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Peter Lynch
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# THE EMERGENCE OF NUMERICAL WEATHER PREDICTION

## Richardson's Dream

In the early twentieth century, Lewis Fry Richardson dreamt that scientific weather prediction would one day become a practical reality. The method of computing changes in the state of the atmosphere that he mapped out in great detail is essentially the method used today. Before his ideas could bear fruit several advances were needed: better understanding of the dynamics of the atmosphere; stable computational algorithms to integrate the equations of motion; regular observations of the free atmosphere; and powerful automatic computer equipment.

By 1950, advances on all these fronts were sufficient to permit the first computer weather forecast to be made. Over the ensuing 50 years progress in numerical weather prediction has been dramatic, allowing Richardson's dream to become a reality. Weather prediction and climate modelling have now reached a high level of sophistication.

This book tells the story of Richardson's trial forecast, and the fulfilment of his dream of practical weather forecasting and climate modelling. It has a complete reconstruction of Richardson's forecast, and analyses in detail the causes of the failure of this forecast. It also includes a description of current practice, with particular emphasis on the work of the European Centre for Medium-Range Weather Forecasts. This book will appeal to everyone involved in numerical weather forecasting, from researchers and graduate students to professionals.

PETER LYNCH is Met Éireann Professor of Meteorology at University College Dublin (UCD) and Director of the UCD Meteorology and Climate Centre. Prior to this he was Deputy Director of Met Éireann, the Irish Meteorological Service. He is a Fellow of the Royal Meteorological Society, the Royal Astronomical Society, the Institute of Mathematics and its Applications, and the Institute of Physics.

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## Richardson's Dream

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# Guiding signs

Richardson was considerate in providing 'guiding signs' to assist readers in navigating his book, *Weather Prediction by Numerical Process*. We follow his example.

(i) *Weather Prediction by Numerical Process* is denoted *WPNP* throughout.
(ii) In general, quantities are given in SI units. However, Richardson used the older CGS system and, where apppropriate, values of quantities are given in this system, with due indication.
(iii) Equations are numbered sequentially within each Chapter. Thus, the reference (2.20) denotes equation number 20 in Chapter 2.
(iv) The generic term 'gravity waves' is used for pure gravity waves, gravity-inertia waves and acoustic-inertia waves.
(v) Historians of meteorology may find Chapters 1, 3, 6, 7 and 10 of primary interest.
(vi) Chapters 2 and 3 are the most mathematically involved. On first reading they may be skimmed over, as the bulk of the remaining material should be accessible without detailed knowledge of them.
(vii) The current state of the science of numerical weather prediction is presented in Chapter 11.
(viii) A list of the main symbols is given in Appendix 1 (p. 251).



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# Preface

Accurate weather forecasts based on computer simulation of the atmosphere are now available routinely throughout the world. Numerical Weather Prediction (NWP) has developed rapidly over the past fifty years and the power of computer models to forecast the weather has grown impressively with the power of computers themselves. Earth System Models are capable of simulating climates of past millennia and are our best means of predicting future climate change, the major environmental threat facing humankind today.

It is remarkable that the basic techniques of numerical forecasting and climate modelling in use today were developed long before the first electronic computer was constructed. Lewis Fry Richardson first considered the problem of weather forecasting in 1911. He had developed a versatile technique for calculating approximate solutions of complicated mathematical equations – nonlinear partial differential equations – and he realised that it could be applied to the equations that govern the evolution of atmospheric flows. Recognising that a practical implementation of his method would involve a phenomenal amount of numerical calculation, Richardson imagined a fantastic forecast factory with a staff of thousands of human computers busily calculating the terms in the fundamental equations and combining their results in an ingeniously organised way to produce a weather forecast.

Richardson did much more than set down the principles of scientific weather prediction: he constructed, in complete detail, a systematic procedure or algorithm for generating the numerical solution of the governing equations. And he went further still: he applied the procedure to a real-life case and calculated the initial changes in pressure and wind. Although the resulting 'forecast' was unrealistic, Richardson's numerical experiment demonstrated that his procedure was self-consistent and, in principle, feasible. However, there were several major practical obstacles to be overcome before numerical prediction could be put into practice.

In this book we discuss Richardson's method in detail, showing how his numerical procedure is constructed by application of his finite differencing technique to the



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atmospheric equations. The resulting algorithm is ideally suited for programming on a modern computer. We describe the implementation of Richardson's algorithm as a computer program, and show that his forecast results can be replicated accurately. Richardson was meticulous and methodical; the consistency between the original and reconstructed predictions is more a demonstration of the validity of the computer program than a confirmation of the correctness of Richardson's calculations.

Although mathematically correct, Richardson's prediction was physically unrealistic. The reasons for this are considered in depth. The core of the problem is that a delicate dynamic balance that prevails in the atmosphere was not reflected in the initial data used by Richardson. The consequence of the imbalance was the contamination of the forecast by spurious noise. Balance may be restored by small but critical adjustments to the data. We show that after such modification, called initialisation, a physically realistic forecast is obtained. This further demonstrates the integrity of Richardson's process. We examine his discussion on smoothing the initial data, relating it to the initialisation procedure and showing how close he came to overcoming the difficulties in his forecast.

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 tended to deter others from following the trail mapped out by him. But his work was of key importance to the pioneers who carried out the first automatic forecast on an electronic computer, in 1950. One of them, Jule Charney, addressing the Royal Meteorological Society some years later, said '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'.

Richardson expressed a dream that, 'some day in the dim future', numerical weather prediction would become a practical reality. Progress was required on several fronts before this dream could be realised. 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 50 years has been dramatic. We review the current status of numerical prediction, both deterministic and probabilistic, with particular emphasis on the work of the European Centre for Medium-Range Weather Forecasts. Richardson's remarkable prescience and the abiding value of his work are illustrated by the wide range of ideas, central to modern weather and climate models, that originated with him. Thus, it may be reasonably claimed that his work is the basis of modern weather and climate forecasting.

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My interest in Richardson's forecast stems from discussions with my doctoral adviser and colleague, Ray Bates. Ray has provided advice and assistance on a multitude of meteorological matters. The idea of initialising Richardson's data and repeating his forecast occurred to me when I first read George Platzman's learned and comprehensive overview of *Weather Prediction by Numerical Process*. Written after the appearance of the Dover edition, this article has been a continuing source of inspiration. I greatly enjoyed visiting Professor Platzman in Chicago and have derived much assistance from correspondence with him, particularly relating to the introductory chapter and the section on the ENIAC integrations.

I first read Oliver Ashford's biography of Richardson while a visiting scientist at the Royal Netherlands Meteorological Institute (KNMI) in 1985, and I recall several fruitful and fascinating conversations about it with my Dutch colleagues. Following the appearance of my article on Richardson's barotropic forecast, in 1992, Oliver invited me to contact him. I have since enjoyed several visits to his home and have benefited from many conversations with him about Richardson and his work. Thanks also to Oliver for providing a photograph of Richardson.

Serious work on the reconstruction of the forecast began in Spring 1991 during a visit to the International Meteorological Institute (IMI) in Stockholm. I am grateful to Erland Källén for inviting me to visit IMI. While there, I analysed the initial mass fields for the forecast while Élias Hólm analysed the winds. Work on digital filtering initialisation, which I began with Xiang-Yu Huang in Stockholm, was also crucial for the success of the project.

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a visit to the National Center for Atmospheric Research (NCAR); the visit was facilitated by Joe Tribbia. Sections of the chapter on operations at the European Centre were reviewed by Tim Palmer, Adrian Simmons and Sakari Uppala, and I thank them for their comments.

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