Weather Prediction by Numerical Process

Second Edition

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Foreword

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Accurate weather forecasts based on computer simulation are now produced as a routine, and have reached such a level of reliability that the rare forecast failures evoke a strong reaction in the media and amongst users. 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 modelling date from long before the first electronic computer was constructed. These techniques were first developed by Lewis Fry Richardson about a century ago, and set down in this book. Richardson was concerned with establishing a scientific method of predicting the weather. Since he was not aware of the dominant role of dynamics in the short-term, he gave as much weight to small-scale physical processes as to large-scale dynamics. As a result, the algorithm he produced amounts, in essence, to a general circulation model of the atmosphere, capable of describing both weather and climate.

The first explicit analysis of the weather prediction problem from a scientific viewpoint was undertaken by the Norwegian scientist Vilhelm Bjerknes. Richardson's forecasting scheme amounts to a precise and detailed implementation of Bjerknes' programme. Richardson had developed a versatile technique for calculating approximate solutions of nonlinear partial differential equations by numerical approximation. Realizing that it could be applied to the evolution of atmospheric flows, he laid out the principles of scientific weather prediction in this book. He constructed a systematic algorithm for generating the numerical solution of the governing equations, and he applied it to a real-life case, calculating the initial changes in pressure and wind.

Although mathematically correct, Richardson's prediction was physically unrealistic. The essence of the problem is that a delicate dynamical balance between the fields of mass and motion prevails in the atmosphere. This was absent from the initial data used by Richardson; only later did he come to understand this problem. The consequence of the imbalance was the contamination of the forecast by spurious noise. As a result, his 'forecast' was a failure. The significance of Richardson's work was not therefore immediately evident, and his book had little influence in the initial decades after its appearance. The computational complexity of the process and the disastrous results of the single trial forecast tended to deter others from following the trail mapped out by him.

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Richardson's life and work are discussed in a biography by Oliver Ashford and his *Collected Papers* have been published by Cambridge University Press. Lewis Fry Richardson was born in 1881, the youngest of seven children of David Richardson and Catherine Fry. He was educated at Bootham, the Quaker school in York, entered King's College, Cambridge in 1900 and graduated in 1903. In 1909 he married Dorothy Garnett. Richardson began serious work on weather prediction in 1913 when he joined the Meteorological Office and was appointed Superintendent of Eskdalemuir Observatory. In May 1916 he resigned from the Met Office in order to work with the Friends Ambulance Unit in France. During his two years as an ambulance driver, he carried out the computations for the trial forecast that he describes in this book. After the War, he rejoined the Met Office to work at Benson with W. H. Dines. However, when the Office came under the authority of the Air Ministry, he felt obliged, as a committed pacifist, to resign once more. His meteorological research now focused primarily on atmospheric turbulence. Several of his publications during this period are still cited by scientists. In one of these he derived a criterion for the onset of turbulence, introducing what we now call 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. From about 1935 until his death in 1953, Richardson thrust himself energetically into *peace studies*, developing mathematical theories of human conflict and the causes of war. He pioneered the application of quantitative methods in this extraordinarily difficult area. In the course of these studies, he digressed to consider the lengths of geographical borders and coastlines, discovering the scaling properties that later resulted in the theory of fractals.

Richardson's genius was to apply mathematical methods to problems that had traditionally been regarded as beyond quantitative assault. The continuing relevance and usefulness of his work confirms the value of his ideas. The approximate methods that he developed for the solution of differential equations are extensively used today in the numerical treatment of physical problems.

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Ch. 1 of the book is a summary of its contents. Richardson's plan is to apply his finite difference method to the problem of weather forecasting. The fundamental idea is that the numerical values of atmospheric pressures, velocities, etc., are tabulated at certain latitudes, longitudes and heights so as to give a general description of the synoptic state of the atmosphere. The physical laws determine how these quantities change with time. The laws are used to formulate an arithmetical procedure which, when applied to the numerical tables, yields the corresponding values after a brief 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, until the desired forecast length is reached.

In Ch. 2 the method of numerical integration is illustrated by application to a simple linear 'shallow-water' model. Richardson's step-by-step description of his method and calculations is clear and explicit and still serves as a good introduction to the process of numerical weather prediction. It is a remarkable coincidence that the initial state that Richardson chose (illustrated on page 6) corresponds closely to a natural oscillation of the atmosphere, the gravest symmetric rotational Hough mode or 'five-day wave' (the pressure and meridional winds are identical; only the zonal winds differ). This mode progresses westward, with a period of about five days. Richardson was unaware of this and, observing that 'actual cyclones move eastward', rejected geostrophic initial winds as unsuitable.

Ch. 3 describes the choice of coordinates and the discrete grid to be used. The following three chapters, comprising half the book, are devoted to assembling a set of equations suitable for Richardson's purposes. The complete system of fundamental equations was, for the first time, set down in a systematic way in Ch. 4. Richardson formulated a description of atmospheric phenomena in terms of seven differential equations. To solve them, he divided the atmosphere into discrete columns of extent 3° east-west and 200 km north-south, giving 12,000 columns to cover the globe. Each of these columns was divided vertically into five boxes. The values of the variables were given at the centre of each box, and the differential equations were approximated by expressing them in finite difference form — the computational grid is illustrated on the frontispiece of the book. The rates of change of the variables could then be calculated by arithmetical means.

Hidden away on page 66 is Richardson's famous rhyme, 'Big whirls have little whirls that feed on their velocity, and little whirls have lesser whirls and so on to viscosity', that beautifully encapsulates the turbulent energy cascade in the atmosphere. Scientists are still debating the nature of this multi-stage energy transfer. As Richardson assumed an atmosphere in hydrostatic balance, there was no prognostic equation for the vertical velocity. Ch. 5 is devoted to the derivation of a diagnostic equation for this quantity, a major contribution to dynamic meteorology. Ch. 6 considers the special measures that must be taken for the uppermost layer, the stratosphere, a region later described by Richardson as 'a happy hunting-ground for meteorological theorists'. Ch. 7 gives details of the finite difference scheme, explaining the rationale for the choice of a staggered grid.

In Ch. 8 the forecasting 'algorithm' is presented in detail. The description of the method is sufficiently detailed and precise to enable a computer program based on it to be written. Ch. 9 describes the celebrated trial forecast and its unfortunate results. The preparation of the initial data is outlined—the data are tabulated on page 185. The calculations themselves are presented on a set of 23 Computer Forms, rather like in a modern spread-sheet program. But the forms were completed manually: 'multiplications were mostly worked by a 25 centim slide rule'. The rate of rise of surface pressure, found on Form P_{XIII}, was 145 millibars in 6 hours, a totally unrealistic value. Richardson described his forecast as 'a fairly correct deduction from a somewhat unnatural initial distribution'.

In Ch. 10 Richardson discusses five smoothing techniques. Such methods are crucial for the success of modern computer forecasting models. In a sense, this chapter contains the key to solving the difficulties with Richardson's forecast. He certainly appreciated its importance for he stated, at the beginning of the following chapter, 'The scheme of numerical forecasting has developed so far that it is reasonable to expect that when the smoothing ... has been arranged, it may give forecasts agreeing with the actual smoothed weather.' Ch. 11 considers 'Some Remaining Problems' relating to observations and to eddy diffusion, and also contains the oft-quoted passage depicting the forecast factory (page 291). Finally, Ch. 12 deals with units and notation and contains a full list of symbols, giving their meanings in English and in Ido, a then-popular international language.

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In the aftermath of the First World War, there was considerable delay in printing the book. It was thoroughly revised in 1920–21 and was finally published by Cambridge University Press in 1922 at a price of 30 shillings (£1.50), the print run being 750 copies. The book was certainly not a commercial success. 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 regard to the forecast, he observed that the wildest guess at the pressure change would not have been wider of the mark. The book was re-issued in 1965 as a Dover paperback and the 3,000 copies, priced at $2, about the same as the original hard-back edition, were sold out within a decade. The Dover edition was identical to the original except for a six-page introduction by Sydney Chapman.

In his Preface, Richardson wrote that the investigation of numerical prediction 'grew out of a study of finite differences and first took shape in 1911 as the fantasy which is now relegated to Ch. 11/2.' Richardson's forecast was confined to the calculation of the initial changes in two columns over central Europe, one for mass variables and one for winds. The computation of these *twenty numbers* (which appear on page 211) took him some two years. Recognizing that a practical implementation of his method would involve a phenomenal amount of numerical calculation, he imagined a fantastic Forecast Factory with a huge staff of human computers busily calculating the terms in the fundamental equations and combining their results in an ingeniously organized way to produce a weather forecast. This may be the earliest example of massively parallel processing. Richardson estimated that 64,000 people would be required to compute the atmospheric changes at the speed that they were taking place. The fastest computer in the TOP500 list as of June 2005 was the IBM BlueGene/L with 65,536 (64K) processors!

Richardson expressed a dream that, 'some day in the dim future', numerical weather prediction would become a practical reality. However, 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 modelling over the past fifty years has been dramatic. The useful range of deterministic prediction is increasing by about one day each decade, and seasonal forecasting skill is expected to increase significantly in the near future. As our knowledge of the atmosphere grows, so does our understanding of Richardson's remarkable vision and audacity. While his book had little effect in the short term, his methods are at the core of atmospheric simulation and it may be reasonably claimed that his work is the basis of modern weather and climate forecasting.

Start by marking â€œWeather Prediction by Numerical Processâ€ as Want to Read: Want to Read savingâ€¦ Want to Read.Â Weather prediction and climate modelling have now reached a high level of sophistication, and are witness to the influence of Richardson's ideas. This edition contains a new foreword by Peter Lynch that sets the original book in context. ...more. Get A Copy. Amazon. Numerical weather prediction (NWP) is a method of weather forecasting that employs a set of equations that describe the flow of fluids. These equations are translated into computer code and use governing equations, numerical methods, parameterizations of other physical processes and combined with initial and boundary conditions before being run over a domain (geographic area).Â Each important physical process that cannot be directly predicted requires a parameterization scheme based on reasonable physical or statistical representations. Used to approximate the bulk effects of physical processes too small, brief, complex or poorly understood to be explicitly represented by the governing equations and/or numerical methods. Right image: probability of heavy rainfall, derived by neighbourhood processing the 12 ensemble members. 2015 to 2017 - Cray XC40 supercomputer. The first part of the Met Officeâ€™s latest supercomputer arrived in 2015 and was fully installed by 2017.Â Golding BW and Mylne K. 2004. The history and future of numerical weather prediction in the Met Office. Weather. 59: 299â€“306.