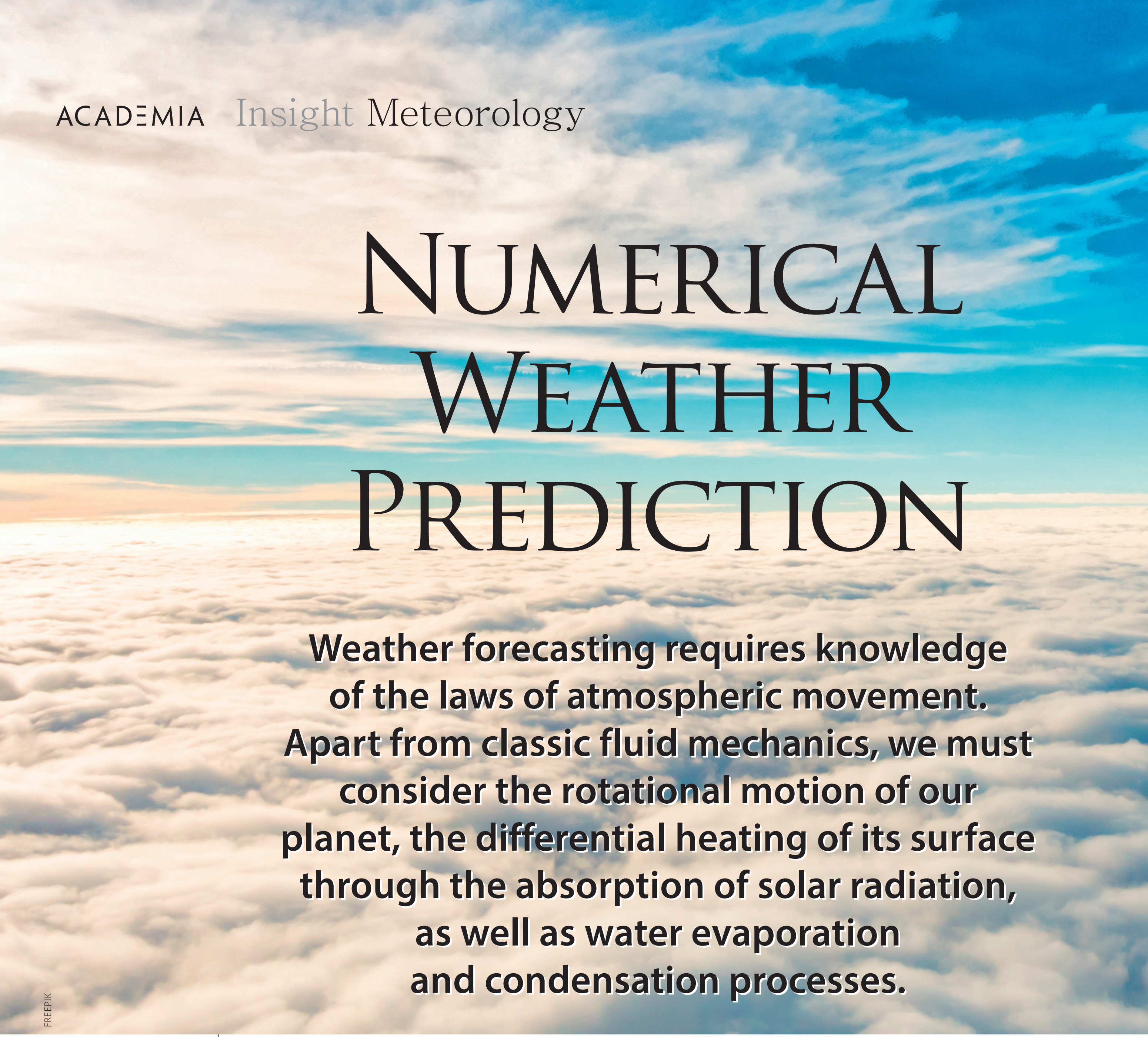

FREEPIK

NUMERICAL WEATHER PREDICTION

Weather forecasting requires knowledge of the laws of atmospheric movement. Apart from classic fluid mechanics, we must consider the rotational motion of our planet, the differential heating of its surface through the absorption of solar radiation, as well as water evaporation and condensation processes.

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The system of equations describing the dynamics of the atmosphere contains mass, momentum, and energy conservation equations, cast in a rotating reference frame associated with the Earth's surface, together with the thermodynamic equation of state. The general analytical solution of this system is unknown, therefore meteorological forecasts are made by approximate solutions of the approximate system of equations using numerical methods. These approximations should take into account two seemingly contradictory postulates: firstly, they should correctly reflect the behavior of the atmosphere in states close to conditions of hydrostatic and geostrophic balance. Secondly, they should describe the deviations from equilibrium states as accurately as possible, as these deviations determine the evolution of atmospheric flow over several days.

Background

At the beginning of the 20th century, Norwegian physicist and meteorologist Vilhelm Bjerknes formulated a two-stage meteorological forecast algorithm. The pressure, density, temperature, humidity, and velocity fields determined in the first stage provided the initial conditions needed to integrate the system of atmosphere dynamics equations during the second, prognostic stage. Lacking an analytical or a numerical

method, Bjerknes focused on graphical methods for finding a solution.

Lewis Fry Richardson, a British mathematician, was the first to attempt forecasting by calculations. He presented the complete concept of the meteorological forecast algorithm, using numerical methods to solve the equations developed by Bjerknes. Richardson's work culminated in an attempt to forecast the weather over Germany based on aerological data collected during an international ballooning day on 20 May 1910. Unfortunately, his attempt ended in a spectacular failure. After one 6-hour integration step, the calculated pressure changes exceeded the observed values by two orders of magnitude. Richardson correctly identified the root cause of the problem: significant errors in wind speed measurements. Regardless of the measurement errors, however, the forecast was also doomed to fail because the integration time step was grossly too large.

Atmospheric states in hydrostatic and geostrophic equilibrium

Atmospheric flows are driven by the so-called pressure gradient force resulting from pressure differences due to differential heating. The balance of forces in the horizontal plane in the atmosphere also includes forces related to the turbulent transport of momentum (friction forces), and inertia forces as the Coriolis force associated with the Earth's rotation, centrifugal force in rotational motion, and the inertia force related to local accelerations.

The structure of steady-state motion in a free atmosphere, above the boundary layer in which friction forces are present is determined by the ratio of the inertia forces, i.e. centrifugal force to the Coriolis force, called the Rossby number (Ro). In low-pressure systems, typical Rossby values range between 0.1–1, which means that the Coriolis force plays a dominant role. In the case of tornadoes, Rossby values are high, in the thousands, and the motion is cyclostrophic (the horizontal pressure gradient is balanced by the centrifugal force). In the special case of Ro = 0 we are dealing with so-called geostrophic movement, in which the Coriolis force balances the force of the horizontal pressure gradient, and the movement is parallel to rectilinear isobars, perpendicular to the direction of the pressure gradient force.

An important consequence of the Coriolis force is the limitation of the horizontal extent of motions in the Earth's atmosphere, which shapes the multicellular system of global atmospheric circulation. The largest vertical forces, gravity and vertical pressure gradients, are several times the magnitude of the horizontal forces. These forces balance each other out almost exactly (we call this state hydrostatic equilibrium), and only in small spatial scales can we observe more significant differences in their values, which result in vertical accelerations. It can be said that the state of the atmosphere observed on a sufficiently large spatial scale does not depart significantly from the hydrostatic and geostrophic balance.

Over the more heated areas, the air expands, which causes the column containing a specific mass of air with a unitary horizontal section to increase its height. This causes the elevation and slope of isobaric surfaces over the heated area. This in turn forms the horizontal pressure gradient, which causes the mass to escape from the heated area and reduces the pressure in its center. At the same time, the Coriolis force deflects the path of motion, leading to the rotational motion around the center of the low-pressure system. This is the main mechanism behind atmospheric movements on a large spatial scale.

Wave movements are an important part of atmosphere dynamics. Mass outflow from one area is associated with its accumulation in another. This chain of events can be seen, for example, in the waving motion of isobaric surfaces around the equilibrium. From the point of view of the evolution of baric systems in moderate latitudes, the most important type of waveforms are Rossby waves, which maintain the angular momentum in movements associated with changes in latitude. Predicting the development and movement of Rossby waves is one of the main conditions for accurate meteorological forecasting.

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Apparently, the failure of Richardson's method deterred potential followers. It was not until the mid-1940s that a brilliant American mathematician and a computer science pioneer, John von Neumann, became interested in this problem. In 1946, he started a research project at the Princeton Institute for Advanced Studies, which was joined in 1948 by Jule Charney, the creator of the quasi-geostrophic theory. Charney discovered that a system of equations allowing only Rossby waves can be obtained through the geostrophic approximation. This discovery, combined with the vorticity equation, led to the formulation of the first effective, though simple, numerical weather prediction model. In March 1950, the team was granted access to the ENIAC computer at a military facility in Aberdeen, Maryland for 33 days, which allowed them to make four 24-hour and two 12-hour forecasts that were surprisingly accurate. However, it took a good while for this solution to be implemented. It was not until 1954 that the first operational numerical meteorological forecasts were launched in Sweden, followed by the U.S. a year later and Japan in 1959.

The model developed by Charney and von Neumann's team reflected the most important element of atmospheric dynamics, but ignored the primary causes of disturbances. These reasons were explained by the quasi-geostrophic theory which gave rise to quasi-geostrophic models, capable of predicting cyclogenesis caused development by vertical currents, the convergence of the wind field at the Earth's surface, and divergence near the tropopause. The quasi-geostrophic model remained in use by weather service in the United States until 1966.

In 1959, Karl-Heinz Hinkelmann made successful predictions using a system of equations similar to those initially used by Bjerknes and Richardson. The key to his success was improving the quality of the input data, significantly shortening the integration time step, and using a special procedure adjusting the spatial distributions of individual fields. The latter procedure is now referred to as initialization, while the equations are called primitive equations. These models were implemented in the United States and Germany in 1966, and in Great Britain in 1972. The models currently used for short- and medium-term forecasts in weather services around the world are based on various versions of the primitive equation system, while initialization is seen as the key factor to the success of the entire undertaking.

Predictability

In the early 1960s, the American mathematician and meteorologist Edward N. Lorenz conducted computational experiments with a highly simplified atmosphere model, performing a series of runs using the results obtained each time from a previous run as initial data. He noted that rounding of intermediate data drastically changed the final results. Lorenz showed that the chaotic nature of the atmosphere related to the non-linearity of the system, the occurrence of positive feedback and instability makes it impossible to predict its behavior for more than several days in advance, even with a perfect model and precise knowledge of the initial state. Lorenz's discovery is known as the "butterfly effect," derived from his joking question whether a butterfly fluttering its wings in Brazil could trigger a tornado in Texas. Lorenz responded that this wasn't the case, but pointed out that small, random factors may in fact determine the location or time of occurrence of such phenomena, although this does not change the probability of their occurrence.

During that time, achieving decent verifiability of two-day forecasts was a big problem. Today's forecasting systems have nearly reached Lorenz's threshold. However, the occurrence of some phenomena, such as the Southern Oscillation (El Niño), can often be predicted much earlier, several months in advance.

Clearly, weather forecasting is extremely difficult and inherently uncertain. Imagine a pencil placed on a table standing up on its blunt end. Under ideal conditions, it could stand like that for any length of time. Yet if someone bumps the table, the pencil will surely fall. However, it is very difficult to predict in which direction. This is the level of difficulty meteorologists are faced with when dealing with numerical weather forecasting.

The modern age

The desire to extend the forecast horizon has led to the introduction of global models. In the American weather service, a global atmosphere model began to operate in August 1980. In 1985, a global model was brought into use at the European Center for Medium-Term Forecasts (ECMWF), now considered the world's best. In the late 1980s and early 1990s, global models were built and launched by the meteorological services of Great Britain, Australia and Canada, followed by France, Japan and Germany in the following decade.

The sensitivity to initial conditions observed by Lorenz gave rise to two important trends in numerical forecasts. One of them was the development of variational data assimilation techniques. The introduction of four-dimensional variation assimilation in the 1990s brought about a rapid improvement in forecasts. Another trend was ensemble forecasting, which involves creating an entire set of forecasts with artificially disturbed initial conditions that were only slightly varied. In this way, instead of a single forecast, a whole set of possible scenarios is obtained. By analyzing them one can usually determine the most probable events, as well as identify extreme scenarios that can predict dangerous situations.

Weather forecasting in Poland

Before 1980, the Polish meteorological service used a quasi-geostrophic model. Later, since it was not possible to upgrade computing equipment, foreign forecasting products were used. In the early 1990s, a miniature supercomputer Cray EL-98 equipped with eight vector processors was installed at the Interdisciplinary Center for Mathematical and Computational Modeling at the University of Warsaw, in which the British UM (Unified Model) was launched in a regional configuration in June 1994. This model produced perfect forecasts during the 1997 flood, showing strongly localized heavy rainfall in the upper Oder basin that caused a second flood wave, which was later considered unpredictable by synoptic methods.

After that flood, a decision was made to strengthen the country's hydrometeorological protection system. As a result, the Institute of Meteorology and Water Management (IMGW) purchased a radar system and a Silicon Graphics Origin computer, on which the regional COSMO-LM model was installed, developed by the COSMO consortium focused around the German meteorological service. This model is currently the basis of the national forecasting system. Earlier, the Kraków branch of IMGW partnered with the ALADIN consortium, created by Meteo-France, and began using its model. Also at the end of the 1990s, a team of scientists from the Warsaw University of Technology began working with a team from the University of York in Toronto, developing an advanced model of atmospheric chemistry based on the Canadian regional climate model MC2. After the global successor of MC2, the GEM model, was launched in the Canadian weather service, the integrated meteorological and chemical model GEM-AQ began to be used in research, and over the next decade underwent various improvements on both sides of the ocean. At the beginning of the last decade, GEM began being used for operational work on air quality forecasting. Since the beginning of 2019, this system has been operating at the Institute of Environmental Protection – National Research Institute, providing short-term forecasts of air quality, promoted by the Chief Inspectorate of Environmental Protection. This model also provides forecasts for a pan-European, publicly available combined air quality forecast as part of the Copernicus Atmosphere Monitoring Service. A side effect of these activities is a meteorological forecast carried out for the entire globe, Europe and Poland.

In recent years, there has been much more interest in the issue of atmospheric pollution. An integrated American model WRF-Chem (Weather Research and Forecast) is used in several centers for this purpose. It is a model mainly intended for R&D of weather forecasts. As a community-based model it is available free of charge and relatively easy to operate, thanks to good instructions, input data ready to use, and a ready-made system for analyzing and visualizing results so that even amateur enthusiasts can operate it. So today, even with an ordinary computer, some technical knowledge, and a bit of free time and determination, you can run a modest version of a modern weather forecasting system for your own use.

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Further reading:

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