EDITORIAL

100 Years of L. F. Richardson's *Weather Prediction by Numerical Process*

While *Monthly Weather Review* is celebrating its 150th year, another milestone in meteorology this year is the 100th anniversary of the publication of Lewis Fry Richardson's *Weather Prediction by Numerical Process.* As we describe in this month's editorial, Richardson's meticulous attempt at hand-calculating the weather failed spectacularly but showed future workers the way forward. Their efforts helped to make *Monthly Weather Review* one of the leading journals for numerical modeling of the atmosphere.

The basic ideas of numerical forecasting and climate modeling were developed about 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 (Abbe 1901; Bjerknes 1904). Apparently independently, they each specified the required process: analysis of the initial state and time integration of the governing equations from that initial state. They listed the system of mathematical equations needed and outlined the steps required to produce a forecast. Willis and Hooke (2006, p. 322) compared the two articles, arguing that "Abbe recognized more fully the extreme technical challenge posed by initializing the equations of motion with observations." Eliassen (1999, p. 6) also noted that Bjerknes (1904) made the "technical blunder" to use the second law of thermodynamics rather than the continuity equation for water, which prevented him from formulating a consistent algorithm. 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. Exner followed a radically different line from Abbe and Bjerknes. Instead of the full system of hydrodynamic and thermodynamic equations, Exner assumed that the atmospheric flow was geostrophically balanced and that the thermal forcing was constant in time. Using observed temperature values, he deduced a mean zonal wind. He then derived a prediction equation representing advection of the pressure pattern with constant eastward speed, modified by the effects of diabatic heating. It yielded a realistic forecast for the case illustrated in Exner (1908). Despite the restricted applicability of his technique, his work was a first attempt at systematic, scientific weather forecasting.

In stark contrast to Exner, Richardson attempted a direct solution of the full equations of motion. Although he had produced a first draft of the book in 1916, he wanted a practical example illustrating his systematic algorithm for generating a forecast (Ashford 1985, p. 49). Thus, he attempted a 6-h forecast for a point near Munich, Germany, by solving the mathematical equations and starting from the most complete set of observations available (0700 UTC 20 May 1910 from analyzed maps provided by Bjerknes). The results were egregious, with a predicted pressure change of 145 hPa in 6 h, as opposed to the observed pressure, which was nearly steady (Richardson 1922, p. 187).

The cause of the catastrophic results has been established beyond doubt. When the analyzed data were balanced through the process of initialization, using a digital filter, a realistic value of pressure change was obtained (Lynch 1992, 1999, 2003, 2006). An analogy best explains why Richardson failed. It was as if Richardson were standing on an ocean beach trying to predict the slow daily changes of the ocean tides by extrapolating the instantaneous changes in height from individual waves (Lynch 2006, section 1.1).

The book, *Weather Prediction by Numerical Process*, was published by Cambridge University Press for a price of 30 shillings (£1.50). Not a commercial success with a print run of just 750 copies, it was still in print 30 years after publication. It was reissued in 1965 as a Dover paperback. The content was identical to the original except for a six-page introduction by Sydney Chapman. Following its appearance, a masterful appraisal of Richardson's work by George Platzman was published in the *Bulletin of the American Meteorological Society* (Platzman 1967). Cambridge University Press reissued 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.

The initial response to the book's publication in 1922 was mixed. It was widely reviewed with generally favorable comments, but the impracticality of the method and the abysmal failure of the solitary sample forecast inevitably attracted adverse criticism. Edgar Woolard, who would later

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become the editor of *Monthly Weather Review* (1936–45), wrote a review of the book in *Monthly Weather Review* (Woolard 1922) upon its publication, which says in part

> [t]his book is an admirable study of an eminently important problem; being a first attempt in this extraordinarily difficult and complex field, it necessarily possesses, self-confessedly, many imperfections; and is by no means, of course, the final word; however, it indicates a line of attack on the problem, and invites further study with a view to improvement and extension.

On the other hand, Harvard meteorology professor Alexander McAdie wrote that the book "will probably be quickly placed on a library shelf and allowed to rest undisturbed by most of those who purchase a copy" (McAdie 1923). Indeed, this is essentially what happened.

Richardson's work was not taken seriously by most meteorologists at the time of publication, 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. Last, the development of digital computers provided a way of attacking the enormous computational task involved in weather forecasting; all of these advances led to the first weather prediction by computer (Charney et al. 1950). That history leading to modern operational numerical weather prediction is described by Lynch (2006, 2008), Harper (2006), and Harper et al. (2007).

The development of comprehensive models of the atmosphere is undoubtedly one of the finest achievements of meteorology in the twentieth century, recognized in part by the Nobel Prize awarded to Syukuro Manabe in 2021. Numerical models continue to develop, with *Monthly Weather Review* leading the way in publishing the latest developments in model architecture, data assimilation to produce improved initial conditions, new model architectures and numerical algorithms for more precise and faster computations, and model verification studies to determine the best experimental approaches to employ 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.

In his review of Richardson (1922), Woolard asked, "What satisfaction is there in being able to calculate to-morrow's weather if it takes us a year to do it?" Answering that question eight years earlier, Bjerknes (1914) wrote, "If only the calculation shall agree with the facts, the scientific victory will be won." He continued, "It may require years to bore a tunnel through a mountain. Many a laborer may not live to see the cut finished. Nevertheless this will not prevent later comers from riding through the tunnel at express-train speed." Woolard continued, "It is sincerely to be hoped that the author will continue his excellent work along these lines, and that other investigators will be attracted to the field which he has opened up." Although Richardson would later move from meteorology to research in other fields, many other investigators did develop his ideas about forecasting, as the pages of *Monthly Weather Review* over the next century proudly reveal.

Today, we are those later comers.

David M. Schultz
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