. And the last stage is a period of dumping of the wave motion in the atmosphere, characteristic of this form. These three stages have a definite succession in their formation and can be used in forecasting the GAC macrotransformation. It follows that determination of the atmospheric circulation forms and different stages of their development is an important objective of the analysis and long-range forecasting of the circulation regime.

It is logical to believe that typical features of the above mentioned stages in the development of specific atmospheric processes should be also expressed in the formation process of averaged characteristics of such large-scale GAC stage as a circulation epoch.

The studies have confirmed our suggestions. In fact the processes of any found circulation epoch undergo three stages in their development. The first stage covers the period in which a successive growth of typical components of the circulation forms governing the name of the epoch is observed. Then a comparatively short period of equilibrium or unstable development of the processes of this form follows. The period of the degradation of the processes of the dominating circulation form covers much of the epoch.This is a period when features of the processes that are decisive for the next circulation epoch become more intensive. And it has been found that the processes of the progressive development period are mainly formed due to the types of the same epoch of the circulation form that are included to the first group. And the processes of the degradation period are formed due to a gradual increase in the processes of the second group of this form.

In confirmation let us present the results of analysing the interannual and intraannual development of atmospheric processes for the period of the current circulation epoch (1949-1990).

Table 1. Intraannual periods of the homogeneous development of macroprocesses in the stages of circulation epochs

<table>
<tr><th>Epochs</th><th>Epoch</th><th>Macroproc</th><th>IX</th><th>X</th><th>XI</th><th>XII</th><th>I</th><th>II</th><th>III</th><th>IV</th><th>V</th><th>VI</th><th>VII</th><th>VIII</th><th>IX</th><th>X</th><th>XI</th><th>XII</th><th>I</th></tr>
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<tr><td>5.1916</td><td>W_{M1}</td><td></td><td colspan="5">E_{M2}</td><td colspan="4">$(W+E)_{M1}$</td><td colspan="3">W_{Z}</td><td></td><td></td><td></td><td></td></tr>
<tr><td>6.1921</td><td>W_{M1+Z}</td><td></td><td></td><td></td><td></td><td colspan="4">E_{Z}</td><td colspan="5">W_{M1}</td><td colspan="3">$(W+E)_{Z+M1}$</td><td></td></tr>
<tr><td>7.1925</td><td>W_{Z}</td><td></td><td></td><td></td><td></td><td colspan="2">W_{Z+M2}</td><td colspan="3">E_{Z}</td><td colspan="4">W_{Z+M1}</td><td colspan="3">$(W+E)_{Z+M2}$</td><td></td></tr>
<tr><td rowspan="3">epoch E</td><td>1.1929</td><td>$(E+W)_{Z}$</td><td></td><td></td><td colspan="3">E_{Z+M2}</td><td colspan="3">E_{M1+M2}</td><td colspan="6">$(W+E)_{Z}$</td><td></td><td></td><td></td></tr>
<tr><td>2.1934</td><td>E_{M2+M1}</td><td></td><td colspan="9">E_{M2}</td><td colspan="4">E_{M1+M2}</td><td></td><td></td><td></td><td></td></tr>
<tr><td>3.1938</td><td>E_{M2}</td><td></td><td colspan="4">E_{M2}</td><td colspan="5">$(E+W)_{M2}$</td><td colspan="3">E_{M1}</td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">epoch C</td><td>1.1940</td><td>C_{Z+M2}</td><td></td><td></td><td></td><td></td><td colspan="4">E_{M2}</td><td colspan="2">E_{M2}</td><td colspan="3">E_{M2+Z}</td><td colspan="3">E_{Z+M1}</td><td></td></tr>
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<tr><td>3.1957</td><td>$(C+E)_{Z}$</td><td></td><td></td><td></td><td colspan="3">$(E+E)_{Z}$</td><td colspan="5">E_{Z}</td><td colspan="4">$(E+E)_{Z}$</td><td></td><td></td></tr>
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<tr><td>5.1969</td><td>$(E+C)_{M2}$</td><td></td><td></td><td colspan="3">$(E+E)_{M1}$</td><td colspan="3">E_{Z}</td><td colspan="2">$(E+E)_{M}$</td><td colspan="4">$(E+E)_{M2}$</td><td></td><td></td><td></td></tr>
<tr><td rowspan="5">epoch E</td><td>1.1972</td><td>E_{Z}</td><td></td><td></td><td></td><td></td><td colspan="3">E_{Z+M1}</td><td>(E+</td><td colspan="2">E_{Z+M2}</td><td colspan="2">E_{M2+Z}</td><td>E_{M2}</td><td colspan="3">E_{Z+M1}</td><td></td></tr>
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<tr><td>3.1981</td><td>E_{Z}</td><td></td><td></td><td></td><td></td><td colspan="2">$(E+C)_{Z}$</td><td colspan="2">E_{Z}</td><td colspan="4">E_{Z}</td><td colspan="2">E_{Z}</td><td colspan="2">W_{Z}</td><td></td></tr>
<tr><td>4.1985</td><td>E_{Z}</td><td></td><td></td><td></td><td colspan="3">C_{Z}</td><td>E_{Z}</td><td colspan="3">E_{Z}</td><td colspan="3">$(E+W)_{M2}$</td><td colspan="2">E_{Z}</td><td></td><td></td></tr>
<tr><td>5.1988-</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Note: E,W.C - forms of atmospheric circulation in the Atlantic - Eurasian sector of the Northern hemisphere according to G.Vangengeim (1952);

M1, M2, Z - types of atmospheric circulation in the Pacific - American sector of the Northern hemisphere according to A.Girs (1974).

During this epoch the processes of the E circulation form are extremely developed. They were the governing ones in the years of the period under consideration. That is why it was very important to reveal a character of the relationship between the processes of the first and second groups of this form in the years of the epoch and the direction of the change in this relationship.

Therefore, all types of the natural stage of development (NSD) of the second group that were observed in each year of the series under consideration were selected from the catalogue (Catalogue, 1963). Then their percentage, relative to a general NSD number of the E circulation form was calculated. After calculating the "norm" and deviations from it and smoothing, a diagram (Fig. 2) of interannual variability of the anomalies of occurrence of the types of the second group of processes in the form of integral curve was plotted.

As is seen from this diagram, up to the early 60s the occurrence of the types of the processes of the E circulation form representing a weak interlatitudinal air exchange is less than the normal value and after that the number of these types exceeds the normal values from year-to-year.

Thus, from the 50s to the 60s there were qualitative and quantitative changes in the occurrence of the types of the circulation form dominating in the epoch under study. This indicates that from the early 60s there is a gradually increasing influence of those components of the circulation mechanism that govern an increase in the activity of the zonal transport components.

This feature or a sufficiently persistent tendency of the circulation pattern change is evident in the formation character of some hydrometeorological characteristics over the Hemisphere and in the Arctic.

The results of analysing variability of the whole complex of hydrometeorological elements depending on the GAC structure changes within an epoch are given in (Ivanov, 1978; Vinogradov, 1977, 1983, 1984, 1986). These changes include: a formation character of pressure fields and air temperature in the Arctic, direction of wind flows over the areas of the Arctic

Seas, heat losses of North Atlantic water and water heat content at the transect along Kola meridian, runoff value of the Severnaya Dvina water, ice cover extent of the Arctic Seas and some other elements of the hydrometeorological regime.

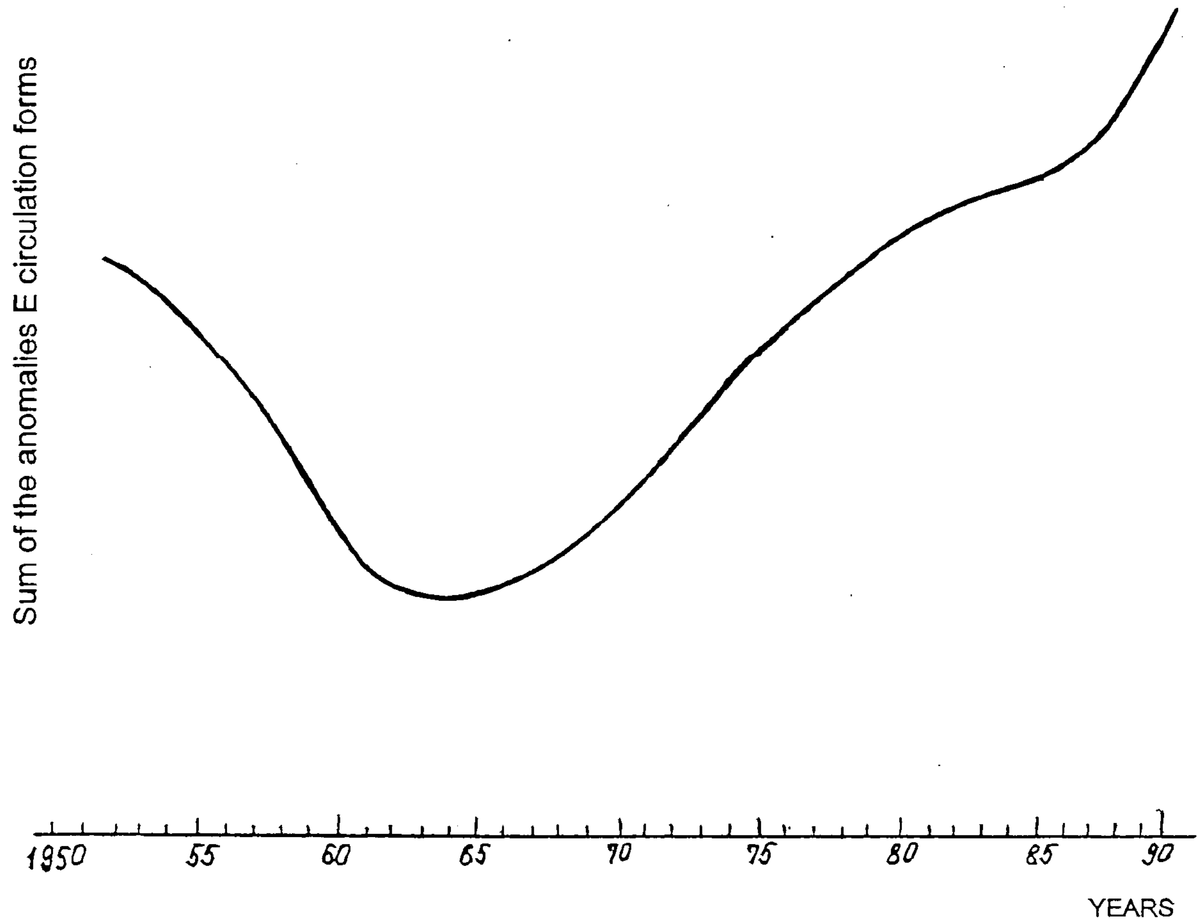

Fig. 2. Integral-difference curve of mean annual anomalies of occurrence of the processes of the second group of the E circulation form

The Report presents the resuls of analysing occurrence frequency of large positive and negative air temperature anomalies, as well as anomalies in the frequency of absolute maxima and minima of this meteorological element over the western Arctic Seas in the period from 1935 to 1990 (Fig. 3 and 4). An analysis of these diagrams shows that in both cases since the 60s there is a decrease in mean air temperature over the western Arctic Seas.

This fact confirms the above conclusion about strengthening of zonal transport components in the structure of the general circulation of the atmosphere, that is, attenuation of the air exchange processes between latitudes of the polar and temporal zones of the Hemisphere during the last three decades.

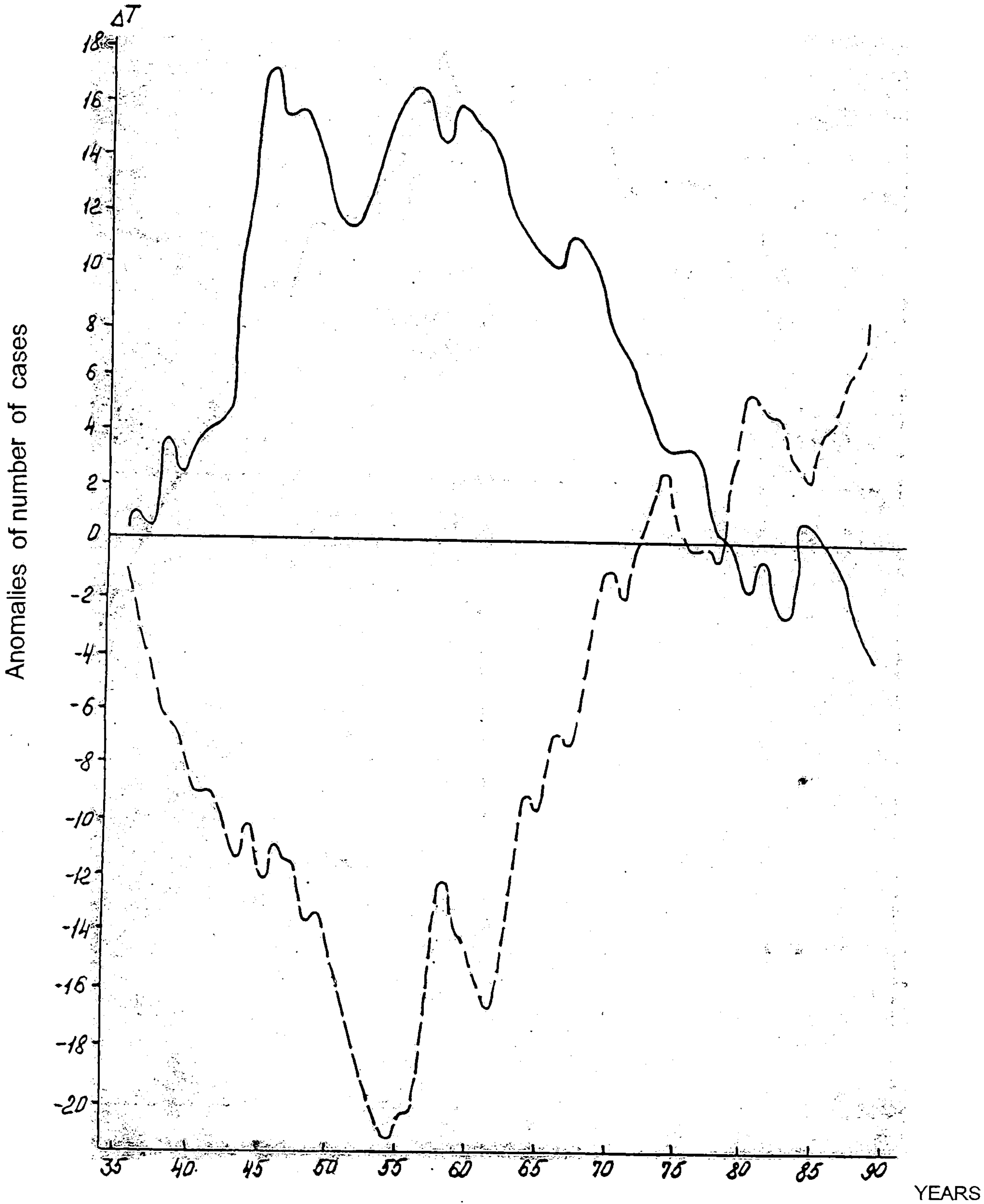

Fig.3. Mass curve of departures from standard frequency of big positiv (————) *and negativ* (—— — ——) air temperature anomalies over the western Arctic Seas

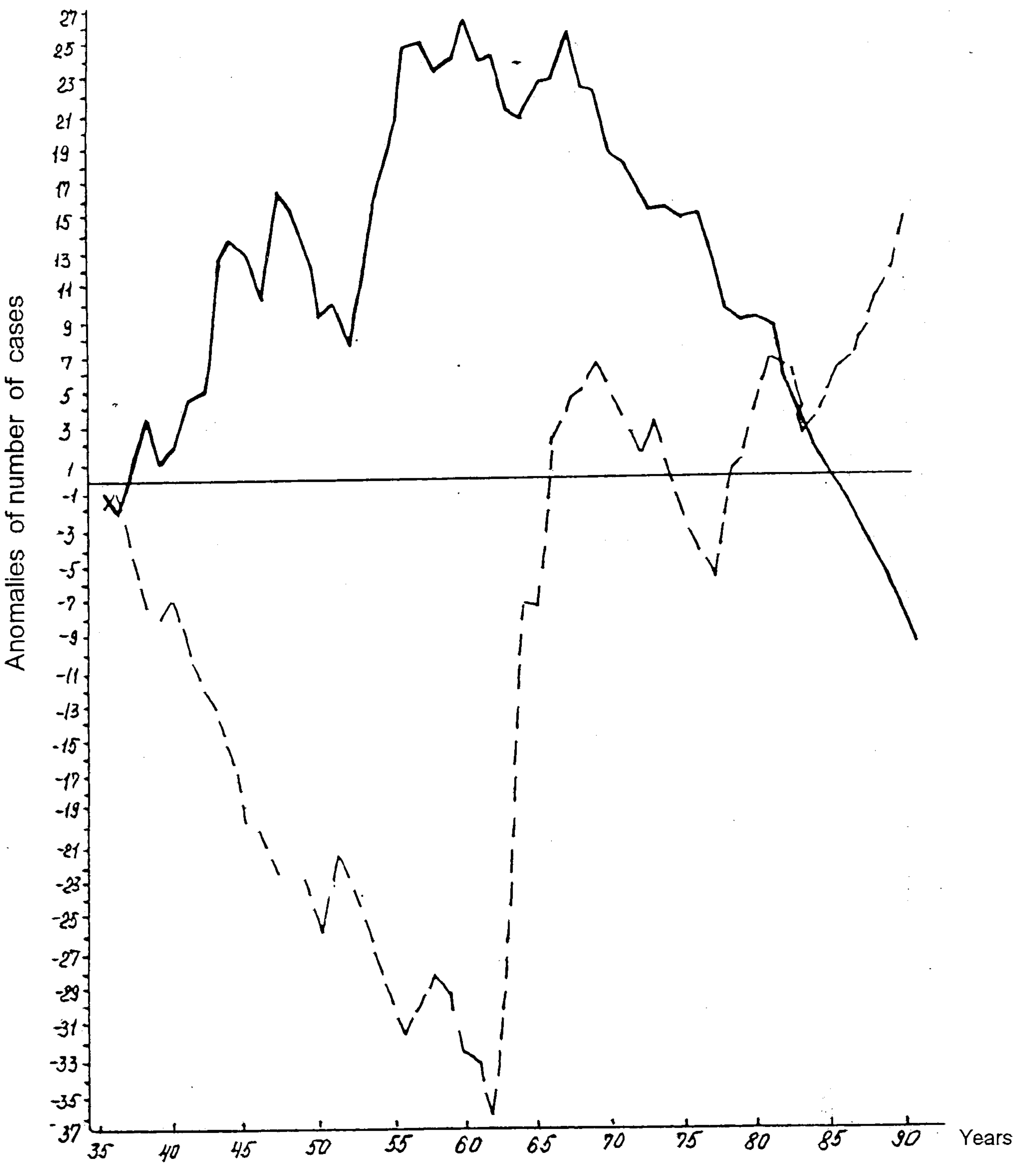

Fig.4. Integral curve of anomalies in occurrence frequency of absolute maxima (————) and minima (—— — ——) over the western Arctic Seas

The latter has a significant practical importance. When diagnosing current atmospheric processes we can reveal not only their place in the chain of a continuous GAC, but also gain an impression about the direction or the way of their further transformation, as well as about the character of the expected formation of the hydrometeorological regime elements.

2.3 Techniques for taking into account circulation and thermal-pressure background in long-range forecasting

The author of the macrocirculation method (G.Ya. Vangengeim) introduced a notion of the homology of the process into the diagnostics. That is, the process that is being diagnosed is analogous to the previous processes not on the basis of external similarity, but on the basis of a number of similar internal genetic indications. This homology is found by studying a chain of processes in their continuous development, taking into account the thermal pressure background that appears during the process of longer fluctuations of the general atmospheric circulation elements, as compared with the process under diagnosis. The features of these fluctuations and a corresponding thermal-pressure background are indicated by the character of long-term tendencies forming uniaxial macrotransformations over the Hemisphere. During research and operational activities some specific results on the character of long-term tendencies, formation of a complex of hydrometeorological elements and the role of some external factors were obtained. Mean charts of anomalies of air pressure and temperature over the Hemisphere and in the Arctic and integral curves of variability of circulation conditions and hydrometeorological elements were constructed for each temporal stage of a uniaxial formation. The analysis of these data allows determining features of different stages in the development of the macroprocess and find out the peculiarities indicating transformation of the process of one stage into another.

The data mentioned above are used for the following purpose:

1. To reveal the features of macrotransformations in the diagnosed circulation stages (epoch, interannual and intraannual stages of this epoch), determine the location of these transformations in a continuous development chain of the main GAC state and find indications of their subsequent state.

2. To analyse circulation and meteorological background of the current macro-transformation.
3. To delineate more accurately the boundaries of the change of interannual and intraannual stages of circulation epochs.
4. To select "acting" background and seasonal groups.
5. To determine macroprocesses homologous to the initial period.
6. To choose the most probable years-homologues from the selected group of macroprocesses.
7. To determine the character of structural relations in the macroprocesses of the most probable group of homologues and their use for the purpose of forecasting for the next stages.

We have enumerated the main stages or techniques of taking into account the results of a detailed analysis of structural features and relations of the current macroprocess for forecasting. These techniques are described in detail in some of our publications (Vinogradov, 1989; Girs, 1984).

In conclusion, it should be noted that the practice of taking into account the indicated stages of the analysis of macroprocesses in forecasting has resulted in recent years in a more justified predicting of expected atmospheric processes and meteorological elements governed by them in the polar region. Probability of these forecasts is 15-20% higher than probability of long term averages.

2.4 On the most probable character of the transformation of atmospheric macroprocesses

The results of investigating the structural changes of the GAC indicate that at present we are at the stage of a large-scale change of its pattern, i.e. at the transition stage from the circulation epoch with an active interlatitudinal air exchange (the processes of the E and C circulation forms are developed) to the epoch of anomalous development of zonal transport processes (processes of the W circulation form).

It is known that in the periods of high secular level of solar activity (higher than mean multiyear one) a positive anomaly of occurrence of meridional circulation forms is observed. During the periods of low level of solar activity there is an enhanced occurrence of the zonal circulation form processes. In the opinion of specialists, a minimum of the secular cycle of solar activity is expected in the 2016. The two preceding cycles will be comparatively low (close to a minimum). Thus, one may expect the formation of the zonal circulation epoch to commence in the 90s of this century.

Let us note that the processes of each of the three main atmospheric circulation forms have their own corresponding regime of meteorological conditions over the Hemisphere.

In particular, in the case of transition to the epoch of the W circulation form in the polar regions one should expect a formation of lower air temperature and pressure background, more active branches of polar and arctic fronts with a simultaneous shift of the zone of these fronts to lower latitudes and increased precipitation in the temporal zone of the Hemisphere.

Naturally, such large-scale change in the pattern of macrosynoptic processes cannot occur rapidly. A period for the preparation of the conditions of such transition in the existing epoch is necessary, i.e. the period of the formation of features for the future development at the background of current processes. The occurrence of such processes was recorded. Let us consider in brief some results of the expression of these conditions in natural processes.

Since 1976 a trend component of the occurrence of days with a W circulation form has been increasing and in 1992-1993 the anomalies in the number of days with this form are positive, although insignificantly. And the trend of the Caspian Sea level is synchronous. The runoff of the Baltic rivers and Severnaya Dvina also increased, In both sectors of the Eurasian Arctic, (especially western) the number of days with extremely low air temperature anomalies and the number of days with absolute minima sharply increase. The number of days of these elements with opposite signs sharply decreases. In 1992-1994 in the months with positive W values temperature anomalies in most of the Arctic seas are negative.

Regretfully, over the whole observation series available (1891-1994) or during the separation of atmospheric processes into three types of their state (W, E and C forms) such type of large (epoch like) changes in the pattern of macroprocesses was not observed. That is why at present we are not able to answer some questions arising in connection with this tendency in the development of processes. In particular, we cannot more accurately identify the period of the final transition to the new circulation epoch (processes of the W form).

However, knowledge of the tendency for current transformation and formation of background characteristics of meteorological conditions in the Arctic is of great practical importance for choosing more reliable homologues for issuing a background meteorological forecast.

2.5. Mathematical modelling of natural non-stationary processes and a detailed long-range forecast of pressure fields in high latitudes of the Northern Hemisphere

When describing natural phenomena one has to deal with a wide range of motions (or changes) containing quasiperiodic fluctuations with periods from fractions of seconds to tens of thousand years and wave lengths from fractions of a meter to 10 km and probably more and a linear component governed by a non-stationary state of the process. A technique for taking into account a stationary component for developing a numerical scheme of a long-range detailed forecast has been presented in the previous Report. Here a methodology for taking into account a non-stationary part of the motion will be considered.

Methods of mathematical statistics that are known to be widely employed for describing natural processes are applicable only for stationary random processes whose statistical characteristics do not depend on the beginning of the time count. And the theory of non-stationary random processes has been insufficiently developed.

The hydrometeorological systems are characterized by the presence of relatively short quasistationary fluctuations of intensive parameters of the system (temperature, pressure, etc.) appearing due to a periodic excitation of separate freedom degrees of the system at typical frequencies and energy redistribution between these oscillatory freedom degrees. In order to forecast fluctuations of intensive parameters of the system it is desirable to determine typical frequencies of these fluctuations and dynamics of the frequency change in the realizations of full-scale data under study. An application of the theory of stationary random functions for analysing such processes results in uncontroled errors governed in particular, by uncertainty in the choice and time of the analysis of the realization under study. This uncertainty is known to occur because when averaging by an independent variable assuming the process to be ergodic it is desirable to increase the period of its recording for obtaining statistically stable characteristics. At the same time from the point of view of studying the change of temporal structure and dynamics of the development of the process it is necessary to decrease this recording interval. Hence, known methods for analysing random processes based on averaging, do not allow tracing in time the dynamics of the frequency change within observation. This prevents the development of a physically sound method for forecasting a non-stationary process at time intervals significantly exceeding the observation interval.

This problem can be resolved using an analysis method that allows operation with current characteristics of the study process that are determined for the time comparable with the time of local stationarity of the process rather than with intensive parameters averaged by argument. It is most suitable to use $\varphi(t)$ phase and A(t) amplitude as such characteristics (Vakman, 1972), that is, parameters that sufficiently fully reflect properties of an oscillatory process. Let us present the study process in the form

$$U(t)=A(t)\cos\varphi(t) \qquad (1)$$

In a general case the process under consideration in the form (1) can be represented by denumerable infinity of techniques choosing some type of the operator $\mathcal{L}$ or other that prescribes some auxiliary function $y(t) = \mathcal{L}\{U(t)\}$ by means of which functions A(t) and $\varphi(t)$ are determined as

$$A(t)=\sqrt{U^2(t)+y^2(t)}$$
$$\varphi(t)=arctg\frac{y(t)}{U(t)} \qquad (2)$$

From a set of operators $\mathcal{L}$ most justified from a physical point of view is the choice of Gilbert's integral transformation (Vakman, 1972)

$$y(t) = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{U(\tau)}{t-\tau} d\tau \qquad (3)$$

In a limiting case, that is, in the event of harmonic process, the notions of amplitude, phase and frequency ($\omega = \frac{d\varphi}{dt}$), determined on the basis of Gilbert's transformation, are in agreement with a common physical understanding of these notions.

In the case of quasiharmonic fluctuations for the argument values sufficiently remote from the boundaries of fluctuations, the values of function y(t) are little dependent on the character of the process outside these fluctuations. This property of Gilbert's transformation allows identifying quasiharmonic fluctuations, locally stationary in frequency, and their typical frequency in the realization of a random process and determine time intervals of local stationary state at characteristic frequencies.

A method for a phase-frequency analysis of non-stationary processes was developed with regard to the aims of radiotechniques in (Vakman, 1972; Trakhtman, 1969; Kharchenko et al. 1973). A possibility of using this method for hydrometeorological goals was shown in (Nikolayev, 1977). In this work the conjugated function y(t) is determined by means of a series expansion of the initial realization U(t) of the study process by means of trigonometric functions. In this case an integral (3) can be presented in the form

$$y(t) = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{\sum_{k=1}^{\infty} C_k \cos(\omega_k t - \varphi)}{t-\tau} d\tau \qquad (4)$$

from which it follows that

$$y(t) = -\frac{1}{\pi} \sum_{k=1}^{\infty} C_k \sin(\omega_k t - \varphi) \qquad (5)$$

Thus, it can be said that for a mathematical description of non-stationary natural phenomena there is in principle a possibility to approximate a non-stationary wide band realization of this phenomenon, obtained experimentally, by a set of quasiharmonic stationary processes successive in time. Hence, the obtained time sequence of these processes can be considered as a reflection of a really observed non-stationary process at a new generalized description level. The advantage of such description is primarily in a significant reduction of the frequency spectrum of the process under study and in the determination of typical relatively weakly attenuating frequencies.

The presentation of the process under study thus obtained represents some time function. The moments of the frequency change or high rate intervals of its change correspond to transient processes in the system. And they are responsible for the excitation of the degrees of freedom and energy redistribution within the system.

Determination of transient processes, analysis of their succession in time, as well as determination of weakly attenuating typical frequencies are key questions for developing forecasting methods for a non-stationary process outside the interval of its observation.

It should be noted that time representation thus obtained will have by itself a lower degree of non-stationarity compared with the initial real process. However, if necessary, it is possible to further reduce a degree of non-stationarity by means of repeated application of the described procedures to the representation. In the event a degree of non-stationarity is not large (the process is represented by 3-5 typical frequencies), a Fourier expansion and determination of characteristic weakly attenuating frequencies are permissible. These frequencies govern a thin structure of oscillations outside the observation interval that does not depend on external excitation being a consequence of only internal causes that are governed by physical properties of the system.

On the basis of the consideration mentioned above a numerical scheme for a detailed forecast of pressure fields for high and temperate latitudes of the Northern Hemisphere from 10 to 35 days in advance was created. An automated calculation scheme consists of four main software blocks: block of expansion of meteorological fields, block of analysis and forecasting, block of coordination of prognostic fields and block of data gridding and output of prognostic material.

The first block serves for expanding daily fields of geopotential H_{500} and surface pressure in the Northern Hemisphere on the basis of spherical functions over 182 initial days. The expansion procedure is performed in the area of wave numbers from 0 to 18, so that as a result, taking into account a symmetry of coefficients, 380 sets of data for geopotential H_{500} and surface pressure are created. By using a procedure of a harmonic analysis (stationary process) and Gilbert's transformation (non-stationary process) the characteristics of wave disturbances describing the main features of the process in a stationary and non-stationary areas of motion in the free atmosphere are determined. Calculation of prognostic expansion coefficients is made by addition and extrapolation of separate harmonics on the basis of a natural property of the atmosphere as a gaseous medium to preserve a character of occurring fluctuations during a definite period of time. The existence of a spectrum of free long-period oscillations typical of a specific set of wave frequencies is proved in (Yaglom, 1953), V. Yefimov (1987), Yevseyev (1976) on the basis of an analytical solution of linearized motion equations. The presence of such disturbances in real atmosphere on the basis of an analysis of temporal series of expansion coefficients is substantiated, for example, by Yevseyev and Golev (1990).

The third block of the scheme is used for making the prognostic results consistent by means of a hydrodynamic spectral model of the general atmospheric circulation with a resolution up to the wave number L = 18. Model characteristics of the process, such as divergence of the flow, advection, analogue of the vertical speed serve as a basis for calculating the surface pressure field. A correction of the surface pressure spectrum is made on the basis of taking into account prognostic values of expansion coefficients calculated similar to H_{500}. The hydrodynamic modulus does not have an independent prognostic value.

At the final, fourth calculation stage fields of geopotential H_{500} and surface pressure for the Northern Hemisphere are gridded, analysed and the output result is obtained in the form of charts of isohypse of H_{500} surface and isobars of surface pressure fields.

A numerical scheme of such forecast has been verified on a preliminary basis at the AARI using data of 1994.

Before proceeding to analysing estimates of forecasts let us consider features of wave processes in the atmosphere in 1994, whose presence and character served as a basis for forecasting pressure fields. When analyzing a spectrum of harmonic oscillations of expansion coefficients of daily geopotential H_{500} fields for the period from December 4, 1993 to December 4, 1994 (Fig. 5), one can see that mean values of general dispersion fields for the first 36 Fourie-harmonics (excluding the first one) have a number of maxima in low- and high-frequency areas of the spectrum. These maxima are observed in harmonics 2, 4, 7, 11, 22, 29 and 33. This means that during the whole year the oscillations with periods in days, respectively, 183, 91, 52, 33, 17, 13, 11 were most well-defined in the free atmosphere of the Northern Hemisphere.

Fig. 6 presents amplitudes of oscillations that are extreme in the oscillation spectrum for different sets of expansion coefficients. As is seen from this graph, the main contribution to the existence of semi-annual oscillations are made by atmospheric disturbances described by zonal wave numbers L from 1 to 7 and N (meridional wave numbers) from 1 to 3 while the short-period oscillations (11 days) are described by smaller-scale disturbances with wave numbers L from 9 to 12 and N equal to 6.

Thus, an analysis made confirms the fact of the existence of a spectrum of long-period oscillations in the atmosphere, whose periods and amplitudes depend on the scales of appearing disturbances.

An assessment of prognostic fields was made by 50 points of the Arctic region north of 70°N uniformly located in regular grid points according to the data of two forecasts: from October 16 to October 20, 1994 and from December 1, 1994 to January 4, 1995 (Fig. 7, 8).

Table 2 presents values of correlation coefficients between the prognostic and real surface pressure fields, as well as values of the index "ρ" calculated using the formula

$$\rho = \frac{n_{coinc} - n_{non-coinc}}{n}$$

where n_{coinc} - is a number of points in which the sign of the real surface pressure field anomaly coincided with that of prognostic anomaly,

$n_{non\text{-}coinc}$ - number of points where the signs of anomalies did not coincide,
n - total number of points.

An assessment was made for 10, 15, 20, 25, 30 and 35 days of the forecast.

As is seen from this Table, there is a specific correlation between the prognostic and real fields that exceeds by 22% a random correlation (which equals zero). Mean index "ρ" is equal to 20. This means that the signs of the predicted pressure anomalies are correct in 60% of cases (50% + ρ/2).

One should note that of such forecasting for latitudes southward of 70°N is slightly more successfull being 25-30% on the average. This is attributed to a much larger variability in atmospheric processes in the Arctic, as compared with temperate latitudes.

Table 2. Assessment of verification score of detailed long-range forecasts of surface pressure fields in the Arctic

Forecast period	24 h of the forecast	Correlation coefficient	"ρ" index"
16.X-20.XI	10	0.22	0.20
	15	0.22	-0.12
	20	0.51	0.28
	25	0.54	0.40
	30	-0.06	0.20
	35	-0.03	0.24
01.12.94-04.01.95	10	0.39	0.36
	15	0.48	0.44
	20	0.00	0.16
	25	-0.07	0.08
	30	0.23	0.00
	35	0.24	0.20
	Mean	0.22	0.20

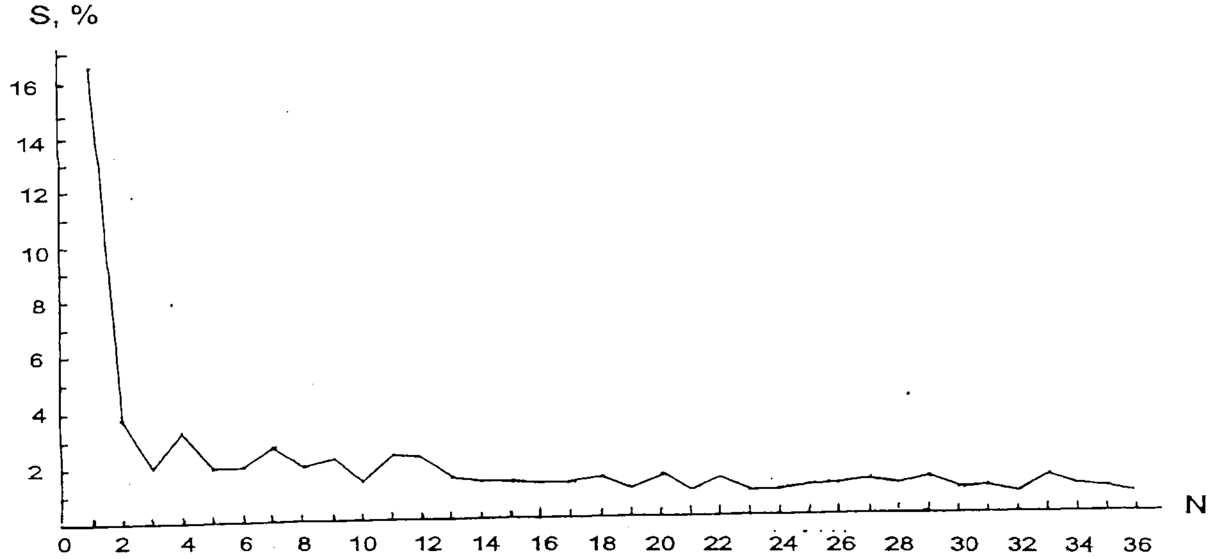

Fig. 5. Mean fractions of total dispersion (S%) that are taken into account by the first 36 Fourier harmonics (K) at a harmonic analysis of 190 time sets of expansion coefficients of daily fields of geopotential H500 of the Northern Hemisphere from December 4, 1993 to December 4, 1994

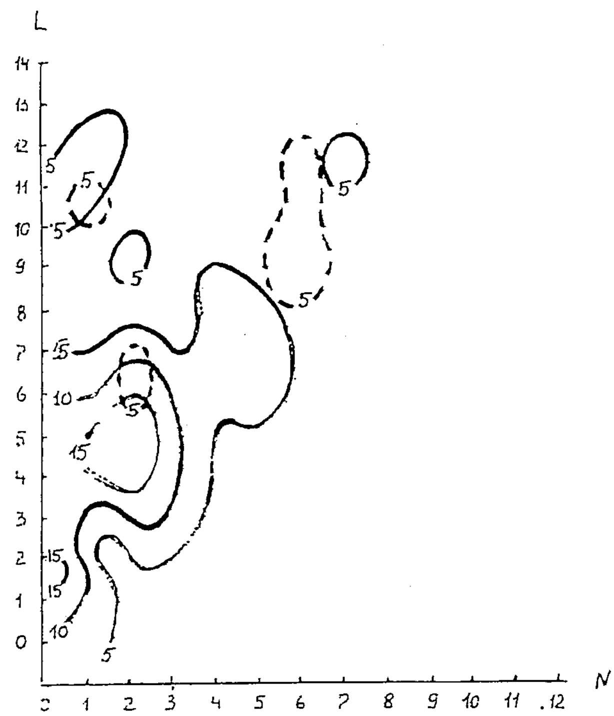

Fig. 6. Amplitudes of oscillations (decameters) of the second (solid line) and thirty-third (dashed line) of Fourier harmonics for the sets of expansion coefficients of daily fields of geopotential H_{500} for the period from December 4, 1993 to December 4, 1994, (L, N - wave numbers)

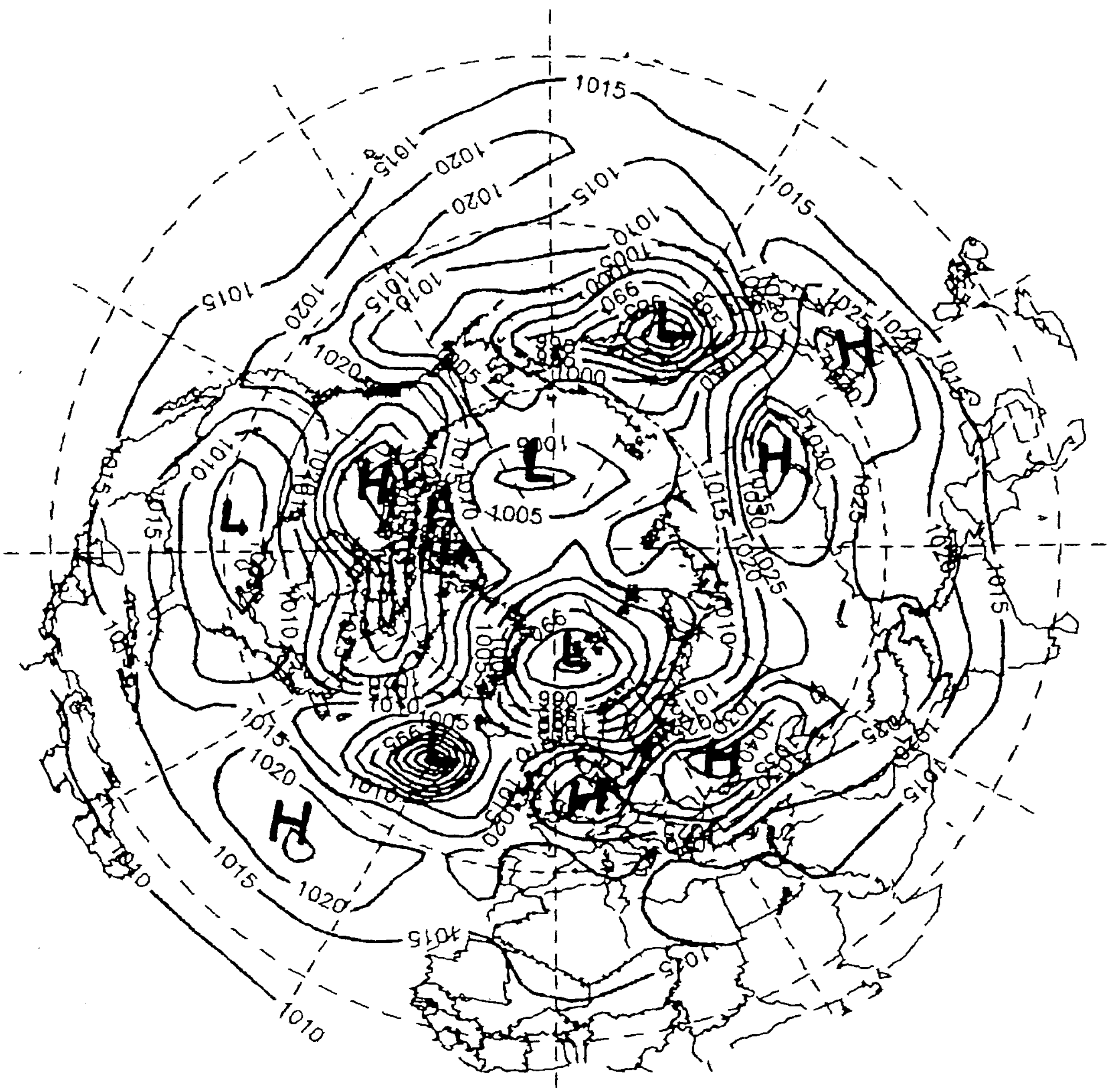

Fig. 7. Surface pressure field forecast for December 25, 1994. Forecast for the 25th day

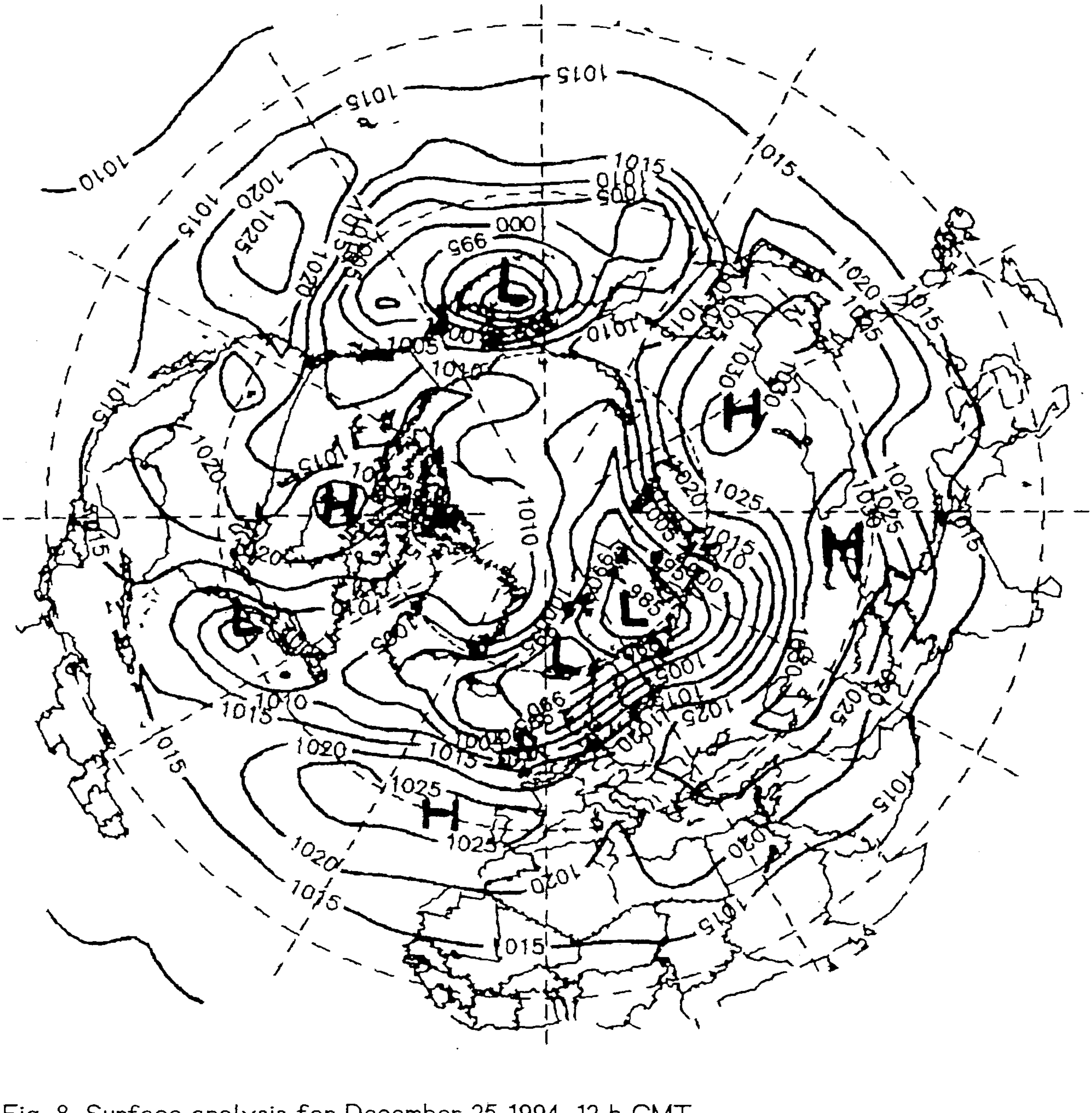

Fig. 8. Surface analysis for December 25 1994, 12 h GMT

3 OCEANOGRAPHIC FORECASTS

As a result of the 1993 stage (Operational tools), a review of the forecasting methods for sea level oscillations and wave that are used for scientific-operational support to shipping along the NSR was made. One of the considered methods for forecasting sea level is a probabilistic method of non-periodic level oscillations. Main attention in this work is devoted to the methods of forecasting dangerous level rises and drops on the limiting segments of the NSR.

3.1 A physical-statistical method for forecasting dangerous level rises and drops

A restricted character of samplings of dangerous level rises and drops along with correlated variables (surface pressure in the points remote from each other at a distance that is significantly less than spatial scales of pressure systems) makes an ordinary regression analysis ineffective due to instability of obtained regression coefficients. That is why we used a model of ridge regression (Hemmerle, 1975) along with the additivity property of correlated variables. The main aim of the ridge regression method is to overcome a small stability in the estimates of coefficients of an ordinary regression model. Unlike the least-square-method that yields unbiased estimates of the equation coefficients, the ridge regression method has biased estimates, but they have a smaller dispersion. Biased estimates can be acceptable if an insignificant estimate bias results in a large decrease in the coefficient dispersion. This is the main advantage of using the ridge regression method.

While in the least-square-method the coefficients are estimated by the formula:

$$\hat{\alpha} = (X'X)^{-1} \quad X'Y, \tag{6}$$

in the ridge regression method similar estimates are obtained from the expression:

$$\hat{\alpha}^* = (X'X + kI)^{-1} \quad X'Y, \tag{7}$$

where X'X - correlation matrix;

kI - a product of a small positive scalar ($0 \leq k \leq 0.5$) and a single matrix;

X' - transposed matrix of independent variables;

Y - function-vector.

All variables are standardized.

In our case the value equal to 0.2 turned out to be the best k parameter value at which the coefficients were "stabilized".

For deriving the final prognostic equation for some point a property of additivity of correlated variables was used that is expressed as follows:

$$\left.\begin{aligned} \alpha_1 X_1 + \beta_1 &= \frac{r_1^2 y}{\sum_i r_i^2} \\ \alpha_2 X_2 + \beta_2 &= \frac{r_2^2 y}{\sum_i r_2^2} \\ &\cdots\cdots\cdots \\ \alpha_m X_m + \beta_m &= \frac{r_m^2 y}{\sum_i r_m^2} \end{aligned}\right\} \qquad (8)$$

$$\sum_{i=1}^{m} \alpha_i X_i + \sum_{i=1}^{m} \beta_i = y \qquad (9)$$

Assuming $\sum_i \beta_i = b,\ X_i = P_{t,i},\ y = h_t + \tau$ we obtain a prognostic equation in the form

$$h_t + \tau = \sum_{i=1}^{m} \alpha_i P_{t,i} + b \qquad (10)$$

where $h_{t+\tau}$ - a prognostic level at a prescribed point 24 hours in advance;

$P_{t,i}$ - surface pressure at the i point for the time t, taken in the deviations from 1000 hPa;

α_i - a weight coefficient of the point i obtained by the ridge regression method;

b - a free term of the equation.

In expressions (8) r_i - a dual coefficient of pressure correlation at the point i and the level at a prescribed point with a shear τ. The location of the points of atmospheric pressure is presented in Fig. 9.

Table 3 presents coefficients of prognostic equations (10) for 4 Arctic sites 24 hours in advance. Table 4 presents criteria of statistical significance of obtained equations. As is seen from Table 3, weight coefficients of some points are equal to zero. In fact they, of course, differ from zero, but we had to make them equal to zero as the use of these points with their true coefficients either increases mean square error of prognostic equations (10) or is not effective due to the coefficients themselves being small (close to zero). Thus the effective coefficients are selected.

The following denominations are assumed in Table.4-7: δ - mean square error;

$|\overline{\Delta}|$ - mean absolute error; R - general correlation coefficient; S - a quality parameter or relative error; A - amplitude of oscillations of initial sampling; N - a number of test situations in the sampling; P(%) - probability of not exceeding mean square error.

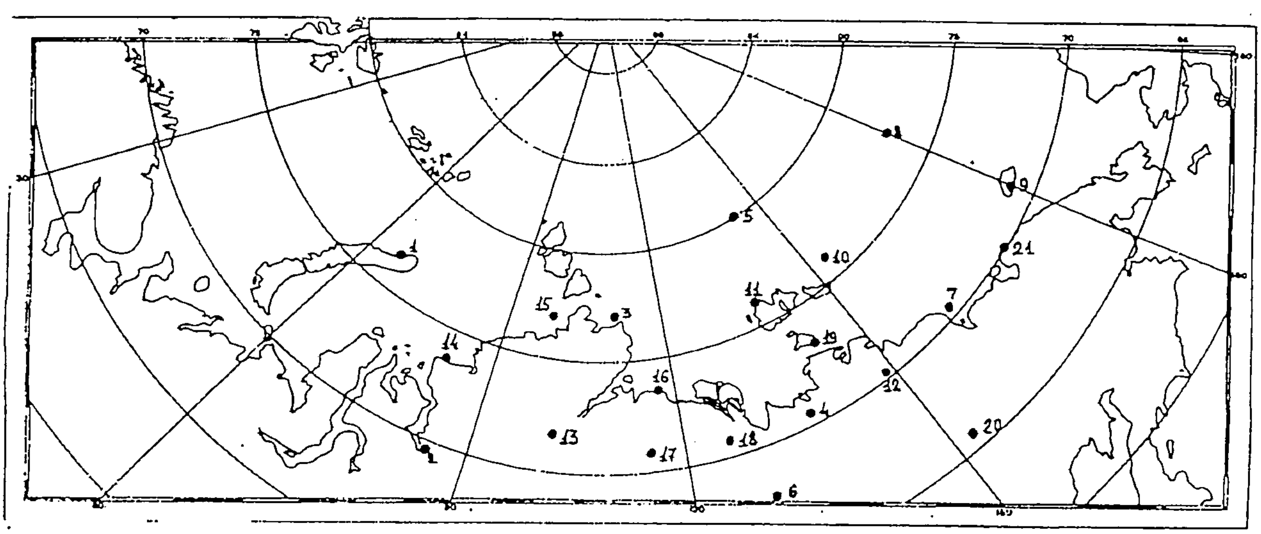

Fig. 9. Location of points from which atmospheric pressure was taken

Table 3. Coefficients of prognostic equations (10) for different Arctic points 24 hours in advance

Point	Numbers of pressure field points and their weight coefficients																					b
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	
Tiksi inlet	-1.05	1.07	0	-1.68	-2.48	0	0	0	0	-1.0	-1.06	0	3.76	1.0	2.93	-3.15	1.67	0	0	0	0	-3.7
Nemkov Island	0	1.49	2.08	0	0	1.12	-1.45	0	0	-2.61	-3.66	0	3.03	0	0	0	0	0	0	0	0	7.9
Ambarchik inlet	0	0.59	0	3.23	-2.13	1.06	-2.43	-0.6	-2.71	0	0	0	0	0	0	0.63	0	1.54	2.06	0	-0.64	8.5
Shmidt Cape	0	0	0.50	0	0	0	2.05	-0.76	-2.41	-1.66	-1.64	1.12	0	0	0	0	2.66	0	0	1.73	-1.30	-4.7

Table 4. Criteria of statistical significance of prognostic equations 24 hours in advance - equation (10)

Point	δ (cm)	$\lvert\bar{\Delta}\rvert$ (cm)	R	S	A (cm)	N	P (%)
Tiksi inlet	39.41	35.27	0.959	0.283	438	35	65.7
Nemkov Island	26.90	21.91	0.942	0.329	245	13	69.0
Ambarchik inlet	32.27	28.00	0.955	0.296	345	26	69.2
Shmidt Cape	41.40	32.80	0.935	0.348	360	28	78.6

Statistical significance criteria indicate a possibility for applying prognostic equations (10) in operational practice as they fully meet the requirements of the Manual on Forecasting Services (1982). For forecasting dangerous level rises and drops the importance of the forecasting error increases very much. That is why one has to look for additional special methods for increasing a forecasting reliability. One of such methods is smoothing of an independent variable by dispersion. This method allows one to suppress to a great extent or reduce random fluctuations of the variable and, respectively, make the relation to a function (predictant) more close in some cases. For this purpose we applied a non-linear transformation of the differences in surface atmospheric pressure in the form:

$$\widetilde{P_m - P_1} = \eta\,(P_m - P_1) \qquad (11)$$

where $\eta = \left(\sqrt{10\,|P_m - P_l|}\right)$, P_m, P_l - pressure at points m and l, respectively.

The prognostic equations were calculated by means of a ridge regression method using a property of the additivity of correlated variables. Selection of transformed pressure differences was made by the value of their pair correlation with a level in a prescribed point. As a result, prognostic equations of the form (10) for each of the four points were obtained.

The criteria of statistical significance of these equations are presented in Table 5.

Table 5. Criteria of statistical significance of prognostic equations on condition that independent variables are smoothed by equation (11)

Point	δ (cm)	$\lvert\bar{\Delta}\rvert$ (cm)	R	S	A (cm)	N	P (%)
Tiksi inlet	37.77	30.83	0.962	0.274	438	35	61.1
Nemkov Island	20.88	18.54	0.967	0.255	245	13	69.2
Ambarchik inlet	27.81	22.37	0.967	0.254	374	26	70.4
Shmidt Cape	30.29	24.64	0.965	0.263	360	28	64.3

As is seen from the comparison of Table 4 and 5, a preliminary smoothing of the predictor by dispersion has a positive effect allowing a slight increase in the accuracy of prognostic relationships.

3.2 Extrapolation of the level

The study of a probabilistic nature of dangerous level deviations from the mean was performed by means of estimating a correlation function and spectral density of the process by levelling. The correlation functions for each of the four Arctic points was estimated separately for surge level rise and drop by an ensemble of realizations. The methods for such estimates were presented earlier in (Andryushenko, 1985; Vanda, 1989). The realizations contained level readings at 4 times with excluded tide. Each realization contained 8 readings preceding a maximum development of the level rise or drop. The number of realizations varied from 66 (Tiksi) to 18 (Nemkov). The obtained estimates are presented in Tables 6 and 7. An algorithm for calculating estimates of correlation functions provides for effectiveness, consistency and a minimum bias. Such estimates are suitable for calculating an optimal linear extrapolation operator.

Table 6. Estimates of correlation functions of the level drop

Point	τ					N
	1	2	3	4	5	
Tiksi	0.611	0.193	-0.141	-0.439	-0.479	66
Nemkov	0.611	0.278	-0.070	-0.315	-0.433	18
Ambarchik	0.611	0.292	-0.100	-0.390	-0.511	55
Shmidt Cape	0.663	0.266	-0.079	-0.351	-0.489	57

Table 7. Estimates of correlation functions of the level rise

Point	τ					N
	1	2	3	4	5	
Tiksi	0.632	0.208	-0.112	-0.408	-0.516	64
Nemkov	0.525	0.159	-0.095	-0.287	-0.418	19
Ambarchik	0.600	0.248	-0.089	-0.426	-0.501	53
Shmidt Cape	0.714	0.312	-0.094	-0.469	-0.562	52

Another important advantage of obtained estimates is that they allow calculating spectrum estimates without application of any spectral axes. This is governed by the fact that any section of the correlation function is smoothed by ensemble and this, in turn, provides a consistency of spectral density functions. A Fourier transformation of the correlation function was made using the expresson:

$$S_i(\omega) = 2\Delta t\left[r_0 + 2\sum_{\tau=1}^{\tau_{m-1}} r_\tau Cos\frac{\pi i \tau}{m} + (-1)^i r_\tau\right] \quad (12)$$

where Δt - 6 h (level for 4 observation times);

$r_0 = 1$, r_τ - correlation function;

i = 0.1,..., m; m - a maximum shear of the correlation function ($M = \tau m$).

Over all spectra a peak at a frequency 0.0167 h^{-1} is pronounced, this corresponds to a 60 h period. It should be noted that the suggested algorithm for estimating the correlation function allows us to find out this period sufficiently reliably. And both the technique for forming realizations and the procedure for smoothing by ensemble permitting an identification of the most typical features of the study process, contribute to it.

The coefficients of optimal extrapolation operators were determined from generalized estimates of the correlation functions by solving a system of equations. All initial realizations of the surge level drop and rise are characterized by a pronounced non-stationary state. That is why the extrapolation coefficients found from the equation system cannot be sufficiently effective. The contradiction is possible to resolve by introducing a free term for the extrapolation operator. The expression for a free term is found empirically and has the form:

$$b = \overline{h}_4 r_\tau\left(1 + \frac{1}{4}\tau\right) \quad (13)$$

where $\overline{h}_4$ - mean of the four values of the curve of level variations preceding a maximum development of the phenomenon.

It follows from (13) that a free term is a function of τ. This fact helps to overcome the non-stationarity of the process. Extrapolation is made 4 steps forward. At each step a new free term is used. At each successive extrapolation step the result of the preceding step is used without changing the extrapolation coefficients.

Thus, extrapolation formulas are recurrent and have the form:

$$\hat{h}_{t+1} = a_1 h_{t-3} + a_2 h_{t-2} + a_3 h_{t-1} + a_4 h_t + b \qquad (14)$$

The selection of the equation type "level rise" or "level drop" is made by diagnosing the initial synoptic situation at the forecast time. Implementation of each extrapolation step (1 step=6h) is obligatory. A final extrapolation result is the result obtained at the 4th step (τ=24 h). Mean square error (δ) refers exactly to the 4th step.

As is seen from the δ value (Tables 4, 5), the accuracy of the extrapolation forecast is significantly less than that of the forecast by pressure field. However, both forecasts are independent and can be used in one probabilistic forecasting scheme increasing the reliability of the final result.

3.3 Algorithm for a single probabilistic-statistical forecasting scheme

Assuming the distribution law of level forecasting errors by pressure field and level extrapolation errors to be normal, one can find a probability of the level exceeding or reaching the prescribed mark according to the Laplace formula:

$$P_e\{h > \xi\} = \frac{1}{2} - \Phi\left(\frac{\xi - \hat{h}_e}{\delta_e}\right)$$
$$or \qquad (15)$$
$$P_p\{h > \xi\} = \frac{1}{2} - \Phi\left(\frac{\xi - \hat{h}_p}{\delta_p}\right)$$

where ξ - a prescribed level mark (for example, critical);

P_e and P_p - probability by extrapolation and probability by pressure field, respectively;

$\Phi(X)$ - Laplace function;

h_e, h_p - calculated (prognostic) level values by extrapolation and pressure field, respectively;

δ_e, δ_p - mean square errors of both calculations.

The probability that a prescribed level mark will not be reached in the first case is equal

$$P_e\{h < \xi\} = 1 - P_e\{h \geq \xi\}$$

and in the second case

$$P_p\{h < \xi\} = 1 - P_p\{h \geq \xi\}$$

Since both forecasts are independent, total probability of the level not reaching a prescribed mark will be equal to the product of probabilities of the first and the second case, i.e.

$$P\,\{h < \xi\} = (1 - P_e\{h \geq \xi\})\ (1 - P_p\{h \geq \xi\}) = \\ = 1 - P_e\{h \geq \xi\} - P_p\{h \geq \xi\} + P_e P_p\{h \geq \xi\}$$

Hence, total probability of the level reaching or exceeding a prescribed mark is:

$$P\,\{h \geq \xi\} = P_e\{h \geq \xi\} + P_p\{h \geq \xi\} - P_e P_p\{h \geq \xi\} \tag{16}$$

Substituting calculated values (15) in (16) we derive a prognostic probability of the level reaching or exceeding a prescribed mark.

At present practical tests of prognostic equations are being made on the NSR. Positive results have been obtained for the Ambarchik point (probability of forecasts at a permissible error 29.5 cm is 61-90%, for other points the tests are being continued. During navigation of 1995 the tests of a single probabilistic-statistical scheme for level forecasting will be carried out.

4 GENERAL PURPOSE ICE FORECASTS

4.1 Development of computer software for searching informative predictors for an automated system of long-range ice forecasts over the NSR seas

On the basis of the concept presented in section 4.4 of the subprogram I of Project I.6.1 - 1994 the computer software for an automated forecasting system (AFS) was elaborated.

Utilization of the automated forecasting system "PEGAS" has shown its obvious effectiveness not only for forecasting, but for research as well. Using the AFS "PEGAS", one can succesfully study data sets of large volume and single out optimal predictors from them, estimate a statistical dependency between predictors and predictants and construct linear regression models.

The need for elaborating a computer version of the AFS "PEGAS" was caused by a wider range of problems whose sulution requires the use of "PEGAS". Moreover, the development of local information grids has expanded the access of the AFS "PEGAS" to hydrometeorological databases of different spatial-temporal scales existing at the State Research Center AARI.

All service possibilities of the software were preserved when elaborating the computer variant. Using the AFS one can estimate a statistical relation between the predictor and predictant, select the predictors with the most statistically significant connection with predictants (by the criterion of the correlation coefficient critical value prescribed by the user).It also allows unification of the selected predictors into a general (generalized) one taking into account their significance (that is determined by a squared correlation coefficient value) and construction of forecasting schemes (linear regression equations) of a prescribed advance period.

The number of predictors is not limited. Predictors represent time-series of hydrometeorological elements (for example, a series of mean monthly air temperature at the Dikson polar station), spatial series (for example, the values of surface atmospheric pressure in the grid points) or spatial-temporal series (for example, the values of atmospheric pressure in the grid points for a number of observation years).

The length of the observation series should not exceed 100 terms. The number of arguments in a spatial-temporal set of predictors (for example, the grid cells) should not exceed the N number, where N = 2000/L (L - the length of the observation series). For example, if the length of the observation series is equal to 50, the number of arguments, i.e. the grid cells should not exceed 40.

If the data sets already introduced into the databases are used as predictors and their regrouping is difficult, a possibility for using for calculation the data taken from any value is provided. This gives an opportunity to combine data sets of different length. According to the user's choice any of the successive data sets can be ignored. This also gives an opportunity to perform calculations on a selective basis not changing the existing data set. The prescription of a critical level of statistical relation between the predictor and predictant is provided. If the correlation coefficient between the predictor and predictant turns out to be less than a given critical level, such predictor will not be considered when calculating the generalized predictor.

As for spatial-temporal sets of predictors represented by the values of the hydrometeorological element in the grid cells (for example, atmospheric pressure), the opportunity to use not only the values of this element but also the differences between separate grid cells is also provided; in some cases it has a definite physical sense (for example, the difference of atmospheric pressure values between the grid cells is atmospheric pressure gradient).

Elaboration of the AFS "PEGAS" computer variant requires a significant revision of the procedure for the initial data preparation and grouping.

The initial data in the software computer variant are read from the files of electronic tables of the standard package "Paradox". This package of electronic tables has not been chosen by chance. Besides different advantages (vast system of database management) the "Paradox" has considerable possibilities to import and export data in the formats of some other packages of electronic tables such as "Lotos-1-2-3", "Windows", "Quattro Pro", etc. This extends the possibilities for using the AFS. The AFS can be applied to any data that are imported to the electronic tables of the "Paradox" package.

The basic working databases used for developing a long-term ice forecast - mean monthly surface atmospheric pressure fields for the Northern Polar area in the grid cells and mean monthly air temperature values over the regions were also formed in the "Paradox" package electronic tables.

The data set of each predictor begins with an information series describing the predictor and the order of its utilization in the program (service information No.2), and the series of arguments in the predictor set (there are 21 series for pressure fields according to the grid points and 1 series for air temperature). The length of the series used for calculation is prescribed by the user. If a smaller or incomplete length of the series is used in the program it should be indicated in the service information No. 2 and then sampling of the required series fragment will be automatic.

The fields of predictors and predictants are supplemented and prepared in the "Paradox" electronic tables. Here the service information No.2 describing each set of predictors is prescribed. This description includes:

- name and number of the predictor set;
- quantity of arguments in the predictor set (for time-series this value is equal to 1, for spatial-temporal ones it depends on the quantity of the grid points);
- indication of the calculation type (either initial predictor values or the differences between two arguments in the predictor set are considered);
- type of calculation result printing (full, brief and short print are provided);
- critical value of correlation coefficient below which the relationship between the predictor and predictant is considered to be negligible and the predictor is ignored;
- quantity of the first sampling terms that are missed and not used.

The sets of predictors prepared for calculations are exported in the ASCII codes into the "pre-or.dat" file. Service information No. 1 describing general conditions of calculation is given in the file "inform1.dat". It includes: length of time-series used for calculations, quantity of the sets of predictors, quantity of the sets of predictants, initial date of calculation. The program is run by the executive file "pegas.exe". Calculation results are written into the file "res.dat". All files are collected in the "PEGAS" directory, occupying the memory of about 0,3 MB and require not more than 1 diskette 3,5' HD. The utilization of the AFS "PEGAS" is possible on any IBM-compatible PC.

Effectiveness of the elaborated computer software has been tested by the example of preparing a long-term forecast of the ice cover extent in the Arctic seas 6 months in advance.

The fields of mean monthly surface atmospheric pressure for July-December of the preceding year presented in 21 grid cells covering a vast zone of the Arctic for the period from 1954 to 1994 were used as initial data for calculations (Fig.10). The ice cover extent of one of the Kara sea regions in July- first half of August from 1954 to 1994 was taken as an element to be forecasted.

As a result of consecutive calculations made by means of the program, the final prognostic result for all years used for calculations is printed. An example of the calculation by "PEGAS-M" program written by A.V.Yulin in 1993 is presented below.

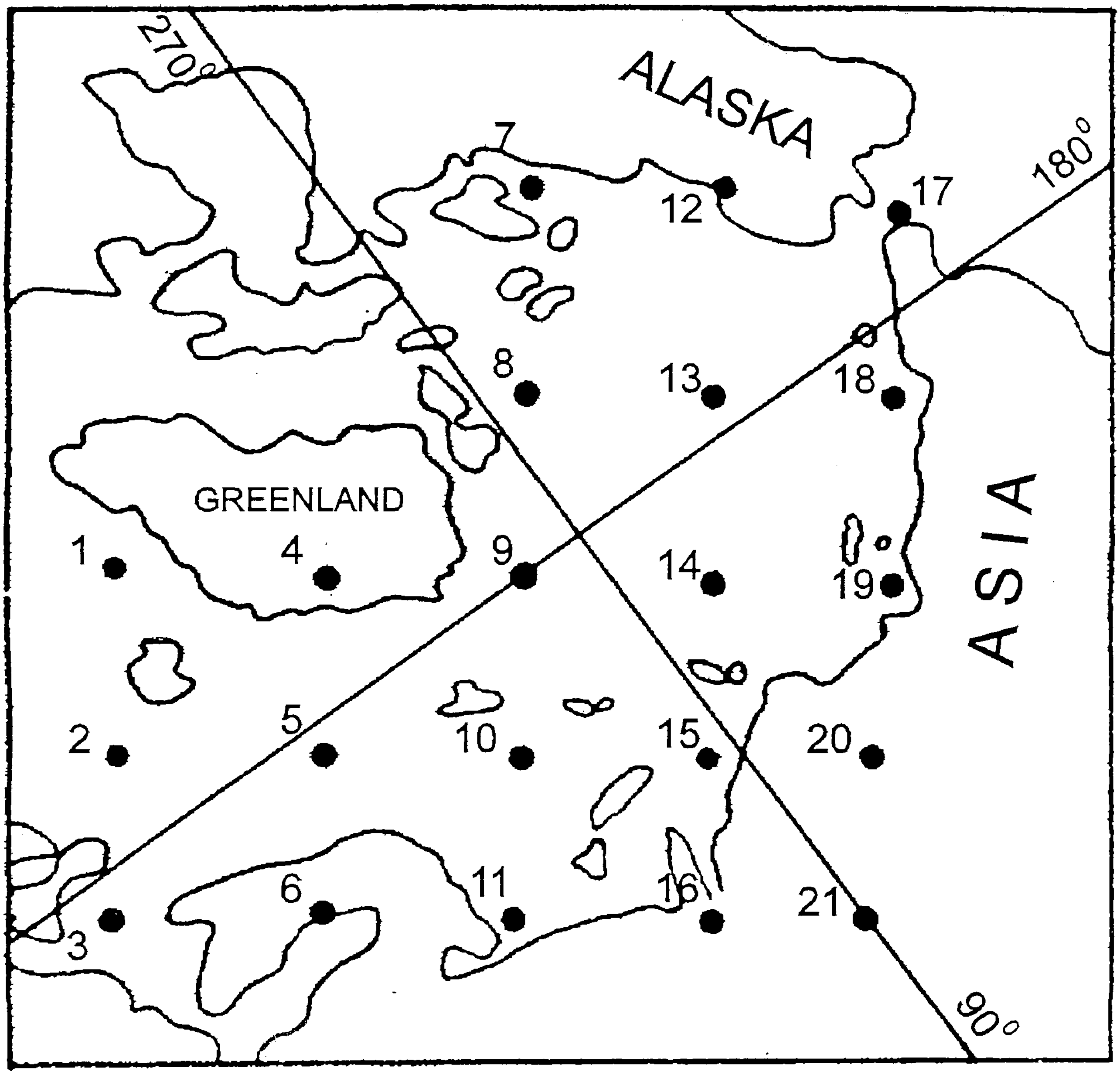

Fig. 10. Grid area cells for characterizing the pressure field (Δx ≈ 1200 km)

An example of the calculation using the "pegas-m" software

```
---------------------------------------------------------
   FUNCTIONS  01        PREDICTORS SETS  6
---------------------------------------------------------
  SET      7 LENGTH 41  PREDICTORS     22  R. CRIT.  .00
  AP'1  AP'2    AQ      A1       R      R²
   1  16   51.754     .237     .541     .293
  SET      8 LENGTH 41  PREDICTORS     22  R. CRIT.  .00
  AP'1  AP'2    AQ      A1       R      R²
  19  22   21.738     .282     .428     .183
  SET      9 LENGTH 41  PREDICTORS     22  R. CRIT.  .00
  AP'1  AP'2    AQ      A1       R      R²
  13  20   51.832     .136     .399     .159
  SET     10 LENGTH 41  PREDICTORS     22  R. CRIT.  .00
  AP'1  AP'2    AQ      A1       R      R²
  18  20   57.897    -.308    -.559     .312
  SET     11 LENGTH 41  PREDICTORS     22  R. CRIT.  .00
  AP'1  AP'2    AQ      A1       R      R²
   1   4   70.094     .221     .377     .142
  SET     12 LENGTH 41  PREDICTORS     22  R. CRIT.  .00
  AP'1  AP'2    AQ      A1       R      R²
  15  21   67.327     .114     .375     .140
  3TO'***********************************
```

AQ	A1	R	R^2
-88.087	12.946	.780	.608

Years	SR	I_a	I_f	ΔI
1955	8.988	29.00	28.27	0.72
1956	9.448	38.00	34.23	3.76
1957	12.729	62.00	76.71	-14.71
1958	12.066	78.00	68.12	9.88
1959	12.154	38.00	69.26	-31.26
1960	11.070	56.00	55.22	0.77
1961	10.004	31.00	41.42	-10.42
1962	11.843	53.00	65.23	-12.23
1963	11.717	81.00	63.59	17.40
1964	11.941	73.00	66.50	6.49
1965	10.414	54.00	46.73	7.27
1966	13.467	95.00	86.25	8.74
1967	10.798	59.00	51.71	7.28
1968	11.012	62.00	54.48	7.51
1969	12.603	85.00	75.07	9.92
1970	11.757	75.00	64.11	10.88
1971	10.472	48.00	47.49	0.51
1972	11.668	60.00	62.97	-2.97
1973	11.022	54.00	54.61	-0.61
1974	11.579	73.00	61.81	11.18
1975	10.061	49.00	42.16	6.83
1976	8.816	24.00	26.04	-2.04
1977	9.600	38.00	36.19	1.80
1978	11.204	74.00	56.96	17.03
1979	11.612	66.00	62.24	3.75
1980	10.903	79.00	53.06	25.93
1981	12.709	63.00	76.45	-13.45
1982	10.877	44.00	52.72	-8.72
1983	10.256	50.00	44.68	5.31
1984	9.910	24.00	40.21	-16.21
1985	10.876	38.00	52.71	-14.71
1986	10.097	52.00	42.62	9.37
1987	12.283	72.00	70.92	1.07
1988	10.852	40.00	52.40	-12.40
1989	9.388	36.00	33.45	2.54
1990	9.822	29.00	39.06	-10.06
1991	10.360	35.00	46.03	-11.03
1992	10.509	36.00	47.96	-11.96
1993	10.050	35.00	42.02	-7.02
1994	11.191	48.00	56.79	-8.79
1995	9.613	49.00	36.36	12.63

The calculation results contain:

- quantity of sets used for the calculation (in this particular case they are 7: 6 sets contain the pressure field information from July to December, the 7th contains ice cover extent);
- the number of grid cells characterizing the pressure field (21 grid cells); the additional 22nd grid cell contains pressure values equal to zero (such method allows obtaining the informative characteristics directly from pressure values in one of the grid cells and also from pressure differences);
- the following six lines contain the most informative selected differences of pressure (Arg 1, Arg 2) and regression equation of this difference with ice cover extent (where AQ is a free term, A1 is regression coefficient, R is correlation coefficient, R^2 is squared correlation coefficient);
- SR value is a generalized index for all pressure fields from 1955 to 1995;
- regression equation between a generalized index (SR) and actual ice cover extent (I_a);
- the following lines contain calculated (forecasted) values of ice cover extent (I_f) and their difference from actual ones ($\Delta I = I_a - I_f$).

A comparison of the forecast errors (ΔI) with a value of admissible errors (δ) which is considered to be a criterion for testing the forecast verification gives an opportunity to estimate the probability of the forecast method (the ratio of the correct number of forecasts to the total number of forecasts for available data series at admissible error).

In the given case at admissible error δ=16% the probability of the ice cover extent forecast (P_f) is equal to 90 %, while the theoretical probability of the long term average (P_N) is equal only to 58%.

Thus, the effectiveness of the forecast method when compared to the probability of the forecast based on long term average is quite high.

In the future it is planned to test the suggested software on mass material, create a data archive of atmospheric pressure fields all-year-round from 1937 to 1995, as well as of air temperatures in some regions of the Arctic Seas necessary for taking them into account along with dynamic factors.

4.2 Construction of the block of automated visualization of ice data that are used in local-genetic ice forecasting methods for the Kara Sea

Forecasting of ice conditions in the Kara Sea from one 10-day period to 3 months in advance with a 10-day interval is performed by means of the method of a local-genetic subdivison into types. This method allows an identification of specific ice conditions as a variation of some typical development of ice processes. It also allows forecasting the most probable ice cover change in natural uniform regions of the Kara Sea. The methods envisage a possibility of forecasting the following ice cover characteristics:

- drifting ice edges,
- close ice boundaries,
- distribution of ice cover concentration,
- distribution of isochrones of stable ice formation.

During the period 1990-1994 the forecasts on the basis of a local-genetic method were prepared at the Department for Ice Regime and Forecasting of the AARI, in scientific operational groups of the Western Arctic and for specialized ice support to navigation along the NSR.

A need for creating a specialized system for an automated visualization of ice data has arisen in connection with the development and more detailed analytical and prognostic studies.

By using such system the following is possible:

- computer-based visualization of ice conditions in the Kara Sea,
- identification of a typical ice cover state by amount and distribution of ice of different concentration,
- determination and localization of anomalies of the most probable change of ice conditions for the period of forecasting,

- forecasting of the distribution of ice cover concentration, position of ice edge and close ice boundaries from 10 days to 3 months in advance in natural sea regions,
- comparison of prognostic and actual fields,
- mean multiyear (climatic) estimates of ice cover state in specific local-geographic conditions of the Kara Sea.

Contents of initial data

The information on sea ice total concentration taken from integrated 10-day period ice charts prepared at the AARI is used as initial data. Digital data were obtained by gridding ice charts with rectangular grid corresponding to a polar stereographic projection with a spatial resolution 50 km. Data were prepared for ten intervals - from the 3rd 10-day period of June to the 3rd 10-day period of September for the total period from 1940 to 1994, i.e. data describe summer-autumn variability of total concentration in interannual respect. Data coding is executed according to a 0-100 % scale with a 5 % step.

Data have no temporal and spatial gaps, that is, data are prepared as a sequence of 550 matrices, each matrix contains 368 information points that cover the whole Kara Sea area. Data gaps which have an order of several % were eliminated by special methods elaborated on the basis of a local-genetic approach, and also using additional information sources (visual air surveys, polar station observations). Among the evident advantages of these data one should mention the following:

- a unique length of observation time-series (55 years);
- absence of spatial and temporal gaps;
- optimal temporal and spatial resolution that takes into account long-term (not less than 10 days) trends in variability of ice conditions beyond the synoptic scale of variability of natural processes;
- experience of data utilization on the NSR for extreme (heavy and easy) ice conditions.

Structure of the output data base

The following data sets are included into the data base:

1. Total ice concentration in GRID format with initial resolution 50x50 km presented as a time sequence of matrices with corresponding identificators. Logically, all data are included into one file (KARA50.DAT) that has the following structure:

■ matrix identificator, 10 bytes, including year, month, 10-day period number (for example - "1940 06-3");
■ matrix of total concentration values 32 by 22 points (368 information points + 336 "false" points belonging to land or being beyond the Kara Sea area); data are written line by line in 32f4.1 format (FORTRAN-77); false points are coded by value "-1.0";
■ matrix identificator;
■ matrix of the values of characteristics.

In addition, file KARA50.XY contains geographic coordinates of the points (latitude, longtitude) written line-by-line in 2f7.2 format (FORTRAN-77).

The given presentation format is suitable for different kinds of classification for definite ice conditions in the Kara Sea, climatic estimates, modelling of ice conditions.

2. Total concentration in GRID format in the form of a temporal sequence of the values of characteristics in the cells of a regular grid. Data are presented as a set of files; each file corresponds to one 10-day period. File name depicts the date and has the following structure: year (2 figures), month, 10-day period number (for example: 4006-3.DAT). Each file has the following structure:

■ total number of points (always 704);
■ rectangular coordinates of the point (x,y) and the value of total concentration written in (2i4.3,f5.1) format (FORTRAN-77); false points are also coded by value "-1.0";
■ etc.

For transformation of rectangular coordinates into geographical ones the file KARA50.XY can be used.

Logically, this form of the characteristics presentation is suitable for:

- importing into GIS INSROP;
- importing and processing within MSDOS mathematic software (e.g. WINSURF or MCAD).

3. Total concentration in GRID format with a spatial resolution 12.5x12.5 km in the form of a temporal sequence of matrices with corresponding identificators. Logically, all data are presented as one file (KARA12.W1) with the following structure:

- matrix identificator, 10 bytes, including: year, month, 10-days period number (for example: "1940 06-3");
- total concentration matrix with 128 by 128 dimensions (5888 information points + 5376 "false" points belonging to land or lying beyond the Kara Sea area); data are written line by line in 128a1 format (FORTRAN-77).
- etc.

Data transformation from a 50x50 km grid to a 12.5 x 12.5 km grid was executed by a simple repetition of the characteristics for four times. The matrix of land points is based on the data of the AARI Global Sea Ice Data Bank. In addition to the file KARA12.W1 there is file KARA12.XY that contains values of geographic coordinates of the points (latitude, longtitude) written line by line in 2f7.2 format (FORTRAN-77).

Logically, such form of data presentation is suitable for computer visualization and browsing of the Kara Sea ice conditions in historical respect.

Coding of points is as follows:

Total concentration value	Code
0	"0"
0.5	"1"
1.0-1.5	"2"
2.0-2.5	"3"
3.0-3.5	"4"
4.0-4.5	"5"
5.0-5.5	"6"
6.0-6.5	"7"
7.0-7.5	"8"
8.0-8.5	"9"
9.0	"A"
9.5	"F"
10.0	"G"
land point	"-"
no information	"*"

Computer visualization of data

This section deals with the means of data computer visualization elaborated for use under MS DOS operational system. The visualization is executed in the form of a map in polar stereographic projection by colouring the zones of diffirent total concentration values.

A special program module WX.EXE is elaborated for processing data under MS DOS operational system. In order to work succesfully with WX.EXE module one should:

- modify (if necessary) initialization file KARA.WX1;
- type command line: WX.EXE @kara.wx1;
- browse data and execute necessary graphic operations in interactive regime;

Principal key words of the parameter file are as follows:

- keypress= [yes/no] - switch on/off the keyboard;
- input_path= - path to input file;
- sign_mask=[nnnnnnnn] - location of the signs of parallels and meridians (left - right - up - down ...);
- sign_par= 060 005 000 010 - the first signed parallel, latitude step, the first signed meridian, longitude step;
- repeat= zooming (repeatition) factor;
- title= title which will appear during browsing;
- file_name= the name of input file.

Principal commands of interactive regime are as follows:

- <+>/<-> - zooming;
- <arrows> - moving picture or legend at the screen;
- <PgUP>/<PgDown> - browsing data forward/backward;
- <Space> - browsing data forward;
- <Shift> - activating 5 moving/browsing step;
- <ScrollLock> - activating 50 moving/browsing step;
- <CapsLock> - change picture/legend moving;
- <F> - picture refresh;
- <L> - legend visualization;
- <K> - delineation of zones;
- <J> - delineation of land contours;
- <G> - activating geographical grid;
- <Shift><F1> - smoothing picture by mask 3 by 3 elements;
- <I> - background color inversion.
- <Delete>, <BackSpace> - deleting displayed information.

As an example of the visualization of the distribution of ice cover concentration, Fig. 11 presents actual situation (a) and a smoothed field (b) of total concentration for the third 10-day period of June of 1947.

A computer visualization is a necessary initial stage for the preparation and presentation of data for effective functioning of a specialized system for analysing and forecasting ice conditions in the Kara Sea and other Arctic Seas by means of the method of a local-genetic subdivision into types. In the framework of the INSROP project the most effective continuation of this work will be:

- creation of a sub-system of automated classification and division into types of ice conditions for identification and verification of the ice cover state in the Kara Sea,
- creation of a subsystem for automated forecasting of typical changes of ice conditions in natural uniform regions of the Kara Sea,
- creation of a subsystem for an expert analysis and correction of a prognostic distribution of concentration at the advance period from 10 to 90 days.

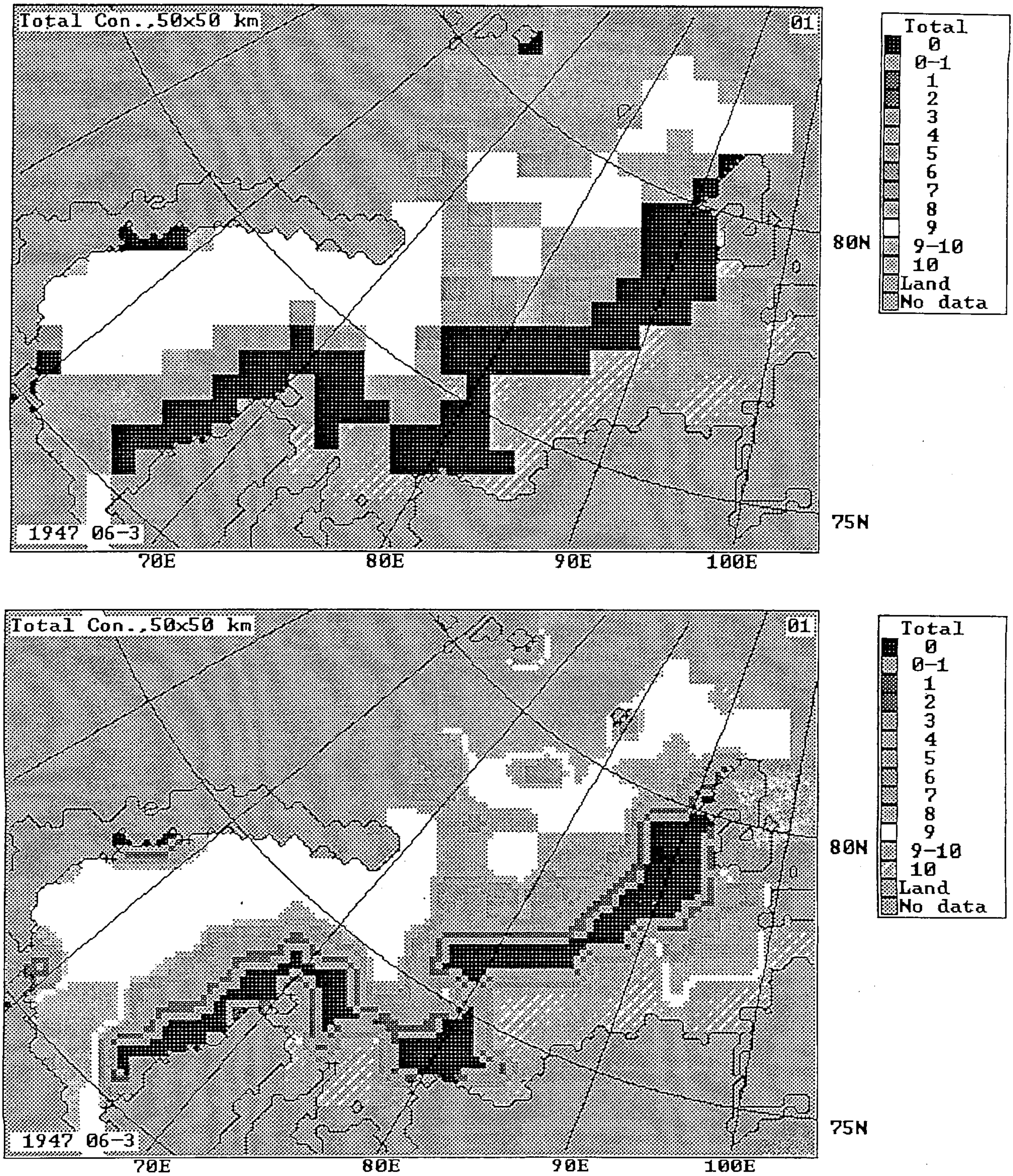

Fig. 11. A computer variant of the ice concentration field visualization in the third 10-day period of June 1947, a - actual distribution, b - smoothed concentration field.

4.3 Automated technology for issuing ice forecasts 1-8 days in advance for the Kara Sea during melting

An important condition for successfully using ice forecasts shipping support is an automated preparation of initial hydrometeorological information and presentation of the calculation results in the form suitable for developing navigation recommendations.

Automation of the most laborious stages of elaborating ice forecasts allows not only a decrease in time consumption, but also the development of a specific technological succession in preparing ice forecasts that reduces the influence of the subjective factor. Also, a possibility for rapid calculations under conditions of a frequently appearing uncertainty in initial meteorological and ice data allows consideration of several variants of the development of ice processes.

On the whole, the experience of the AARI in the area of scientific-operational support to navigation in the Russian Arctic Seas allows a conclusion that for introducing numerical forecasts, a suitable interface is not less important than the content of a mathematical model that serves as a basis for the method.

A method for numerical forecasting of ice redistribution in the Kara Sea during melting is based on the ice cover evolution model developed at the AARI and considered at the previous stage of the INSROP Program. Improvement of the method included a transition to the calculation grid with a 25 km spacing, development of the algorithms for transformation of operational information to the form suitable for using as initial data, creation of an automated technological succession in the ice forecast preparation. The advance period of the method is 1-8 days.

Actual distribution of ice cover and forecasting of the atmospheric pressure field used as initial information require constant updating and transformation. Mean multiyear hydrometeorological fields and some empiric constants that are used are prescribed at a model adjustment to the chosen region and do not change for the next forecast preparation. On the basis of calculations a prognostic map of the distribution of ice cover concentration and edge position is compiled.

For automation of initial information assimilation and transformation of the calculation results an original package of softwares for preparing ice forecasts has been developed at the AARI. After the entry to the software kit it is managed by selecting menu items where the main software functions are determined.

At present operational hydrometeorological information support has two forms for reporting atmospheric pressure forecast:

- a digital set of prognostic pressure values stored in points of a regular geographical grid,
- synoptic charts on which isobars of a pressure forecast are plotted.

The developed technology for the ice forecast preparation envisages a possibility for choosing any of this forms or their combination. This allows the use of meteorological forecasts obtained by means of different methods: mathematical modelling, synoptic method, method of homologues, etc. for its preparation.

In the first case the prognostic pressure is interpolated from a regular geographical grid into a uniform Cartesian grid using a spatial polinomial of the second degree. For calculating polinomial coefficients the prognostic pressure values are taken at 9 points that are most near to the calculation grid point.

When a direct access to the pressure sets on magnetic media is impossible, the synoptic maps of forecasted pressure are used. They are received by phototelegraph communication channels and are more available at present as compared with meteorological information in the digital form. In this case it is necessary to take the prognostic pressure of polar stations located on the coast and islands of the Kara Sea from the chart and introduce it into computer in accordance with a constant list envisaged by the technology for the forecast preparation. Since a spatial location of polar stations is non-uniform, a multiple linear interpolation is applied to obtain a prognostic pressure field in a regular grid allowing obtaining of a smooth pressure field.

Concentration is considered to be the main ice cover characteristics, governing navigation conditions. On the basis of data from different information sources (satellite images, visual and instrumental airborne ice reconnaissance, etc.) an ice chart is prepared where fast ice boundaries, zones of drifting ice of equal concentration, ice edge position are delineated. Software envisages two techniques for entering this initial ice information.

The first technique is more simple when information is transferred by key board or mouse from the chart to the computer monitor using a specially created graphic editor.

The second technique is oriented to assimilation of a sequence of coordinates of lines contouring uniform ice zones. Within each zone the so-called "information point" is placed in which ice concentration in the zone, its age and other characteristics are prescribed. For example, one of the working software versions is adjusted to the format of telegrams that are being received from aircraft equipped by a side looking radar station. If the observation region does not fully coincide with the boundaries of the calculation grid, then by means of a graphic editor the received operational information is supplemented by data from other sources. When necessary, a graphic editor also allows entry of "missing information points".

After plotting a computer chart (Fig. 12) in accordance with the ice cover characteristics stored in the "information points" the ice zones are covered by a specific colour. Coloured computer (Fig. 13) charts are plotted for ice cover concentration and thickness. Since, as a rule, not thickness, but ice age category is observed, the technology for the ice forecast preparation envisages recalculation of ice age characteristics to thickness. The transition from age categories to thickness is carried out on the basis of empiric typical features for different sea regions that relate ice age at the beginning of melting, time passed from the beginning of melting and observed concentration to thickness.

Coloured computer charts are used for obtaining matrices of ice cover thickness and concentration means by the calculation area cells that serve as initial data for the ice cover evolution model. An algorithm for determining mean concentration for the cell includes calculation of a number of minimum pixels of different colour in one cell and further summation taking into account a specific weight of different concentration gradations (colour) in the cell. The matrix of initial ice cover thickness is determined similarly.

After prescribing initial information a prognostic distribution of drifting ice is calculated. As a calculation result, a colour computer chart is formed (Fig. 14) on whose basis the forecast of ice redistribution is made and reported to the interested users along the Northern Sea Route.

The forecast preparation requires experience and knowledge of ice regime features on different route segments. But formally the procession of a calculated prognostic chart means plotting of lines contouring the location of uniform ice zones by means of a graphic editor.

A set of coordinates of the boundaries is combined into a telegram or used for plotting the prognostic chart of the distribution of ice cover concentration in the traditional form that can be output for printing or directly transmitted by different communication channels.

The use of the technology considered above has reduced the time for the ice forecast preparation from 6-8 to 2 hours.A wide application of this technology for all seas of the Russian Arctic shelf creates a system for a common prognostic provision of ice forecasts 1-8 days in advance along the Northern Sea Route.

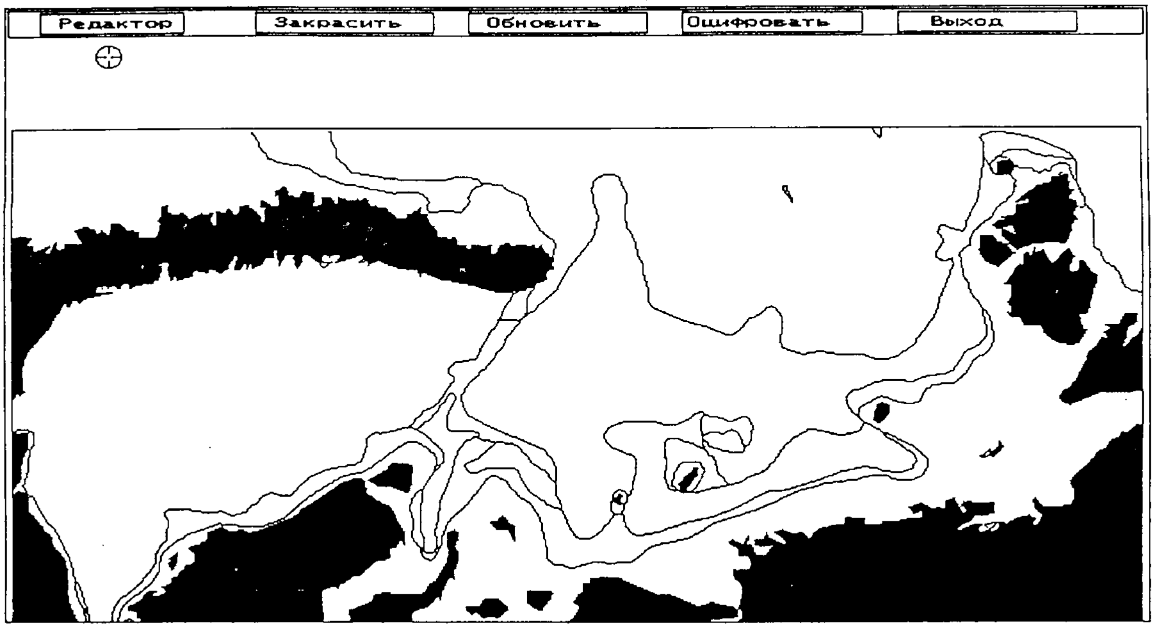

Fig. 12. A computer chart of ice distribution in the Kara Sea on May 25, 1988, constructed by coordinates of the lines contouring uniform ice zones. Each closed contour has an "information point" that contains a set of values of ice cover characteristics. On their basis each zone was delineated.

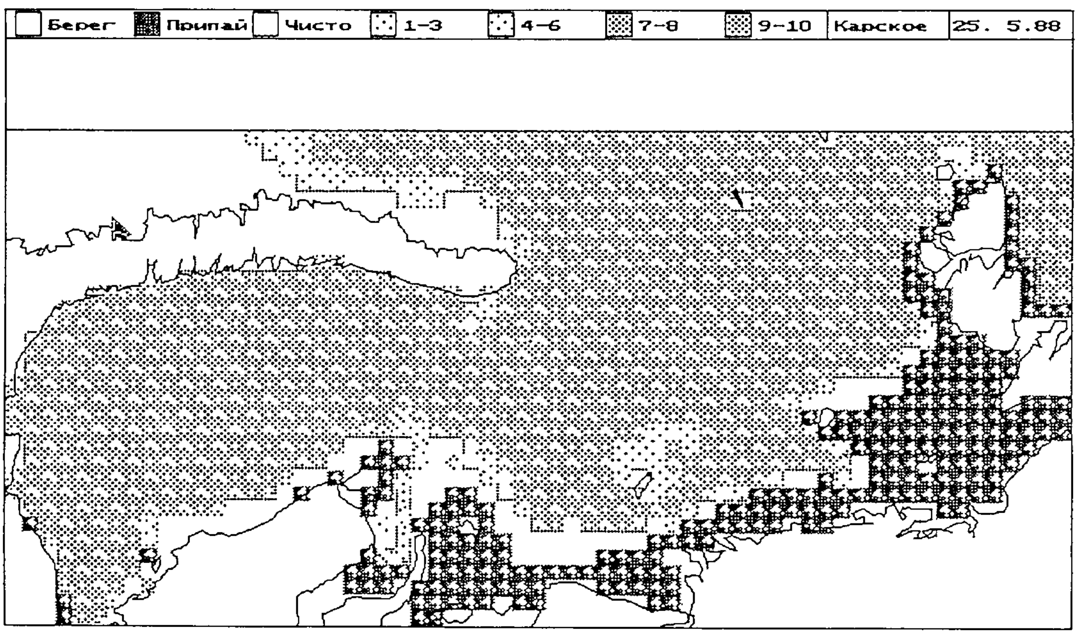

Fig. 13. A black-white visualization of a coloured computer chart of ice concentration obtained after averaging of ice zones given in Fig. 12 by cells.

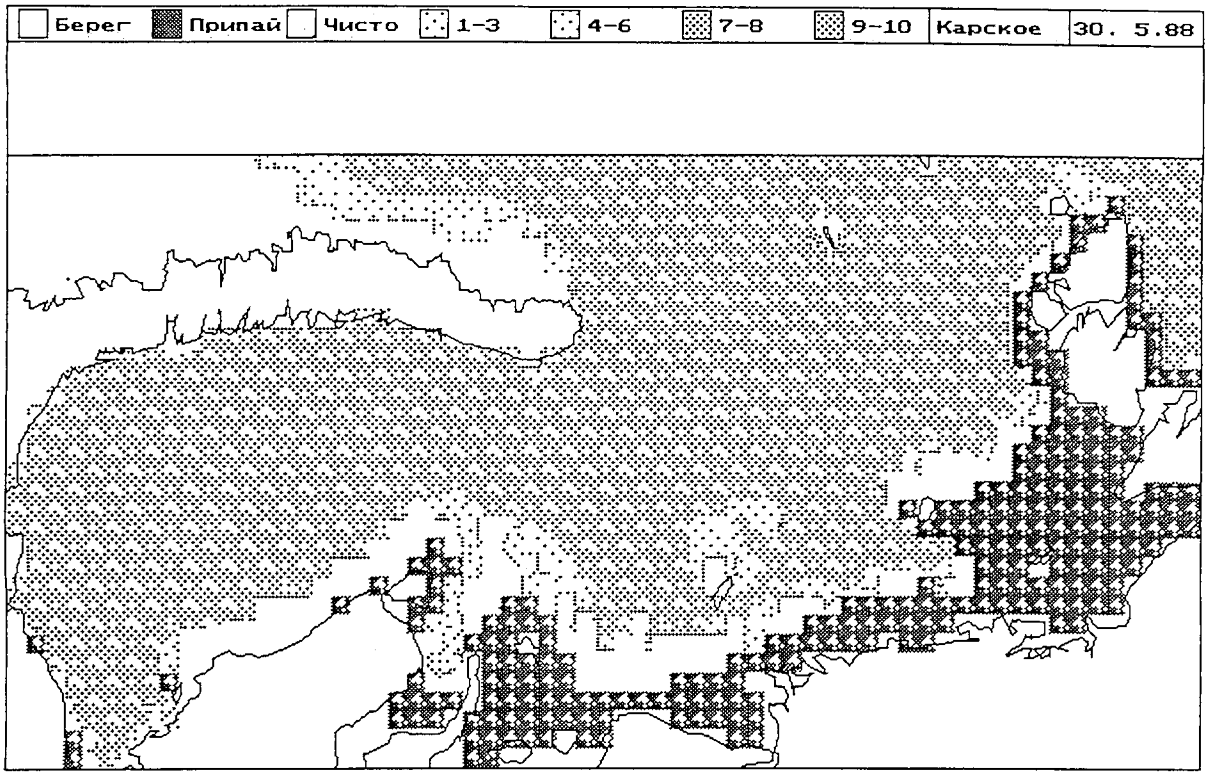

Fig. 14. A black-white visualization of a coloured computer chart of forecasted ice distribution in the Kara Sea, May 30, 1988.

5 SPECIALIZED ICE FORECASTS FOR SHIPPING ALONG THE NSR

In accordance with the concept of multilevel system of specialized ice forecasts for shipping (INSROP Report I.6.1 - 1994) and plans for the II stage the work was carried out in several directions.

The first direction was connected with supplement, storage and presentation of initial data on ice navigation conditions. Such need has arisen in connection with a wide introduction of standard packages of electronic tables with a developed DBMS (Data Base Management System) into practice and large capabilities for data export and import.

The second direction is governed by updating the existing methods for forecasting navigation conditions (in ice) in connection with the development of computer technologies for data collection and processing. The method for specialized forecasting of 10-day types of navigation conditions has required updating in connection with the development of a computer version of the Automated Forecasting System (AFS)"Pegas" that is used in this forecasting method.

The third direction is directly related to analysing spatial-temporal varibility of ice navigation conditions, study of hydrometeorological processes affecting them, study of a possibility for their long-range forecasting. The variability and a possibility for forecasting mean monthly types of ice navigation conditions and position of an optimal variant of the motion of ships have been investigated.

5.1 Methods for establishing a data archive for forecasting ice navigation conditions

The preparation of the forecast of ice navigation conditions using the AFS "Pegas" requires a large amount of the sets of initial and forecasted data. For plotting prognostic equations the AFS "Pegas" uses the whole series of predictors and predictants. When the observation series increase, the regression parameters are recalculated. A constant supplement of the archives of initial data is a necessary condition for using the AFS "Pegas" in the forecasting method.

Also, availability of a systematized elctronic data archive allows resolving some other problems on an operational basis: obtaining of regime-reference information on ice navigation conditions, the use of data for different research tasks.

At present there is no common understanding of the structure and methodological principles for a general database on ice navigation conditions. Such work is being performed at the Laboratory for Ice Navigation Studies of the AARI.

For establishing a data archive on ice navigation conditions a package "Quattro Pro" of electronic tables has been selected. It meets two main requirements for the data archives: a developed DBMS and a possibility for the data export to the formats of other standard packages of electronic tables.

The data archive for forecasting ice navigation conditions should consist of a set of tables, each of them presenting a separate data file. The table contains data on one navigation segment, for example, Dikson-Cheluskin, for the summer navigation period (June-October) and a specific type of ship or convoy.

The table consists of the blocks containing data on ice navigation conditions for one 10-day period. Each block includes 10 positions (columns) where specific indicators of navigation conditions and comments are given (Table 8). A 10-day period block includes the following data:

- value of ΔT (increase in time for navigating in ice)
- type of ice navigation conditions
- position of an optimal navigation variant
- total time consumption - ΣT_{total}
- coefficients of the difficulty of navigation - K_d;
- operating navigation velocities - V_{ion};
- four free columns are for any necessary information on ice navigation conditions on this segment.

The table envisages a possibility for including additional information. Its dimensions are moderately flexible, thus leaving a possibility for increasing the number of lines (lengths of observation series), and the number of columns (increase in the observation period). When necessary, the table may include 10-day periods for the fall-winter.

Table 8. The form for recording data on ice navigation conditions in electronic tables

Route segment: Dikson-Cheluskin nuclear icebreaker "Arktika" + 1 UL								
Year	June - first 10-day period					...	October - third 10-day period	
	1st indicator	2d indicator	3d indicator	...	8th indicator	...	9th indicator	10th indicator
1	2	3	4	...	11	...	150	151

The data archive on the navigation segment Dikson-Cheluskin for the summer period will consist of two files. The first file - a table of navigation conditions of nuclear icebreaker of the "Arktika" type, the second file - table for navigation conditions of the convoy: nuclear icebreaker of the "Arktika" type with one ship UL (intensified ice class). The ice navigation conditions for the next route segments are described in other files.

Probably, the suggested methods are not devoid of shortcomings. But, first of all, this is primarily first experience of working with the data archive on ice navigation conditions.And secondly, taking into account the possibilities of a chosen package for data export the archive can be transformed into a format of another package and transferred to electronic tables that are more suitable for use.

5.2 Adaptation of initial data to a computer version AFS "PEGAS"

The method for forecasting types of ice navigation conditions for the route segment Dikson-Cheluskin for the summer period from one to three 10-day periods in advance uses the AFS "Pegas" as a statistical instrument for searching optimum predictors and constructing prognostic equations. A transition to its computer version required updating of the method that concerned only the system for data input-output. The computer version of the AFS "Pegas" and the requirement for formation of initial data sets are described in detail in section 4 of this Report. The data input to the files of predictors (pr-or.dat) and predictants (pr-nt.dat) is by data export in the ASCII format from "Quattro Pro" electronic tables.

5.3 Analysis of variability of navigation conditions for determining a possibility for their forecasting

The division of ice navigation conditions into types that is based on criterion ΔT and the method for forecasting 10-day period types of navigation conditions from one to three 10-day periods in advance developed on its basis, turned out to be quite effective (INSROP Report 1994).This allowed the use of this method for forecasting mean monthly types of navigation conditions 1 month in advance. Simultaneously a possibility for forecasting mean monthly type of ice navigation conditions up to three months in advance is being investigated. This specialized prognostic information meets the objectives of the stage of general planning of marine operations along the NSR (INSROP Report I.5.5, section 1 - 1995).

Mean monthly value ΔT was determined as a mean of its values for three 10-day periods. Boundary values of ΔT for determining types of navigation conditions were found according to the same rules as for 10-day types. The boundaries were assumed in such a way that mean type included 50% of observed cases and extreme types - 25% each. The boundaries of ΔT intervals for each type are given in Table 9.

The division of navigation conditions into types by ΔT value and an analysis of identified types have shown that each type has a certain set of characteristics (ice and operating) that describe sufficiently fully navigation conditions. Having derived a prognostic value of ΔT for a specific month and then obtaining by ΔT type of navigation conditions, one can use mean typical ice and operating characteristics (V_{ion}, K_d, L_i)of navigation conditions.

An analysis of mean monthly values ΔT has shown them to be sufficiently stable at a temporal shift of 1 month. The probability for the type of navigation conditions to be preserved in the next month is more than 60% during the whole summer (Table 11).

An analysis of the correlation matrix of the relationship between ΔT values (Table 10) has shown all correlation coefficients for neighboring months to be significant and sufficiently high. In June, August and September they are 0.7-0.8. This also allows a conclusion about a non-*random* character of variability of ice navigation conditions and their succession in neighboring months.

Similar to the method for forecasting 10-day types of navigation conditions it was assumed that ΔT value being a function of the ice cover state can itself serve, in turn, as a generalized indicator of this state. The change of these characteristics reflects intensity of all changes in the ice cover in the preceding period. The inertial state of this value is related to intensity of the subsequent processes that will occur in the ice cover.

Thus,

$$\Delta T_{i+1} = f\ (\Delta T_i,\ \Delta T^*_{i+1,i})$$

where ΔT_{i+1} - expected ΔT value the next month;

ΔT_i - actual ΔT value in the preceding month;

$\Delta T^*_{i+1,i}$ - intensity in the change of ΔT value between months i and i+1.

In this scheme there are one actual (ΔT_i) and one prognostic ($\Delta T^*_{i+1,i}$) indicators.

The value $\Delta T^*_{i+1,i}$ depends on a large number of factors: on the change in ice thickness, concentration, decay, hummocking, air transport and melting intensity. All these factors are interrelated and the use of multiple correlation for forecasting $\Delta T^*_{i+1,i}$ is undesirable. The probability of false correlation due to multicollinearity is rather high.

Table 9. Boundary values of ΔT for a self-contained motion of nuclear icebreaker of the "Arktika" type and UL ship on the segment Dikson island - Gol'chikha cape for determining type of navigation conditions

Month	Boundary conditions ΔT (h)		
	easy type (E)	medium type (M)	heavy type (H)
VI	≤58.9	59.0-121.9	≥122.0
VII	≤17.9	18.0-47.9	≥48.0
VIII	≤1.9	2.0-10.9	≥11.0
IX	≤0.9	1.0-2.9	≥3.0
X	≤2.1	2.2-6.9	≥7.0

Table 10. A correlation matrix of the relationship between ΔT mean monthly values

Month	VI	VII	VIII	IX	X
VI	1	0.8	0.3	0.4	0.3
VII		1	0.5	0.3	0.1
VIII			1	0.7	0.3
IX				1	0.8
X					1

Table 11. Probability (%) for mean monthly type of ice navigation conditions to be preserved the next month

Month	VI	VII	VIII	IX
P, %	79	60	65	61

Table 12. Correlation coefficients between mean monthly ΔT* values and indicators of different hydrometeorological and ice processes

Month	Pressure and temperature(PT) Preceding period that has been taken into account				Occurrence of on-shore flows	ΔT of the preceding month	S of close ice in the region
	1st month	2d month	3d month	4th month			
VI	0.44	0.48	0.55	0.55	0.10	0.69	0.50
VII	0.52	0.55	0.60	0.61	0.03	0.70	0.54
VIII	0.49	0.53	0.58	0.59	0.05	0.53	0.40
IX	0.45	0.49	0.55	0.55	0.12	0.60	0.43
X	0.49	0.51	0.56	0.57	0.06	0.64	0.48

An assessment of the relation of $\Delta T^{*}_{i+1,i}$ value to each of these factors separately did not allow finding the determining predictor on the basis of which a linear-regression equation could be constructed.

That is why the prognostic system "Pegas" was used. Its main method is to choose optimal predictors from the field of hydrometeorological elements by means of an elementary discriminant analysis and construct a linear regression equation on their basis. This system is described in detail in (Kovalev, 1981; Kovalev et al., 1981; Yulin, 1990; INSROP Report, 1994). This allows analysing the fields and series of hydrometeorological elements that are used as predictors, estimate their informativity, select optimum predictors and combine them taking into account the influence coefficient into a generalized predictor. A generalized predictor is used for constructing a linear regression equation.

The following characteristics were considered as predictors: mean monthly pressure fields, mean accumulated temperature over the region from the time of melting, mean 10-day occurrence of on-shore and off-shore flows, value of ΔT of the preceding period, close ice area and ice cover extent of the region. We shall not dwell on the physical significance of selected predictors, it has been covered in detail in (Kovalev, 1988; Kovalev, Yulin, 1990). Let us analyse the results.

The values of correlation coefficients with occurrence of on-shore flows are very small. The correlation coefficients with pressure and temperature fields are significant. Their allowance is most effective for the 2-3 preceding months. When pressure and temperature fields for a longer preceding period are taken into account, the values of correlation coefficients do not increase. The largest statistical relation is observed to be to mean monthly ΔT values for the preceding month (correlation coefficients not less than 0.6). These predictors are more informative than mean monthly values of the ice massif area for the preceding month in the north-eastern Kara Sea (Table 4).

Optimal predictors chosen by means of a discriminant analysis taking into account their informativity were combined into a dimensionless objective predictor on the basis of which a linear regression equation was constructed

$$\Delta T^{*}_{i+1,i} = kQ + A$$

where k - regression equation coefficient;

Q - generalized predictor for all fields and series of hydrometeorological elements;

A - free term.

The calculated value $\Delta T^{*}_{i+1,i}$ allows forecasting ΔT value according to the following scheme:

$$\Delta T_{i+1} = \Delta T_i + \Delta T^{*}_{i+1,i} ,$$

where i - initial month;

i+1 - prognostic month.

Type of ice navigation conditions during the month that is being forecasted is determined by means of the calculated value ΔT_{i+1} and Table 1.

An assessment of the forecasting probability was performed in accordance with the following principle:

- coincidence of the forecasted type with an actual one means that the forecast verification was good and it is estimated to be 100%;
- non-coincidence of the forecasted type with an actual one means that the forecast verification was poor and it is estimated to be 0%.

On the average, the probability of test forecasts (P_f) 1 month in advance was 78%, while the theoretic probability of long term average is 58%. The effectiveness of the proposed method (P_f - P_N) is 20%.

It is known (Kovalev, 1990) that with the use of independent data sampling the forecast verification is 10-12% less as compared with the probability estimated method using dependent data. Taking this into consideration one may expect that verification score of the forecasts using the suggested methods will exceed standard verification by 10%, on the average.

5.4 A possibility for forecasting an optimal navigation variant with a 10-day interval for navigation from June to October up to 1 month in advance on a segment Dikson Island - Cheluskin cape

The position of an optimum navigation variant is important ice-navigation characteristics. These characteristics meet the objectives of tactical planning of marine operations along the NSR (INSROP Report I.5.5, Part 1 - 1995). An optimal navigation variant is the most economical and favourable route of icebreaker, convoy of ships or single ship in ice as compared to other possible variants in specific ice conditions. Its position is closely connected with a character of spatial ice cover distribution in the Arctic Seas, wind regime and its variability. On-shore and off-shore air flows contribute to ice compacting or diverging and on the whole to its redistribution.

Mean multiyear occurrence of on-shore and off-shore air flows by 10-day periods is within 40-60% and does not have a pronounced tendency for the dominance of one of them.

Three standard routs were chosen on the NSR segment Dikson-Cheluskin. An optimal variant can be near them depending on the distribution of ice with different characteristics: 1 - coastal route, 2 - northward of the Russky Island, 3 - northward of the Isachenko Island - Russky Island. The position of an optimal navigation variant on the chosen routes was determined for each 10-day period of summer Arctic navigation (June-September) by 10-day review of ice charts for 1946-1984. Thus, for the first time ice conditions were estimated along a "fixed" optimum variant. Then occurrence of the optimum navigation variant position for each 10-day period was calculated by types of ice navigation conditions (E, M, H - see table 9), and also by types of the general ice distribution in the north-eastern Kara Sea according to Kuznetsov (Kuznetsov, 1965). Also, a comparison of an optimal navigation variant occurrence taking into account types of navigation conditions with occurrence of off-shore air flows was performed.

The study of the occurrence of the optimal variant position in the years grouped by navigation conditions (E, M, H) has allowed an identification of common features:

- in June-July there is enhanced occurrence of favourable shipping conditions on route "3";
- during the time from the second 10-day period of July to the second 10-day period of August there is a change of an optimal variant from route "3" to route "1" or "2". This is caused by fast ice break-up, drifting fast ice redistribution and the change in the tendency of the formation of navigation conditions;
- from the second or third 10-day period of August (depending on type of navigation conditions) there is enhanced occurrence of an optimal variant "1" or "2".

A comparison of the occurrence of the optimal variant position with occurrence of on-shore air flows and types of general ice distribution (according to Kuznetsov) has shown an absence of consistency between these characteristics.

A comparison of the occurrence of the optimal variant position in typical years (E, M, H) with occurrence of on-shore air flows has not shown well-pronounced consistency too. At the same time in some 10-day periods there is a similar tendency for their change.

Ice inertia is known to be one of the ice regime features in the Arctic Seas (Gudkovich et al., 1972). The calculation of the probability for an optimal variant to preserve its position for one-three 10-day periods has shown:

- inertia is indicated quite clearly in the preservation of an optimal variant position "1" and "3" one-three 10-day periods in advance during the time from the first 10-day period of June to the second 10-day period of July (probability is 70-100% and significantly exceed the probability of the long term average, P_N);
- an optimal variant "2" has enhanced occurrence (75-100%) one-two 10-day periods in advance from the initial one only during the time from the third 10-day period of June to the second 10-day period of July.

Thus, using inertia as a basis, it is possible to forecast the position of optimal variants of shipping one-two 10-day periods in advance within the indicated limits with a probability exceeding that of long term average.

The following main directions in the activities at the next INSROP stage can be suggested:

- to continue supplementing the data archive on ice navigation conditions using the suggested methods of an electronic archive;
- to carry out tests of the method for forecasting mean monthly type of navigation conditions for the route segment Dikson-Cheluskin in summer with participation of the authors and investigate the possibilities for extending the forecasting period up to 3 months in advance;
- to continue studies for searching informative predictors to forecast the position of an optimal navigation variant.

6 CONCLUSION

The information presented in the Report under Project I.6.1 (with the Report for 1994) allows gaining a sufficiently full impression about a system for provision of hydrometeorological information on current conditions, as well as meteorological, oceanographic and ice forecasts with different periods in advance for shipping along the Northern Sea Route.

The Report presents the results of the studies for improving a number of forecasting methods that are promising for scientific-operational support to navigation.

The role of actual and prognostic hydrometeorological information constantly becomes more and more important in relation to the need for increasing the accuracy of decision-making with regard to specific operations. This leads to a constant improvement in the forecasting methods.

Further studies in this field of meteorological forecasting can aim at the following:

- to develop a scientific basis for foreseeing the direction of the general atmospheric circulation changes;
- to develop methods for estimating the expected changes in large-scale elements of the hydrometeorological regime in the Arctic;
- to find a possibility for an accurate determination of the dates of the transition to a new structural epoch of atmospheric circulation;
- to specify a spectrum of long-range fluctuations, periods and amplitudes of disturbances occurring in the atmosphere;
- to develop techniques for more fully taking into account variability of atmospheric processes in forecasting.

Among the oceanographic forecasts much should be done to extend the method for forecasting dangerous level changes on the limiting segments of the route and at the unloading points over the whole of the NSR. Further studies are required for searching methods for more objective fields of hydrological characteristics to be used in forecasting.

Many issues should also be adressed in the area of ice forecasts. In particular, the following problems should be mentioned:

- creation of a specialized data archive on air pressure and temperature field in the Arctic during the whole year;
- search for informative indications for forecasting during the cold period of the year;
- development of the method for ice distribution forecasting in winter;
- extension of the system for automated classification and division into types of ice conditions with a 10-day period over all seas of the NSR;
- adaptation of the elements of a local-genetic method for forecasting ice distribution over all regions of the Arctic Seas;
- increased accuracy in taking into account fields of a number of hydrometeorological characteristics, for example, wind fields, gradient currents, internal interaction forces in ice cover in numerical forecasts;
- use of the suggested technology for numerical ice forecasts 1-8 days in advance for all seas of the Arctic shelf;
- a maximum possible automation and computerized preparation of initial and current information fields for numerical forecasts from 1 to 30 days in advance;
- constant improvement of the technology for preparing ice calculations and forecasts with different periods in advance.

It is still important to improve a multilevel system for providing shipping with all types of information of a general and specialized character. The main goals in this respect are:

- expansion of an electronic data archive on ice conditions of navigation;
- continuous search for informative indicators for forecasting the position of an optimal navigation variant 1-3 months in advance.

The existing components of this multilevel system for providing support to navigation in the Arctic in combination with the work for improving all links of this system create a real basis for regular transit navigation along the NSR with minimum losses caused by severe natural conditions.

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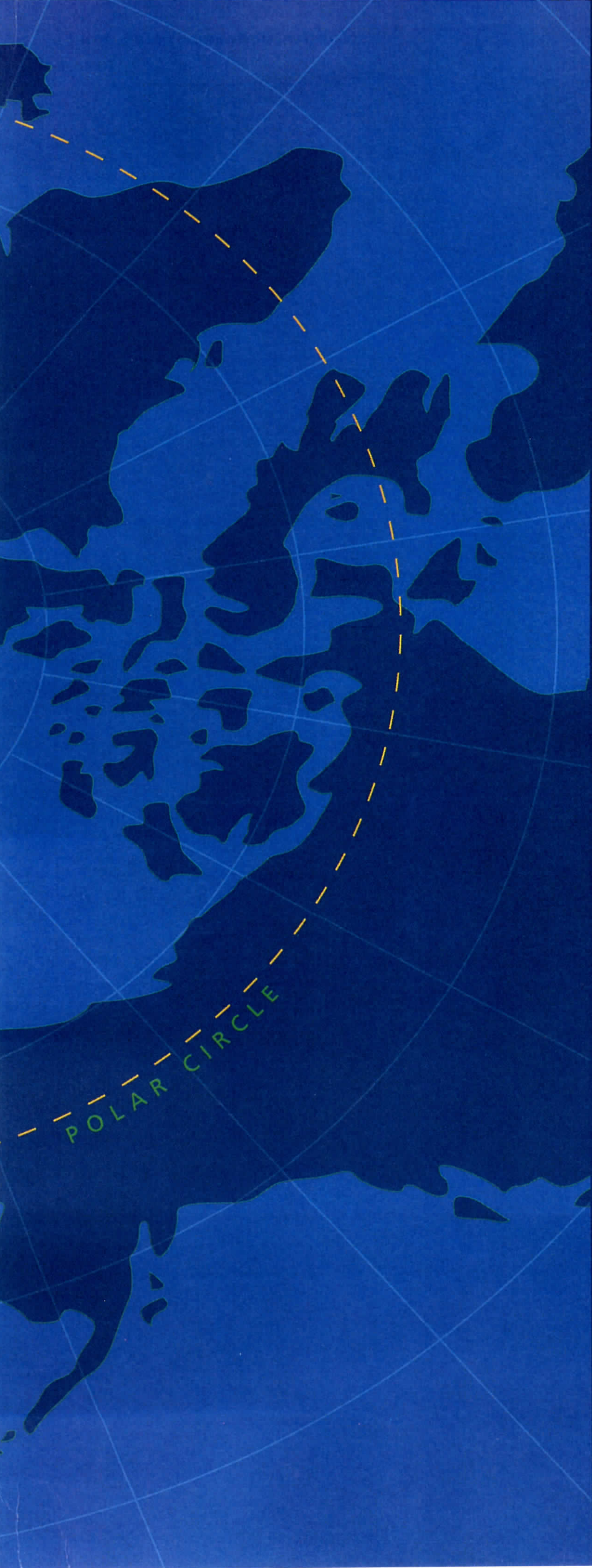

The three main cooperating institutions of INSROP

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 stockholding 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 multidisciplinary approach, entailing extensive cooperation with other research institutions both at home and abroad. The INSROP Secretariat is located at FNI.