



The origins of computer weather prediction and climate modeling

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Abstract

Numerical simulation of an ever-increasing range of geophysical phenomena is adding enormously to our understanding of complex processes in the Earth system. The consequences for mankind of ongoing climate change will be far-reaching. Earth System Models are capable of replicating climate regimes of past millennia and are the best means we have of predicting the future of our climate.

The basic ideas of numerical forecasting and climate modeling were developed about a century ago, long before the first electronic computer was constructed. There were several major practical obstacles to be overcome before numerical prediction could be put into practice. A fuller understanding of atmospheric dynamics allowed the development of simplified systems of equations; regular radiosonde observations of the free atmosphere and, later, satellite data, provided the initial conditions; stable finite difference schemes were developed; and powerful electronic computers provided a practical means of carrying out the prodigious calculations required to predict the changes in the weather.

Progress in weather forecasting and in climate modeling over the past 50 years has been dramatic. In this presentation, we will trace the history of computer forecasting through the ENIAC integrations to the present day. The useful range of deterministic prediction is increasing by about one day each decade, and our understanding of climate change is growing rapidly as Earth System Models of ever-increasing sophistication are developed.

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1. Introduction

Among the most significant scientific advances of the past century is our ability to simulate complex physical systems using numerical models and therewith to predict their evolution. One outstanding example is the development of general circulation models (GCMs) of the atmosphere and ocean, which have brought two great advantages: We can now predict the weather for several days in advance with a high degree of

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confidence, and we are gaining great insight into the factors causing changes in our climate, and their likely timing and severity.

A century ago, weather forecasting was a haphazard process, very imprecise and unreliable. Observations were sparse and irregular, especially for the upper air and over the oceans. The principles of theoretical physics played little or no role in practical forecasting: the forecaster used crude techniques of extrapolation, knowledge of local climatology and guesswork based on intuition; forecasting was more an art than a science. The observations of pressure and other variables were plotted in symbolic form on a weather map and lines drawn through points with equal pressure revealed the pattern of weather systems – depressions, anticyclones, troughs and ridges. The forecaster used his experience, memory and a variety of empirical rules to produce a forecast map. The primary physical process attended to by the forecaster was *advection*, the transport of fluid characteristics and properties by the movement of the fluid itself. But the crucial quality of advection is that it is *nonlinear*; the human forecaster may extrapolate trends using an assumption of constant wind, but is quite incapable of intuiting the subtleties of complex advective processes.

1.1. The pre-history of scientific forecasting

The development of thermodynamics in the 19th century resulted in a completion of the set of fundamental physical principles governing the flow of the atmosphere. By about 1890, the great American meteorologist Cleveland Abbe (Fig. 1, left panel) had recognized that “meteorology is essentially the application of hydrodynamics and thermodynamics to the atmosphere” [28]. In his paper, *The physical basis of long-range weather forecasting*, Abbe [1] proposed a mathematical approach to forecasting. He expressed a hope that atmospheric scientists would “take up our problems in earnest and devise either graphical, analytical, or numerical methods” of solving the equations. A more explicit analysis of the weather prediction problem from a scientific viewpoint was undertaken shortly afterwards by the Norwegian scientist Vilhelm Bjerknes (Fig. 1, centre panel). Bjerknes set down a two-step plan for rational forecasting [3]: A *diagnostic* step, in which the initial state of the atmosphere is determined using observations; and a *prognostic* step, in which the laws of motion are used to calculate how this state changes over time.

There was a severe shortage of observations, particularly over the seas and for the upper air, but Bjerknes was optimistic: international observation programs were already under way, organized by the International Commission for Scientific Aeronautics, which might provide a reasonable diagnosis of the state of the atmosphere. The prognostic step was to be taken by assembling a set of equations, one for each dependent variable describing the atmosphere. Bjerknes listed seven basic variables: pressure, temperature, density, humidity and three components of velocity. He then identified seven independent equations: the three hydrodynamic equations of motion, the continuity equation, the equation of state and the equations expressing the first and second laws of thermodynamics (in fact, he should have specified a continuity equation for water rather than the second thermodynamic law).

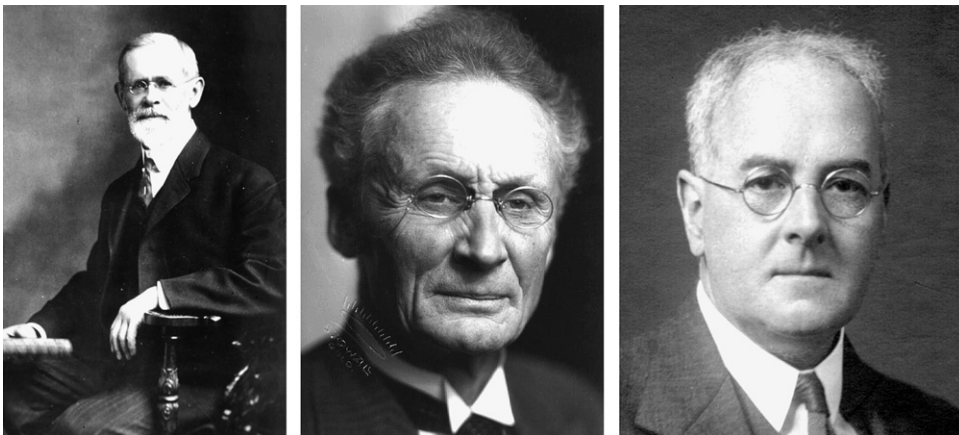


Fig. 1. Left: Cleveland Abbe (1838–1916). Centre: Vilhelm Bjerknes (1862–1951). Right: Lewis Fry Richardson (1881–1953).

Bjerknes developed a qualitative, graphical method for solving the equations, as he could not solve them numerically and an analytical solution was out of the question. His idea was to represent the initial state of the atmosphere by a number of charts giving the distribution of the variables at different levels. Graphical methods based on the fundamental equations could then be applied to construct a new set of charts describing the atmosphere some hours later. This process could be iterated until the desired forecast length was reached. Bjerknes contrasted the methods of meteorology with those of astronomy, for which predictions of great accuracy are possible, and he stated his goal: to make meteorology an exact science, a true physics of the atmosphere.

1.2. Richardson's dream

Bjerknes saw no possibility to put his ideas to practical use. The English Quaker scientist Lewis Fry Richardson was bolder, attempting a direct solution of the equations of motion. Richardson (Fig. 1, right panel) first heard of Bjerknes' plan for rational forecasting when he took up employment with the Meteorological Office in 1913. In the Preface to his book *Weather Prediction by Numerical Process* [24] he writes

The extensive researches of V Bjerknes and his School are pervaded by the idea of using the differential equations for all that they are worth. I read his volumes on *Statics* and *Kinematics* soon after beginning the present study, and they have exercised a considerable influence throughout it.

Richardson's book opens with a discussion of then-current practice in the Meteorological Office. He describes the use of an *Index of Weather Maps*, constructed by classifying old synoptic charts into categories. The Index [12] assisted the forecaster to find previous maps resembling the current one and therewith to deduce the likely development by studying the evolution of these earlier cases. But Richardson was not optimistic about this method. He wrote that "The forecast is based on the supposition that what the atmosphere did then, it will do again now. . . . The past history of the atmosphere is used, so to speak, as a full-scale working model of its present self" [24]. Bjerknes had contrasted the precision of astronomical prediction with the 'radically inexact' methods of weather forecasting. Richardson returned to this theme:

— the *Nautical Almanac*, that marvel of accurate forecasting, is not based on the principle that astronomical history repeats itself in the aggregate. It would be safe to say that a particular disposition of stars, planets and satellites never occurs twice. Why then should we expect a present weather map to be exactly represented in a catalogue of past weather?

Richardson's forecasting scheme amounts to a precise and detailed implementation of the prognostic component of Bjerknes' program. It is a highly intricate procedure: as Richardson observed, 'the scheme is complicated because the atmosphere is complicated.' It also involved a phenomenal volume of numerical computation and was quite impractical in the pre-computer era. But Richardson was undaunted:

Perhaps some day in the dim future it will be possible to advance the computations faster than the weather advances But that is a dream.

Today, forecasts are prepared routinely on powerful computers running algorithms that are remarkably similar to Richardson's scheme – his dream has indeed come true.

1.3. Richardson's forecast

Richardson began serious work on weather prediction in 1913 when he was appointed Superintendent of Eskdalemuir Observatory, in the Southern Uplands of Scotland. He had had little or no previous experience of meteorology when he took up this position 'in the bleak and humid solitude of Eskdalemuir'. Perhaps it was his lack of formal training in the subject that enabled him to approach the problem of weather forecasting from such a breathtakingly original and unconventional angle. Richardson's idea was to express the physical principles which govern the behavior of the atmosphere as a system of mathematical equations and to apply his finite difference method to solve this system. He had previously used both graphical and numerical methods for solving differential equations and had come to favor the latter. The basic equations had already been

identified by Abbe and Bjerknes, but they had to be simplified using the hydrostatic assumption and transformed to render them amenable to approximate solution. The fundamental idea is that atmospheric pressures, velocities, etc., are tabulated at certain latitudes, longitudes and heights so as to give a general description of the state of the atmosphere at an instant. Then these numbers are processed by an arithmetical method which yields their values after an interval of time Δt . The process can be repeated so as to yield the state of the atmosphere after $2\Delta t$, $3\Delta t$, and so on.

Richardson was not concerned merely with theoretical rigor, but wished to include a fully worked example to demonstrate how his method could be put to use. Using the most complete set of observations available to him, he applied his numerical method and calculated the changes in the pressure and winds at two points in central Europe. The results were something of a calamity: Richardson calculated a change in surface pressure over a six-hour period of 145 hPa, a totally unrealistic value. The calculations themselves are presented in his book, on a set of 23 Computer Forms, rather like a modern Excel spread-sheet. These were completed manually, and the changes in the primary variables over a six hour period computed. Richardson explains the chief result thus:

The rate of rise of surface pressure . . . is found on Form P_{XIII} as 145 millibars in 6 hours, whereas observations show that the barometer was nearly steady. This glaring error is examined in detail . . . and is traced to errors in the representation of the initial winds.

Richardson described his forecast as ‘a fairly correct deduction from a somewhat unnatural initial distribution’. He speculated that reasonable results would be obtained if the initial data were smoothed, and discussed several methods of doing this. In fact, the spurious tendencies are due to an imbalance between the pressure and wind fields resulting in large amplitude high frequency gravity wave oscillations. The ‘cure’ is to modify the analysis so as to restore balance; this process is called *initialization*. A numerical model has been constructed, keeping as close as possible to the method of Richardson, except for omission of minor physical processes, and using the same grid discretization and equations as used by him [18]. The results using the initial data which he used were virtually identical to those obtained by him; in particular, a pressure tendency of 145 hPa in 6 hours was obtained at the central point. The initial data were then initialized using a digital filter, and the forecast tendencies from the modified data were realistic.

In Table 1 we show the six-hour changes in pressure at each model level. The column marked LFR has the values obtained by Richardson. The column marked MOD has the values generated by the computer model. They are very close to Richardson’s values. The column marked DFI is for a forecast from data initialized using a Dolph–Chebyshev filter [18]. The initial tendency of surface pressure is reduced from the unrealistic 145 hPa/6 h to a reasonable value of less than 1 hPa/6 h (bottom row, Table 1). These results indicate clearly that Richardson’s unrealistic prediction was due to imbalance in the initial data used by him. Complete details of the forecast reconstruction may be found in Lynch [18].

The initial response to *Weather Prediction by Numerical Process* was unremarkable, and must have been disappointing to Richardson. It was widely reviewed, with generally favorable comments – Ashford [2] includes a good coverage of reactions – but the impracticality of the method and the apparently abysmal failure of the solitary example inevitably attracted adverse criticism. The true significance of Richardson’s work was not immediately evident; the computational complexity of the process and the disastrous results of the single trial forecast both tended to deter others from following the trail mapped out by him. Despite

Table 1
Six-hour changes in pressure (units: hPa/6 h)

Level	LFR	MOD	DFI
1	48.3	48.5	−0.2
2	77.0	76.7	−2.6
3	103.2	102.1	−3.0
4	126.5	124.5	−3.1
Surface	145.1	145.4	−0.9

LFR: Richardson; MOD: Model; DFI: Filtered.

the understandably cautious initial reaction, Richardson's brilliant and prescient ideas are now universally recognized among meteorologists and his work is the foundation upon which modern forecasting is built.

2. The beginning of modern NWP

While Richardson's dream appeared unrealizable at the time his book was published, a number of key developments in the ensuing decades set the scene for progress. There were profound developments in the theory of meteorology, which provided crucial understanding of atmospheric dynamics. There were advances in numerical analysis, which enabled the design of stable algorithms. The invention of the radiosonde, and its introduction in a global network, meant that timely observations of the atmosphere in three dimensions were becoming available. And, finally, the development of the digital computer provided a means of attacking the enormous computational task involved in weather forecasting.

2.1. John von Neumann and the meteorology project

John von Neumann was one of the leading mathematicians of the 20th century. He made important contributions in several areas: mathematical logic, functional analysis, abstract algebra, quantum physics, game theory and the theory and application of computers. A brief sketch of his life may be found in Goldstone [13] and a recent biography has been written by Macrae [19].

In the mid 1930s von Neumann became interested in turbulent fluid flows. The non-linear partial differential equations which describe such flows defy analytical assault and even qualitative insight comes hard. Von Neumann saw that progress in hydrodynamics would be greatly accelerated if a means of solving complex equations numerically were available. It was clear that very fast automatic computing machinery was required. He masterminded the design and construction of an electronic computer at the Institute for Advanced Studies (IAS) in Princeton. This machine was built between 1946 and 1952 and its design had a profound impact upon the subsequent development of the computer industry. The Electronic Computer Project was 'undoubtedly the most influential single undertaking in the history of the computer during this period' [13, p. 255]. The Project comprised four groups: (1) Engineering, (2) Logical design and programming, (3) Mathematical, and (4) Meteorological. The fourth group was directed for the period 1948–1956 by Jule Charney (Fig. 2).

Von Neumann recognized weather forecasting, a problem of both great practical significance and intrinsic scientific interest, as an ideal problem for an automatic computer. Moreover, according to Goldstone (p. 300), Von Neumann "knew of the pioneering work ... of Lewis F Richardson. "During the 1920s, Courant, Friedrichs and Lewy [11] had studied the numerical solutions of partial differential equations, and had shown that there is a limitation on the time-step for a given space step; this is now known as the CFL criterion. Von Neumann was in Göttingen in the 1920s, and he fully appreciated the practical implications of this work. Von Neumann made estimates of the computational power required to integrate the equations of



Fig. 2. Jule Charney (1917–1981) (© Nora Rosenbaum).

motion and concluded tentatively that it would be feasible on the IAS computer. A formal proposal was made to the U.S. Navy to solicit financial backing for the establishment of a Meteorology Project. According to Platzman [23] this proposal was ‘perhaps the most visionary prospectus for numerical weather prediction since the publication of Richardson’s book a quarter-century earlier’. The proposal was successful in attracting support, and the Meteorological Research Project began in July, 1946.

A meeting – the Conference on Meteorology – was arranged at the Institute the following month to enlist the support of the meteorological community and many of the leaders of the field attended. Von Neumann had discussed the prospects for numerical weather forecasting with Carl Gustaf Rossby, who arranged for Jule Charney to participate in the Princeton meeting. Charney was at that time already somewhat familiar with Richardson’s book. Richardson’s forecast was much discussed at the meeting. It was clear that the CFL stability criterion prohibited the use of a long time step such as had been used by Richardson [24].

The initial plan was to integrate the primitive equations; but the existence of high-speed gravity wave solutions required the use of such a short time step that the volume of computation might exceed the capabilities of the IAS machine. And there was a more fundamental difficulty: the impossibility of accurately calculating the divergence from the observations. Thus, two obstacles loomed before the participants at the meeting: how to avoid the requirement for a prohibitively short time step, and how to avoid using the computed divergence to calculate the pressure tendency. The answers were not apparent; it remained for Charney to find a way forward.

2.2. The ENIAC integrations

In his baroclinic instability study, Charney had derived a mathematically tractable equation for the unstable waves ‘by eliminating from consideration at the outset the meteorologically unimportant acoustic and shearing-gravitational oscillations’ [6]. The multi-scale nature of atmospheric dynamics, with low-frequency and high-frequency components, is also found in a wide range of other physical contexts. The advantages of a filtered system of equations would not be confined to its use in analytical studies. The system could have dramatic consequences for numerical integration. Charney analysed the primitive equations using the technique of *scale analysis*, and was able to simplify them in such a way that the gravity wave solutions were completely eliminated [7]. The resulting equations are known as the *quasi-geostrophic* system. In the special case of horizontal flow with constant static stability, the vertical variation can be separated out and the quasi-geostrophic potential vorticity equation reduces to a form equivalent to the nondivergent barotropic vorticity equation

$$\frac{d(\zeta + f)}{dt} = 0,$$

where ζ is the vorticity of the motion and f is the planetary vorticity. The barotropic equation had, of course, been used by Rossby in his analytical study of atmospheric waves, but nobody seriously believed that it was capable of producing a quantitatively accurate prediction of atmospheric flow.

By early 1950 the Meteorology Group had completed the necessary mathematical analysis and had designed a numerical algorithm for solving the barotropic vorticity equation. The scientific record of this work is the much-cited paper in *Tellus* by Charney et al. [10]. Arrangements were made to run the integration on the only computer then available, the Electronic Numerical Integrator and Computer (ENIAC) in Aberdeen, Maryland (Fig. 3). The ENIAC integrations were truly ground-breaking; indeed, weather forecasting has been regarded as a ‘Grand Challenge’ problem throughout the history of computing. The story of the mission to Aberdeen was colorfully told by Platzman [23]. Four 24-hour forecasts were made, and the results clearly indicated that the large-scale features of the mid-tropospheric flow could be forecast barotropically with a reasonable resemblance to reality. Each 24 hour integration took about 24 hours of computation; that is, the team were just able to keep pace with the weather.

Addressing the Royal Meteorological Society some years after the ENIAC forecast, Jule Charney said that ‘... to the extent that my work in weather prediction has been of value, it has been a vindication of the vision of my distinguished predecessor, Lewis F. Richardson ...’ [5]. It is gratifying that Richardson was made aware of the success in Princeton; Charney sent him copies of several reports, including the paper on the ENIAC

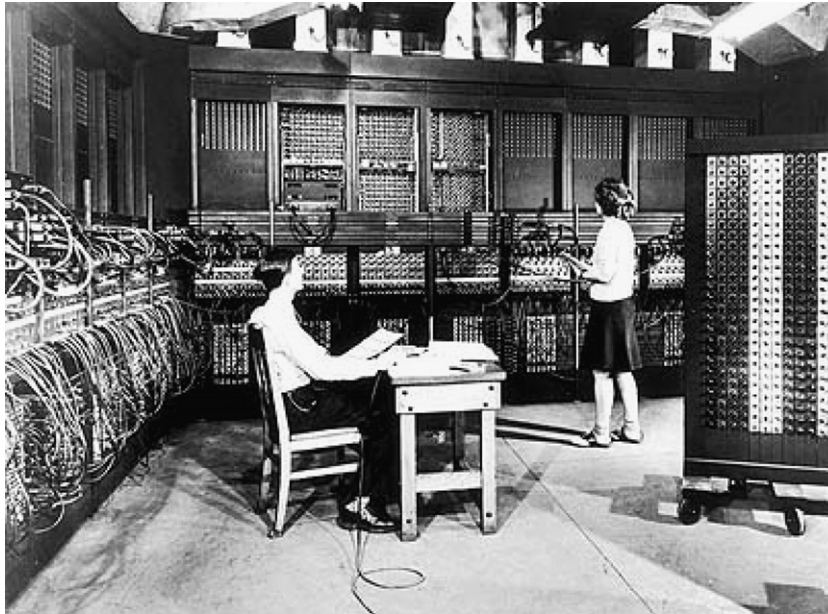


Fig. 3. The Electronic Numerical Integrator and Computer (ENIAC).

integrations. Richardson responded that the ENIAC results were ‘an enormous scientific advance’ on the single, and quite wrong, forecast in which his own work had ended.

2.3. From barotropic to multi-level models

The encouraging initial results of the Princeton team generated widespread interest and raised expectations that operationally useful computer forecasts would soon be a reality. Within two years there were research groups at several centres throughout the world. In an interview with Platzman (see [17]) Charney remarked: ‘I think we were all rather surprised ... that the predictions were as good as they were’. Later, Fjørtoft described how the success of the ENIAC forecasts ‘had a rather electrifying effect on the world meteorological community’. In fact, as Platzman observed in his review of the ENIAC integrations [23], nobody anticipated the enormous practical value of this simple model and the leading role it was to play in operational prediction for many years to come.

Several baroclinic models were developed in the few years after the ENIAC forecast. They were all based on the quasi-geostrophic system of equations. The Princeton team studied the severe storm of Thanksgiving Day, 1950 using two- and three-level models. After some tuning, they found that the cyclogenesis could be reasonably well simulated. Thus, it appeared that the central problem of operational forecasting had been cracked. However, it transpired that the success of the Thanksgiving forecast had been something of a fluke. Shuman [25] reports that the multi-level models were consistently worse than the simple barotropic equation; and it was the single-level model that was used when regular operations commenced in 1958.

2.4. Primitive equation models

The limitations of the filtered equations were recognized at an early stage. In a forward-looking synopsis in the *Compendium of Meteorology*, Charney [8] wrote: “The outlook for numerical forecasting would indeed be dismal if the quasi-geostrophic approximation represented the upper limit of attainable accuracy, for it is known that it applies only indifferently, if at all, to many of the small-scale but meteorologically significant motions.” Charney discussed the prospects for using the primitive equations, and argued that if geostrophic initial winds were used, the gravity waves would be acceptably small.

In his 1951 paper ‘The mechanism of meteorological noise’, Karl-Heinz Hinkelmann [14] tackled the issue of suitable initial conditions for primitive equations integrations. Hinkelmann had been convinced from the outset that the best approach was to use these equations. He knew that they would simulate the atmospheric dynamics and energetics more realistically than the filtered equations. Moreover, he felt certain, from his studies of noise, that high frequency oscillations could be controlled by appropriate initialization. A number of other important studies of initialization, by Charney [9], Phillips [22] and others, followed. The first application of the primitive equations was a success, producing good simulation of development, occlusion and frontal structure [15]. Routine numerical forecasting was introduced in the Deutscher Wetterdienst in 1966; this was the first ever use of the primitive equations in an operational setting. A six-level primitive equation model was introduced into operations at the National Meteorological Center in Washington in June, 1966, running on a CDC 6600 [26]. There was an immediate improvement in skill: the S_1 score for the 500 hPa one-day forecast was reduced by about five points.¹

The view in the U.K. Met. Office was that single-level models were unequal to the task of forecasting. As a result, barotropic models were never used for forecasting in the UK and, partly for this reason, the first operational model was not in place until the end of 1965. In 1972 a 10-level primitive equation model was introduced. Previous models had been essentially dynamical, without any adequate representation of the wide range of ‘physical’ processes that determine the weather. The new model incorporated a sophisticated parameterization of physical processes and with it the first useful forecasts of precipitation were produced.

2.5. General circulation models and climate modeling

A declaration issued at the World Economic Forum in Davos, Switzerland in 2000 read: *Climate change is the greatest global challenge facing humankind in the 21st century*. There is no doubt that the study of climate change and its impacts is of enormous importance for our future. Global climate models are the best means we have of anticipating likely changes.

Phillips [21] carried out the first long-range simulation of the general circulation of the atmosphere. He used a two-level quasi-geostrophic model on a beta-plane channel with rudimentary physics. The computation, done on the IAS computer (MANIAC I), used a spatial grid of 16×17 points, and the simulation was for a period of about one month. Starting from a zonal flow with small random perturbations, a wave disturbance with wavelength of 6000 km developed. Phillips examined the energy exchanges of the developing wave and found good qualitative agreement with observations of baroclinic systems in the atmosphere. He presented this work to a meeting of the Royal Meteorological Society, where he was the first recipient of the Napier Shaw Prize. Von Neumann was hugely impressed by Phillips’ work, and arranged a conference at Princeton University in October 1955, *Application of Numerical Integration Techniques to the Problem of the General Circulation*, to consider its implications. The work had a galvanizing effect on the meteorological community. Within ten years, there were several major research groups modeling the general circulation of the atmosphere.

Following Phillips’ seminal work, several general circulation models (GCMs) were developed. One early model of particular interest is that developed at the National Center for Atmospheric Research (NCAR) by Kasahara and Washington [16]. A distinguishing feature of this model was the use of height as the vertical coordinate (most models used pressure p or normalized pressure σ). The vertical velocity was derived using Richardson’s Equation; indeed, the dynamical core of this model was very similar to that employed by Richardson. The Kasahara–Washington model was the first in a continuing series of climate models. Various physical processes such as solar heating, terrestrial radiation, convection and small-scale turbulence were included in these models. The Community Atmosphere Model (CAM 3.0) is the latest in the series. CAM also serves as the atmospheric component of the Community Climate System Model (CCSM) a fully-coupled, global climate model that provides state-of-the-art computer simulations of the Earth’s past, present, and future climate states.

Coupled atmosphere-ocean general circulation models are used at the U.K. Hadley Centre for climate modeling. HadCM3 uses a conventional formulation of the dynamics while HADGEM is based on the new

¹ The S_1 score [27] measures forecast skill by comparing the spatial gradients of the prediction and of the verifying analysis.

dynamical formulation. Many early coupled models needed a flux adjustment (additional artificial heat and moisture fluxes at the ocean surface) to produce good simulations. The higher ocean resolution of HadCM3 was a major factor in removing this requirement. The atmospheric component of HadCM3 has 19 levels and a latitude/longitude resolution of $2.5^\circ \times 3.75^\circ$, with grid of 96×73 points covering the globe. The resolution is about 417×278 km at the Equator. The physical parameterization package of the model is very sophisticated. The oceanic component of HadCM3 has 20 levels with a horizontal resolution of $1.25^\circ \times 1.25^\circ$ permitting important details in the oceanic current structure to be represented. HadCM3 and HADGEM have been used for a wide range of climate studies which provided crucial inputs to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), published in 2007.

The development of comprehensive models of the atmosphere is undoubtedly one of the finest achievements of meteorology in the 20th century. Advanced models are under continuing refinement and extension, and are increasing in sophistication and comprehensiveness. They simulate not only the atmosphere and oceans but also a wide range of geophysical, chemical and biological processes and feedbacks. The models, now called *Earth System Models*, are applied to the eminently practical problem of weather prediction and also to the study of climate variability and mankind's impact on it.

3. Numerical weather prediction today

It is no exaggeration to describe the advances made over the past half century as revolutionary. Thanks to this work, meteorology is now firmly established as a quantitative science, and its value and validity are demonstrated daily by the acid test of any science, its ability to predict the future. Operational forecasting today uses guidance from a wide range of models. In most centres a combination of global and local models is used. By way of illustration, we will consider the global model of the European Centre for medium-range weather forecasts.

3.1. The European centre for medium-range weather forecasts

Perhaps the most important event in European meteorology over the last half-century was the establishment of the European Centre for medium-range weather forecasts (ECMWF). The mission of ECMWF is to deliver weather forecasts of increasingly high quality and scope from a few days to a few seasons ahead. The Centre has been spectacularly successful in fulfilling its mission, and continues to develop forecasts and other products of steadily increasing accuracy and value, maintaining its position as a world leader. The first operational forecasts were made on 1 August, 1979. The Centre is currently undergoing enlargement. A new Convention has been agreed and is in the process of ratification.

The ECMWF model is a spectral primitive equation model with a semi-lagrangian, semi-implicit time scheme and a comprehensive treatment of physical processes. It is coupled interactively to an ocean wave model. Its spatial resolution is 25 km and there are 91 vertical levels. Initial data for the forecasts are prepared using a four-dimensional variational assimilation scheme, which uses a large range of conventional and satellite observations over a 12-hour time window. A sustained and consolidated research effort has been devoted to exploiting quantitative data from satellites, and now these observations are crucial to forecast quality.

ECMWF produces a wide range of global atmospheric and marine forecasts and disseminates them on a regular schedule to its Member States. The primary products are listed here (explanations of technical terms will follow).

- Forecasts for the atmosphere out to 10 days ahead, based on a T799 (25 km) 91-level (L91) deterministic model are disseminated twice per day.
- Forecasts from the ensemble prediction system (EPS) using a T399 (50 km) L62 version of the model and an ensemble of 51 members are computed and disseminated twice per day.
- Forecasts out to one month ahead, based on ensembles using a resolution of T255 (78 km) and 62 levels are distributed once per week.
- Seasonal Forecasts out to six months ahead, based on ensembles with a T159 (125 km) L40 model are disseminated once per month.

The basis of the NWP operations at ECMWF is the integrated forecast system (IFS). The IFS uses a *spectral representation* of the meteorological fields. Each field is expanded in series of spherical harmonics; for example,

$$u(\lambda, \phi, t) = \sum_{n=0}^N \sum_{m=-n}^n U_n^m(t) Y_n^m(\lambda, \phi),$$

where $Y_n^m(\lambda, \phi)$ are spherical harmonics and the coefficients $U_n^m(t)$ depend only upon time. The coefficients U_n^m of the harmonics provide an alternative to specifying the field values $u(\lambda, \phi)$ in the spatial domain. When the model equations are transformed to spectral space, they become a set of equations for the spectral coefficients U_n^m . These are used to advance the coefficients in time, after which the new physical fields may be computed. The truncation of the spectral expansion, specified by the total wavenumber N , determines the spatial resolution. There is a computational grid, called the Gaussian grid, corresponding to this spectral truncation.

The IFS system underwent a major upgrade in Spring, 2006. The horizontal and vertical resolution of its deterministic, ensemble prediction (EPS) and monthly forecasting systems were substantially increased. The truncation of the deterministic model is now $T799$, which is equivalent to a spatial resolution of 25 km (it was previously 40 km). The number of model levels in the vertical has been increased by 50%, from 60 to 91. The new Gaussian grid for IFS has about 8×10^5 points. With 91 levels and five primary prognostic variables at each point, about 3×10^8 numbers are required to specify the atmospheric state at a given time. That is, the model has about three hundred million degrees of freedom. The computational task of computing forecasts with such high resolution is truly formidable.

The Centre carries out its operational program using a powerful and complex computer system. At the heart of this system is an IBM High Performance Computing Facility (HPCF). Phase 3 of HPCF comprises two identical p690+ clusters. Each cluster consists of 68 compute servers, each having 32 CPUs with a clock frequency of 1.9 GHz. The peak performance is 16.5 TeraFlops for each cluster, so the complete system has a peak performance of 33 TeraFlops or 33 trillion calculations per second. The HPCF is about 10 orders of magnitude faster than the ENIAC. It represents an increase in computer power over the intervening 50 years which is broadly in agreement with Moore's Law, an empirical rule governing growth of computers. According to this rule, chip density doubles every 18 months. Over 50 years, this implies an increase of $2^{50/1.5} \approx 10^{10}$. The increase in computational speed from ENIAC to HPCF is in good agreement with this rule.

3.2. Ensemble forecasting

The chaotic nature of the atmospheric flow is now well understood. It imposes a limit on predictability, as unavoidable errors in the initial state grow rapidly and render the forecast useless after some days. The most successful means of overcoming this obstacle is to run a series, or ensemble, of forecasts, each starting from a slightly different initial state, and to use the combined outputs to deduce probabilistic information about future changes in the atmosphere. Since the early 1990s, this systematic method of providing an a priori measure of forecast skill has been operational at both ECMWF and at the National Centers for Environmental Prediction (NCEP) in Washington. For a description of the American system, see Kalnay, 2003, Section 6.5. In the ensemble prediction system (EPS) of ECMWF, an ensemble of forecasts (51 in the present system) is performed, each starting from slightly different initial conditions and each having a resolution half that of the deterministic forecast. Probability forecasts for a wide range of weather events are generated and disseminated for use in the operational centres. These have become the key guidance for medium-range prediction. For a recent review, see Buizza et al. [4].

Seasonal forecasts, with a range of six months, are also prepared at the European Centre. They are made using a coupled atmosphere/ocean model, and a large number of forecasts are combined in an ensemble each month. These forecast ensembles have demonstrable skill for tropical regions. Recent predictions of the onset of El Niño and La Niña events have been impressive. However, in temperate latitudes, and in particular for the European region, no significant skill has yet been achieved, and they are not yet used in operations for this region. Indeed, seasonal forecasting for middle latitudes is one of the great problems facing us today.

3.3. Applications of NWP

Short-range forecasting requires detailed guidance that is updated frequently. Many National Meteorological Services run limited-area models (LAMs) with high resolution to provide such forecast guidance. These models permit a free choice of geographical area and spatial resolution, and forecasts can be run as frequently as required. LAMs make available a comprehensive range of outputs, with a high time resolution. Nested grids with successively higher resolution can be used to provide greater local detail. The Weather Research and Forecasting (WRF) Model is a next-generation mesoscale NWP system, developed in a partnership involving American National agencies (NCEP and NCAR) and universities. It is designed to serve both operational forecasting and atmospheric research needs. WRF is suitable for a broad range of applications, from metres to thousands of kilometres. It is currently in operational use at NCEP. Full details of the system are available online (<http://www.wrf-model.org>).

Another exciting recent development in NWP has been the decision of two major European groups to combine their activities. The scientists of the HIRLAM (High Resolution Limited Area Modeling) Project and of the ALADIN (Aire Limitée Adaptation dynamique Développement InterNational) Project have joined forces to develop a new model called HARMONIE (Hirlam-Aladin Research on Mesoscale Operational NWP In Eur-omed). This is a non-hydrostatic model based on the evolving model AROME, originating at Météo-France. It includes a comprehensive package of micro-physical processes. The system is coded to run on massively parallel computers. A variational assimilation system is at an advanced stage of development. The operational implementations will have typical horizontal resolution of about 2 km.

NWP models are used for a wide range of applications. Perhaps the most important application is to provide timely warning of weather extremes. Great financial losses can be caused by gales, floods and other anomalous weather events. The warnings which result from this additional guidance can enable great saving of both life and property. Transportation, energy consumption, construction, tourism and agriculture are all sensitive to weather conditions. There are expectations from all these sectors of increasing accuracy and detail of short range forecasts, as decisions with heavy financial implications must continually be made.

NWP models are used to generate special guidance for the marine community. Predicted winds are used to drive wave models, which predict sea and swell heights and periods. Forecast charts of the sea-state, and other specialized products can be automatically produced and distributed to users. Prediction of road ice is performed by specially designed models which use forecasts of temperature, humidity, precipitation, cloudiness and other parameters to estimate the conditions on the road surface. Trajectories are easily derived from limited area models. These are vital for modeling pollution drift, for nuclear fallout, smoke from forest fires and so on. Aviation benefits significantly from NWP guidance, which provides warnings of hazards such as lightning, icing and clear air turbulence. Automatic generation of terminal aerodrome forecasts (TAFs) from LAM and column model outputs enables servicing of a large number of airports from a central forecasting facility.

4. Conclusions

Prior to the computer era, weather forecasting was in the doldrums. Petterssen [20] described the advances as occurring in ‘homeopathic doses’. The remarkable progress in forecasting over the past 50 years is vividly illustrated by the record of skill of the 500 hPa forecasts produced at the National Meteorological Center, now NCEP, as measured by the S_1 score [27]. The 36 hour scores are the longest verification series in existence, dating from the very beginning of operational NWP. The skill scores, expressed as percentages of maximum possible skill, have improved steadily over the past 50 years and each introduction of a new prediction model has resulted in further improvement (Fig. 4). The sophistication of prediction models is closely linked to the available computer power; the introduction of each new machine is also indicated in the figure. The horizontal bar indicates a 15 year delay for the 72 hour forecast to attain the skill previously attained at 36 hours. This is consistent with the general experience of a one-day-per-decade increase in forecast skill.

Developments in atmospheric dynamics, instrumentation and observing practice and digital computing have made the dreams of Bjerknes and Richardson an everyday reality. Numerical weather prediction models are now at the centre of operational forecasting. Forecast accuracy has grown apace over the half-century of NWP activities, and progress continues on several fronts.

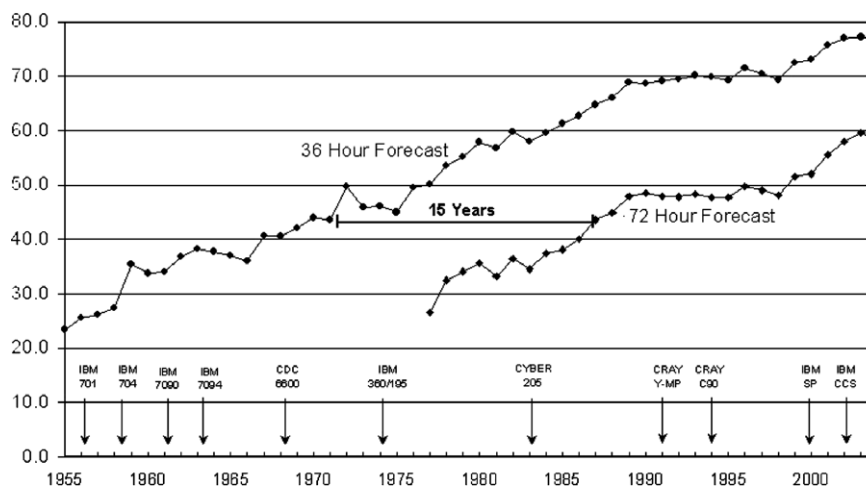


Fig. 4. Skill of the 36 hour (1955–2004) and 72 hour (1977–2004) 500 hPa forecasts produced at NCEP. Forecast skill is expressed as a percentage of an essentially perfect forecast score. Thanks to Bruce Webster of NCEP for the graphic of S1 scores.

Despite the remarkable advances over the past 50 years, some formidable challenges remain. Sudden weather changes and extremes cause much human hardship and damage to property. These rapid developments often involve intricate interactions between dynamical and physical processes, both of which have fast and slow time-scales. The effective computational coupling between the dynamical processes and physical parameterizations is a significant challenge. Nowcasting is the process of predicting changes over periods of a few hours. Guidance provided by current numerical models occasionally falls short of what is required to take effective action and avert disasters. Greatest value is obtained by a systematic combination of NWP products with conventional observations, radar imagery, satellite imagery and other data. But much remains to be done to develop optimal nowcasting systems, and we may be optimistic that future developments will lead to great improvements in this area.

At the opposite end of the time-scale, the chaotic nature of the atmosphere limits the validity of deterministic forecasts. The ensemble prediction technique provides probabilistic guidance, but so far it has proved quite difficult to use in many cases. Interaction between atmosphere and ocean becomes a dominant factor at longer forecast ranges. Although good progress in seasonal forecasting for the tropics has been made, the production of useful long-range forecasts for temperate regions remains to be tackled by future modellers. Another great challenge is the modeling and prediction of climate change, a matter of increasing importance and concern.

Perhaps the most frequently quoted section of Richardson's book is Section 11.2, 'The Speed and Organization of Computing', in which he describes in detail his fantasy about a *Forecast Factory* for carrying out the process of calculating the weather.

Imagine a large hall like a theatre, except that the circles and galleries go right round through the space usually occupied by the stage. The walls of this chamber are painted to form a map of the globe. The ceiling represents the north polar regions, England is in the gallery, the tropics in the upper circle, Australia on the dress circle and the antarctic in the pit. A myriad computers are at work upon the weather of the part of the map where each sits, but each computer attends only to one equation or part of an equation. The work of each region is coordinated by an official of higher rank. Numerous little "night signs" display the instantaneous values so that neighboring computers can read them. Each number is thus displayed in three adjacent zones so as to maintain communication to the North and South on the map. From the floor of the pit a tall pillar rises to half the height of the hall. It carries a large pulpit on its top. In this sits the man in charge of the whole theatre; he is surrounded by several assistants and messengers. One of his duties is to maintain a uniform speed of progress in all parts of the globe. In this respect he is like the conductor of an orchestra in which the instruments are slide-rules and calculating machines. But instead of waving a baton he turns a



Fig. 5. An artist's impression of Richardson's Forecast Factory (© François Schuiten).

beam of rosy light upon any region that is running ahead of the rest, and a beam of blue light upon those who are behindhand [24, p. 219].

Richardson estimated that 64,000 people would be needed to keep pace with the atmosphere. Since the ENIAC was about five orders of magnitude faster than human computation, the Forecast Factory would have been comparable in processing power to this early machine.

An impression of the Forecast Factory by the artist François Schuiten appears in Fig. 5. Richardson's fantasy is an early example of *Massively Parallel Processing*. Each computer is responsible for a specific gridpoint, receives information required for calculation at that point and passes to neighboring computers the data required by them. Such message passing and memory distribution are features of modern machines, such as the HPCF in use at the European Centre. But, at peak computational power, the HPCF is about 15 orders of magnitude faster than a single human computer, and equivalent in purely number-crunching terms to about 10 billion of Richardson's Forecast Factories.

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