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BOOK REVIEW

THE EMERGENCE OF NUMERICAL WEATHER PREDICTION: RICHARDSON'S DREAM, by Peter Lynch (CUP, November 2006), pp. xi + 280, hardback £40.00, ISBN 0521857295

Peter Lynch, who made notable contributions to numerical weather prediction (NWP) in the Irish Meteorological Service, has now written a very original and engaging book explaining the evolution of NWP. This is an exciting story, with the mistakes, false starts, controversies and outstanding individual contributions that have always been characteristic of great developments in science and technology. I am a firm believer in teaching science via its history, and this book should be recommended as a text for quantitative environmental courses that include an introduction to weather and climate models.

The first part of the book and its conclusion focus on both the mathematical and physical concepts and the original calculations of L. F. Richardson, which in 1922 he brought together in his typically British book *Weather Prediction by Numerical Process*. One is reminded of how Rayleigh's similarly comprehensive book on the theory and practice of sound was criticized by a French reviewer as being 'like entering a kitchen'. (For an account of Richardson's life, see the splendid biography by Ashford (1985)).

Vilhelm Bjerknes had suggested when he was lecturing on scientific forecasting in 1914 that 'the problem of accurate pre-calculation that was solved for astronomy must now be attacked in all earnest for meteorology'. However, Margules (who discovered the basic theory of sloping geostrophic fronts) profoundly disagreed. He argued in 1904 that not only did the mathematical sensitivities of the equations make NWP computationally impossible, but any attempt to overcome these difficulties would be 'immoral and damaging to the character of a meteorologist' – a point of view sometimes heard even today among oceanographers and solar physicists. Nevertheless Napier Shaw, then director of the Met Office, encouraged Richardson to take on the post of superintendent of Eskdalemuir observatory in Scotland and apply his new methods for the numerical integration of equations to weather forecasting (a demanding job description by today's standards). At University College London, working with Karl Pearson (another Quaker with revolutionary ideas about both society and science (Porter, 2004)), he had developed these methods for calculating the relatively smooth variations of water flow in peat and of stresses in a masonry dam, with well-defined boundaries in both cases. But would they work in the more complex physical environment of the atmosphere, with its sharply-varying flows (at fronts, for example) and uncertain upper boundary where the atmospheric density becomes very small?

Lynch guides the reader through the theoretical questions about predicting the temporal and spatial development of the winds and density in the atmosphere, given data about their spatial distribution at some initial time. Building on the work of Bjerknes, Richardson derived, from the basic equations of fluid flow and of thermodynamics, a simpler, approximate set of equations that describe the thin layers of the atmosphere (whose thickness is about one-thousandth of its lateral extent). Once the hydrostatic approximation, to ignore the vertical accelerations (which was only relaxed in the 1990s with the availability of large electronic computers) was made, the main theoretical controversies concerned: (a) the calculation of the horizontal divergence and the vertical variations with height of the small but vitally-important vertical velocities (Richardson's equation); (b) whether the upper boundary for the flow should be a rigid lid (which Lynch says would be satisfactory for a first approximation) or dynamically varying (as Richardson insisted was necessary); and (c) what to assume, from the incomplete measurements at the initial moment, about the atmospheric motions and how to describe them mathematically.

In fact, none of these approximations and assumptions caused the great discrepancy between Richardson's prediction of a large pressure rise (145 hPa in six hours) and the very small observed change. Furthermore, in this and other calculations his model predicted that cyclones should move to the west: a relatively rare event. Richardson's hand calculations (which he repeated twice) were based on a horizontal grid of 25 squares each 150 km wide, with five vertical levels, and were applied to the development of a weak anticyclonic flow over Germany in 1910. (The surface and balloon data for this case had earlier been analysed by Bjerknes.) Lynch has repeated Richardson's calculations and found that they were arithmetically accurate.

The explanation for the error is now well known, although it was not understood in Richardson's day. When equations are valid for all the scales of motion, their solutions for the atmosphere tend to be dominated by energetic wave motions on scales of the order of 1 km, which are much smaller than the length scales of synoptic weather patterns. Lynch introduces the nice analogy with computing ocean or river currents, which always smooth out or 'filter' the small-scale and high-frequency waves on the surface. Because he failed to filter out in his equations the waves in the atmosphere (which are more familiar in the form of lee waves over mountains or clear-air turbulence), Richardson's approximate solutions 'blew up'. Lynch draws on more recent mathematical research (e.g. Norbury and Roulstone, 2002) that demonstrates how these types of nonlinear partial differential equations have solutions that are a combination of faster and slower oscillations or waves; he illustrates this by analysing the behaviour of a long spring that oscillates quite fast while swinging slowly like a pendulum.

Lynch goes on to show that if Richardson's initial data are modified to filter out the fast waves, his model can be used to obtain plausible results (for situations without large temperature changes) over the whole globe and for five days ahead, thus demonstrating that his basic assumptions were correct except for the one critical element of internal waves. Lynch explains why Richardson's own explanation of the error, namely that it was caused by inaccurate and insufficiently detailed initial data, could not account for the prediction of a huge increase in surface pressure.

It is hard to imagine now how confident Richardson must have been to publish a book whose centrepiece was a calculation that appeared to differ so strongly from the data, and how persuasive he must have been with the publisher. Perhaps Richardson's offer to Cambridge University Press to help pay for the book had some influence?

The last part of the book takes us rapidly from the first dramatic steps of applying electronic computers to NWP in the late 1940s up to the present age of massively-parallel ensemble computing, highly-developed numerical methods and data assimilation. Von Neumann's Princeton project was, as Lynch explains, a great achievement, but something of a false start as seen from the present perspective. To avoid Richardson's problem of internal wave oscillations, Charney proposed using a mathematical representation of the atmosphere as a single layer that behaves like a river (with the important difference that the Earth's rotation controls the cyclones, and of course – except near mountains – there are no banks to steer the flow). For certain types of vigorous cyclones travelling around the globe, this model was successful – and showed what computers and upper-layer observations could do to improve meteorological forecasting. It was not surprising that a meteorological service in a high-latitude country where meteorology is really understood, namely Sweden, should be the first to apply this barotropic model for operational forecasts, in 1956. But for most atmospheric conditions over the globe, thermal (or baroclinic) effects are too important to be described by such a one-layer model. This was why, despite gloomy warnings from senior meteorologists (especially in the UK) that no further progress was possible, NWP gradually reverted to Richardson's original idea of using the basic (or 'primitive') equations and accounting for separate motions in several layers (starting with three). The first such operational models were introduced in Germany and the UK in 1965–66.

Once such equations had begun to be used, questions arose about the future possibilities and limitations, which indeed were touched upon in Richardson's book in 1922. Despite the discoveries by Lorenz about the sensitivity of forecasts to initial conditions and the chaotic forms of the solutions of simplified nonlinear equations, and despite the predictions of some theorists that atmospheric eddy motion would limit forecasts to less than five days, it turns out that after about one day the errors in forecasts grow quite slowly (linearly for cyclones and hurricanes (Cullen, 2002)). The self-organization and persistence of these and other types of atmospheric motion is probably why the range and accuracy of forecasts continues to improve. However, it is clear that Richardson was over-optimistic in suggesting that with more detailed atmospheric measurements forecasts could one day be as accurate as the astronomical computations of the nautical almanac. Many of these encouraging developments are well described in the concluding chapters, and full references are provided to other books and articles.

Perhaps Lynch might have mentioned the controversial but now accepted approach in meteorological and other kinds of modelling of not only calculating a number of possible solutions to the equations in a given situation, but also comparing and combining the results of models from different centres (e.g. Palmer and Hagedorn, 2006). This is a kind of computer Esperanto: a universal language, which Richardson thought in the 1920s might be the answer to international misunderstanding and conflict!

The book ends with a nice comparison between Richardson's dream of a 'forecast factory' of 64,000 mathematicians making hand calculations of weather predictions in a building like the Albert Hall, and one of the largest parallel computers currently used for weather forecasting, which in 2005 had 65,536 processors.

I hope many students will read this book, and, as well as learning about NWP, will appreciate the richness of recent meteorological history.

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