12
Fulfilment of the dream

> Little did Bjerknes know that Richardson would start to bore the tunnel just a few months later. Still less could he have imagined that express trains would be driving throught the tunnel within about forty years.
>
> (*Ashford, 1985,* p. 80)

12.1 Richardson's explanation of his *glaring error*

There is no doubt that Richardson's outlandish forecast results acted as a deterrent to others who might have been tempted to continue his work. We have seen that the unrealistic tendencies arose from a disharmony between the fields of mass and of motion; the causes of the forecast failure were discussed in detail in §7.4. It is of interest to examine Richardson's understanding of the reasons why his forecast failed.

At the outset, Richardson stated that the forecast was 'spoilt by errors in the initial data for winds' (*WPNP*, p. 2) arising from the irregular distribution of pilot balloon stations and from the sparsity of upper air data. Throughout the book, he repeatedly referred to errors in the winds as the cause of the forecast failure. He discussed only the egregious *pressure tendency*, even though all his other tendency predictions were also unrealistic. Richardson was, of course, aware that 'spurious convergence' would yield an unrealistic tendency of pressure but, although he was fully conversant with the Dines' compensation effect, he never mentioned the lack of vertical compensation in his data as a contributary cause. Similarly strange is his omission of any mention of the strongly ageostrophic nature of the initial winds, which resulted in large momentum tendencies. Of course, he knew the consequences of such imbalance: in his introductory example (*WPNP*, Chapter 2) he observed that the initial pressure field might be chosen arbitrarily, but that 'if the assumed pressure gradients be unnaturally steep, the consequent changes will be perplexingly violent'. Moreover, the winds could be chosen completely independently of the pressure 'with a qualification similar to that mentioned above'. For this example he chose geostrophic winds, but he never discussed the disharmony between mass and wind in his data for 20 May 1910.

Richardson's proposed method of rectifying the forecast process was to smooth the initial winds; we have discussed his five smoothing methods in §9.2. However, we have seen that smoothing the initial winds does not guarantee a noise-free evolution. Put another way, smoothing the winds may not get us closer to the slow manifold, or to the climate attractor. Richardson never considered smoothing of the mass field. Sverre Petterssen related the following anecdote apropos the meeting convened by Bjerknes in Bergen in 1921:

> Richardson used to draw isobars which, as seen by Bergen-school eyes, seemed somewhat unorthodox. The philosophy of smooth fields was dominant while Richardson's isobars represented rather the opposite extreme. On one occasion an analyst invited Richardson's attention to the absence of smoothness, but Richardson was quite undisturbed and answered, 'It doesn't matter what they look like as long as we know the values at grid points'.
>
> *(Quoted from Platzman, 1968)*

This certainly indicates a misplaced confidence in the ability of spot values of pressure to represent the synoptic flow without further adjustment. More significantly, there was no mention anywhere in *WPNP* of the need for a *mutual adjustment of the mass and wind fields*. Richardson's second smoothing method was to take a time average of the wind observations over a period of hours. Had he also suggested applying a similar averaging to the mass field, he would have proposed what was, in effect, a digital filtering initialisation technique. However, he did not do that. We are forced to conclude that Richardson's understanding of the causes of his forecast failure was quite incomplete. Moreover, his claim that smoothing of the initial winds would yield a realistic forecast (*WPNP*, p. 217) is seen to be unsustainable.

In Chapter 2 of *WPNP* Richardson made reference to the tidal theory of the atmosphere but he did not appear to appreciate its relevance: 'Much of tidal theory is applicable, but its interest has centred mainly in forced and free oscillations, whereas now we are concerned with unsteady circulations' (*WPNP*, p. 5). Again in Chapter 4 he referred to Lamb's *Hydrodynamics*, specifically to the section dealing with Laplace's theory of the tides on a rotating globe (see Lamb, 1932, Arts. 213–223). But he made no mention of gravity waves in the atmosphere, nor did he appear to recognise their role in causing his forecast failure. Richardson was a master of numerical analysis, and well understood the problems that arise from combining disparate scales. In his paper on the deferred approach to the limit, he introduced a sample function that is everywhere continuous and differentiable to all orders, $f(x) = \sin x + \sin(100x) + \sin(10000x)$:

The analyst finds it pleasant, but to the computer it is an intractable horror. A step h which is large enough to allow satisfactory progress in exploring the variation of $\sin x$ is far too large to reveal the detail of $\sin(10000x)$. Let us call these rapid oscillations, superposed on much slower variations, by the name 'frills'. *(Richardson, 1927)*

The high frequency gravity wave oscillations superimposed on a quasi-balanced flow are precisely the frills that Richardson spoke of but, unfortunately, he was unable to make the connection between his spurious tendencies and the existence of gravity wave oscillations in the atmosphere. One of the reviewers of *WPNP*, F. J. W. Whipple of the Met Office, actually identified the *waves which are propagated with the velocity of sound* as the culprits (see p. 18 above). It is one of the quirks of history that nobody thought it worthwhile looking more deeply into this at the time. We may suppose that there were so many other obstacles to a practical implementation of numerical weather prediction when *WPNP* was published that the scientists of that time did not regard it as a fruitful area of research.

It would appear that Richardson came to realise the need for adjustment of the initial data only after he had completed his forecast. His explanation of the errors of predicted tendency in terms of spurious values of divergence is incomplete, but it is consistent with the analysis of Margules (see §7.5). Had Richardson been aware of Margules' results, he might well have decided not to proceed with the trial forecast, or sought a radically different approach. It is possible that he realised the significance of Margules' results when he read Exner's book but, in that case, it seems inexplicable that he did not refer to Margules, or to the relevant section of Exner, explicitly. He had completed a Homeric numerical forecast and included it in his book, and Margules' results showed that his approach was, from the outset, doomed to failure. Although such a realisation would have been devastating, one cannot doubt that Richardson would have faced it with honesty. Later, Richardson did realise that his original method was unfeasible. Reference was made in §7.5 to a note (undated) in the *Revision File*, where he wrote that the equation of continuity must be eliminated. He further speculated that the vorticity might be a suitable prognostic variable, but we have no evidence that he or any of his contemporaries pursued this line, which later proved so fruitful in the hands of Rossby and Charney.

The theory of atmospheric fronts was undergoing rapid development in Bergen at the time *WPNP* was being finished. Richardson was aware of this development: Vilhelm Bjerknes visited him in Benson in November 1919 and Richardson participated in two scientific conferences convened by Bjerknes in Bergen, in 1920 and 1921. In the preface to *WPNP*, Richardson wrote that '... in the last two years Prof. V. Bjerknes and his collaborators ... have enunciated the view, based on detailed observation, that discontinuities are the vital organs supplying the energy to cyclones'. Shortly after his visit to Benson, Bjerknes wrote to Robert Wenger, his successor in Leipzig, of a conversation with Richardson about the reasons for

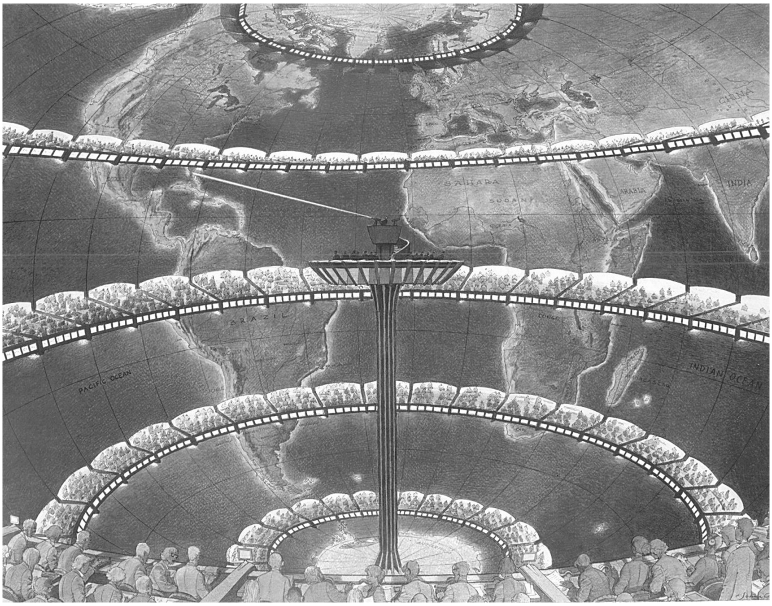

Figure 12.1 An artist's impression of Richardson's forecast factory. (Thanks to artist François Schuiten for permission to reproduce image)

his 'meaningless' forecast results: 'We agreed that the interloper discontinuity was most probably one of the main causes of his failure.' Bjerknes' perspective was perhaps over-influenced by the dramatic progress in frontal theory under way in Bergen: Richardson himself did not make reference, in *WPNP* or elsewhere, to fronts as the cause of his problems. However, he recognised that the numerical process would have to be specially modified to handle such discontinuities. Indeed, he later wrote that, if a second edition of his book were to be produced, he should include a new chapter on the processing of discontinuities.

12.2 The 'forecast factory'

Despite the many obstacles to be overcome before NWP could become a reality, Richardson showed remarkable foresight when he penned his famous *fantasy* of a 'forecast factory' (Fig. 12.1). This has been reproduced widely, but it is so striking that it merits another full exposure:

After so much hard reasoning, may one play with a fantasy? Imagine a large hall like a theatre, except that the circles and galleries go right round through the space usually occupied by the stage. The walls of this chamber are painted to form a map of the globe. The ceiling represents the north polar regions, England is in the gallery, the tropics in the upper circle, Australia on the dress circle and the antarctic in the pit. A myriad computers are at work upon the weather of the part of the map where each sits, but each computer attends only to one equation or part of an equation. The work of each region is coordinated by an official of higher rank. Numerous little "night signs" display the instantaneous values so that neighbouring computers can read them. Each number is thus displayed in three adjacent zones so as to maintain communication to the North and South on the map. From the floor of the pit a tall pillar rises to half the height of the hall. It carries a large pulpit on its top. In this sits the man in charge of the whole theatre; he is surrounded by several assistants and messengers. One of his duties is to maintain a uniform speed of progress in all parts of the globe. In this respect he is like the conductor of an orchestra in which the instruments are slide-rules and calculating machines. But instead of waving a baton he turns a beam of rosy light upon any region that is running ahead of the rest, and a beam of blue light upon those who are behindhand.

Four senior clerks in the central pulpit are collecting the future weather as fast as it is being computed, and despatching it by pneumatic carrier to a quiet room. There it will be coded and telephoned to the radio transmitting station. Messengers carry piles of used computing forms down to a storehouse in the cellar.

In a neighbouring building there is a research department, where they invent improvements. But there is much experimenting on a small scale before any change is made in the complex routine of the computing theatre. In a basement an enthusiast is observing eddies in the liquid lining of a huge spinning bowl, but so far the arithmetic proves the better way. In another building are all the usual financial, correspondence and administrative offices. Outside are playing fields, houses, mountains and lakes, for it was thought that those who compute the weather should breathe of it freely.

Richardson's description is certainly whimsical but it is also remarkably prescient. There are surprising similarities between his forecast factory and a modern massively parallel processor (MPP). Richardson envisaged a large number of processors – 64 000 by his estimate – working in synchrony on different sub-tasks. The fastest computer in the Top 500 list as of June 2005 was the IBM BlueGene/L with 65 536 processors! The silicon-based processing elements of modern computers are incomparably more powerful than the carbon-based 'computers' proposed by Richardson. The IBM machine is rated at 136.8 TFlops (136 trillion calculations per second; see http://www.top500.org). The BlueGene is perhaps nine orders of magnitude faster than Richardson's forecast factory. In the fantasy, the forecasting job is sub-divided, or parallelised, using domain decomposition, a technique often used in MPPs today. Richardson's *night signs* provide nearest-neighbour communication, analogous to message-passing techniques in MPPs. The man in the pulpit, with his blue and rosy beams, acts as a synchronisation and control unit. Thus, while the processing speeds differ by many orders of magnitude, the logical structures of the forecast factory and the MPP have much in common.

The dawn of the atomic era brought with it the need for mathematical computations on a scale greater than ever before. The Manhattan Project had access to the most advanced technology available, though it was primitive by modern standards. The workhorse for scientific computing was an electro-mechanical machine, the Marchand calculator, which could add, subtract, multiply and (with difficulty) divide numbers of up to ten digits. At Los Alamos the computations were organised like a factory assembly line (Gleick, 1992). The staff – mostly the wives of the scientists, working on reduced wages – worked in a large array, like the cogs of a great machine, each computing an individual component of a complex system of equations, cranking the handle of her Marchand and communicating results to her neighbours; the arrangement was analogous to the forecast factory. The output from the production line was a detailed calculation of the behaviour of the expanding ball of fire in a thermo-nuclear explosion. This would hardly have met with the approval of the pacifist Richardson. Some of the early numerical weather forecasts were computed using a man–machine mix or, perhaps more accurately, woman–machine mix, like that in Los Alamos. One such example in Germany, where access to computers was unavailable in the aftermath of the war, was described by Edelmann (see page 201). Fortunately, powerful automatic data processing soon took over the drudgery of such calculations.

12.3 Richardson's dream

We opened with a quotation expressing Richardson's dream: 'Perhaps some day in the dim future it will be possible to advance the computations faster than the weather advances . . . .' The ensuing chapters have described how that dream, utterly fanciful in the dim past, has been fulfilled in a spectacular fashion. Progress in numerical weather prediction has been dramatic and has been of huge benefit to humankind. It has brought us far beyond anything Richardson could have imagined, and continues to develop apace. Satellite systems now observe the atmosphere and oceans continuously, dedicated communication networks distribute weather data at the speed of light, and powerful computer systems using sophisticated numerical algorithms perform prodigious calculations to predict the weather for many days ahead.

There is a strong symbiosis between numerical weather prediction and theoretical meteorology. Advances in our understanding of the physics and dynamics of the atmosphere and ocean are soon exploited in computer models, and these models themselves provide us with a powerful method of exploring the behaviour of the real atmosphere and ocean. George Cressman, an early pioneer of numerical prediction, once remarked that 'the problems of NWP can be considered to be the problems of all meteorology'. More than ever, this is true today. Numerical weather prediction has now reached a high level of sophistication. Forecasts up to a week or more ahead are of value, and progress is under way in monthly and seasonal prediction.

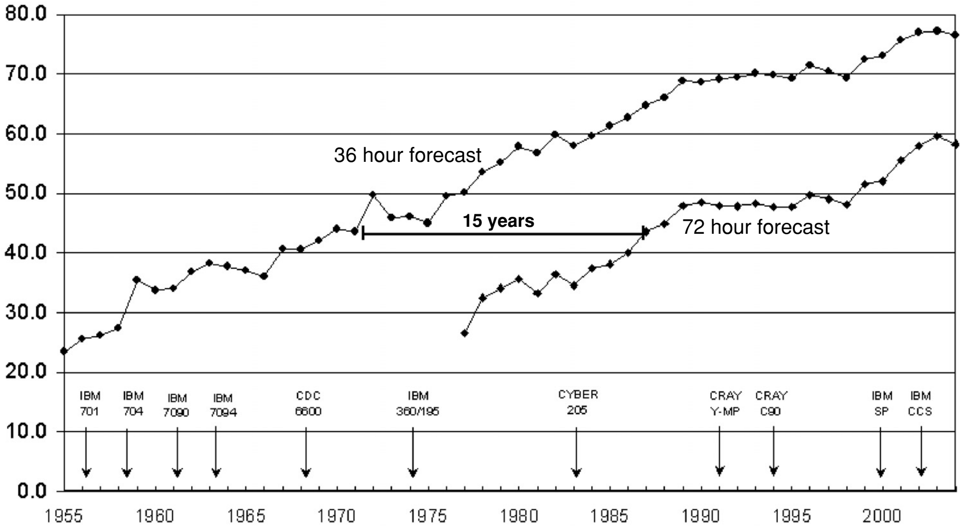

Figure 12.2 Skill of the 36 hour (1955–2004) and 72 hour (1977–2004) 500 hPa forecasts produced at NCEP. Forecast skill is expressed as a percentage of an essentially perfect forecast score. The accuracy of prediction is closely linked to the available computer power; the introduction of new machines is indicated in the figure. Thanks to Bruce Webster of NCEP for the graphic of S_1 scores.

At longer timescales, models of the sort first formulated by Richardson are our best means of anticipating changes in global climate, which may have profound consequences for humanity.

Prior to the computer era, weather forecasting was in the doldrums. Petterssen (2001) described the advances as occuring in 'homeopathic doses'. The remarkable progress in forecasting over the past 50 years is vividly illustrated by the record of skill of the 500 hPa forecasts produced at the National Meteorological Center, now NCEP, as measured by the S_1 score (Teweles and Wobus, 1954). The 36 hour scores are the longest verification series in existence, dating from the very beginning of operational NWP. The skill scores, expressed as percentages of maximum possible skill, have improved steadily over the past 50 years and each introduction of a new prediction model has resulted in further improvement (Fig. 12.2). The sophistication of prediction models is closely linked to the available computer power; the introduction of each new machine is also indicated in the figure. The horizontal bar indicates a 15 year delay for the 72 hour forecast to attain the skill previously attained at 36 hours. This is consistent with the general experience of a one-day-per-decade increase in forecast skill.

A pioneer of numerical weather prediction, Fred Shuman, concluded his historical review of NWP at the National Meteorological Center thus:

> All the meteorological world was watching the work ... [of JNWPU] in the 1950s. Our job was no less than to revolutionize weather forecasting, which had begun almost a century earlier as a centralized operation, and which had not changed much since then in its fundamental processes. *(Shuman, 1989)*

It is no exaggeration to describe the advances made over the past half century as revolutionary. Thanks to this work, meteorology is now firmly established as a quantitative science, and its value and validity are demonstrated on a daily basis by the acid test of any science, its ability to predict the future.

Richardson's forecast came to grief through his use of uninitialised data: his calculated pressure tendency was two orders of magnitude too large, due to anomalously large amplitude gravity wave components in his data. Initialisation using a digital filter produces data that yields realistic tendencies. Richardson's methodology was unimpeachable and is essentially the same as current practice in NWP. He was not alone in foreseeing the emergence of numerical forecasting. Bjerknes played a critical part by formulating weather prediction as a scientific problem, and Helmholtz had earlier contributed by completing the system of equations through his developments in thermodynamics. But it was Richardson who actually had the vision and the audacity to put to a practical test what earlier scientists had seen only in a theoretical context. For that alone, he is worthy of our admiration.