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Methodological Issues of Improving the Efficiency of Meteorological Support for Regional Air Transportation

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***Abstract*— The paper discusses methodological issues of improving the efficiency of meteorological support for regional air transportation. The authors provide a justification of the relevance of research aimed at improving the efficiency of meteorological support, taking into account regional features of the formation of hazardous meteorological conditions. The greatest attention was paid to the study of the climatic features of the Arctic region. The geographical location of the Arctic determines the specific annual and seasonal course of meteorological elements, the specifics of the formation of special (dangerous) conditions for Aviation flights. The possibilities of integrating the output of global hydrodynamic atmospheric models from leading meteorological centers of the Global Data-Processing and Forecasting System in the technology of medium-term multi-model forecasting of pressure fields are considered in this part. The authors propose to combine models of physico-statistical forecasting of weather elements with the method of synoptic interpretation of the output of the atmospheric hydrodynamic model for an average time. To solve the problem of the lack of observational data, the authors propose a methodological basis for constructing a complex of automated meteorological support for aircraft operations, which allows one to take into account regional climatic features of their areas of implementation.**

Keywords—meteorological assurance, hazardous weather, optimization of air traffic planning, air traffic safety

I. Introduction

The prosperity of the Russian Federation is directly related to the large-scale development of remote territories and the economic development of regions, including the Arctic. The goal can not be achieved without the proper level of development of transport communication. Aviation accounts for a significant share of all freight and passenger traffic, since aircraft is one of the most reliable and efficient types of transport, often the only possible one for certain regions.

With the continuous growth of air traffic intensity, the introduction of new routes, weather conditions largely determines the risks and efficiency of air transportation. A significant proportion of flight delays and aviation accidents are associated precisely with the hitting of aircraft in adverse meteorological conditions, which have their own specifics of formation for different geographic areas.

Thus, studies aimed at improving the efficiency of meteorological support, taking into account regional features of the formation of hazardous meteorological conditions, are highly relevant.

II. Regional Features of the Development of Hazardous Weather and Adverse Weather Conditions in the Arctic Region

The authors focus on improving the means of obtaining meteorological information, weather forecasting methods, creating automated complexes for analyzing meteorological conditions and warning about the development of weather phenomena dangerous for flying aircraft (thunderstorm, rain, turbulence, icing, fog, wind, snow).

The task of the work is, on the one hand, to study regional features of the development of hazardous weather and adverse weather conditions using the example of the Arctic region, methodological studies of how to improve forecasting methods of hazardous weather and their integrated use in automated meteorological systems for aviation operations.

The greatest attention was paid to the study of the climatic features of the Arctic region, since in addition to regional and national air travel, since 2001, a system of cross-polar routes connecting the continents of North America with the continent of Southeast Asia and the Pacific has been formed. When organizing flights in the Arctic, one should take into account that the region in question is poorly covered by meteorological observations and is characterized by special climatic conditions.

The geographical location of the Arctic determines the specific annual and seasonal course of meteorological elements, the specifics of the formation of special (dangerous) conditions for Aviation flights. The Arctic is characterized by high repeatability of low clouds, fogs, smoke, and supercooled precipitation (in summer); strong winds, phenomena that impair visibility (snowfall, blizzards), low temperatures and high humidity (in winter).

In accordance with the results of the analysis of the available data, weather conditions that are difficult to fly are observed in arctic regions throughout the year.

Analysis of the climatic data presented in the Climate Features Report on the Territory of the Russian Federation for 2017 (2018, Moscow.69 p.) [1] suggests that against the background of global warming, the temperature in the Arctic rises faster than in other regions. According to the AARII, during the last thirty years, the growth of the average annual temperature there was 0.75 °C / 10 years, i.e. 2.25 ° C for 30 years. Against the background of climate warming, a decrease in the duration of the occurrence of snow cover and a decrease in the ice cover are observed. According to the AARI (www.aari.ru), the minimum monthly average sea ice area in 2017, observed in September, was 4.74 million square km. A decrease in precipitation during the warm season is also noted.

One of the characteristic features of the region under consideration is the regular formation of mesovortices or polar mesocyclones (Polar Low). These are small cyclones with a diameter of about 100 ... 200 km. Sharp temperature contrasts between the warm air mass forming above the water surface in the area of the warm Gulf Stream and the cold one forming above the ice of the Arctic lead to their formation. This is a local phenomenon, causing a significant increase in the wind. It is often accompanied by heavy snowfall, heavy snowstorms and, associated with them, deterioration of visibility. In view of the rare observational network, the prediction of such a mesoscale process is a rather difficult task.

III. Multi-Model Medium-Term Forecasting Method for Meteorological Fields

In the planning and management of air traffic, it is necessary to take into account the state of the environment in points and areas of space in which the aircraft will be located when flying along the route.

Meteorological information should provide the ability to control the aircraft at all stages of the flight, ranging from takeoff and flight on a given route and ending with the landing of the aircraft at the destination.

The information base of modern technologies for the development of medium-term forecasts of meteorological fields is global observing systems and automated technologies for collecting and processing meteorological information, which are elements of the Global Data-Processing and Forecasting System (GDPFS) of the World Meteorological Organization. The tasks of developing medium-term meteorological field forecasts are carried out at the World, Regional Specialized and National Meteorological Centers of the GDPFS on the basis of hydrodynamic atmospheric models (GDAM) and automated technological complexes for numerical weather prediction. The quality of forecasting meteorological fields largely determines the success of forecasts of weather elements developed in the systems of physical-statistical and synoptic interpretation of the output of GDAM. The proposed method is of particular importance against the background of the emerging climate changes, noted by a number of authors.

Currently, global GDMAs provide satisfactory results for medium-term forecasting of large-scale meteorological fields on the earth's surface for up to 3–5 days, and up to 5–7 days at tropospheric levels and in the lower stratosphere [1, 2]. Numerical experiments show potential increasing of the lead time of forecasts of meteorological fields to 8-10 days. However, the success of the developed forecasts, even on the basis of modern GDMA, is significantly deteriorating by as much as 6–7 days due to the errors of integration of hydrodynamic equations that accumulate over time.

One of the promising directions for increasing the limit of predictability of atmospheric hydrodynamic models and increasing the success of meteorological field forecasts can be the method of integrating output forecast products of leading meteorological centers of the GDPFS.

It should be noted that the output predictive output of different meteorological centers depends on the following objective factors [3]: accuracy of initial data, horizontal resolution of the model, parametrization of convection, consideration of processes in the planetary boundary layer, vertical resolution, initialization of the initial state, accuracy of water temperature data oceans, vertical diffusion of heat and moisture, the diurnal variation of the parameters of the atmosphere and underlying surface, model representations of cloudiness and the hydrological regime of the continents, Processes sub-grid scale.

Modern systems for numerical forecasting of fields of meteorological quantities and weather phenomena consist of six subsystems [4]: observational, telecommunication, computational, data assimilation, modeling processes in the atmosphere, soil and ocean, post-processing (presenting numerical results of models in a form convenient for the consumer). It is quite natural that in various forecasting centers there are some differences in the substantive part of each of the subsystems of numerical forecasting, which should be reflected in the success rates of the developed forecasts of the fields of meteorological quantities.

Let us consider the possibilities of integrating the output of global GDMA from leading meteorological centers of the GDPFS in the technology of medium-term multi-model forecasting of pressure fields. The first version of the adaptive multi-model method of medium-term forecasting of meteorological fields was developed by the authors in 2011 [5]. The proposed prediction method is based on a model for estimating the mathematical expectations of meteorological parameters in the class of linear functions for non-equal forecasts for each point of a given grid area using several GDMAs.

To estimate the mathematical expectations of the prognostic values of meteorological parameters, this version uses the ratio:

$$\widehat{\widehat{M}}_{\hat{x}} = \sum_{j=1}^{n} c_j \hat{x}_j \,, \qquad j = 1(1)n, \tag{1}$$

where $\hat{x}_j$ is the predicted value of the meteorological parameter j of that GDMA, c_j- is the weighting factor of the j-th prediction method in the composition of the selected set of models, n is the number of forecasts in the training set for which the weighting coefficients are estimated.

The formulation of the problem of finding weight coefficients for the predicted values of $\hat{x}_j$ in the framework of the linear model (1) is as follows [7].

Let the characteristics of the accuracy of the forecast meteorological values from forecast to forecast change so that the value of the meteorus $\hat{x}_j$ obtained for the j-th forecast has a variance:

$$\hat{\tilde{D}}_{\hat{x}_j} = \tilde{D}_j, \qquad j = 1(1)n\,, \tag{2}$$

and its expectation for each point of the grid area remains constant over a certain time interval, i.e.:

$$M_{\hat{x}_j} = M_{\hat{x}} = \bar{x}. \tag{3}$$

In this case, the estimate of the mathematical expectation of the predicted value is a function of the prediction sample of the form:

$$\hat{\tilde{M}}_{\hat{x}} = \tilde{M}_{\hat{x}}(\hat{x}_1, \hat{x}_2, \dots, \hat{x}_n). \tag{4}$$

In [5, 7], it was shown that the expectation estimate $\hat{\tilde{M}}_{\hat{x}}$ will meet the requirements of unbiasedness, efficiency, and consistency, provided that the weighting factors c_j in model (1) are inversely proportional to the variances of $\hat{x}_j$, and the sum of the coefficients is 1. We introduce the notation $\tilde{d}_j = \frac{1}{\tilde{D}_j}$. Taking into account the introduced designation, the ratio for the weighting factors of the prognostic model (1) takes the form:

$$c_j = d_j \Big/ \sum_{i=1}^{n} d_j \;, \tag{5}$$

An equally important task, in addition to choosing the interval for estimating weights, is the task of determining the composition of the leading operational forecasting centers included in the multi-model complex, taking into account the success of the hydrodynamic forecasts developed by them, as well as the possibilities of obtaining forecasting products through message switching centers, the Internet and other channels communications of the GDPFS.

In essence, the problem of choosing predictors to be included in the right-hand part of the predictive model (1) should be solved. To solve this problem, an analysis was made of the number of prognostic samples received for the periods of 00 and 12 UTC from the leading forecasting centers of the GDPFS. It turned out that, through the centers for the collection of forecasting products, for each of the main periods of the forecasts being developed, qualitative forecasting information can be obtained, as a rule, from 5-6 meteorological centers. In this regard, in the training sample there is the possibility of including from two to five preliminary predictors presented by the results of forecasting meteorological fields. The final decision on the number and composition of predictors can only be made on the basis of numerical experiments.

Practical implementation of the method is possible in any operational forecast center equipped with software complexes of message switching centers and the formation of databases with the results of analyzes and forecasts of output products of leading meteorological centers of the GDPFS. Only minor revision of special software of automated workplaces such as “GIS Meteo Synoptic”, “GIS Meteo Avia” and some others is required.

IV. INTEGRATED USE OF FORECASTING METHODS

Various methods (synoptic, physical-statistical, hydrodynamic) can be used to obtain actual and prognostic information about hazardous phenomena and adverse weather conditions for aviation. The authors propose to use the methods of synoptic climatology in automated systems of statistical interpretation of the output of prognostic hydrodynamic models of the atmosphere. At the same time, it seems appropriate to combine models of physico-statistical forecasting of weather elements with the method of synoptic interpretation of the output output of the hydrodynamic model of the atmosphere for an average time [2].

Within the framework of the existing concept of forecasting GMU, pressure fields (geopotential heights) are predicted first, then using the synoptic or physico-statistical methods, the GMU are predicted in specified areas. Therefore, to predict clouds, we suggest using all available data from hydrodynamic forecasting results, then using the synoptic-statistical models developed by us for probabilistic forecasting of the total number of clouds based on the interpretation of the pressure field.

When developing models of probabilistic forecasting of phenomena, statistical relations between the characteristics of the phenomenon and the fields of meteorological quantities are usually used. The authors of the article propose to use the components of the field of the Laplacian of the surface pressure and the components of the pressure gradient. The Laplacian of surface pressure p_0 characterizes the cyclicality of the baric field. It is calculated by the formula:

$$\nabla^2 p_0 = \frac{\partial^2 p_0}{\partial x^2} + \frac{\partial^2 p_0}{\partial y^2}, \tag{6}$$

where x and y are the axes of the coordinate system, p_0 is the atmospheric pressure. The x axis is directed to the east, the y axis is to the north.

The magnitude of the modulus of the horizontal component of the pressure gradient and its direction are determined by the formulas [3, 4]:

$$|grad_n p_0| = \sqrt{p_x^2 + p_y^2}, \tag{7}$$

$$\alpha_x = arcsin\left(\frac{p_x}{\sqrt{p_x^2+p_y^2}}\right) + 90^0. \quad (8)$$

where $p_x = \frac{\partial p_0}{\partial x}$, $p_y = \frac{\partial p_0}{\partial y}$ are the components of the pressure gradient along the x and y axes of the selected coordinate system;
α_x is the angle between the x axis and the isobar.

In the further presentation of the material we will use the following notation:

$$p_{xx} = \frac{\partial^2 p_0}{\partial x^2}; \qquad p_{yy} = \frac{\partial^2 p_0}{\partial y^2}. \quad (9)$$

The components of the Laplacian surface pressure field (p_{xx}, p_{yy}) and the terms of the pressure gradient (p_x, p_y) allow us to determine the type of synoptic object numerically.

Then, for the specified areas, based on a priori cloud data, the probabilities of gradation of the number of clouds are estimated, which can be used to refine the flight schedule. The probability distributions of cloud gradations should be considered as prognostic cloud models of the atmosphere.

The basis of synoptic-statistical models, it is advisable to put probabilistic models linking predictors - characteristics of the baric field (obtained after integration), with the total number of clouds in the specified gradations.

To develop multi-phase predictions of gradations of the total number of clouds based on the pressure field, you should rely on a discrete random variable $\widehat{\Phi}$ as a ratio.

$$P_{\widehat{\Phi}}\left(\widehat{\boldsymbol{\Phi}}_{\langle r\rangle}/X_{\langle k\rangle}\right) = P\left(\widehat{\Phi} = \Phi_{\langle r\rangle}\right),\ [r = 1(1)R],\ [k = 1(1)K], \quad (10)$$

where $P\left(\widehat{\Phi} = \Phi_{\langle r\rangle}\right)$ - a series of probability distribution of a discrete value $\widehat{\Phi}$ (predicted gradations of the total number of clouds), in which each value of the predictor vector $X_{\langle k\rangle}$ should correspond to its own probability distribution of gradations of the number of clouds; $P_{\widehat{\Phi}}\left(\widehat{\Phi}_{\langle r\rangle}/X_{\langle k\rangle}\right)$ - statistical estimates of the probabilities of the occurrence of the r-th gradation of the number of clouds (predictor) at the k - th values of the predictor combination.

It should be noted that the results of applying the proposed method depend on the quality of prognostic fields of meteorological variables derived from atmospheric hydrodynamic models. In turn, the results of the work of the hydrodynamic models of the atmosphere depend on the accuracy and completeness of the initial data. Therefore, this paper focuses on topical issues in the use of hydrodynamic forecasting methods based on solving a system of hydrodynamic equations under given initial and boundary conditions.

Currently, prognostic centers of foreign countries and the Hydrometeorological Center of the Russian Federation have developed a number of mesoscale atmospheric models, the characteristics of which are considered in [6, 7]. Three major meteorological consortia ALADIN, COSMO, HIRLAM (www.hirlam.org) are known in Europe. Since 2011, the non-hydrostatic model of the COSMO-Ru mesoscale short-term weather forecast has been operating for meteorological support of various territories in Russia.

In particular, COSMO-Ru7 is used for meteorological support of Central and Eastern Europe, the Urals and parts of Western Siberia with a 7 km pitch, a forecast time of 78 hours. The COSMO-Ru2 model was used during the “Kazan 2013 Summer Universiade” and the “Sochi Winter Olympics. - 2014”. The resolution of the COSMO-Ru2 version is 2.2 km, the grid dimension is 420 * 470 knots, 40 levels for the atmosphere up to a height of 23 km above sea level and 7 layers of soil up to 7 meters in depth, the lead time is up to 24 hours.

For a number of years in the Russian Federation, the generally available mesoscale model of the atmosphere WRF (www.wrf-model.org) with the dynamic core of the ARW National Atmospheric Research Center (NCAR, USA) [8] has been used. The model includes an initialization module, a parameterization block for physical processes, and a data assimilation block. For the possible assimilation of meteorological measurement data (ground-based, remote), the 3D-variational 3DVAR method is used; in the latest versions, the four-dimensional 4DVAR variational method and the Kalman ensemble filter method are supported. The initial data are analyzes and forecasts from large-scale models, the results of observations, as well as data on the relief and underlying surface [9, 10]. The most frequently used results are the global forecast of the National Center for Environmental Prediction NCEP. But it is possible to use data from the Hydrometeorological Center of the Russian Federation, which is currently a higher priority.

V. Results and Discussion

To solve the problem of the lack of observational data, the authors propose a methodological basis for constructing a complex of automated meteorological support for aircraft operations, which allows to take into account regional climatic features of their areas of implementation. The proposed approach is based on the integrated use of existing forecasting methods (hydrodynamic, physical-statistical, synoptical-climatic) using current data on atmospheric parameters obtained using modern means of obtaining meteorological information.

The creation of such a software and hardware complex requires a range of applied research and development in the field of aeronautical meteorology and climatology in order to improve the methods of taking meteorological conditions into account when planning flights along regional routes and international routes and managing air traffic.

To implement the methods proposed in the article in order to improve the efficiency of meteorological support for aircraft operations, the authors propose methodological foundations for creating a software and hardware complex for meteorological support for aircraft operations and air traffic control bodies. The proposed complex is designed for meteorological support for planning, organizing and ensuring the implementation of aircraft flights along regional and international routes and is one of the priorities in the field of improving meteorological support for aircraft operations.

The organization of processes ensuring the achievement of the objectives of the complex's operation implies the mandatory inclusion of the following subsystems (blocks) in its composition:

subsystem for receiving primary meteorological information;

data assimilation subsystems;

subsystem for processing and analyzing meteorological information;

subsystems modeling processes in the atmosphere, soil and ocean;

subsystem of physico-statistical interpretation of the results of hydrodynamic forecasting;

subsystem adaptation forecasting methods;

verification subsystem of the developed forecasts;

the subsystem for developing recommendations for recording meteorological information about weather conditions when making decisions on departure or landing and during the flight en route;

archiving subsystem;

subsystem of visualization and documentation of information;

subsystem for the transmission of actual and prognostic specialized meteorological information and recommendations to air traffic control authorities.

The given structure of a prospective software and hardware complex determines its system-technical appearance and (system-engineering) appearance of its elements (subsystems).

Primary meteorological information receiving subsystem

The primary meteorological information receiving subsystem is designed to receive digital hydrometeorological information transmitted via the satellite communication system channels and the Global Telecommunication System of the World Meteorological Organization and the Roshydromet Automated Data Transmission System, receiving initial meteorological information from all observational meteorological systems and other asynoptic observation data.

Data acquisition subsystem

The data assimilation subsystem assumes the following functions:

sorting the received meteorological information according to the types of messages and summaries;

saving received reports in the database;

decoding received reports;

quality control of the decoded values of hydrometeorological quantities and the preservation of the values of hydrometeorological quantities in the database of primary meteorological information. The following types of control should be provided: syntactic control, likelihood control (limit checks), consistency (consistency checks), vertical control, horizontal control;

transmission of decoded secondary GMI from GRIB, GRIB-2, BUFR codes and primary meteorological information that has passed the control procedure to the requesting subsystems.

The output information in the form of corrected (if necessary) values of meteorological quantities and the corresponding values of quality indicators is stored in the database of primary meteorological information.

Subsystem for processing and analyzing hydrometeorological information

The subsystem for processing and analyzing hydrometeorological information is intended for approximating the fields of various meteorological parameters and presenting them in a form suitable for further processing and hydrodynamic forecasting. The subsystem assumes the following functions:

obtaining initial information for hydrodynamic forecasting;

control of information received from Roshydromet and world meteorological centers;

interpolation and approximation of hydrometeorological fields in the nodes of a regular grid;

aggregation of the data;

preparation of initial conditions for the functioning of the hydrodynamic model of the atmosphere.

The subsystem modeling processes in the atmosphere, soil and ocean

The subsystem is designed to obtain prognostic fields of hydrometeorological quantities. The function of the complex that implements the task of this subsystem is the integration of the mesoscale model of the atmosphere.

Output information in the form of prognostic fields of meteorological quantities and the corresponding values of forecast success indicators should be stored in a database of prognostic meteorological information and transmitted to software and hardware systems for further interpretation of hydrodynamic forecasting results in order to provide specialized prognostic meteorological information for air traffic control bodies.

The subsystem of physical-statistical interpretation of the results of hydrodynamic forecasting

The subsystem of interpretation of hydrodynamic forecasting results is intended for the development of specialized meteorological information and implements the functions of developing a forecast for a specific phenomenon or meteorological quantity that have an impact on safety.

Subsystem of forecasting methods adaptation

The subsystem of adaptation of forecasting methods is designed to implement the following functions:

assessing the quality of forecasting methods implemented in the complex;

clarification of parameters of a number of physical-statistical methods for forecasting meteorological quantities and phenomena;

issuing recommendations on the preference of methods for predicting the same weather or meteorological phenomenon.

The possibility of improving the quality of the prediction method as a result of adaptation is due to the following factors:

the influence of local physiographic and climatic conditions of a particular area on the nature of the processes occurring in the atmosphere;

an increase in the size of the statistical sample on which the decision rule is applied.

Verification subsystem developed forecasts

The verification subsystem of the developed forecasts is designed to evaluate the success of forecasts of the fields of meteorological variables in full in accordance with the Methodological Guidelines for conducting production (operational) tests of new and improved methods of hydrometeorological and heliogeophysical forecasts.

The subsystem of developing recommendations for air traffic control authorities to take into account meteorological conditions when making decisions for landing or departure or when refining the flight schedule

The subsystem of developing recommendations for taking into account meteorological conditions when making management decisions involves providing air traffic control authorities with the implementation of a software and hardware complex of the following functions:

determination and archiving of the functions of the influence of hydrometeorological conditions on the use of flight operations (including in the form of their boundary values);

calculation of the actual values of specialized indicators of meteorological conditions;

comparison of current and boundary values of indicators of affecting meteorological conditions;

integration of the results of the comparison and development of recommendations for taking into account the forecast or actual meteorological conditions when planning flights of aircraft and managing them in the course of their implementation.

The subsystem of visualization and documentation of information is intended for:

displaying and documenting the results of the receiving subsystem of the primary meteorological information, the subsystem modeling processes in the atmosphere, soil and ocean, the subsystem of interpretation of the results of hydrodynamic forecasting and the subsystem of developing recommendations for taking into account meteorological conditions when making a decision;

ensuring user interaction in solving problems of collecting, assimilating, processing and transmitting meteorological information.

The subsystem for the transmission of actual and prognostic is specialized meteorological information and recommendations to air traffic control authorities

The subsystem is designed to transmit actual and prognostic specialized meteorological information and recommendations to air traffic control authorities in the form of easy-to-make decisions when planning and managing aircraft flights.

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