Weather Forecasting:
from Woolly Art to Solid Science.

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When the Royal Meteorological Society was founded, weather forecasting was a sorry business: methods were dubious and results unreliable. Worse still, prospects for improvement looked bleak. Around 1900, Vilhelm Bjerknes realised that the development of thermodynamics had completed the jig-saw of atmospheric laws, and that these laws provided a rational basis for precise scientific forecasting. But his was a method without a means: he saw no possibility to put his ideas to practical use. Lewis Fry Richardson was bolder, attempting a direct assault on the equations of motion. His methodology was unimpeachable but his results disastrously wrong. His glorious failure discouraged further investigation along these lines.

Developments in meteorology and numerical analysis in the ensuing decades, and the invention of the radiosonde and digital computer, led to the possibility of a practical implementation of Bjerknes' and Richardson's ideas. In 1950 the first computer forecast was made using a greatly simplified mathematical model. It was so successful that within ten years computer predictions were used in operational forecasting. Numerical weather prediction has advanced rapidly, with the development of efficient algorithms and refinement of the treatment of physical processes. By Trojan efforts, assimilation techniques have been devised to squeeze benefits from quantitative satellite data. Forecasts with some skill up to a week ahead are now routine.

Progress since 1950 has been spectacular. Advances have been based on sound theoretical principles so that the woolly art of weather forecasting has been ennobled to a precise scientific discipline.

1. The Pre-history of Scientific Forecasting

At the time the Royal Meteorological Society was founded, weather forecasting was very imprecise and unreliable. Moreover, there was little practical improvement, or indeed much hope of improvement, for the following fifty years. Observations were scarce and irregular, especially for the upper air and over the oceans. The principles of theoretical physics played little or no rôle 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 of similar patterns in the past and a menagerie of empirical rules to produce a forecast map. To a great extent it was assumed that what had been happening up to now would continue for some time. 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.

The difficulties of forecasting during this period are illustrated by the tragic fate of Admiral Robert Fitzroy. Around 1860, Fitzroy started to issue forecasts and storm warnings for coastal regions, which were published in the London Times. However, with so few observations and such limited understanding of the atmosphere, he had no real hope of success. The forecasts generated considerable hostility and indeed some unjustified criticism of Fitzroy, which contributed to his untimely death.

1.1 Vilhelm Bjerknes

The first explicit analysis of the weather prediction problem from a scientific viewpoint was undertaken at the beginning of the last century when the Norwegian scientist Vilhelm Bjerknes (Fig. 1) set down a two-step plan for rational forecasting (Bjerknes, 1904):

> If it is true, as every scientist believes, that subsequent atmospheric states develop from the preceding ones according to physical law, then it is apparent that the necessary and sufficient conditions for the rational solution of forecasting problems are the following:
>
> 1. A sufficiently accurate knowledge of the state of the atmosphere at the initial time.
> 2. A sufficiently accurate knowledge of the laws according to which one state of the atmosphere develops from another.

Bjerknes used the medical terms *diagnostic* and *prognostic* for these two steps (Friedman, 1989). The diagnostic step requires adequate observational data to define the three-dimensional structure of the atmosphere at a particular time. There was a severe shortage of observations, particularly over the seas and for the upper air, but Bjerknes was optimistic:

> We can hope ... that the time will soon come when either as a daily routine, or for certain designated days, a complete diagnosis of the state of the atmosphere will be available. The first condition for putting forecasting on a rational basis will then be satisfied.

In fact, such designated days, on which upper air observations were made throughout Europe, were organized around that time by the International Commission for Scientific Aeronautics.

The second or 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. As pointed out by Eliassen, 1994, Bjerknes was in error in listing the second law of thermodynamics; he should instead have specified a continuity equation for water substance. The same error was repeated in the inaugural address at Leipzig (Bjerknes, 1914a). While this may seem a minor matter it proves that, while Bjerknes outlined a general philosophical approach, he did not attempt to formulate a detailed procedure, or algorithm, for applying his method. Indeed, he felt that such an approach was completely impractical.

Since Bjerknes knew that an exact analytical integration was beyond human ability, he developed instead a more qualitative, graphical method. 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 realised that the prognostic procedure could be separated into two stages, a purely hydrodynamic part and a purely thermodynamic part; the hydrodynamics would determine the movement of an airmass over the time interval and thermodynamic considerations could then be used to deduce changes in its state.

In 1912 Bjerknes became the first Director of the new Geophysical Institute in Leipzig. In his inaugural lecture he returned to the theme of scientific forecasting. He observed that 'physics ranks among the so-called exact sciences, while one may be tempted to cite meteorology as an example of a radically inexact science.' He contrasted the methods of meteorology with those of astronomy, for which predictions of great accuracy are possible, and described the programme of work upon which he had already embarked: *to make meteorology into an exact physics of the atmosphere.* Considerable advances had been made in observational meteorology during the previous decade, so that now the diagnostic component of his two-step programme had become feasible:

> Now that complete observations from an extensive portion of the free air are being published in a regular series, a mighty problem looms before us and we can no longer disregard it. We must apply the equations of theoretical physics not to ideal cases only, but to the actual existing atmospheric conditions as they are revealed by modern observations. ... The problem of accurate pre-calculation that was solved for astronomy centuries ago must now be attacked in all earnest for meteorology (Bjerknes, 1914a).

Bjerknes expressed his conviction that the acid test of a science is its utility in forecasting: 'There is after all but one problem worth attacking, *viz.,* the precalculation of future conditions.' He recognised the complexity of the problem and realised that a rational forecasting procedure might require more time than the atmosphere itself takes to evolve, but concluded that, if only the calculations agreed with the facts, the scientific victory would be won. Meteorology would then have become an exact science, a true physics of the atmosphere. He was convinced that, if the theoretical problems were overcome, practical and applicable methods would soon follow:

> It may require many years to bore a tunnel through a mountain. Many a labourer may not live to see the cut finished. Nevertheless this will not prevent later comers from riding through the tunnel at express-train speed.

At Leipzig, Bjerknes instigated the publication of a series of weather charts based on the data which were collected during the internationally-agreed intensive observation days and compiled and published by Hergessel in Strassbourg. One such publication (Bjerknes, 1914b) was to provide Richardson with the initial conditions for his forecast.

1.2 Lewis Fry Richardson

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. 2) first heard of Bjerknes' plan for rational forecasting in 1913, when he took up employment with the Meteorological Office. In the Preface to his book *Weather Prediction by Numerical Process* (Richardson, 1922, denoted WPNP) 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 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:

> The forecast is based on the supposition that what the atmosphere did then, it will do again now. There is no troublesome calculation, with its possibilities of theoretical or arithmetical error. The past history of the atmosphere is used, so to speak, as a full-scale working model of its present self (WPNP, p.vii).

Bjerknes had contrasted the precision of astronomical prediction with the 'radically inexact' methods of weather forecasting. Richardson returned to this theme in his Preface:

> —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? ... This alone is sufficient reason for presenting, in this book, a scheme of weather prediction which resembles the process by which the *Nautical Almanac* is produced, in so far as it is founded upon the differential equations and not upon the partial recurrence of phenomena in their ensemble.

Richardson's forecasting scheme amounts to a precise and detailed implementation of the prognostic component of Bjerknes' programme. 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 and at a cost less than the saving to mankind due to the information gained. But that is a dream.

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

We shall not consider Richardson's life and work in detail, but refer readers to a number of valuable sources. A comprehensive and readable biography has been written by Ashford (1985). The Royal Society Memoir of Gold (1954) provides a more succinct description and the recently published *Collected Papers* of Richardson (Drazin, 1993; Sutherland, 1993) include a biographical essay by Hunt. The article by Chapman (1965) is worthy of attention and some fascinating historical background material may be found in the superlative review article by Platzman (1967).

1.3 Richardson's Forecast

Richardson began serious work on weather prediction in 1913 when he was appointed Superintendent of Eskdalemuir Observatory, in 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 this lack of formal training in the subject which 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 behaviour 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 favour the latter:

> whereas Prof. Bjerknes mostly employs graphs, I have thought it better to proceed by way of numerical tables. The reason for this is that a previous comparison of the two methods, in dealing with differential equations, had convinced me that the arithmetical procedure is the more exact and the more powerful in coping with otherwise awkward equations. (WPNP, p.viii)

The basic equations had already been identified by 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 an 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 rigour, 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, Richardson 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. 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 $\mathrm{P}_{\mathrm{XIII}}$ as 145 millibars in 6 hours, whereas observations show that the barometer was nearly steady. This glaring error is examined in detail below ... 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 discretisation and equations as used by him (Lynch, 1999). 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 filter (Lynch, 1997). 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. Fuller details of the forecast reconstruction may be found in Lynch, 1999.

Table 1. Six-hour Changes in Pressure (units: hPa/6h)
[LFR: Richardson; MOD: Model; DFI: Filtered.]

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

The initial response to *Weather Prediction by Numerical Process* was unremarkable, and must have been disappointing to Richardson. It was widely reviewed, with generally favourable comments—Ashford (1985) 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 the understandably cautious initial reaction, Richardson's brilliant and prescient ideas are now universally recognised 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 huge 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 twentieth 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 Goldstine (1972) and a recent biography has been written by Macrae (1999).

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. 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' (Goldstine, 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. 3).

Von Neumann recognized weather forecasting, a problem of both great practical significance and intrinsic scientific interest, as a problem *par excellence* for an automatic computer. Moreover, according to Goldstine (p.300), Von Neumann

> knew of the pioneering work ... [of] Lewis F Richardson .... Richardson failed largely because the Courant condition had not yet been discovered, and because high speed computers did not then exist. But von Neumann knew of both.

Von Neumann had been in Göttingen in the 1920s when Courant, Friedrichs and Lewy were working on the numerical solution of partial differential equations and he fully appreciated the practical implications of their findings. However, Goldstine's suggestion that the CFL criterion was responsible for Richardson's failure is wide of the mark. This erroneous explanation has also been widely promulgated by others. Von Neumann made estimates of the computational power required to integrate the equations of 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 (1979) 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 in WPNP.

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' (Charney, 1947). 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 (Charney, 1948). 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

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

The barotropic equation had, of course, been used by Rossby (1939) 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, Fjørtoft and von Neumann (1950). Arrangements were made to run the integration on the only computer then available, the Electronic Numerical Integrator and Computer (ENIAC). The story of the mission to Aberdeen was colourfully told by Platzman (1979). 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 ...' (Chapman, 1965). 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 integrations. His letter of response is reprinted in Platzman (1968). Richardson wrote 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 The Barotropic Model

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 Lindzen, *et al.*, 1990) 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' (Taba, 1998, p.367). In fact, as Platzman observed in his review of the ENIAC integrations (Platzman, 1979), nobody anticipated the enormous practical value of this simple model and the leading rôle it was to play in operational prediction for many years to come.

Not everyone was convinced that the barotropic equation was useful for forecasting. The attitude in some quarters to its use for prediction seems to have been little short of antagonistic. At a discussion meeting of the Royal Meteorological Society in January, 1951 several scientists expressed strong reservations about it. In his opening remarks, Sutcliffe (1951) reviewed the application of the Rossby formula to stationary waves with a somewhat reluctant acknowledgement:

> Although the connection between non-divergent motion of a barotropic fluid and atmospheric flow may seem far-fetched, the correspondence between the computed stationary wavelengths and those of the observed quasi-stationary long waves in the westerlies is found to be so good that some element of reality in the model must be suspected.

Scorer expressed his scepticism more vehemently, dismissing the barotropic model as 'quite useless':

> Even supposing that wave theory did describe the actual motion of moving disturbances in the atmosphere there is nothing at all to be gained by applying formulae derived for a barotropic model to obtain a forecast because all it can do is move on disturbances at a constant velocity, and can therefore give no better result than linear extrapolation and is much more trouble (Sutcliffe, *et al.*, 1951).

The richness and power encapsulated in its non-linear advection were greatly underestimated. Sutcliffe reiterated his doubts in his concluding remarks, saying that 'when a tolerably satisfactory solution to the three-dimensional problem emerges it will derive little or nothing from the barotropic model—which is literally sterile'. These meteorologists clearly had no confidence in the utility of the single-level approach.

The 1954 Presidential Address to the Royal Meteorological Society, *The Development of Meteorology as an Exact Science*, was delivered by the Director of the Met. Office, Sir Graham Sutton. After briefly considering the methods first described in Richardson's 'strange but stimulating book', he expressed the view that automated forecasts of the weather were unlikely in the foreseeable future:

> I think that today few meteorologists would admit to a belief in the possibility (let alone the likelihood) of Richardson's dream coming true. My own view, for what it is worth, is definitely against it (Sutton, 1954).

The prevalent view in the Met. Office at that time was that, while numerical methods had immediate application to dynamical research, their use in practical forecasting was very remote. This cautious view may well be linked to the notoriously erratic nature of the weather in the vicinity of the British Isles and the paucity of data upstream over the Atlantic Ocean. Despite various dissenting views, evidence rapidly accumulated that even the rudimentary barotropic model was capable of producing forecasts superior to those produced by conventional manual means.

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 (Charney, 1954). 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 (1989) 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 (1951) 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.

He 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 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 (1955), Phillips (1960) and others, followed. The first application of the primitive equations was a success, producing good simulation of development, occlusion and frontal structure (Hinkelmann, 1959). Routine numerical forecasting was introduced in the Deutscher Wetterdienst in 1966; according to Reiser (1986), 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 NMC in June, 1966, running on a CDC 6600 (Shuman and Hovermale, 1968). There was an immediate improvement in skill: the S_1 score for the 500 hPa one-day forecast was reduced by about five points.

We have seen that the view in the 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 (Bushby and Whitelam, 1961) was not in place until the end of 1965. In 1972 a ten-level primitive equation model (Bushby and Timpson, 1967) was introduced. This model incorporated a sophisticated parameterisation of physical processes and with it the first useful forecasts of precipitation were produced.

The remarkable progress in computer forecasting since the ENIAC integrations is vividly illustrated by the record of skill of the 36 hour 500 hPa forecast produced at NCEP (formerly, NMC, Washington). The forecast skill, expressed as a percentage of an essentially perfect forecast score, is plotted in Fig. 4, for the period 1955–1999. The score has improved steadily over this period. The sophistication of prediction models is closely linked to the available computer power; the introduction of new machines is indicated in the figure. Each introduction of faster computer machinery or major enhancement of the prediction model has been followed by increased forecast accuracy.

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 and the local model called HIRLAM (High Resolution Limited Area Model) used for short-range forecasting.

3.1 ECMWF

The European Centre for Medium-range Weather Forecasts celebrated its twenty-fifth anniversary in 2000. This world-leading meteorological centre provides an extensive range of products for medium-range forecasting to the eighteen member states and to cooperating states. 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 about 60 km and there are 60 vertical levels. Initial data for the forecasts are prepared using a four-dimensional variational assimilation scheme, which uses a huge range of conventional and satellite observations over a twelve-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. Forecasts out to ten days are made, starting from the mid-day analysis each day. These deterministic ten-day forecasts are the primary products of the Centre, but are complemented by many other forecast products.

The computer system in current use at ECMWF is a Fujitsu VPP5000, with one hundred processing elements and a peak computation speed of one Teraflops, that is, one million-million floating-point operations per second, more than nine orders of magnitude faster than the ENIAC. It represents an increase in computer power over the intervening fifty 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 fifty years, this implies an increase of $2^{50/1.5} = 1.08 \times 10^{10}$. The increases in memory size and computational speed from ENIAC to Fujitsu, indicated in Table 2, are in good agreement with this rule.

Table 2: Comparison of ENIAC and Fujitsu VPP5000/100
Computation Speed and Memory Size

	ENIAC	VPP5000	Ratio
Speed	500 Flops	1 TeraFlops (10^{12} Flops)	**2,000,000,000** 2×10^9
Memory	10 Words (40 bytes)	400 Gbytes (4×10^{11} bytes)	**10,000,000,000** 10^{10}

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. An Ensemble Prediction System (EPS) of fifty forecasts is run daily at ECMWF, each forecast 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.* (2000).

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.

The primary products prepared and disseminated by ECMWF are:

- Forecast to 10 days from 12Z analysis (60 km)
- 50-member EPS Forecast to 10 days (120 km)
- Forecast to 21 days from 12Z analysis (120 km)
- Global Ocean Wave Forecast to 10 days (60 km)
- North Atlantic Ocean Forecast to 5 days (0.25 degrees)
- Ensemble Seasonal Forecast to 6 months

The deterministic full-resolution forecasts are the basis for forecasts in the early medium range, three to five days. The EPS is most valuable for the range six to ten days, beyond the threshold of deterministic predictability, where probabilistic forecasting is more appropriate.

Progress over the period of operations at ECMWF is illustrated by Fig. 5. It shows the anomaly correlation (AC) for the 500 hPa height forecast for the Northern Hemisphere, as a function of forecast length. It is generally agreed that the minimum value of AC for useful forecasts is 0.6. The three curves are for different winters. In 1972 forecasts out to $3\frac{1}{2}$ days were providing useful guidance. By 1980 this threshold had reached $5\frac{1}{2}$ days. By 1998, the limit of usefulness by this measure had reached almost eight days. Thus, the representative range of useful forecasts is now greater than a week! This must be seen as quite remarkable progress over the lifetime of the European Centre.

3.2 HIRLAM

Short-range forecasting requires detailed guidance which is updated frequently. Virtually all European weather 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.

Eight European countries currently combine their efforts in the HIRLAM (High Resoluton Limited Area Modelling) Project. They are Denmark, Finland, Iceland, Ireland, Netherlands, Norway, Spain and Sweden. The HIRLAM analysis and forecasting system is the basis for operational short-range forecasting in these countries. As HIRLAM has a limited geographical domain, appropriate values must be specified on the lateral boundaries. ECMWF carries out special model integrations to generate boundary data for limited area models. The boundary condition project at ECMWF has recently been extended to provide more timely and accurate data.

An outline of the structure of the HIRLAM model and its practical applications will be given here (See Lynch, *et al.* (2000) for further details). The forecast model is a hydrostatic primitive equation grid-point model. It includes a comprehensive package of physical processes. The system is coded to run on massively parallel computers. A semi-lagrangian advection scheme and a digital filtering initialization scheme have recently been introduced. The physics package has been enhanced by a higher-order turbulence scheme and a new condensation and convection scheme. A new package for parameterisation of surface processes is close to operational implementation. A variational assimilation system is at an advanced stage of development. The operational implementations of HIRLAM differ in horizontal and vertical resolution, and in details of the physical parameterisations. However, the typical resolution used is 20km, with about 30 vertical levels.

The HIRLAM model is used in the member countries for a wide range of applications. Perhaps the most important application is to provide timely warning of weather extremes. Huge 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.

Limited area models such as HIRLAM are used to generate special guidance for the marine community. Winds predicted by the LAM are used to drive wave models, which predict sea and swell heights and periods. Forecast charts of the sea-state, and other specialised 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 modelling pollution drift, for nuclear fallout, smoke from forest fires and so on. Aviation benefits significantly from LAM 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

In 1976, Jule Charney was awarded the Bowie Medal of the American Geophysical Union, 'for his outstanding contribution to fundamental geophysics and for unselfish cooperation in research'. In his acceptance speech he said:

> I have seen the growth of meteorology from an immature science dominated by the pragmatics of weather forecasting, with theory a weak and ineffectual handmaiden of observation, to a mature science, in which theory and observation exist on an equal footing, where weather prediction has been transformed from an art to a science . . . (AGU, 1976).

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.

Despite the remarkable advances over the past fifty years, some formidable challenges remain. Sudden weather changes and extremes cause much human hardship and damage to property. 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 modelling and prediction of climate change, a matter of increasing importance and concern.

Perhaps the most frequently quoted section of Richardson's book is §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 neighbouring 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 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 (WPNP, p219).

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. (In fact, Richardson's 'staggering figure', although enormous, was a significant under-estimate. The correct number of people required was over 200,000;

see Lynch, 1993).

An impression of the Forecast Factory by the artist François Schuiten appears in Fig. 6. Richardson's fantasy is an early example of a *Massively Parallel Processor*. Each computer is responsible for a specific gridpoint, receives information required for calculation at that point and passes to neighbouring computers the data required by them. Such message passing and memory distribution are features of modern machines, such as the Fujitsu VPP5000 in use at the European Centre. But, at peak computational power, the Fujitsu is more than fourteen orders of magnitude faster than a single human computer, and equivalent in purely number-crunching terms to about *three billion* of Richardson's Forecast Factories.

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Figure Captions

Figure 1. A recent painting (from photographs) of the Norwegian scientist Vilhelm Bjerknes (1862–1951) (original in the Geophysical Institute, Bergen).

Figure 2. Lewis Fry Richardson (1881-1953). From Richardson's *Collected Works*, reproduced with permission of Bassano and Vandyk Studios.

Figure 3. Jule Charney (1917–1981). From the cover of EOS, Vol. 57, August, 1976 (© Nora Rosenbaum).

Figure 4. Skill of the 36 hour 500 hPa forecast produced at NCEP. Forecast skill is expressed as a percentage of an essentially perfect forecast score, for the period 1955–1999. The accuracy of prediction is closely linked to the available computer power; the introduction of new machines is indicated in the figure. Thanks to Bruce Webster of NCEP for the graphic of S1 scores.

Figure 5. The anomaly correlation (AC) for the 500 hPa height forecast for the Northern Hemisphere, as a function of forecast length. The three curves are for different winters: Black, 1972; Green, 1980; Red, 1998. Thanks to David Burridge, Director of ECMWF, for the graphic.

Figure 6. An artist's impression of Richardson's *Forecast Factory*, described in §11.2 of his book. Richardson estimated that 64,000 'computers' would be needed to keep pace with the atmosphere. Thanks to the artist, François Schuiten, and to Jean-Pierre Javelle, Météo-France, for providing the image.