SHORT-TERM WEATHER FORECASTING

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Contents

Summary

Weather forecasting is a kind of scientific and technological activity, which contributes to social and economic welfare in many sections of the human community to-day. In this context, the purpose of short-range weather forecasting is to provide information on the expected weather with forecast projection times ranging from a few hours to two or three days for both particular locations and areas covering a few million square kilometers. Almost all currently used short-range forecasting techniques involve dynamic prediction models based on an application of compressible fluid mechanics equations to the atmosphere. The models provide information necessary not only for the weather prediction but also for many other applications (aviation, ship routing etc.). As a rule, the

models are running within computerized real-time forecasting systems, which involve automated collection, processing, checking, and numerical analysis of observations necessary for weather forecasting. According to the space-time scales of predicted weather systems, to completeness and quality of available input data, and to the capability of the data communication and processing equipment, the models differ in scales of simulated weather-creating processes and in the resolution of numerical implementations as well as in the accounting for various physical factors. Within this general approach, the particular techniques for local weather forecasting may involve means for statistical treatment of the model output in terms of weather parameters. The techniques used for very short-range forecasting of local-scale hazardous weather phenomena (tornadoes, heavy showers, local thunderstorms etc.) are based by now on application of the forecaster-computer interactive systems with the use of real-time satellite and radar observations, and of the output provided by mesoscale dynamic models. Advances in the atmospheric sciences and in atmospheric modeling as well as in the development of weather observation systems and automated data processing and computation techniques, have resulted in immutable rise of the weather forecasting skill, which has been going since the implementation of first dynamical forecasting models in the 1950s.

1. Introduction

The science of weather forecasting has come a long historical way from accumulation of observation and measurement data on various meteorological elements to theoretical generalization in terms of weather phenomena and weather-producing atmospheric mechanisms, and to subsequent application in the weather forecasting practice. This way is similar to that one passed by all geophysical sciences.

The purpose of short-range weather forecasting to-day is to provide various users with information on the anticipated weather over forthcoming two or three days for the sites in the areas of a few million sq. kilometers to take necessary precautions beforehand and thus to reduce the damage of adverse weather conditions, as well as to gain maximum advantage from those favorable for various kinds of the human activity.

Attempts to predict weather on the basis of simple qualitative rules and subjective judgments have a multi-century history. From the ancient times on, human civilizations have tried to find relationships between various weather and celestial events and to use them in weather forecasting, mainly for sailing and crop production purposes. However the quantitative and fully objective approach to weather forecasting has proved to be feasible only by describing the atmospheric weather-producing mechanisms using the basic laws of the fluid dynamics. Advances in the application of fluid dynamics to the investigation of various processes and motions in fluids and gases have attracted the scientists' attention to the dynamical weather prediction already in the 19th century. In this context, the earth's atmosphere should be considered as a viscous and compressible baroclinic fluid, which is exposed to the thermal and dynamical effect of the underlying surface, to the absorption and emission of the radiation in various spectral domains and to the heating and cooling due to phase transformations of atmospheric moisture. The equations describing evolution of this fluid are constructed on the basis of three fundamental physical laws: the laws of the conservation of momentum, mass, and energy. The first of these laws leads to three equations of motion for a fluid exerting action of the gravity force and the Coriolis force that results from the earth's rotation, the second one leads to the equations of continuity for air and water vapor, and the third one leads to the thermodynamic energy transfer equation (or the first law of the thermodynamics) which describes the air temperature, pressure, and density variations in both the presence and absence of external sources and sinks of heat (radiation emission and absorption, water phase transformations, and turbulent heat exchange). The principal problem arising when these equations are applied to the dynamical weather forecasting lies in the necessity to define and separate the atmospheric weather-producing processes among the variety of other processes occurring in the atmosphere and described by these equations (e.g., propagation of acoustic waves). This necessity has been understood only after a number of unsuccessful attempts to use the equations for straightforward prediction of the weather elements.

Probably, the German mathematician and physicist H. von Helmholtz was the first who studied the set of the fluid dynamics equations as a possible means of dealing with meteorological problems as early as in 1858. However, implementation of this idea has proved to be impossible due to many causes. In the first place, the equations in their general form are too complex to be integrated using methods and computing means available in the 19th century. In mathematical terms, the difficulty is one of solving a boundary- and initial-value problem for a system of six nonlinear partial differential equations in three dimensions. The second obstacle to the early development of dynamical weather prediction stems from the absence of necessary observation data on the structure and evolution of the atmosphere. Owing to this fact, the dynamical meteorologist of those days did not really know what kind of phenomena he had to consider and explain.

The next contribution to finding ways for dynamical weather prediction is related to the works of the Norwegian (Bergen) school of meteorologists, led by V. Bjerkness, in the early 1900s. Building on von Helmholtz ideas, V. Bjerkness and his colleagues carried out a systematic study of idealized (usually linearized) mathematical models of atmospheric dynamics.

One of the turning points in the development of dynamical weather prediction was the meteorologists' realization that hydrodynamic equations could be integrated in principle by numerical methods. British meteorologist-mathematician-statistician L.F. Richardson who also had a lively interest in the new finite-difference methods of numerical integration undertook the attempt of this kind in 1916. Proceeding from available surface and upper-air observations in Europe, L.F. Richardson has integrated numerically the weather dynamics equations by hand over many months. However his 24-h forecast has proved to be wrong. The calculations predicted that the large-scale atmospheric disturbances would travel at about the speed of acoustic waves. There are various causes responsible for the failure of Richardson's heroic attempt. The principal of them is that his approach did not provide a means to separate the atmospheric weather-producing mechanisms from processes of all other scales, which are described by the equations.

The way to solve this problem was found by I.A. Kibel' in the former USSR in 1940. He has succeeded in removing the principal defects of Richardson's approach through exclusion from the equations the description of processes whose spatial and temporal scales are much smaller than those of the synoptic-scale atmospheric processes - about 1000 km and 24-hs, respectively. This was accomplished by representation of the wind velocity components in the form of a power series of a small dimensionless parameter (about 0.1) that occurs in the equations when the system is made dimensionless under the characteristic length and time scales of 1000 km and 24-hs, respectively. The first term in these series corresponds to the exact balance between the horizontal pressure-gradient force and the Coriolis force (geostrophic wind) in the large-scale processes. Together with proper separation of the atmospheric boundary layer effects, which reduces the dynamical prediction problem to modeling adiabatic processes in the inviscid fluid, this provided a means to develop simple formulas suitable for 24-h prediction of the surface pressure and temperature with reasonable accuracy in operational environment through performing computations by hand. The developed forecasting technique has been used for daily routine weather forecasting until the early 1950s.

Another fruitful approach to the exclusion from the solutions of the atmospheric dynamics equations the effects of small-scale processes is related to the use of the A.A. Fridman's vorticity transport equation as one of the prognostic equations instead of the equations of motion for the horizontal wind components. This approach has been suggested in 1938 by C.-G. Rossby in the USA who has found a way to isolate from the totality of various kinds of atmospheric motions the waves which are responsible for transferring large-scale mid-latitude weather systems such as cyclones, anticyclones, and atmospheric fronts. The waves of this type, called the Rossby waves, have the wavelength of a few thousand kilometers and travel east- or westward at the altitude of 4-5 km with the speed in the order of about 10 m s^{-1}. The principal common feature of both approaches is that they imply that the horizontal pressure-gradient force and Coriolis force are close to balance in the large-scale atmospheric motions, which is true with accuracy of 80-90 per cent for the free atmosphere in the extratropics. This provides an example how the generalization of observation data may contribute to theoretical deduction.

All the above findings and experiments together with subsequent studies of J.G. Charney in the USA on the scales of atmospheric motion (1948) have laid a firm base for further systematic development and implementation of numerical methods into the weather prediction practice and research, which is one of the most significant advances over their long and dramatic history.

The first concerted attack on the problem of dynamical prediction on the new theoretical basis began in the late 1940s in the USA by a group of meteorologists led by J.G. Charney and J. von Neumann at the Institute for Advanced Study in Princeton, N.J. Its first outcome was the design and numerical implementation of a simplest forecast barotropic model for idealized atmosphere in which the air density is uniform, the motion is purely horizontal and whose initial state is identified with real atmospheric conditions at the height of about 5 km. The model's behavior is described with the nonlinear vorticity transfer equation in quasi-geostrophic approximation, and is governed by a single dynamical law of vorticity conservation, which states that each fluid element conserves its initial vorticity throughout subsequent motion.

This implies that the number and intensity of cyclonic and anticyclonic vortices cannot change. Hence, a model of such type may predict evolution of existing cyclones and anticyclones in the atmosphere but fails to predict formation of the new ones. J.G. Charney, R. Fjortoft, and J. von Neumann first numerically integrated the equation governing this model from real initial conditions in 1950. The results obtained in this experiment as well as in those carried out in different countries in the 1950s showed that this simplest of the dynamical methods based on the barotropic voracity transfer equation in quasi-geostrophic approximation can predict the motion of large-scale atmospheric patterns (including the Rossby waves) at the altitude of about 5 km and, consequently, the movement of weather systems over 24-36 h with an accuracy comparable to that attained by a skilled weather forecaster.

The predictions have proved to be accurate enough to put them into daily routine practice as consulting aid for weather forecasting and other applications provided that the necessary input data and computing facilities are available.

The experience gained from the application of simplest dynamical models in routine weather forecasting together with increase in power of the computers available at the meteorological services has stimulated further developments and improvements of dynamical forecast models. The main directions and objectives of these developments are:

- design and implementation of baroclinic models that can predict formation of large-scale atmospheric vortices like cyclones and anticyclones to replace the barotropic models;
- rejection of the quasi-geostrophic approximation and inclusion into the models of description of the weather producing mechanisms whose scales are much less than those accounted for and reproduced under this approximation; and
- enhancement of the model physics by improved treatment of the effects of diabatic processes in the atmosphere.

A significant increase of the skill in short-range weather forecasting, which has been attained in this way in the 1960-1980s, has offered the possibility to develop dynamic methods for prediction of local weather patterns, and also provided increase of efficiency in various forecasting techniques based on the usage of the outputs from hydrodynamical models for prediction of meteorological fields (e.g., statistical and synoptical methods in short-range weather forecasting, aviation weather service etc.). In this context, the to-day practice of the short-range weather forecasting involves the following components:

- prediction of large-scale atmospheric dynamical and thermodynamical characteristics; and
- modeling of the local weather patterns.

Sections 2 and 3 below provide an outline of status and future trends and perspectives in the former and latter components, respectively.

The following books may be recommended for further in-depth studies of various aspects in short-range weather forecasting and related branches of the theoretical and applied meteorology (see Bibliography): Barry and Chorley (1998), Kibel' (1963), Marchuk (1974), and Thompson (1961).

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Biographical Sketches

Solomon L. Belousov, (1923 – 2000) received Ph. D. in Mathematical Physics , He developed the first operational numerical prediction model in USSR. Author of about 70 scientific papers and two monographs

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He has about 30 presentations at International and National conferences and meetings.