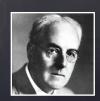


# Richardson's Forecast:

## The Dream and the Fantasy



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remarkable book on weather forecasting was published just one hundred years ago. Written by the brilliant and prescient applied mathematician, Lewis Fry Richardson, Weather Prediction by Numerical Process [1] was published by Cambridge University Press and went on sale in 1922 at a cost of 30 shillings (£1.50). With a print run of just 750 copies, it was not a commercial success and was still in print thirty years after publication. It was re-issued in 1965 as a Dover paperback. Cambridge University Press reprinted the book in 2007, with a foreword by Peter Lynch. Described as a second edition, it differs in no essential way from the 1922 edition.

Weather Prediction by Numerical Process (WPNP) is a strikingly original scientific work, one of the most remarkable books on meteorology ever written. In it, Richardson described a systematic mathematical method for predicting the weather and demonstrated its application by carrying out a trial forecast. Richardson's innovative approach was fundamentally sound, but the method devised by him was utterly impractical at the time of its publication and the results of his trial forecast appeared to be little short of outlandish. As a result, his ideas were eclipsed for decades. For a brief biographical sketch of Richardson, see the Benchmark article by Lea [2] and for a full biography, see Ashford [3].

#### Background to Scientific Forecasting

The basic ideas of numerical forecasting and climate modelling were developed more than a century ago, long before the first electronic computer was constructed. American meteorologist Cleveland Abbe and Norwegian physicist Vilhelm Bjerknes recognized that predictions of meteorological phenomena could be based on the application of hydrodynamics and thermodynamics to the atmosphere [4,5]. They each specified the required process: analysis of the initial state and time integration of the governing equations from that state. They listed the system of mathematical equations needed and outlined the steps required to produce a forecast. Realizing the numerous practical difficulties, neither Abbe nor Bjerknes attempted to implement their techniques.

A first tentative trial to produce a forecast using the laws of physics was made by Felix Exner in 1908, working in Vienna. His efforts yielded a realistic forecast for the particular case that he chose. Despite the restricted applicability of his technique, his work was a first attempt at systematic, scientific weather forecasting. However, it involved some drastic simplifications and was far from providing anything of use for practical forecasting.

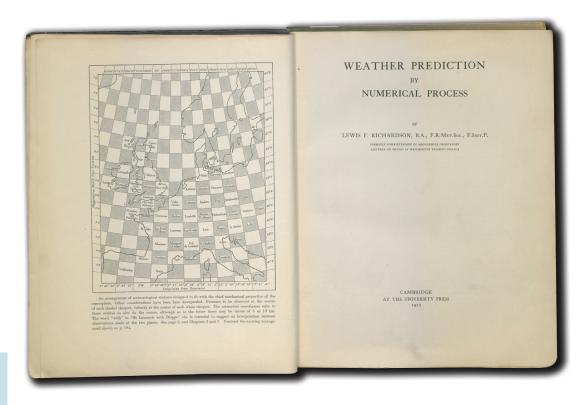
#### Weather Prediction by Numerical Process

Lewis Fry Richardson first learned of Bjerknes' plan for rational forecasting in 1913, when he took up employment with the Meteorological Office. 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 an enormous volume of numerical computation and was quite impractical in the precomputer era. But Richardson was undaunted, expressing his dream that "some day in the dim future it will be possible to advance the computations faster than the weather advances."

Earlier, Richardson had applied an approximate numerical method to the solution of partial differential equations to investigate the stresses in masonry dams. He realized that this method had potential for use in a wide range of problems. The idea of numerical weather prediction appears to have germinated in his mind for several years. Around 1911, Richardson had begun to think about the application of his approach to the problem of forecasting the weather. He stated in the Preface of WPNP that the idea "grew out of a study of finite differences and first took shape in 1911 as a fantasy." The fantasy was that of a forecast factory, which we will discuss below.

Upon joining the Met Office, Richardson was appointed Superintendent of Eskdalemuir Observatory in the Southern Uplands of Scotland and began serious work on numerical forecasting. In May 1916 he resigned from the Met Office in order to work with the Friends Ambulance Unit in France. By this time, he had completed the formulation of his scheme and had set down the details in the first draft of his book. But he was not concerned merely with theoretical rigour and wished to include a fully worked example to demonstrate how the method could be put to use.

Richardson assumed that the state of the atmosphere at any point could be specified by seven numbers: pressure, temperature, density, water content and velocity components eastward, northward and upward. He formulated a description of atmospheric phenomena in terms of seven partial differential equations. To solve them, he divided the atmosphere into discrete columns of extent 3 degrees east-west and 200 km north-south, giving 120 x 100 = 12,000 columns to cover the globe. Each of these columns was divided vertically into five cells. The values of the variables were given at the centre of each cell, and the differential equations were approximated by expressing them in finite difference form. The rates of change of the variables could then be calculated by arithmetical means. These rates enabled Richardson to calculate the variables at a later time.



Richardson calculated the initial changes over a six-hour period in two columns over central Europe, one for mass variables and one for winds. This was the extent of his forecast. In this trial forecast, he calculated a change of atmospheric pressure, at a point near Munich, of 145 hPa in 6 hours. This was a totally unrealistic value, two orders of magnitude too large. The failure may be explained in terms of atmospheric dynamics. We return to the cause of this after first considering the reaction of other researchers to Richardson's work.

#### Initial Reactions to WPNP

The initial response to Richardson's book was unremarkable and must have been disappointing to him. WPNP was widely reviewed with generally favourable comments, but the impracticality of the method and the abysmal failure of the solitary sample forecast inevitably attracted adverse criticism. Napier Shaw, reviewing the book for *Nature*, wrote that Richardson "presents to us a magnum opus on weather prediction". However, in reference to the trial forecast, he observed that "the wildest guess [at the pressure change] would not have been wider of the mark." He also questioned Richardson's conclusion that wind observations were the real cause of the error, and his dismissal of the geostrophic wind.

Edgar W. Woolard, later an editor of *Monthly Weather Review*, wrote a positive review of the book for that journal, expressing the hope that other investigators would be inspired by Richardson's work to continue its development. However, nobody else continued working along his lines, perhaps because the forecast failure acted as a deterrent, perhaps because the book was so difficult to read, with its encyclopaedic but distracting range of topics. Alexander McAdie, Professor of Meteorology at Harvard, wrote "It can have but a limited number of readers and will probably be quickly placed on a library shelf and allowed to rest undisturbed by most of those who purchase a copy". Indeed, this is essentially what happened to the book.

A most perceptive review by F. J. W. Whipple of the Met Office came closest to understanding Richardson's unrealistic forecast, postulating that rapidly-travelling waves contributed to its failure: "The trouble that he meets is that quite small discrepancies in the estimate of the strengths of the winds may lead to comparatively large errors in the computed changes of pressure." Whipple appears to have had a far clearer understanding than Richardson himself of the causes of the forecast catastrophe.

Richardson's work was not taken seriously by most meteorologists of the day and his book failed to have any significant impact on the practice of weather forecasting during the decades following its publication. Nevertheless, his work is the foundation upon which modern forecasting is built. Several key developments in the ensuing decades set the scene for later progress. Timely observations of the atmosphere in three dimensions were becoming available following the invention of the radiosonde. Developments in

the theory of meteorology provided crucial understanding of atmospheric dynamics and the filtered equations necessary to calculate the synoptic-scale tendencies. Advances in numerical analysis led to the design of stable algorithms. Finally, the development of digital computers provided a way of attacking the enormous computational task involved in weather forecasting, all leading to the first weather prediction by computer [6]. The history leading to the emergence of modern operational numerical weather prediction is described in Lynch, 2006 [7].

#### Solution of the "Noise" Problem

In the atmosphere there are long-period variations dominated by the effects of the Earth's rotation — these are the meteorologically significant rotational modes — and short-period oscillations called gravity waves, having speeds comparable to that of sound. For many purposes, the gravity waves, which are normally of small amplitude, may be disregarded as noise. However, they are solutions of the governing equations and, if present with spuriously large amplitudes in the initial data, can completely spoil the forecast.

The most obvious approach to circumventing the noise problem is to construct a forecast by combining many time steps which are short enough to enable accurate simulation of the detailed high frequency variations. If Richardson had extended his calculations, taking a large number of very small time steps, his results would have been noisy, but the mean values would have been meteorologically reasonable. Of course, the attendant computational burden made this utterly impossible for Richardson.

A more practical approach to solving the problem is to modify the governing equations so that the gravity waves no longer occur as solutions. This process is known as *filtering* the equations. The first successful computer forecasts were made with the barotropic vorticity equation [6], which has low frequency but no high frequency solutions. Another approach is to adjust the initial data so as to reduce or eliminate the gravity wave components. The adjustments can be small in amplitude but large in effect. This process is called initialization, and it may be regarded as a special form of smoothing.

Lynch [7] showed that the *digital filtering* initialization method yields realistic tendencies when applied to Richardson's data. He found that when appropriate smoothing was applied to the initial data, using a simple digital filter, the initial tendency of surface pressure was reduced from the unrealistic 145 hPa in 6 hours to a reasonable value of less than 1 hPa in 6 hours. The forecast was in good agreement with the observed pressure change. The rates of change of temperature and wind were also realistic. This confirmed the root cause of the failure of Richardson's trial forecast: unavoidable errors in the analysed winds resulted in spuriously large values of divergence, which caused the anomalous pressure tendencies. In effect, the analysis contained gravity wave components of unrealistically large amplitudes.

The absence of gravity waves from the initial data results in reasonable initial rates of change, but it does not automatically allow the use of large time steps. The existence of high frequency solutions of the governing equations imposes a severe restriction on the size of the time step allowable if reasonable results are to be obtained. The restriction, known as the CFL criterion, can be circumvented by treating those terms of the equations that govern gravity waves in a numerically implicit manner; this distorts the structure of the gravity waves but not of the low frequency modes. In effect, implicit schemes slow down the faster waves, thus removing the cause of numerical instability. Most modern forecasting models avoid the pitfall that trapped Richardson by means of initialization followed by semi-implicit integration.

#### Richardson's Later Work

After the First World War, Richardson's research focussed primarily on atmospheric turbulence. He had encapsulated the essence of the cascade of turbulent energy in a simple and oft-quoted rhyme embedded in the text of WPNP: Big whirls have little whirls that feed on their velocity, and little whirls have lesser whirls and so on to viscosity. Richardson's dense writing style is occasionally lightened in this way by a whimsical touch as, when discussing the tendency of turbulence to increase diversity, he writes "This one can believe without the aid of mathematics, after watching the process of stirring together water and lime-juice" (WPNP, page 101). Several of his publications during this period are still cited by scientists. In one of the most important — The supply of energy from and to atmospheric eddies — he derived a criterion for the onset of turbulence, introducing what is now known as the Richardson Number.

Around 1926, Richardson made a deliberate break with meteorological research. He was distressed that his turbulence research was being exploited for military purposes. Indeed, this knowledge impelled him to destroy a large volume of his research papers. In a much later study, Richardson investigated the separation of initially proximate tracers in a turbulent flow and arrived empirically at his "four-thirds law": the rate of diffusion is proportional to the separation raised to the power 4/3. This was later established more rigorously by Andrey Kolmogorov using dimensional analysis.

### Advances in Computing: From ENIAC to PHONIAC

The first weather forecast (technically, a hindcast) made with a digital computer was performed on the ENIAC (Electronic Numerical Integrator and Computer) by a team of scientists at Princeton. The Princeton team were aware that Richardson's initial tendency field was completely wrong because he was not able to evaluate the divergence. They realised that a filtered system of equations would have dramatic implications for numerical integration. It would obviate the problem of gravity-wave noise and would permit a much larger time step to be used. They integrated the barotropic vorticity equation from real initial conditions and produced four realistic, if far from perfect, forecasts. For a full account, see Chapter 10 of Lynch, 2006 [7].

It is gratifying that Richardson was made aware of the success in Princeton; Jule Charney sent him a copy of the *Tellus* paper [6] In his response, Richardson congratulated Charney "on the remarkable progress which has been made in Princeton; and on the prospects for further improvement which you indicate". He concluded by saying that the ENIAC results were "an enormous scientific advance" on the single, and quite wrong, forecast in which his own work had ended.



Figure 1: ENIAC v 'PHONIAC' – The 'PHONIAC' (a standard Nokia 6300 from 2008) could compute a 24-hour forecast in less than one second, compared to the 24 hours it took the ENIAC, circa 1946.

To illustrate the dramatic growth in computer power since the days of the ENIAC, one of the forecasts was re-run on a small mobile phone, a Nokia 6300, which had raw computational power comparable to a CRAY-1, the first super-computer acquired by the European Centre for Medium-Range Weather Forecasts (ECMWF). The computation time for a 24-hour forecast on ENIAC was about 24 hours. The time on the Nokia, christened Portable Hand Operated Numerical Integrator and Computer (PHONIAC), was less than one second [8].

#### Richardson's Fantastic Forecast Factory

The computation of his forecast was prodigious, taking Richardson some two years to complete. How could the enormous number of calculations necessary for a practical forecast ever be done? Richardson estimated that it would require 64,000 people just to keep up with the weather. In WPNP, he described his fantasy: a "Forecast Factory" like a large theatre-in-the-round – think of the Royal Albert Hall – a circular building with a great central chamber, the walls painted to form a map of the globe. A large team of (human) computers are busy within the building calculating the future weather. The work is coordinated by a Director of Operations. Standing on a central dais, he 'conducts the

computations' by signalling with a spotlight to those who are racing ahead or behindhand.

In 1986, an Irish artist, Stephen Conlin, created an illustration of the forecast factory (Figure 2). This painting, in ink and water colours, is a remarkable work, replete with narrative details. The painting depicts a large spherical building with a vast central chamber. Four banners identify major pioneers of computing: John Napier, Charles Babbage, George Boole and the first computer programmer, Ada Lovelace. The painting is described in detail in an article in *Weather* [9].

There are surprising similarities between Richardson's forecast factory and a modern massively parallel processor (MPP). Richardson envisaged a large number of (human) computers working in synchrony on different sub-tasks. In the fantasy, the forecasting job is sub-divided using domain decomposition, a technique often used in parallel computers today. Richardson's scheme involved nearest-neighbour communication, analogous to message-passing techniques used in MPPs. The man in the pulpit functioned like a synchronization and control unit. Thus, the logical structures of the forecast factory and an MPP have much in common.

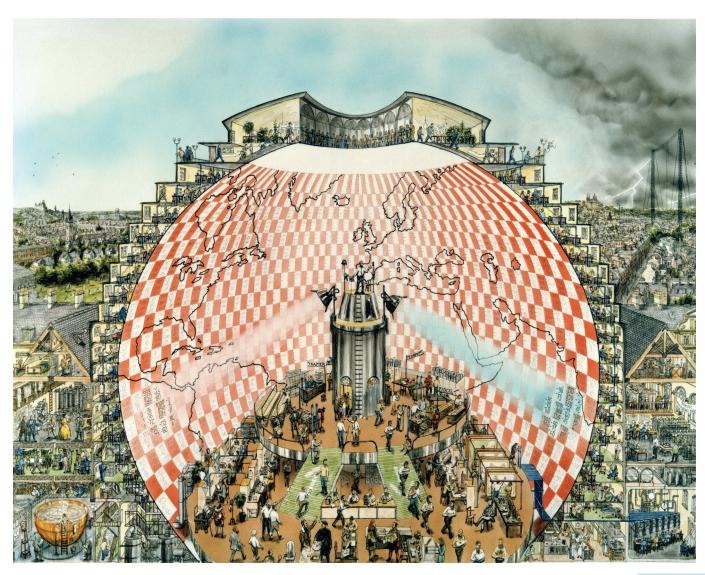


Figure 2: A visualisation of Richardson's Weather Forecasting Machine, based on advice from Prof. John Byrne, TCD.

#### Summary

Richardson's dream was that scientific weather forecasting would one day become a practical reality. Modern weather forecasts are made by calculating solutions of the mathematical equations governing the atmosphere. The solutions are generated by complex simulation models implemented on powerful computer equipment. His dream has indeed come true.

The development of comprehensive models of the atmosphere is undoubtedly one of the finest achievements of meteorology in the twentieth century. Numerical models continue to evolve, with substantial developments in data assimilation to produce improved initial conditions, new numerical algorithms for more precise and faster computations, and a probabilistic approach with ensemble forecasts that quantify uncertainties in an operational environment. These developments have made the dreams of Abbe, Bjerknes and Richardson an everyday reality. 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.

#### References

The small selection of reference here may be supplemented by the extensive bibliography in Lynch, 2006 [7]

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Much of Peter's career was spent with the Irish Meteorological Service, where he worked developing models for weather prediction. In 1982 he was awarded a PhD from Trinity College Dublin, for research in dynamical meteorology. He later became Head of Research and then Deputy Director of Met Eireann.

Peter carried out extensive research on the development of computer weather forecasting. In 2006 he completed a monograph, *The Emergence of Numerical Weather Prediction: Richardson's Dream*, which was published by Cambridge University Press.

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Peter is a keen walker. Over a thirteen-year period, he completed a walk around the coastal counties of Ireland. This is described in his book *Rambling Round Ireland: A Commodius Vicus of Recirculation*, published in 2010 by The Liffey Press.

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