Weather Prediction by Numerical Process

Second edition

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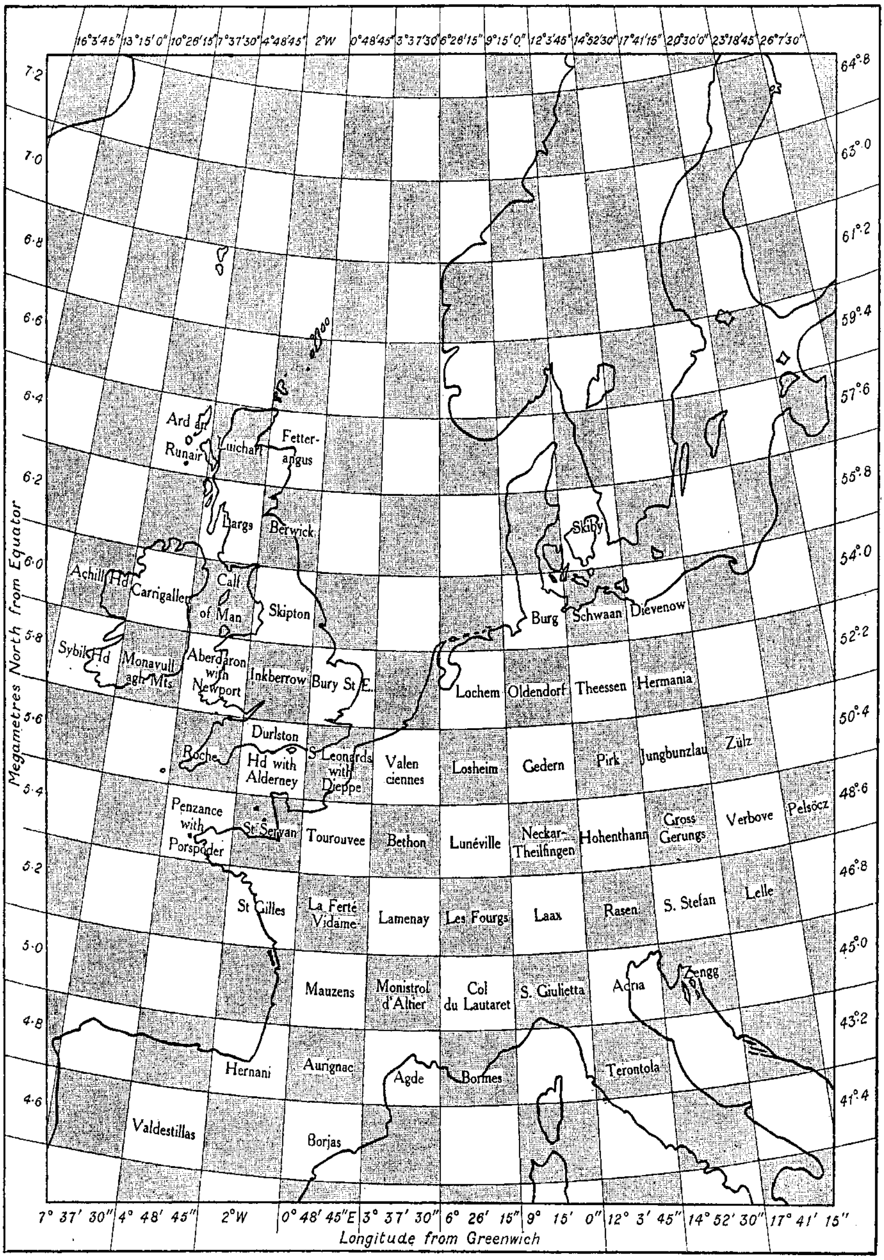
Lewis Fry Richardson
Frontmatter
More information



An arrangement of meteorological stations designed to fit with the chief mechanical properties of the atmosphere. Other considerations have been here disregarded. Pressure to be observed at the centre of each shaded chequer, velocity at the centre of each white chequer. The numerical coordinates refer to these centres as also do the names, although as to the latter there may be errors of ·5 or 10 km. The word "with" in "St Leonards with Dieppe" etc. is intended to suggest an interpolation between observations made at the two places. See page 9, and Chapters 3 and 7. Contrast the existing arrangement shown on p. 184.

WEATHER PREDICTION

BY

NUMERICAL PROCESS

Second edition

BY

LEWIS F. RICHARDSON, B.A., F.R.MET.SOC., F.INST.P.

FORMERLY SUPERINTENDENT OF ESKDALEMUIR OBSERVATORY
LECTURER ON PHYSICS AT WESTMINSTER TRAINING COLLEGE

with a Foreword by Peter Lynch
University College, Dublin

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FOREWORD

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 iniplementation 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.

* * *

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 focussed 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.

* * *

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', which 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.

* * *

In the aftermath of the First World War, there was considerable delay in printing the book. It was thoroughly revised in 1920–1 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 3000 copies, priced at $2, about the same as the original hardback 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. Coincidentally, 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.

Peter Lynch
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PREFACE

THE process of forecasting, which has been carried on in London for many years, may be typified by one of its latest developments, namely Col. E. Gold's *Index of Weather Maps**. It would be difficult to imagine anything more immediately practical. The observing stations telegraph the elements of present weather. At the head office these particulars are set in their places upon a large-scale map. The index then enables the forecaster to find a number of previous maps which resemble the present one. 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.

But—one may reflect—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? Obviously the approximate repetition does not hold good for many days at a time, for at present three days ahead is about the limit for forecasts in the British Isles. 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.

The scheme is complicated because the atmosphere is complicated. But it has been reduced to a set of computing forms. These are ready† to assist anyone who wishes to make partial experimental forecasts from such incomplete observational data as are now available. In such a way it is thought that our knowledge of meteorology might be tested and widened, and concurrently the set of forms might be revised and simplified. 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.

The present distribution of meteorological stations on the map has been governed by various considerations: the stations have been outgrowths of existing astronomical or magnetic observatories; they have adjoined the residence of some independent enthusiast, or of the only skilled observer available in the district; they have been set out upon the confines of the British Isles so as to include between them as much weather as possible; or they have been connected with aerodromes in order to

* *Meteor. Office Geophysical Memoir*, No. 16, deals mainly with types of pressure distribution but foreshadows a more general indexing.

† Printed blank forms may be obtained from the Cambridge University Press, Fetter Lane, E.C. 4.

exchange information with airmen. On the map the dots representing the positions of the stations look as if they had fallen from a pepperpot. The nature of the atmosphere, as summarized in its chief differential equations, appears to have been without influence upon the distribution. We shall examine in Ch. VII what would happen if these differential equations were the sole consideration. The result is represented in the frontispiece.

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; especially, for example, in the adoption of conventional strata, in the preference for momentum-per-volume rather than of velocity, in the statical treatment of the vertical column, and in the forced vertical motion at the ground. But 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. Graphical methods are sometimes elegant when the problem involves irregularly curved boundaries. But the atmospheric boundary, at the earth, nearly coincides with one of the coordinate surfaces, so that graphs would have no advantage over arithmetic in that respect.

It has been customary to regard line-squalls and other marked discontinuities as curious exceptions to the otherwise smoothly gradated distribution of the atmosphere. But in the last two years Prof. V. Bjerknes and his collaborators J. Bjerknes, H. Solberg and T. Bergeron at Bergen have enunciated the view, based on detailed observation, that discontinuities are the vital organs supplying the energy to cyclones‡. The question then arises: how are we to deal with discontinuities by finite differences? For such purposes graphs have a special facility which numerical tables lack. But it is not to be expected that a knowledge of the position and motion of surfaces of discontinuity will prove to be sufficient for forecasting, any more than "vital" organs alone would suffice to keep an animal alive. So probably the most thorough treatment will be reached by tabulating quantities numerically, where they vary continuously, and by drawing a line on the table where there is a discontinuity. The line will be a notification to the computer that one may interpolate up to it from either side, but not across it.

This investigation 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. Serious attention to the problem was begun in 1913 at Eskdalemuir Observatory with the permission and encouragement of Sir Napier Shaw, then Director of the Meteorological Office, to whom I am greatly indebted for facilities, information and ideas. I wish to thank

* Carnegie Institution, Washington, 1910, 1911.

† L. F. Richardson, *Phil. Mag.* Feb. 1908; *Proc. Roy. Soc. Dublin*, May 1908; *Phil. Trans.* A, Vol. 210, p. 307 (1910); *Proc. Phys. Soc. London*, Feb. 1911.

‡ *Q. J. R. Met. Soc.* 1920 April, and *Nature*, 1920, June 24.

Mr W. H. Dines, F.R.S., for his interest in some early arithmetical experiments, and Dr A. Crichton Mitchell, F.R.S.E., for some criticisms of the first draft. The arithmetical reduction of the balloon, and other observations, was done with much help from my wife. In May 1916 the manuscript was communicated by Sir Napier Shaw to the Royal Society, which generously voted £100 towards the cost of its publication. The manuscript was revised and the detailed example of Ch. IX was worked out in France in the intervals of transporting wounded in 1916—1918. During the battle of Champagne in April 1917 the working copy was sent to the rear, where it became lost, to be re-discovered some months later under a heap of coal. In 1919, as printing was delayed by the legacy of the war, various excrescences were removed for separate publication, and an introductory example was added. This was done at Benson, where I had again the good fortune to be able to discuss the hypotheses with Mr W. H. Dines. The whole work has been thoroughly revised in 1920, 1921. As the cost of printing had by this time much increased, an application was made to Dr G. C. Simpson, F.R.S., for a further grant in aid, and the sum of fifty pounds was provided by the Meteorological Office. For the construction of the index we are indebted to Mr M. A. Giblett, M.Sc. The discernment and accuracy with which the Cambridge Press have set the type have been constant sources of satisfaction.

L. F. R.

LONDON
1921 *Oct.* 10

GUIDING SIGNS

For finding one's way about this book it is most helpful to realise that:—

(i) A complete list of symbols and notation is given in Ch. XII at the end of the book.

(ii) An impression such as (Ch. 9/12/3) is intended to refer the reader to the 3rd subdivision of the 12th division of Chapter IX.

(iii) The mark # is used to refer to equations, expressions, or statements which have had numbers assigned to them in the right-hand margin. Thus (Ch. 9/12/3 # 16) means the equation, expression or statement numbered 16 in the aforesaid subdivision. The mark # is often omitted where the meaning is plain without it.

(iv) The physical units are those of the centimetre-gram-second system, unless a different unit is expressly mentioned. Temperatures are in degrees centigrade absolute. Energy, whether by itself or as involved in entropy or specific heats, is expressed in ergs not in calories.