FOCUS • History of NWP (part 1)

The first equations of fluid mechanics were formulated by Leonhard Euler in 1755, using the differential calculus invented by Isaac Newton in 1665, Gottfried Wilhelm Leibniz in 1675, and using partial derivatives devised by Jean le Rond d'Alembert in 1746.

Terms for molecular viscosity were added by Claude-Louis Navier in 1827 and George Stokes in 1845. The equations describing fluid motion are often called the **Navier-Stokes equations**. These primitive equations for fluid mechanics were refined by Herman von Helmholtz in 1888.

About a decade later Vilhelm Bjerknes in Norway suggested that these same equations could be used for the atmosphere. He was a very strong proponent of using physics, rather than empirical rules, for making weather forecasts.

In 1922, Lewis Fry Richardson in England published a book describing the first experimental numerical weather forecast — which he made by solving the primitive equations with mechanical desk calculators. His book was very highly regarded and well received, as one of the first works that combined the many physical theories in a thorough, interactive way.

It took him 6 weeks to make a 6 h forecast. Unfortunately, his forecast of surface pressure was off by an order of magnitude compared to the real weather. Because of the great care that Richardson took in producing these forecasts, most of his peers concluded that NWP was not feasible. This discouraged further work on NWP until two decades later.

John von Neumann, a physicist at Princeton University's Institute for Advanced Studies, and Vladimir Zworykin, an electronics scientist at RCA's Princeton Laboratories and key inventor of television, proposed in 1945 to initiate NWP as a way to demonstrate the potential of the recently-invented electronic computers. Their goal was to simulate the general circulation as a first step toward climate modification. During the first few years they couldn't agree how to approach the problem.

Von Neumann brought together a group of theoretical meteorologists, including Carl-Gustav Rossby, Arnt Eliassen, Jule Charney, and George Platzman. Eventually, they realized the necessity to simplify the full primitive equations in order to focus their limited computer power on the long waves of the general circulation.

The first electronic computer, the ENIAC, filled a large room at Princeton and used vacuum tubes that generated tremendous heat and frequently burned out. Its limited capacity precluded solution of the full primitive equations, a predicament that was happily accepted, knowing Richardson's failure with the primitive eqs.

Charney and von Neumann developed a simple one-layer barotropic model (conservation of absolute

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FOCUS • History of NWP (part 2)

vorticity) that Charney presented at NWP conferences in 1948 and 1949.

The research team had many hurdles: translating the differential equations into discrete form, writing the code in machine language (FORTRAN and C++ had not yet been invented), deciding how large a forecast domain was necessary, and doing many feasibility calculations by hand (using slide rules and mechanical calculators).

Their first ENIAC forecasts were made in March-April 1950, for three case studies over North America. The results were quite promising. Soon thereafter, Bert Bolin, Joseph Smagorinsky and Norman Phillips joined the research team, and they made several more numerical forecasts.

Meanwhile, Rossby returned to his native Sweden to begin a NWP effort there. Together with Bolin (back from Princeton) and Phillips, they developed a barotropic model based on a simplified physical picture of the atmosphere. A Swedish electronic computer called BESK became operational in 1953, and at the time was the most powerful computer in the world.

With support from the Swedish Air Force, the first routine operational numerical forecasts were started in Sweden in December 1954. These were 24, 48, and eventually 72-hour forecasts of 50 kPa heights, not of surface conditions. This phase of operational forecasts ended in May 1955, by which time 60 to 70 forecasts had been produced with good skill.

In 1953 in the USA, IBM announced its specifications for a new computer. The US Weather Bureau, USAF Air Weather Service, and Navy WX Service formed a Joint Numerical Weather Prediction Unit (JNWPU) in 1954 to use this computer, with director George Cressman.

This group decided to focus on operational weather forecasts using the quasi-geostrophic baroclinic model that had been derived in 1948 by Charney and Eliassen. Computer power limited the model to three layers, eventually placed at 40, 70, and 90 kPa. In 1955 the IBM 701 computer was introduced, and by May the JNWPU began its first routine operational numerical weather forecasts for North America. Also, Hans Panofsky proposed a scheme for automated analysis of weather data.

Meanwhile, Phillips and Smagorinsky were using NWP in a research mode to learn more about how the general circulation works. However, after von Neumann left Princeton in 1955 (and died in 1956), the NWP group began to fall apart. The US military services ceased their support, Charney and Phillips left for MIT, and Rossby died in 1957.

The numerical weather forecasts were often of poor quality, and were not appreciated by the experienced human forecasters. During the first two years of

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FOCUS • History of NWP (part 3)

operation of the JNWPU, the numerical forecasts were largely ignored.

In 1958, the National Meteorological Center (NMC) was organized to perform the operational numerical forecasting for the National Weather Service. The USAF organized a Global Weather Central in Omaha, Nebraska, to handle their numerical forecasting, and the Navy's numerical modeling moved to Monterey, California.

At first, the numerical forecasts were initialized using hand-analyzed data, where the observations were manually interpolated to the model grid points. By the mid 1950's, a variety of automated schemes were employed. Eventually, an **objective analysis** method was adopted of fitting new observations to previous forecast fields.

The first baroclinic (multi-layer) models used in 1955 and 1956 failed because they were poorly calibrated and awkward to use. Modelers then retreated to the barotropic model. Because this model had only one layer, it left the computer underutilized. To take advantage of the extra computer power, modelers expanded the barotropic domain to the hemisphere, but were disappointed to discover deteriorated forecast quality.

These barotropic models did not include topography (due to computer limitations), and the resulting long-waves in the general circulation were quite unrealistic in their westward movement. It was found that the forecast quality improved by fudging the longest waves (eliminating them from the forecast, and then re-inserting them later). This was a very disappointing time in NWP.

Eventually, Cressman and Phillips found a solution by altering the characteristics of the air above the modeled troposphere. The resulting 50 kPa barotropic forecasts were of such high quality that ten years elapsed before baroclinic models could beat them.

Finally, in 1963 the new computers were powerful enough that a six-layer primitive equation (PE) model could be implemented. Forecast scores dramatically improved, finally making NWP a useful forecast tool.

Since then, improvements in forecast quality have been closely tied to growth in computer power (memory, speed, & file storage, see Fig 14.2). Added to the models were more layers, a finer mesh of grid points in the horizontal, an increase to a fully global domain (in 1966), topography, and landscape characteristics including snow and ice coverage. Also improved were parameterizations of physical processes such as radiation, clouds, precipitation, and turbulence.

The NMC regional (limited-domain) models evolved into a limited-area fine-mesh (LFM) model in 1976, which was phased out in 1994. A nested-grid model (NGM) was introduced in 1990 to make 2-day forecasts. The NGM used a grid-point representation of the

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FOCUS • History of NWP (part 4)

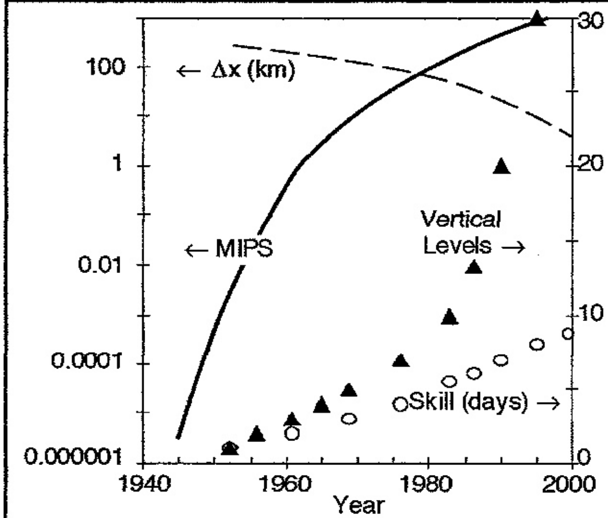

Figure 14.2
Improvement in horizontal grid resolution (Δx), number of model levels, and duration of a skillful 50 kPa forecast as a function of computer power (MIPS = millions of instructions per second). These data are smoothed.

hydrostatic primitive equations. It had 16 layers, and horizontal resolutions of 80 and 160 km on inner (N. America) and outer (N. Hemisphere) grids.

An "eta" hydrostatic, grid-point model was introduced by NMC in the early 1990's. It had greater vertical resolution (38 layers) to handle topography better. It made a 2-day forecast over 1/3 of the N. Hem. By 1999 it had 32 km horiz. resolution and 45 layers.

Spectral representations of horizontal fields replaced grid points in the NMC global models at about 1980. By the late 1990s, these models evolved into a hydrostatic Global Spectral Model (GSM), with 42 layers, and 80 km horizontal resolution. The GSM was used for 5-day aviation (AVN) forecasts, and for medium-range forecasts (MRF) out to 15 days, using a time step of 9 minutes, and taking 14 min runtime/day on a Cray YMP.

In the mid 1990's, U.S. military numerical forecasts were consolidated in Monterey at the Fleet Numerical Meteorological and Oceanographic Center (FNMOC). NMC was reorganized into the National Centers for Environmental Prediction (NCEP), with their Environmental Modeling Center still near Washington, DC. They introduced a MesoEta model, which by 1999 had 10 km horizontal grid spacing, and 60 layers. The Canadian Meteorological Center (CMC) developed a Global Environmental Multiscale (GEM) model in the late 1990s, with variable grid resolution as fine as 15 km.

Meanwhile, in the mid 1970s the European Community established a European Centre for Medium-Range Weather Forecasts (ECMWF) in Reading,

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FOCUS • History of NWP (part 5)

England. Their first medium-range forecast in 1979 was based on a grid-point model. In the 1990s, their 10-day forecasts were produced with spectral models.

Starting in 1992, ECMWF began running an Ensemble Prediction System (EPS). By the end of 1999, 50 alternative analyses were constructed every day from the one operational analysis. These perturbed analyses differed slightly at those locations where small analysis errors could grow rapidly. The 50 analyses were used as starting points for 50 different ten-day forecasts, run on a slightly coarser grid mesh. The spread of the resulting 50 forecasts were used as a measure of forecast confidence, and provided probability information.

By late 1999, the ECMWF numerical forecasts had one of the highest verification skills in the world. Their model had a horizontal resolution equivalent to about 60 km, with 60 layers in the vertical. This works out to 8.3 million grid points in the model, at which tens of meteorological variables were computed every 20 minutes. This ten-day forecast took approximately one and a half hours on a Fujitsu VPP700 computer utilizing 24 processors, and involved approx. 10^{14} computations. [*For a thorough history of NWP, see F. Nebeker, 1995: "Calculating the Weather". Academic Press. 255 pp.*]

ON DOING SCIENCE • Mathematics

"To have to translate one's verbal statement into mathematical formulae compels one to scrutinize the ideas therein expressed. Next the possession of formulae makes it much easier to deduce the consequences. In this way absurd implications, which might have passed unnoticed in a verbal statement, are brought clearly into view & stimulate one to amend the formula.

Mathematical expressions have, however, their special tendencies to pervert thought: the definiteness may be spurious, existing in the equation but not in the phenomena to be described; and the brevity may be due to the omission of the more important things, simply because they cannot be mathematized. Against these faults we must constantly be on our guard."

– L.F. Richardson, 1919