A general introduction to the life and work of L. F. Richardson[†]

by J. C. R. Hunt

The discoveries of many great scientists and mathematicians, including Lewis Fry Richardson's, are directly related to the political, economic and other human concerns of their period. He expressed himself clearly at the outset of his career (1908:1)[‡], 'The root of the matter is that the greatest stimulus of scientific discovery are its practical applications'.

During the period of his life from 1881 to 1953 science and its applications developed rapidly and in quite new directions. It is well known how the lives of those involved in the developments of modern physics are woven into the history of this century, such as Einstein and Bohr, to name but two. But pioneers of other branches of mathematical sciences have also contributed to the great changes in the world by their discoveries; and as with the physicists, the researches and the lives of many of these scientists and mathematicians were also strongly influenced by the history of this period, especially the two world wars and their peacetime repercussions. Richardson was one of these pioneers, and was outstanding in making important contributions to several different fields. One can add his name to the inventors of computational mathematics (such as von Neumann, Courant, Turing); of modern meteorology and fluid mechanics (V. Bjerkens, Taylor, Prandtl); of quantitative techniques in psychology and social sciences (W. James); and of analysis and modelling of complex systems (Wiener). In all these fields his work is still cited in current research papers. In one citation index there were over 200 references between 1980 and 1984.

Knowing something about the lives and beliefs of creative people usually helps one understand and appreciate their work; this is especially so for Richardson, much of whose scientific work changed and evolved as a direct result of the political and technological changes during his life, and his reactions to them as a Quaker. One of the reasons for collecting his papers in these two volumes is to show how a mathematical scientist can respond to the problems of the world around him, and, one might add, not necessarily in accordance with the ways currently favoured or promoted by the established organizations that direct and finance science.

Richardson's special contribution to all these fields was to apply quantitative and mathematical thinking to problems that were considered outside the scope of mathematics at that time, and to have been so effective in his thinking that his formulae and his methods are still used daily by working scientists and mathematicians. His

[†] Much of this introduction is based on the biographical accounts by Ashford (1985) and Gold (1954). It is also based on recollections by various members of Lewis and Dorothy Richardson's family, including myself.

[‡] In this book Richardson's own publications are cited in this way. An explanation is given on page 47 in the 'Note on the arrangement and presentation of the papers'.

personal stamp on the work is unusual in that many of his results are still referred to by his name. However, he was himself especially conscious of the dangers of applying mathematical ideas and techniques to complex human behaviour and natural phenomena as he aptly summarized in *Mathematical Psychology of War* (1919:1, p. 2).

> Mathematical expressions have, however, their special tendencies to pervert thought: the definiteness may be spurious, existing in the equations but not in the phenomena to be described; and the brevity may be due to the omission of the more important things, simply because they cannot be mathematized. Against these faults we must constantly be on our guard. It will probably be impossible to avoid them entirely, and so they ought to be realized and admitted.

Early life

Born on 11 October, 1881, of Quaker parents, David and Catherine Richardson in Newcastle upon Tyne, Lewis Fry Richardson was the youngest of seven children. David Richardson, who ran a prosperous tanning and leather business, had been trained in chemistry. His technical abilities enabled him to design new machinery and some new production methods. Lewis showed early on an independent mind and an empirical approach, as when he tested at the age of five the proposition learnt from his elder sister that 'money grows in the bank'. He buried some money in the garden and was disappointed to find it did not grow! After a period at Newcastle Preparatory School, where his chief enjoyment was Euclid 'as taught by Mr. Wilkinson', he was sent, aged twelve, to a Quaker boarding school, Bootham, at York. There he had excellent teaching, especially in science, which stimulated a great interest in natural history. He kept a diary of birds, insects, flowers and weather. He collected 167 species of insects and made detailed studies of plants (he returned to collecting statistics, of wars, in the last phase of his research). Another important part of his character was developed by a teacher who 'left me with the conviction that science only has to be subordinate to morals'.

His higher education began in 1898 with two years at Newcastle University (formerly, Durham College of Science) with courses in mathematical physics, chemistry, botany and zoology. He proceeded in 1900 to King's College, at the University of Cambridge, where he was taught Physics in the Natural Science Tripos by (among others) Professor J. J. Thomson (the discoverer of the ratio of the charge to the mass of an electron, e/m) and graduated with a first class degree in 1903.

In Table 1 the main appointments in his career are listed.

Early career 1903–13

In the ten years (1903–13) after graduating L. F. Richardson took a series of short research posts, a career not unfamiliar to today's scientists, first in a government research laboratory (the National Physical Laboratory), then in physics departments (at University College of Wales, Aberystwyth and at Manchester University) and in industry. Some of the research required in these posts clearly did not interest him much (such as in metallurgy and metrology). However, it was as a *chemist* with the National

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More information

Table 1*

1903–4	Student Assistant at the National Physical Laboratory (Metallurgy Department)
1905–6	Junior Demonstrator in Physics, University College, Aberystwyth
1906–7	Chemist to National Peat Industries Ltd, 'whose managing director stole a large sum and fled abroad'
1907–9	Assistant at the National Physical Laboratory (Metrology Department)
1909–12	In charge of the chemical and physical laboratory of the Sunbeam Lamp Co., Gateshead (where he organized a troop of scouts)
1912–13	Demonstrator and Lecturer in Physics, Manchester College of Technology
1913–16	Meteorological Office, Superintendent of Eskdalemuir Observatory
1916–19	In the Friends' Ambulance Unit in a motor convoy (SSA 13) attached to the 16th French Infantry Division
1919–20	Meteorological Office, nominally in charge of experiments in the computation of the sequence of weather by numerical processes. He worked at Benson, Oxfordshire, where W. H. Dines was in charge of 'Upper Air Investigation'. (Richardson revived the village troop of scouts.)
1920–29	In charge of the physics department at Westminster Training College
1929–40	Principal of Paisley Technical College and School of Art
1940–53	Retired to do research on wars. Research also in eddy-diffusion

* From Gold (1954)

Peat Industries Limited from 1906 to 1907 that Richardson began his first pioneering research, although it was in mathematics and not chemistry. He was faced with the problem 'Given the annual rainfall, how must the drains (i.e. channels in the peat moss) be cut in order to remove just the right amount of water?' He found that the percolation of water through the peat could be described by the well-known (eighteenth century) equation of Laplace ($\partial^2\phi/\partial x^2 + \partial^2\phi/\partial y^2 = 0$), but that the boundaries around the region where the equation had to be solved did not usually have the nice shapes, such as circles and rectangles, that had been studied by mathematicians and for which solutions were known. Although he realized that exact mathematical methods could often be found for more complicated regions, these methods were difficult to derive and were not general for any shape; so faster and more general, if less accurate, methods were necessary. His prescient remarks on this dilemma are as relevant today as in 1908 – though most of today's problems require the solution of more complicated equations.

> Further than this, the method of solution must be easier to become skilled In than the usual methods [i.e. analytical solutions]. Few have time to spend in learning their mysteries. And the results must be easy to verify – much easier than is the case with a complicated piece of algebra. Moreover, the time required to arrive at the desired result by analytical methods cannot be foreseen with any certainty. It may come out in a morning, it may be unfinished at the end of a month. It is no wonder that the practical engineer is shy of anything so risky.

Richardson (1908:1) showed first that a broad brush solution for the peat flow could be obtained by drawing lines of the flow free-hand according to certain rules (which would require a good eraser, a soft pencil and some patience) until the lines satisfied these rules – an approach that was still taught to engineering students in the 1960s. But a more accurate and systematic method for obtaining approximate solutions was to convert the differential equation, defining the smooth continuous changes of the variable (say y, the height of a curve), into an approximate equation relating the small changes in the variable (δy) to the small distances (δx) (or steps) over which they occur.

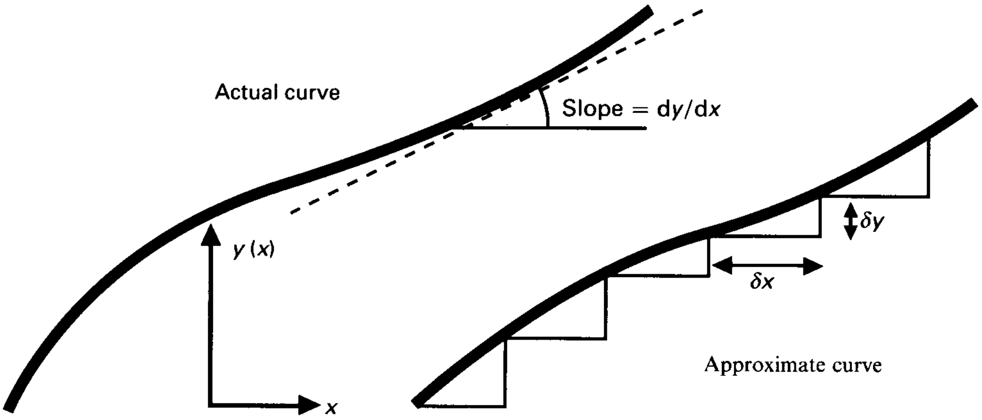

Fig. 1. A sketch to illustrate how a smooth curve is approximated by a series of simple curves between points separated by δx and δy. This is the basis of Richardson's methods for computing the solutions to differential equations.

Then the rules of arithmetic (and algebra) can be used for the sequence of steps rather than the special techniques of differential calculus for continuous functions (in which there are infinitely many steps on the staircase, of infinitesimal size). Richardson (1927:1) later explained that, paradoxically, this approach was an historical regression to a time before the invention of calculus!

Richardson's (1910) paper on this method made use of recent research into finite differences by Sheppard (1899). He also commented that the approximate but more formal methods introduced in Germany by Runge (1895), Kutta and Ganz, for solving differential equations were not suitable, at that time, for solving the kind of practical problem that interested him, such as the percolation of water, the stresses in masonry dams, and, later, meteorology. Not surprisingly to anyone familiar with the scientific and academic worlds this new approach was at first too new for the referees who reviewed the paper for the *Philosophical Transactions of the Royal Society*. It was only after much deliberation and correspondence that it was published (in 1910).

More importantly for Richardson's career this approach to the approximate solution of differential equations was also too new for King's College, Cambridge, where Richardson submitted this work, as a dissertation, in the competition for a Fellowship (i.e. a research and teaching post). Apparently (I am indebted to Professor Huppert for this information from the files of King's College, Cambridge) opinions were sought from the mathematicians at Trinity College, who said this was approximate mathematics and they were not impressed. So Richardson never returned to Cambridge and for the rest of his career he did not work in any of the main centres of academic research. At the time he did not regret this, commenting (apropos of Manchester) that he liked to work 'somewhere where there are fewer people buzzing around'. But this isolation probably affected the development of his research and hindered its appreciation in the scientific community. Perhaps the lack of collaboration with colleagues explained why the presentation of his research was often idiosyncratic, and probably also meant that he did not receive suggestions from other researchers as to how a line of research might profitably develop. It may explain why he moved from one subject to another suddenly and quite often. But one must also recognize that the lack of the 'guiding' influences of colleagues may have been a factor in the great originality and diversity of his research; as G. I. Taylor (1959) commented, Richardson was 'a very interesting and original character who seldom thought on the same lines as his contemporaries and often was not understood by them'.

These early papers helped pioneer the development of 'numerical' methods for the solution of differential equations (reviewed by L. Fox, in Volume 1), a subject he returned to later when it was gaining greatly in importance with the growing use of calculating machines and, later, the arrival of electronic computers (1927:1, 1950:3). At the time Richardson saw the main importance of this work as laying the basis for solving the equations required for predicting weather (reviewed by Charnock, in Volume 1).

Despite the progress he had made in this field of research during this early stage of his career, there were no funds to continue it; indeed, as mentioned earlier, he had to move between short-lived research and teaching posts. No clear direction for his future was emerging. Nevertheless two of these brief projects did reveal his intention of eventually moving away from the physical to the behavioural sciences. He had said to himself as an undergraduate that 'I would like to spend the first half of my life under the strict discipline of physics, and afterwards to apply that training to researches on living things'. According to his own autobiographical notes, 'I kept this programme a secret'.

In 1907 he sold his physics books and briefly went to work as an assistant 'to learn about statistical proof' under Professor Karl Pearson at University College, London, an authority on mathematics, genetics and the philosophy of science. In fact Richardson worked on stresses on masonry dams (1910) and helped prepare an index of the journal *Biometrika* founded for the statistical study of biological problems. He had to leave within a few months because there were no funds for his proposed research into quantitative studies of heredity. This subject together with eugenics were topics he took up between 1912 and 1913 when he was a lecturer at the Municipal School of Technology in Manchester (now the University of Manchester Institute of Science and Technology (UMIST)). He published the first of his papers on the quantitative analysis of 'living things', entitled 'On the measurement of mental "nature" and the study of adopted children' in *Eugenics Review* in 1913:1. It built on some earlier research of Pearson.

During this period of his life L. F. Richardson used to have holidays in a resort on the south coast of England, at Seaview, Isle of Wight, with his friend Stuart Garnett, whom he had met in Cambridge and who, like Richardson, had a wide range of interests; he worked as a barrister, pioneering the new developments in child law, and lived in the East End of London where he helped found the Sea Scouts for the local boys; he also dabbled in Conservative politics and wrote an early book on steam turbines. They stayed with Stuart's parents, William and Rebecca Garnett, who had a substantial seaside house with a boathouse underneath it. Much of the Garnetts' family life was centred on education, boating and religion. William had worked under Professor James Clerk Maxwell as a demonstrator in the Cavendish Laboratory at the University of Cambridge in the 1870s, and later became an administrator and exponent of adult education (after whom Garnett College in London is named). His sons Maxwell, Stuart and Kenneth all excelled in their mathematical studies at Trinity College, Cambridge. Together with their sisters and friends (including also G. I. Taylor from Cambridge) they all joined enthusiastically in sailing and rowing and, on Alpine holidays, in mountaineering.

There, in the Isle of Wight, Richardson met Stuart's sister Dorothy. The family story is that he was attracted by her great sense of fun shown by throwing water over her brothers! They were married in 1909 in London. Dorothy's religion changed from the patriotic, but ascetic, Church of England Christianity of her Garnett family to the pacific Quaker religion of the Richardsons. Nevertheless Dorothy always retained an energetic, optimistic and often headstrong approach to life that was quite a contrast to Richardson's persistently enquiring attitude and his deep and quiet philosophy. Despite the differences in their personalities, their joint sense of fun and adventure led to a happy marriage. Characteristically for that period, Dorothy devoted her life to being his wife and carer of the home and family. However, it turned out that their blood groups were incompatible, so she could not have children. Their three children, Olaf (b. 1917), Stephen (b. 1920) and Elaine (b. 1927) were adopted. Later in the 1930s Dorothy was an energetic voluntary worker and proselytizer for the peace movements, including the League of Nations Union, whose British secretary was her brother Maxwell.

While Richardson and Dorothy were in the Isle of Wight in the Easter holiday of 1912, the large passenger liner *Titanic* collided with an iceberg in the Atlantic, off Newfoundland in foggy weather, and sank with great loss of life. Richardson immediately had the idea that this kind of accident could be avoided if ships sent out a focused beam of sound and then measured the delay time for any echo to be detected by a sensitive receiver. He tested this idea in Seagrove Bay, in a dinghy rowed by Dorothy (as she told the story) to different distances from Seaview Pier (now destroyed). He blew a penny whistle and by measuring the time for the return of the echo, using an umbrella held over his shoulder to amplify the echo, he calculated the distance. He found that the method worked well; so he filed a patent in October 1912, the importance of which led the writers of a text book on fluid mechanics in 1936 (Drysdale *et al.*) to hope that Richardson's 'method will ultimately eliminate the last of the serious dangers of navigation'! This impromptu but highly original experiment was typical of many that Richardson undertook with the minimum of expense, but which usually led to important new ideas. (See also Charnock (1981).)

The sinking of the passenger liner *Titanic* led to a scientific expedition to study the atmosphere and ocean off Newfoundland; the meteorologist was Richardson's great contemporary G. I. Taylor, whose early ideas on turbulence stemmed from his observations there. Richardson's and G. I. Taylor's interest touched again in the next phase of Richardson's career.

1913–16; Meteorology – the first phase

On the recommendation of Richardson's former colleagues at the National Physical Laboratory, he applied for and was appointed to the position of Superintendent of the Eskdalemuir Observatory in Southern Scotland. The Observatory had been set up in a remote location primarily to record magnetic fields and seismic vibration, but also to record meteorological measurements. Richardson had no previous professional experience in meteorology, but, as explained to him in a letter from Napier Shaw, the chairman of the appointments committee (and one of the founders of meteorology as a quantitative science, in Britain), he had been appointed to bring a more theoretical approach to the understanding of meteorology, and a critical examination of the methods of measurement.

This was an attractive position for Richardson, as it came with a house and considerable freedom to pursue his major research interest, that of devising a method for calculating the weather a few hours or days ahead, using the relevant theoretical equations which describe the behaviour of the atmosphere. Although most of the equations were known, there were a number of new aspects of the physics that had to be estimated: also there was the new task of transforming these equations into the appropriate form for some step-by-step method. 'In the bleak and humid solitude of Eskdalemuir', as he described it, he completed the first draft of his book entitled, then, *Weather Prediction by Arithmetical Finite Differences.*

He also participated in some developments of seismography and new techniques for the detection of thunderstorms from their electrical and magnetic fields, using telephone lines. At the same time he was performing the administrative duties of superintendent, which became more onerous after the outbreak of the First World War. Correspondence between Richardson and Napier Shaw (Ashford 1985, p. 50) shows that Richardson was uneasy about using his own and the observatory's scientific knowledge and equipment for military purposes, such as measuring the vibration in the ground caused by distant artillery fire.

Whether or not this was the cause, Richardson resigned from the Meteorological Office on 16 May 1916 to join the Friends' Ambulance Unit in France. He had asked earlier to be released for work with the 'Red Cross Unit of the Ambulance Corps' at the outbreak of war, but had been refused permission. Clearly his parting with the Meteorological Office was amicable, because he was allowed to rejoin in 1919 on his return from France.

1916–19; France and the psychology of war

The Society of Friends always urged its members (Quakers) not to take part in war, and although in the 1914–18 war a few Quakers of military age joined the armed forces, many did not, and either did humanitarian work connected with the war or refused to have anything to do with war activities. Many of the latter were imprisoned, though usually with other conscientious objectors (such as Bertrand Russell).

Richardson followed the pacifist course of action and in 1916 joined the Friends' Ambulance Unit which was financially supported by the Society of Friends. It was set up in 1914, following an initiative by Philip Noel Baker.

At this time many families were divided in their response to the war. Richardson's Cambridge friend and brother-in-law Stuart Garnett was killed while test-flying an aircraft in 1916 in the Royal Flying Corps, and Stuart's younger brother Kenneth, aged 25, died slowly during 1916–17 after being injured with a shrapnel wound in the Battle of the Somme. Richardson was exceptional amongst scientists (in Britain or Germany) in deliberately ceasing to do scientific research financed by the government during the war; other scientists not only continued with their research, but also gave advice to armed forces that was used to great effect, particularly in aerodynamics (such as G. I. Taylor, at Cambridge, L. Prandtl, at Göttingen), ballistics (J. E. Littlewood, at Cambridge), and the chemistry of explosives and gases (C. Weizmann at Manchester).

After initial training Richardson was attached as a driver to the Section Sanitaire Anglaise (SSA 13), a group of fifty-six men with twenty-two ambulances working with the 16th French infantry division. They worked alongside the French military ambulance unit 'Section Sanitaire'. Richardson was, in the words of the ambulance maintenance crew, 'a careful and conscientious driver and managed to avoid careless driving through shell-holes'! For periods of two weeks at a time he was engaged in transporting wounded soldiers, often under shell fire. Then he would have a few days of respite. Occasionally he returned to England for brief periods of leave to see his wife and family.

In his spare time in France Richardson set up and designed various simple meteorological instruments and took readings. Also he had brought along the first draft of his book on numerical weather prediction, and during a six-week period he worked on a specific calculation ('on a heap of hay in a cold wet rest billet') to show how the numerical forecasting system might be used in practice. At one stage the manuscript was lost during the battle of Champagne in April 1917, but fortunately was rediscovered some months later under a heap of coal. The work was finally published in 1922, when he had taken up meteorological research again. In France he also did some 'laboratory' experiments on the motion of water in a vessel on a rotating gramophone turntable; the apparatus was too crude to test the effects of thermal convection and rotation that he was investigating.

The main effect of the war on his research and thinking was to direct him towards studying the causes of wars and how they may be prevented. As usual he began with a quite new approach that was also mathematical. He believed that conflict between nations resulted from a number of factors, chief amongst which were misunderstandings, the general admiration of warlike attitudes, unstable patterns of mutual hostility, the interest of certain industries in war and the absence of effective international organizations for settling differences between governments.

In an unpublished manuscript 'The condition of a lasting peace in Europe' in 1915, he wrote that misunderstandings between peoples and governments could be greatly reduced if there was an international language. He learnt Esperanto, the best known of the international languages at that time, and was a strong advocate of it. (He tried it out on German prisoners of war, but neither they nor any non-Esperanto speaker could or would understand it!) He also wrote about many other psychological and cultural causes of wars, including the factor, so alien to Quakers but common to most societies, of the admiration of military courage for its own sake.

From this beginning he began to develop a mathematical model for how the animosity between two mutually suspicious and well-armed nations might develop over

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time. He suggested that the animosity of each side (the *Entente Cordiale*, i.e. Britain, France, on one side and Germany on the other) could be expressed in terms of numbers derived from measurements. This was therefore a mathematical quantity and could be repesented in equations by the symbols A_E and A_G respectively, which showed how A_E depends on A_G and vice versa. Although mathematics was already in use in various social sciences, it had not previously been used for modelling war *behaviour*. However it had begun to be used for modelling *tactics* of war especially on the basis of the fundamental, and still used, equation of F. W. Lanchester (1916) – another unorthodox Englishman who is equally well known for his pioneering research on aerodynamics, and innovations in automobile engineering.

Richardson wrote up these studies in a fifty-page essay of plain language and equations, *Mathematical Psychology of War* (1919:1) which he dedicated to his 'comrades of the motor ambulance convoy'. They and subsequent readers found the algebra and calculus early on in the text so off-putting that they could not reach the end, where there are understandable and novel conclusions about the circumstances in which the relations between countries can become 'unstable' and wars might ensue.

[Nowadays equations similar to these are taught to students in biology as predator–prey equations. They are not easy, and have to be explained with the use of diagrams and graphs which were missing from Richardson's (1919:1) essay, but were included in his later publication (1939:1).]

The introductory section contains the famous 'apology for the use of mathematics', the first part of which extols the virtues of a mathematical approach in the analysis of complex problems, including those in the social sciences.

> To have to translate one's verbal statements into mathematical formulae compels one carefully to scrutinize the ideas therein expressed. Next the possession of formulae makes it much easier to deduce the consequences. In this way absurd implications, which might have passed unnoticed in a verbal statement, are brought clearly into view and stimulate one to amend the formula.

But, as mentioned earlier, he was also well aware of the dangers of this approach (see Sutherland, below). In arranging to have this essay published. Richardson first approached a commercial publisher, for whom Bertrand Russell reviewed it favourably as an academic book, but Russell also reckoned that it would not sell many copies. The latter point was more important to the publishers, so Richardson had to publish the work privately; three hundred copies cost him £35. But the ideas in this book were certainly not lost; they were the basis of the later mathematical studies of conflict, including Richardson's in the period 1935 to 1953 and much modern research (see Sutherland and Nicholson, below).

Richardson's other early studies of conflict were on how an international assembly, which would have to be created after the war, could function most effectively. Once again he suggested a new measurable quantity – 'internationality' – based in part on international trade, and that this should define the voting strength of a nation in the assembly. Apparently this was considered by a committee of the British Foreign Office; but they preferred the more obvious principle of one vote per state.

1919–26 – Meteorology again; Benson and Westminster College

From France Richardson wrote to Napier Shaw of the Meteorological Office asking whether he could return there, with the specific aim of working on upper-air sounding experiments with a view to making 'weather predictions by a numerical process ... a practical system'. In his letter Richardson floated the idea that, with a large technical staff of twelve to fifteen, he could make rapid progress in overcoming some of the outstanding observational and mathematical problems. If this was not possible he suggested an alternative proposal of a modest research position for himself with an assistant. Shaw replied that the large scheme might be possible technically and even financially, but that other forecasting schemes requiring funds had also been proposed, such as V. Bjerknes' graphical scheme based on the analysis of fronts that had been developed at Bergen during the 1914–18 war, and which subsequently became the basis for understanding weather systems and qualitative weather forecasting throughout the world. Interestingly Bjerknes, who later collaborated with Richardson, had also hinted at the possibility of numerical weather forecasting in 1904, but did not pursue it himself. The outcome was that Richardson was appointed by the Meteorological Office to W. H. Dines' upper-atmosphere research group at Benson, near Oxford.

With a view to providing the data that were a necessary input for the numerical model, and also to test the model, Richardson developed three different kinds of instrument for atmospheric measurements up to several kilometres above the ground; they were all characteristically original, but in fact none were continued after he left Benson (see Charnock, in Volume 1). He developed a complicated method for measuring the upper wind speed by shooting metal spheres of various diameters upwards at small angles to the vertical (1923:1, 1924:1, 1924:2, 1924:4). A nice Richardson touch to the experiments was the arrangement whereby, to protect themselves and record the point of impact, the shooters stood in a shelter underneath a large metal sheet and fired the gun upwards through a central hole (see 1924:4, Fig. 2).

A major task in developing an underlying theory for the numerical method of forecasting was to improve the theory of turbulence and turbulent mixing in the lowest 2 km of the atmosphere. The turbulent eddies determine how rapidly the upper-level atmospheric winds can slip over the earth's surface and how much heat and moisture can be carried up from or down to the earth's surface. The earlier research by Schmidt in Austria, Boussinesq in France, and G. I. Taylor in England had shown that these eddies behave in *some respects* like molecules in a gas so that it was meaningful to define an 'eddy' viscosity or 'eddy' conductivity K (1922:1, p. 67). However, whereas the viscosity or conductivity of a gas is independent of its velocity or kind of motion and independent of the scale over which there are variations in velocity or temperature, and has the same value everywhere (provided the gas is at the same temperature and pressure), none of these properties are true of a turbulent flow. Richardson's research between 1919 and 1926 led to great advances in understanding these special properties of turbulent eddies and in providing a novel kind of physical explanation.

At Benson he followed up some experiments which he had begun in France to study how material randomly disperses in the turbulent eddies in the atmosphere, by measuring the widths of smoke plumes and the distances between floating objects (from seeds to balloons) released into the wind. Some of these experiments provided more data that largely confirmed previous results, such as how K increases with height above