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Conformity to observations and the development of weather prediction

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Conformity to observations takes on a particular significance in relation to weather prediction. Day-to-day weather changes constitute the temporal evolution of a complex and highly chaotic system, and yet the accuracy of weather forecasts can be, and are, readily and regularly assessed by both practitioners and the general public. Here, the development of weather prediction is portrayed against the backcloth of the role played by the criterion of 'conformity to observations' in regulating progress. It has served as a crude banner for castigating an early attempt at forecasting, sustaining an empirically-based but theoretically unsupported approach, summarily dismissing some attempts and yet ignored in another. In more recent developments the criterion has been both deliberately and justifiably weakened, and even turned on its head.

Introduction

One of the foremost criteria regulating the acceptability of a theory is its empirical success or failure. This criterion of 'conformity to observations' has survived, albeit in a variegated form, the development of ideas in the philosophy and sociology of science. In the original Baconian inductive view of science, observations were accorded an elevated status encapsulated in Louis Agassiz's declaration[1] that '… the only scientific system must be one in which the thought, intellectual structure, rises out of and is based upon facts'. In effect conformity is a priori a feature of an inductive theory. In the hypothesis–deductive approach championed by Karl Popper, empirical refutation of a theory heralds its death knell, as Richard Feynmann[2] concluded pithily to a lay audience '… if it disagrees with experiment it is wrong. That is all there is to it.' From this standpoint a theory's lack of conformity to a specific item of empirical evidence provides either grounds for its a posteriori rejection, or at the very least the judicious reassessment of that particular item if the theory provides a persuasive and comprehensive explanation of a raft of other evidence. In the shifting sands of today's sociology of scientific knowledge, conformity to empirical evidence remains an inescapable factor in evaluating a theory's value, notwithstanding the explicit acknowledgement that predispositions can play a role in the gathering, selection and interpretation of empirical evidence and in the pursuit of a particular theory.

Here, we juxtapose the role played by the conformity criterion with an overview of the 150-year development of physically-based weather prediction. The latter is, in essence, an initial-value problem, that is to say it requires a specification of the state of the atmosphere at an initial instant and then the determination of the subsequent temporal evolution of the system. The juxtaposition is of particular interest because weather prediction is pre-eminently an observational science and the apparent ease of verifying forecasts provides the subject with a special flavour. In effect, claims of progress can be (and are) subject to daily critical appraisal by both forecast practitioners and the potential beneficiaries, including the general public. Arguably there is no other branch of science where predictions of the temporal evolution of a complex and chaotic system are assessed so easily and so regularly by so many. In addition to this quasi-political exercise of pursuing science under conditions of significant public interest and ease of scrutiny, the development of weather prediction has also been conducted against the background of societal-cum-economic pressure to provide timely and reliable forecasts to help guide human activity and thereby avert disruption.

The meteorological community's response to the challenge of prediction and, in particular, the role of the 'conformity to observations' criterion in regulating progress is illustrated by highlighting milestones in the development. Overviews are provided of an early cameo attempt in the 1860s, three pioneering yet scientifically prototypical approaches promulgated in the 1900–1920 period, a resurgent effort in the mid-twentieth century, and today's technologically demanding and scientifically refined forecasting methods.

An early exemplar

In the mid-nineteenth century, the scientific community held disparate views on the status of meteorology. On the one hand the prevailing ethos placed emphasis on the solid foundations of science and the reliability of its results. Meteorology could offer neither, and the decree was that it was 'hardly yet a science'. Nevertheless, natural physical phenomena were certainly held to be within the purview of science, and many leading physicists, including Faraday, Kelvin and Helmholtz, were careful observers of the atmosphere and were eager to provide scientific understanding of the accompanying processes.

However, they too recognized the special nature of weather prediction, and Helmholtz[3] surmised

> Under the same firmament on which the eternal stars proceed as the very emblem of nature's unchanging laws, so to clouds gather, rain falls and the winds change symbolising the opposite extreme of the most changeable and capricious of all of nature's phenomena. The latter, transient and intangible, evade every attempt to capture them under the bridle of the law.

On the other hand, the increasing cost of conducting scientific research underlined the need to better explain and justify its value to the wider community, and to harness its power to provide useful predictions. Hence, in 1861, the then-President of the British Association for the Advancement of Science asserted in his presidential address that

> engineering science pre-eminently advanced the power wealth and comforts of mankind.

Moreover, the unforeseen occurrence of extreme weather events with an accompanying loss of life and material was a frequent and stark reminder of the need for reliable weather forecasts.

It was in this setting that Robert Fitzroy, the director of the recently established Meteorological Department of the UK's Board of Trade, proposed in 1859 a visionary initiative to examine the day-to-day development of the weather influencing Europe's western seaboard. He had behind him a chequered career. It included being master of the Beagle during its epic global circumnavigation between 1831 and 1836, with Charles Darwin on board, Governor General of New Zealand during a critical and formative period in the colonies relationship with the Maori, and Fellowship of the Royal Society for his scientific endeavours.

Fitzroy's proposal came at a time when observational data was sparse and irregular, and there was an inadequate recognition of the underlying physical principles. Cyclones impinging upon Europe were thought to be spawned upstream over the Atlantic but maritime data were confined to seafaring observations of weather, wind and barometric pressure change. In addition, there was no coherent theory of cyclogenesis or well-founded principle to help in their prediction. In light of these shortcomings, Fitzroy's proposal was notable on three accounts. First, it was built around the then novel concept of a geographically dispersed observational research programme. He sought[4]

> … in the course of the next twelve months to endeavour to obtain simultaneous observations of wind, weather, and other meteorological information, over the whole Atlantic, and round the coasts of this ocean, by enlisting the aid of observers in every quarter, for one or two observations only, in each day; with a view of getting at the exact state of each portion of the atmosphere, over our

> nearest ocean, during one particular time, on certain days, and then mutually comparing those successive and synoptic *views*, as it were, of the atmosphere, in order to discover the usual or normative sequence or succession of winds and weather, as more particularly affecting seamen and agriculturalists.

Second, the proposal was bolstered by an insightful but essentially intuitively-based hypothesis of cyclogenesis that Fitzroy had first recorded in 1839.[5] He surmised that cyclones formed at the interface of horizontal air currents moving in opposing directions, and he subsequently provided a vivid and not unrealistic depiction of the corresponding wind patterns (Figure 1). Third, effective implementation of the proposal required high level recognition and support from scientific and governmental bodies. A fourth ingredient, not part of the original proposal but evident in his contemporaneous writings, was that Fitzroy also recognized that the programme might also provide the rudiments for a forecasting procedure.

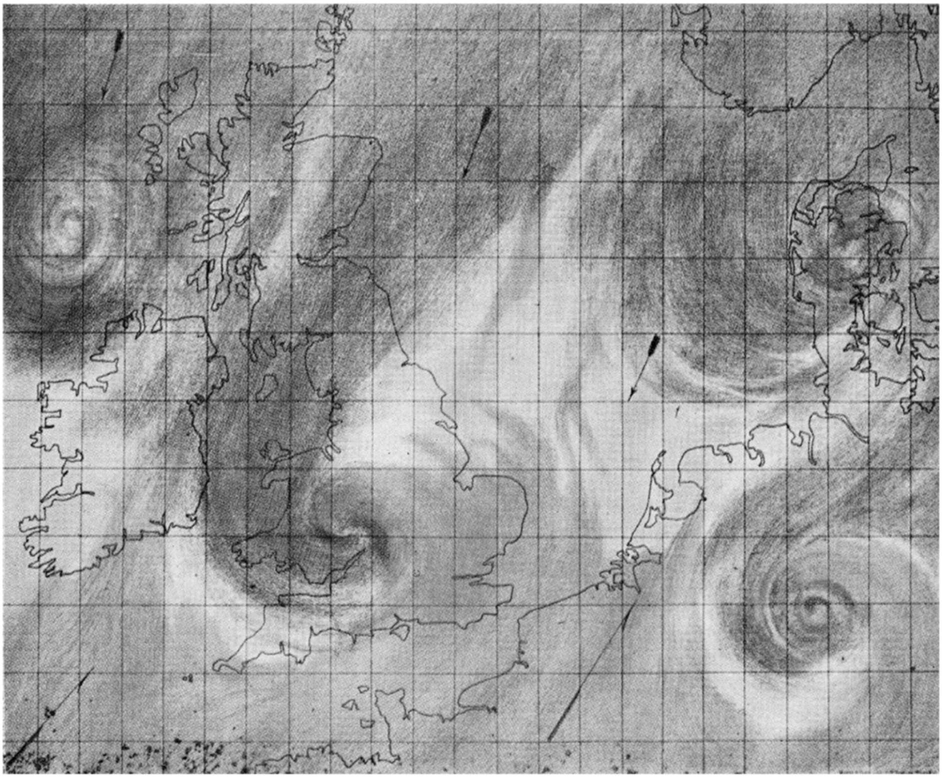

Figure 1. This is Fitzroy's highly schematic depiction (circa. 1862) of cyclonic storms forming at the interface of cold polar and warm tropical airstreams, and pertains to the expected surface pattern. It is recognisably the prototype for the weather patterns that we are used to seeing today.

Fitzroy's proposal was welcomed. He sought and gained the approval of the Royal Society, funding from the British Association, and cooperation from the Admiralty and the Government. The proposal and the response to it coincided with the shipwreck of the *Royal Charter* off the coast of North Wales in 1859. Thus, the project was set in place and operated during the early to mid 1860s.

In addition to executing the pre-stipulated research component of the proposal, Fitzroy also proceeded to produce and disseminate forecasts of coastal storm warnings. The programme's remit and research output hardly merited such an action, and the forecasts met with a mixed reception. On the negative side, Fitzroy was reviled and ridiculed by the press, with for example the *Times* newspaper in London denigrating both the content and terminology of the forecasts. The Royal Society disassociated itself from the forecasting component of the venture, and the issue of the warnings was suspended by November 1886. Later international luminaries of the meteorological community, unwilling to be tarred by the same brush and conscious of the need to portray the discipline in an appropriate light, elected to distance themselves somewhat from the task of 'forecasting'. They advocated that the community should limit itself to issuing guarded advice on the likelihood of severe weather.

On the positive side Fitzroy's effort was highly appreciated by the maritime-user community and by some leading meteorologists. More trenchantly, independent analysis[6] revealed a rapid increase in forecast skill during the project's lifetime. In the year to 31 March 1865, storm warnings issued for England were correct 73% of the time, whilst for northern France they were correct 92% of the time.

In effect, this limited degree of conformity of the forecasts to the observations allied with the lack of a well-founded physically-based forecasting procedure ran counter to the prevailing scientific ethos and led to the project's demise. In retrospect, it is ironic to note that this level of reliability would now be deemed highly creditable given the sparseness of the available observational data, and that the issue of storm warnings was speedily resumed in response to popular request.

Three prototypical approaches

By the end of nineteenth century, many nations had established a network of surface meteorological observation stations, and telegraphy allowed the rapid transmission of the gathered information. Thus, it was possible, with a minimum of delay, to prepare charts displaying the prevailing pattern of surface pressure, and a temporal sequence of such charts gave some indication of the nature of the weather's evolution. Likewise, the underlying physical laws were now established and formulated as mathematical equations.

Against this background, three novel and radically different approaches were proposed to predict the weather in the first two decades of the twentieth century. The approaches encapsulated, respectively, *empirical-inductive*, *hypothesis-deductive* and *complex system modelling* styles of conducting scientific research. These approaches and the responses to them were central to the development of weather prediction and they also serve as early and telling examples of the respective styles.

The Bergen School's approach

In the years around 1920, the Bergen School of meteorologists, led by Vilhelm Bjerknes, honed an approach to weather prediction that was at least portrayed by them as being avowedly Baconian in conception and execution. Bjerknes had already made some fundamental contributions to the theoretical and field study of atmospheric flow.

Domiciled in Bergen during World War I without access to international meteorological observations, Bjerknes established a network of meteorological observing stations covering western Norway, and he sought to develop a forecasting method focusing on the use of surface data. The approach built upon previously accrued knowledge of the structure of day-to-day weather patterns, but now special emphasis was placed upon the existence and evolution of two quasi-discontinuities (i.e. cold and warm fronts) in the surface flow pattern.[7] The fronts were diagnosed to delineate zones of significant weather, and viewed as segments of a single discontinuity. Further, it was asserted that the front underwent a wave-like development with a cyclone forming at each wave's crest, and that the future atmospheric state could be inferred from the current phase of the evolution.[8]

In short, the Bergen School set out an empirical-inductive approach to weather prediction. It entailed a systematic analysis of the limited observations with a view to identifying salient aspects of the currently prevailing weather pattern, and then inferring the future flow evolution by historical analogy. In addition, the Bergen School sought to underpin their approach with a rudimentary hypothesis that cyclogenesis was the result of an intrinsic instability of the front resulting in the formation of a train of wave-cyclones.

Their approach gained widespread acceptance by the mid-1930s. This response hinged in part on three facets. First, it was practical in that the observational requirements were not excessive, the analysis procedure was physically-based, relatively easy to assimilate, and resulted in a bold and clear portrayal of the weather situation. Even in the refined form it acquired over two decades that entailed the construction of charts at various elevations it was judged to be

> … in principle remarkably direct and simple to understand. The many observations of pressure, temperature and humidity, wind and weather phenomena, obtained from a wide area and made more or less synchronously, are plotted on geographical maps of the area and made surveyable by various cartographical methods. …providing the forecaster with three-dimensional model of the atmosphere which he visualises as an entity. The process, which is conveniently referred to as analysis of the situation, is actually a process of synthesis: from the many discrete observations the field distributions of the various properties and phenomena are inferred. From a sequence of observational material the synthesis is extended to the fourth dimension; the forecaster has in mind the changing distribution patterns, … and forecasting is the extrapolation of the model into the future.[9]

Second, the approach was empirically plausible in that, on a routine basis, the analysis could be made to conform reasonably with the available surface observations. Thirdly, the potential linkage to a wave-instability rendered it theoretically attractive and accorded it a scientific pedigree.

Its adoption also carried an element of expediency. In the 1930s, public pressure for better forecasts was certainly a factor and there was no rival new and feasible forecasting scheme. It is noteworthy that the UK weather service's adoption of the approach on 1 March 1933 was preceded a few days earlier by a bad misforecast of a blizzard.

At root, the sustained acceptance of the approach was allied to its avowedly inductive nature. In short, it was difficult to disprove or discard a method that conformed reasonably with observations, was sufficiently elastic to allow for refinement to accommodate new observations and insight, and for the most part provided tolerable forecasts.

However the approach remained bereft of firm theoretical underpinning based on the concept of frontal wave-instability, and was subsequently undermined by the accumulation of empirical evidence plus a complementary theory that emphasized the distinctive and salient aspects of flow at higher elevations. Both the approach and the response illustrate the nature and power as well as the shortcomings of the empirical-inductive approach

Felix Exner's approach

In 1902, the young Felix Exner was embarking upon a research career in Vienna that would be devoted to applying a physico-mathematical approach to the study of atmospheric flow and that would establish him as a leader in the field.

In the early years of that career he grappled with the challenge of numerically simulating the evolution of weather patterns. His first attempt was limited in scope and well founded mathematically but was abandoned after a colleague, Max Margules, pointed out that the available data were not of sufficient accuracy to justify the approach. In effect, theoretical considerations on the inadequacy of the empirical information regulated the development.

His subsequent effort[10] is a forerunner of the application of the hypothesis–deductive approach to geophysical flow systems. In essence, his strategy was to identify a significant feature of the weather, and then to examine its role in to the flow evolution by constructing a highly simplified model to evaluate the impact of the attendant process when it operates in isolation.

His selected feature was the sharp increase in the surface pressure over a region that accompanies the passage of a surge of cold polar air. His model construction was an insightful quest for simplicity. It was based upon two perceptive approximations about the nature of the flow – hydrostatic balance in the vertical between the pressure gradient and the gravitational force, and geostrophic balance in the horizontal between the pressure gradient and the Coriolis force due to the earth's rotation. He further assumed that the horizontal variations of pressure and temperature were co-aligned in the vertical and decreased in amplitude with height. The resulting model reduced the meteorological set of equations to one equation for one unknown – the conservation of a fluid parcel's entropy (i.e. potential temperature) as it moves horizontally with the geostrophic flow. He proceeded to solve the initial value problem for one particular atmospheric event by specifying the requisite initial state for his model and integrating it numerically forward in time. This was a major achievement. Moreover, comparison of his first result with the actual flow development showed that the forecast itself was relatively successful, and a series of further forecasts were creditable at least when cold air outbreaks were a prominent feature of the flow.

However Exner did not persist with this approach. On the basis of empirical evidence he and his colleagues in Vienna became convinced that tropopause-level effects played a significant role in day-to-day weather variations, and he came to view his model as merely providing an estimate of the decidedly limited contribution of the lower-level contribution,

> However in assessing the practical utility of the new method it would appear that it nevertheless can serve to separate the normal from the unusual cases, and thereby offers at least a glimpse of the normal evolution.[10]

He held out the hope that the theoretical framework of his approach could be refined, but did not return to the problem of prediction. Instead he focused on a range of related dynamical problems.[11]

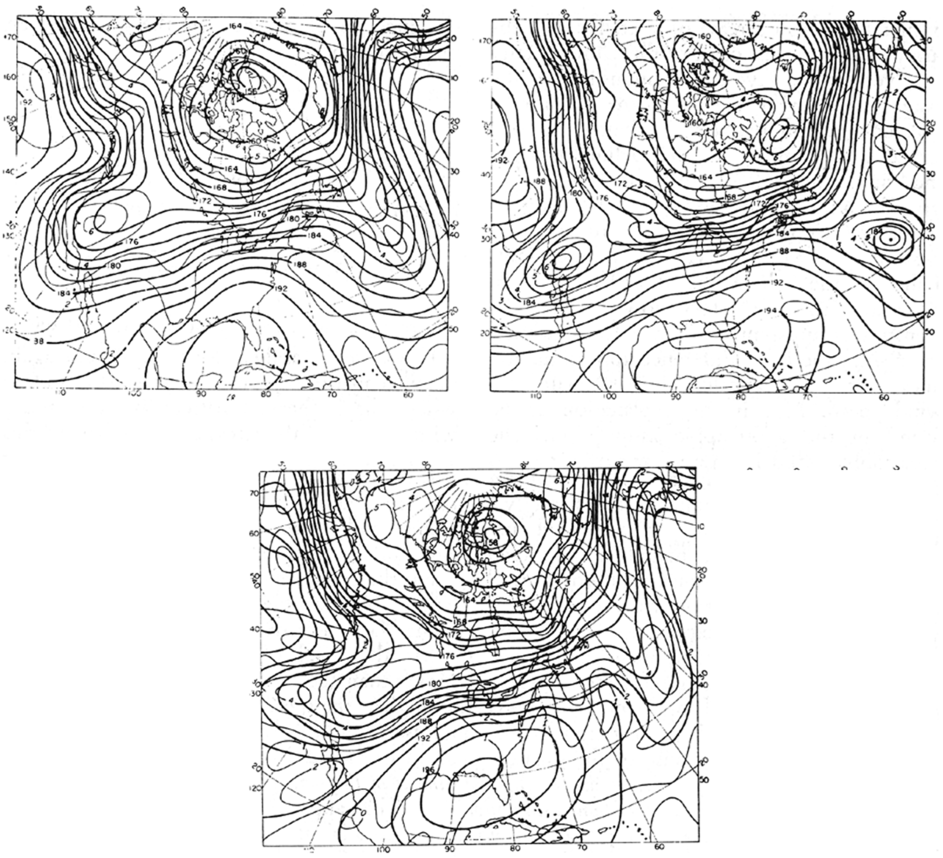

Figure 2. The upper panels show the analysed vorticity distribution (bold isolines) at a mid-tropospheric level for 03:00 GMT on 13 February 1949, and the same field 24 hours later. The lower panel shows the forecasted vorticity field for the latter time as computed by Charney and his colleagues. (The figure is adapted from Ref. 16.)

Exner's approach captures the essence and bears the hallmark of current day studies in the realm of geophysical fluid dynamics. It provides an early and succinct recipe for the hypothesis-deductive approach, and as such includes a willingness to relinquish a promising line of research in the face of persuasive counter empirical evidence.

Lewis Fry Richardson's approach

A stunningly ambitious approach to numerical weather prediction was developed by Lewis Fry Richardson in the mid-1910s and published in his book on the subject in 1922.[12] Richardson was a singular scientist with a notable talent for undertaking highly innovative research that, as well as a treasury of meteorological studies, included for example a rigorous mathematical formulation of an empirically-based theory for international conflict.

His approach to weather prediction epitomizes that adopted in many present-day studies of complex systems. At root, his reasoning was based upon the juxtaposition of two allied considerations. First, atmospheric flow and its interaction with the underlying surface was a complex system governed by a known set of equations that included a myriad of physical processes. Second, the system's temporal evolution could, in principle, be evaluated by solving the governing equations numerically in a forward-marching process subject to an adequate representation of the flow and the initial atmospheric state.

Richardson's approach was nothing less than a direct attack on the problem of physico-mathematical weather prediction. It yielded many notable achievements including: identification of the main governing equations, introduction of a perceptive and major simplification in the form of a diagnostic (rather than prognostic) equation for the vertical velocity, inference of the spatial scale of weather systems and thereby the establishment of criteria for adequate spatial numerical representation, development of simplified representations for a range of physical processes and prescription of the initial atmospheric state from the extant but limited observational data set. He incorporated all these aspects into a comparatively comprehensive numerical model and proceeded to estimate the evolution of the surface pressure.

The resulting forecast judged in quantitative terms was an abject failure with a prediction of a totally unrealistic change in the surface pressure. Fully persuaded that his approach was correct but that conformity to observations was nevertheless the yardstick of success, he encouraged others to follow his method, concluding laconically 'In such a way it is thought that our knowledge of meteorology might be tested and widened'.[12]

Richardson's prediction was first classified as a glorious failure and then with the advent of high-speed computers paraded as a prime example of system modelling. Thus, a subsequent leader in the field noted[13]

> It mattered little that the time was not yet ripe for putting into practice the methods Richardson devised. What is important is that he realized that sooner or later numerical methods must be used for the integration of the atmospheric equations and that it was perfectly feasible to do so.

The failure itself pointed to the need for better observations and highlighted the need for an improved understanding of the nature of the system. Caveats that also confront today's community of system modellers.

Although Bjerknes, Exner and Richardson pursued different approaches to prediction, all three nevertheless placed weight upon the conformity criterion.

Bjerknes[12] affirmed ‘If only the calculation shall agree with the facts, the scientific victory will be won’. Exner[10] had systematically compared his forecasts to examine the ‘correspondence with reality’, and Richardson[12] pointedly asked of his results ‘does it conform to the nature of the external world?’

All three were also versatile researchers open to pursuing different approaches. Bjerknes, in 1904[14] and again in 1913, had issued a clarion call to the meteorological community to engage in weather prediction based upon fundamental physical and dynamical principles and involving the integration of the governing equations. Likewise, Exner was also comfortable conducting empirically-based and statistical studies of large-scale atmospheric flow. Richardson’s research repertoire was strikingly broad and in his hypothesis-deductive approach to the study of international conflict he offers a delightful apologia for that approach,

> Strange to say, it is to the advantage of realism that mathematicians customarily replace the actual world by various idealised models. For they choose models that can be analysed with ease: and thus they are free to think about the resemblance or misfits between the model and the actual world. If, with a solemn feeling of the importance of things as they really are, we were to admit the irregularities of the actual world into the statement of our problems, we should in consequence have to attend to enormous elaborations of mathematics in the process of solution, whereby our attention would for a long time be distracted away from the actual world.[15]

A mid twentieth century breakthrough

In the late 1940s, John von Neumann casting around for a suitably challenging and prestigious task for the newly constructed ENIAC computer in the United States, selected the topic of weather prediction. He gathered around him a group of atmospheric dynamicists under the intellectual leadership of Jule Charney.

They launched a systematic research programme based upon an elegant breakthrough in our understanding of the atmosphere’s large-scale flow (attributable at least in part to Charney himself). On this scale the flow has a subtle character whereby the prevailing slight departure from geostrophic balance serves to maintain that state of quasi-balance and yet allow for the day-to-day weather development! This quasi-balanced development is neatly represented in terms of a single equation for the conservation of a fluid parcel’s potential vorticity as it moves horizontally with the geostrophic flow. Moreover, the prevailing spatial distribution of the esoteric potential vorticity variable itself determines the instantaneous flow and thermal state of the fluid.

This new perspective can be viewed as a major conceptual extension of Exner’s approach. It also accounts for Richardson’s failure since his initial conditions did not capture the quasi-balanced nature of the atmosphere and led to the spurious generation of large amplitude and high frequency buoyancy waves rather then the slower evolution of the meteorologically relevant part of the flow. In effect, Richardson's forecast failure was a symptom of the lack of conformity to the initial atmospheric state. More trenchantly, the new perspective provided a physically consistent set of reduced equations for predicting atmospheric flow development whose numerical solution was feasible using the first generation of computers.

The early predictions[16] were not a spectacular success. Approached for his view of this new attempt at forecasting, Richardson coyly pointed out that based upon inspection of charts for the initial state, the subsequent state, and the forecast of the subsequent state, it was difficult to decide which two charts bore the greatest similarity! (Figure 2 allows the reader to attempt the same exercise.) Notwithstanding this lack of conformity with the subsequent observations, the scientific progress achieved was deemed to be a major advance, and meteorology's position in the mainstream of science became unassailable. By the mid-1960s, forecasts using this new framework were being produced by the weather services of many countries, and they showed a reasonable skill for the 1–2 day period.

Present status

At root, successful numerical weather prediction is hampered by imperfect models, inadequate observational data, and by the nature of the large-scale flow itself. In recent decades considerable advance has been made in improving models, utilizing new forms of data and in grappling with the special character of the flow. In the process, meteorologists have extended, weakened and even turned the conformity criterion on its head, whilst still retaining it as the incontestable core criterion for judging the veracity of a prediction.

In the realm of model improvement, the rapid increase in computer power has been decisive. Prediction is undertaken with state-of-the-art high-speed computers whose current configuration delivers a performance approaching 2 Teraflops (flop denoting 'Floating Point Operation' per second) with an accompanying total memory of a Terabyte. One of the early changes was to resort to Richardson's original set of equations but with care being taken to ensure an appropriate quasi-balance of the initial conditions. This represents an insistence of matching one aspect of the initial state of the model to the conformity criterion. Models used for conducting global ten-day forecasts have a horizontal resolution of ~ 40 km and over 30 layers in the vertical. Thus they include the explicit representation of fine-scale features such as weather fronts, and the implicit representation of a myriad of physical processes related to clouds, radiation and aspects of the atmosphere's interaction with the underlying surface and ocean.

Likewise, the establishment of the initial atmospheric state for the forecasting procedure has benefited from the enormous increase in the quantity and type of observational data. Leading weather centres such as the European Centre for Medium-range Weather Forecasts (ECMWF) now process daily over 800 megabytes of observational data from diverse sources – satellites, aircraft, ships, buoys, balloons and land-based measurements. A key challenge is to exploit not only the data available for the initial time but also the earlier asynchronous historical data. A refined procedure, so-called four-dimensional data assimilation, has been developed for establishing an initial state, and the computer time expended in the process is comparable to that used for the subsequent forecast itself. It involves assigning, in a physically consistent way, relative weights to the observational data and the fields generated in the model's earlier prediction of the atmosphere's evolution to the initial time. Such is the quality of the predictions generated by the current genre of forecasting systems compared with possible observational measurement errors that the assignment of the weights becomes a subtle exercise. This amounts to a strategy of weakening the conformity to observations criterion by seeking a blend of the artificial model data and the possibly erroneous observational data.

Quantitative measures can be, and are, set to assess progress in forecast skill. (Hence the performance of different weather centres can be compared in the meteorological equivalent of an international beauty competition.) For the ECMWF, such a measure indicates that the forecast period for which the prediction retains useful value has increased from an average of 5 days in 1980, to 7 days in 2000, and was approaching 8 days at the end of 2003.

This prompts the question of whether there is an ultimate limit. The answer relates directly to the nature of the atmospheric flow itself. It bears the hallmark of a chaotic system so that two initially similar, and observationally almost indistinguishable, atmospheric states can be expected to deviate rapidly from one another on the time-scale of a few days. This places a bound upon the flow's predictability, and renders regular and accurate extended deterministic prediction not merely difficult but intrinsically unachievable. In effect, the weather forecaster often has a legitimate apologia for a forecast failure!

Confronted with this limit to deterministic predictability, the meteorological community has deftly moved the goalposts for prediction. It now seeks to determine whether some initial atmospheric states are inherently more predictable than others, and whether improving the knowledge of the initial state in some particularly sensitive region could increase the predictability time-horizon.

To address the first question, the approach has been to continue to issue a conventional deterministic forecast, whilst contemporaneously seeking to quantify the reliability of that forecast – in effect to attempt to forecast the skill of the forecast. This is done by performing an ensemble of forecasts, all from the same initial time but with slightly different initial states, and the latter states are chosen circumspectly in an attempt to generate as wide as possible a divergence of the forecasts. Then, having sought diversity, the original forecast is deemed more reliable if that diversity proves to be small. It is a strategy that amounts to reversing the goal of conformity to observations by seeking to generate a set of possible flow evolutions, each characterized by a large departure from the realized flow. An example is the ensemble of forecasts for the wind-storm Lothar that wreaked havoc over Europe immediately after Christmas 1999 (Figure 3).

For the second issue, the idea is to combine theoretical techniques aimed at pinpointing sensitive regions of the flow with observational techniques capable of securing more data in the same regions. It amounts to a strategy of selectively choosing where to seek greater conformity to the realized world.

This new perspective on, and framework for, weather prediction stems from the recognition of the chaotic nature of atmospheric flow. It both underlines

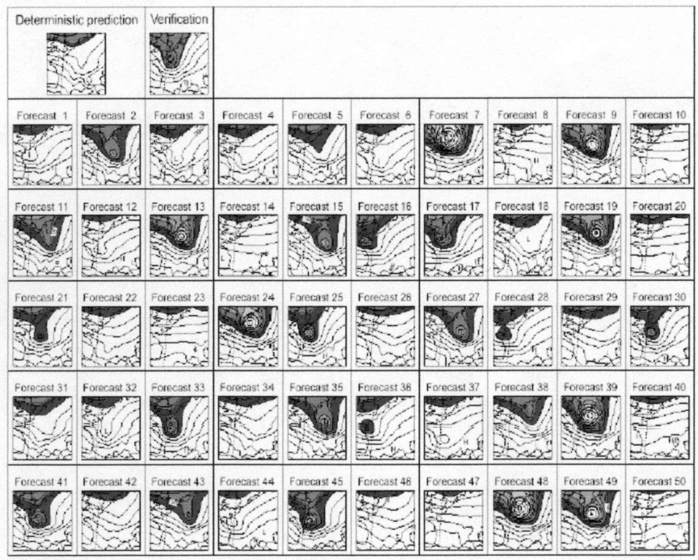

Figure 3. An ensemble of forecasts of the surface pressure 42 hours after the initial start time, for the Lothar storm in France and Germany in 1999 as derived by the European Centre for Medium-range Weather Forecasts (ECMWF). The upper panels show the standard forecast (left) which did not predict the storm and the actual pattern that was found (right). The remaining panels show the results of forecast with slightly different initial conditions used in the calculation. Fourteen of the 50 forecasts predicted a storm of equal or greater intensity to Lothar. The figure is taken from Ref. 17 and is courtesy of the ECMWF.

Helmholtz's view of the flow's capricious nature whilst attempting to capture its essence within the law's bridle.

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