Contribution of fluid mechanics to recent developments in meteorology

J. C. R. Hunt

A number of general fluid dynamical, mathematical and computational questions are considered in this review relating to numerical weather predictions, namely discretization of the governing partial differential equations whose solutions on length scales smaller than that of the discretization have repeatable and characteristic (or 'eigen') elements; optimum use of data in incompletely posed problems; combining statistical and deterministic solutions, and the development of objective methods for choosing between patterns according to certain criteria. Finally the contributions of fluid dynamic and meteorological concepts as aids to human forecasters are emphasized.

THE most important application of the study of meteorology, and meteorological fluid mechanics, is the improvement of forecasting of weather and climate.

In the last century and even today people question whether forecasting is a scientific activity. This problem was raised officially in the Board of Trade and Royal Society report on the Meteorological Office in 1866, which had been founded in 1854, and was issuing two day forecast in the *Times* newspaper in the 1860s. The strictures of the report led to a cessation of forecasts for 12 years from December 6th, 1866! (It is thought that the enquiry leading to this report contributed to the depression and suicide, in 1865, of the pioneering, first director of the Meteorological Office, Vice-Admiral Fitzroy.) Taking a more optimistic view, L. F. Richardson, working at the Meteorological Office in 1913, was so sure of the value of a scientific approach that he reflected whether one day forecasting would 'resemble the process by which the Nautical Almanac is produced'! However, as we learnt later from the research on chaotic dynamical systems by E. N. Lorenz[1] in the 1960s, forecasting can never be that accurate, however elaborate the calculations or comprehensive the data on which they are based. In fact, scientific forecasting follows quite closely the principles set out in Richardson's 1922 book *Weather Prediction by Numerical Process*[2].

Since forecasting began, it has involved physical and fluid dynamical concepts. It still does so; but increasingly it involves mathematical and computational modelling of atmospheric processes by using the results of physical science, particularly fluid dynamics and thermodynamics. More recently, the chemical processes in the atmosphere have also begun to be modelled with a special emphasis on their long term effects on the stratosphere, especially concentrated within the polar vortices where as fluid mechanics has shown, the horizontal diffusion can be quite weak[3].

Principles and problems of numerical meteorological forecasting

The essential procedure for forecasting the atmospheric environment by numerical methods, first set out by Richardson, is (a) to divide the atmosphere into flat grid 'boxes' (that are very shallow near the ground and deep in the stratosphere), (b) using the differential equations of dynamics and thermodynamics to estimate average values of physical quantities (such as pressure and velocity) within these boxes, and (c) using the equations again; this time the equations are used to calculate how these average quantities change with time, which, like space, is divided into discrete intervals. Neither the steps (b) and (c) are exact procedures and so, not surprisingly, even at this advanced stage of numerical weather prediction, there are significant variations in how these approximations are made by different research teams (e.g. the effect on momentum transfer of deep convection[4]).

The methods used by meteorologists for calculating the effects on the larger scale 'resolved' motion of atmospheric processes on the subgrid scale are quite different to those currently used in the numerical simulation of turbulent flows, such as those applied to problems in engineering. Rather than assuming that these motions are simply unstructured chaotic eddying, an

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essentially different assumption is made that within each flat box whose horizontal extent Δx is a few tens of kilometres wide and whose depth (l) ranges from a few hundreds of metres up to a few kilometres, there is a single *type* of atmospheric motion generally having a defined observational characteristic area and internal structure (e.g. particular forms of velocity, humidity and temperature properties dependent on l). This assumption is obviously not valid across weather fronts where there are steep gradients that vary in horizontal and vertical directions. Then, although the model smooths the changes across the front between the states of the atmosphere either side of it, the model does predict these changes and the mean movement and distortion of the front. However, sometimes this lack of *small scale* discrimination leads to *large scale* errors, e.g. in the form of 'cut-off' vortices around low pressure regions.

The secondary assumptions are that there are only a finite number of 'types' and that the 'types' can be defined by the values of the quantities calculated on the scale of the grid box (see Figure 1). For example, convection patterns and cloud types are found to be determined by the degree to which the local mean density and velocity gradients of the resolved scale motions are stable or unstable to small disturbances. This is approximately defined by the Richardson number, $Ri = g\Delta\rho l/\Delta u^2\rho_0$ (ref. 5), where $\Delta\rho$ and Δu are the changes in velocity and potential density across the box.

In the language of mathematical physics one might say that atmospheric motions on the scale less than Δx have a small number of eigen-states; or in the language of turbulence specialists, 'coherent structures'.

I believe that the first person to make this bold hypothesis was Luke Howard[6], who stated:

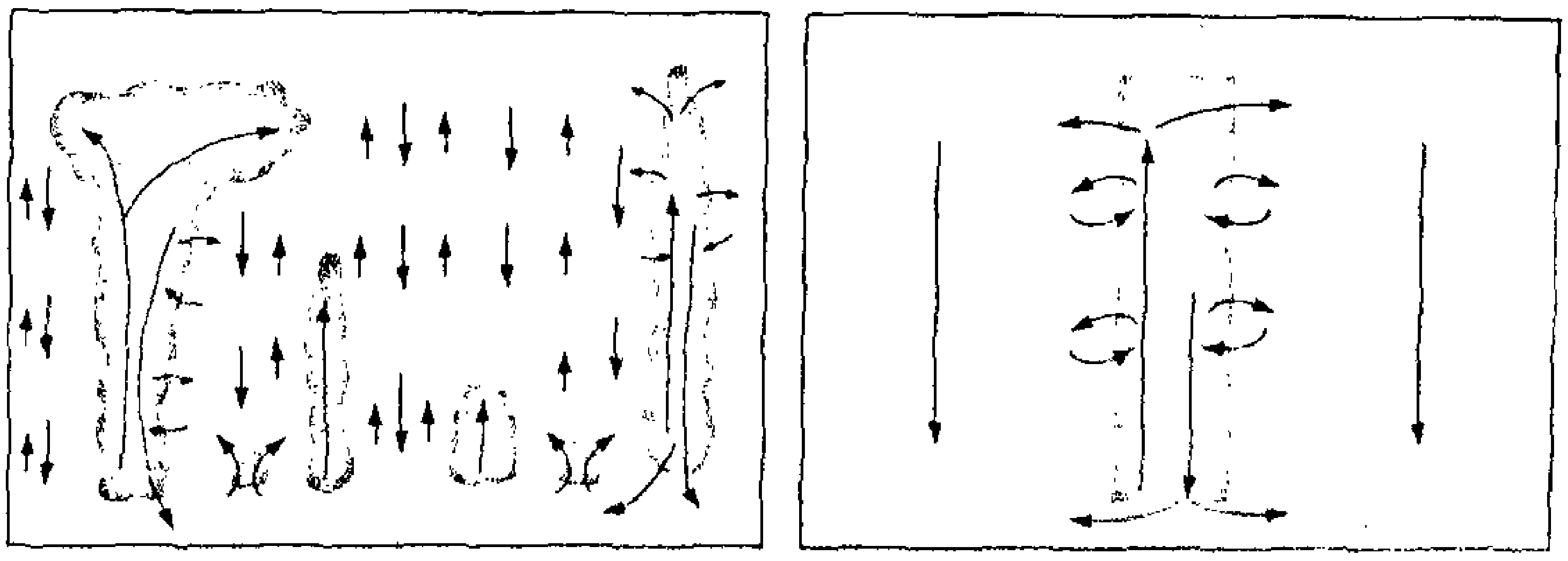
> If clouds were the mere result of the condensation of vapour in the masses of atmosphere which they occupy, if their variations were produced by the movements of the atmosphere alone, then indeed might the study of them be deemed an useless pursuit of shadows, an attempt to describe forms which, being the sport of winds, must be ever varying, and therefore not to be defined.
>
> But however the erroneous admission of this opinion may have operated to prevent attention to them, the case is not so with clouds. They are subject to certain distinct modifications, produced by the general causes which effect all the variations of the atmosphere; they are commonly as good visible indications of the operation of these causes, as is the countenance of the state of a person's mind or body.

This provided the rationale of this classification of clouds that meteorologists have followed ever since. Modern meteorology agrees with Howard in attributing the physical causes to the clouds' forms. But whereas he thought clouds caused their own electrostatic fields, it is now known that they set up their own fluid- and thermo-dynamical fields; that is where science has progressed!

The numerical procedure of deriving equations that only account for the motions of the atmosphere above a certain length scale and time interval can also be performed by representing these motions and other phenomena using the 'spectral technique', in terms of sinusoidal waves – following[7]. The problems of 'averaging out' the smaller scales are similar in the two methods.

In mathematical terms, the problem has now been converted from one of calculus (i.e. solving differential equations) into a very large algebraic calculation, which, as Richardson pointed out, is rather like turning the clock back from Newton, Leibnitz and Bernoulli's analyses of curves by calculus, to Archimedes' analysis by segments!

However, even if the equations describing the behaviour of the atmosphere (at least averaging within each grid box) were exactly correct, the results could not represent the actual state of the atmosphere unless there



ACTUAL

Ensemble of clouds with gravity wave response (up and down in cloud movement).

REPRESENTATION

One cloud with subsidence in environment

Figure 1.

were sufficient data, at a given time, to begin the calculations. Note that the data introduced into the simulations are point measurements; they contain only a fraction of the information about the local atmosphere recorded by a meteorological observer (cloud types at different heights, visibilities in different directions, etc.). One of the reasons why the recently developed techniques of 'data assimilation' enable the forecast calculations to make optimum use of the atmospheric and oceanic data is that, for each stage, the data is inserted in such a way that locally the atmosphere is close to a dynamic balance (otherwise a new data point would produce spurious accelerations[8]). This type of calculation, where the data and the methods are both imperfectly specified, is derived from mathematical control theory. It is beginning to be applied to engineering fluid mechanics, based on similar principles, in predicting the movement of turbulent eddies in order to control the flow by small active wall elements[9].

Once the procedures are defined, the next general question is how to make best use of computers. The obvious choice is to reduce the size of the grid 'boxes' and the time intervals over which the atmospheric behaviour is averaged (the relative magnitudes of these boxes and intervals being approximately determined by the speed and time variation of atmospheric waves, weather patterns and the thermal radiation balance). Other choices are to increase the complexity of numerical modelling (e.g. of advection schemes) and of physical modelling, to improve the accuracy with which measurements are analysed (especially the very costly data from satellites that need to be utilized more effectively) and to spend more computer time on 'data assimilation' calculations to optimize the fit of the modelled atmospheric behaviour to the present and past data.

When operational numerical weather prediction began in the UK in the 1960s, the emphasis was on using computers to reduce the size of the grid boxes in the horizontal and the vertical and time interval. This was because most of the errors were caused by the large grid size, and because it was thought that most of the significant 'weather', especially clouds and rain, were determined by 'dynamic' processes and by the broad patterns of convergence and divergence of the horizontal wind field. This is largely true for the kind of conditions, particularly the frontal systems which dominate weather at high latitudes.

But it is not a valid assumption for weather that is strongly affected by local ground heating/cooling and evaporation, such as those occurring in continental climates, and even in the UK in summer!

Consequently, the present practice is to use increased computer capacity to improve the physical modelling and data analysis, rather more than reducing the grid-boxes' size.

Different ranges of forecasting weather and climate

Different types of calculations and data use are necessary for forecasts over short periods, and for distances that are small compared with the scale of the globe. For specific local calculations, for example wind at an airport or wind energy over a hill, the horizontal size of some 'boxes' may be as small as a few metres. However, for daily forecasts, at least three Meteorological Services in Europe now calculate atmospheric conditions on the mesoscale of 10–15 km. This kind of calculation leads to significant improvements in the forecasts of rainfall patterns, especially where there are strong topographic effects. The next step forward will include assimilation of data from weather radars and satellites, and, a real fluid mechanical challenge, more detailed flow field models, including '$1\frac{1}{2}$' level turbulence models.

Over a longer period, beyond the 5 days of the usual deterministic global forecasts (on a resolution of 90 km), it is found that, when slightly different data are fed into the calculation, on some occasions a number of quite different weather patterns are forecast; but in other circumstances, all the forecast weather patterns remain quite similar to each other. (This is the nearest that weather forecasting has come to make use of 'chaos' theory in practice[10].) In the latter situations, the forecast beyond 5 days should be more reliable. The study of these sets of forecasts may be a way of estimating the reliability of longer range forecasts, a method being investigated in detail at the European Centre for Medium Range Weather Forecasts at Reading, as well as in the UK and US Meteorological Services. These and other services are collaborating to find the best practical use of these 'ensemble forecasts' and, just as important, the best way to communicate their results to the public and customers, possibly by a greater emphasis on making forecasts in probabilistic terms. Some Weather Services consider that these ensemble forecasts provide more useful information for improving extended range forecasts over 6 to 10 days than is provided by the information obtained with a single forecast based on reduced grid size. The greater the number of realizations in these ensemble forecasts, the greater computer time required. Despite the fact that they have to be run with larger and fewer grid boxes, the usefulness of this approach is now widely recognized.

A promising modification to these large number of 'deterministic' calculations from given data (whether actual or with some slight artificial differences) is to make forecasts, of, say, temperature beyond 5 days ahead, by only using computations of the large scale behaviour of the atmosphere, such as whether there will be a static high pressure region or a sequence of depressions carried by strong westerlies. Then this information is combined with statistical information obtained over previous years that link these weather systems with the local information required by the forecasts such as temperature and rainfall. This 'mixed' approach is proving to be more accurate than simply relying on average climatology for forecasts of up to 1 month ahead. It is valuable to certain commercial customers who have to make business decisions based on estimates of the weather 10 to 30 days ahead. Decisions based on computer modelling techniques can benefit most from these long range statistical forecasts. However, the results are of limited use to the general public who would find it difficult to make use of a forecast that is reasonably correct only above 7 times out of 10! (Note that this is a significant achievement, because if average climate statistics only were used, the accuracy would be about 50% (ref. 11).)

In some parts of the world – particularly the Sahel in Africa and NE Brazil – the good statistical correlation between the climate and the slow variations of the temperature of the upper layers of the ocean enables the UKMO to provide satisfactory seasonal forecasts of rain and temperature, that local Met. Services and government agencies find very valuable. (A critical fluid dynamic problem here is to improve the modelling of the depth of the mixed layer of the ocean, which depends on estimating the entrainment processes between a well mixed turbulent region above the 'thermocline inversion' and the stratified region below.)

The methods used for numerical weather prediction over a few days are also being applied to the numerical prediction of 'climate'. This may be broadly defined, as the statistics of the average state of the atmosphere and oceans over many years, or more precisely on the statistics defined over this period, such as the mean and extreme values of rainfall, temperature, etc. Thus, since the weather in any given month varies from year to year, the 'climate' of a country for July is determined by averaging over several years. Therefore, by definition, changes in 'climate' can only be detected by considering how the average, over say 10 years, changes from one decade to the next. It cannot be detected by comparing one or two years with each other. It follows that numerical predictions of climate are also based on calculations over many years, and therefore are not 'forecasts' in the conventional sense; no-one can predict the weather in July 2094, but it might be possible to predict the changes in climate, averaged over a decade, one hundred years from now.

In these numerical models for the prediction of climate, space is also divided up into grid boxes within which the motions are calculated over specific intervals of time. Since, even beyond a month or two, the variation in sea-surface temperature affects the atmosphere, it is clear that climate forecast models must include the behaviour of the oceans. Calculations using a 3-dimensional coupled ocean–atmosphere model require the largest computer systems in the world. There are only 4 such installations at present, one being at the Hadley Centre of the Meteorological Office. Even these computer installations, running full tilt for a few months, only have the capacity to provide climate forecasts for periods of the order of 100 years. A major application of these models has been to forecast how average global temperatures are likely to rise over the next century as a result of increasing concentrations of carbon dioxide and other greenhouse gases in the atmosphere. By allowing for aerosols in the atmosphere, the calculations have to some extent been validated by their reasonably close agreement with the observed trends of average global warming.

Such a model was run by Hansen[12] in the USA to estimate the effects on global temperature of the aerosols caused by the eruption of Mt Pinatubo in 1991. It was predicted in early 1992 that there would be a decrease by about 0.5°C in 1992 and a subsequent rise of about 0.2–0.3°C in 1993, although these values require some correction to allow for the effects of the El Nino Southern Oscillation in the Pacific Ocean. Since both predictions have been borne out by the measurements, this demonstrates that certain features of the global climate are consistent with forecasts. Because 3-dimensional coupled atmosphere–ocean model calculations take so long to perform, computer models have been devised for exploring the effects of many different influences on the global climate. These include very long term effects of variations of the radiation emitted by the sun, or wobbles in the earth's orbit about the sun, both of which lead to seasonal fluctuations in the solar radiations reaching the earth ranging from 2% to 10%. In these models, the behaviour of the atmosphere around the whole surface of the earth at each height is averaged; in the mathematical analysis the atmosphere is divided up, not into boxes, but into concentric skins (like that of an onion). Instead of a million boxes there are now about one hundred layers. Then the state of the atmosphere is calculated in each layer (or onion skin). It has been possible to run such '1-dimensional' models over periods of 10,000 years or longer and simulate many of the climate changes of the ice ages, which have been discovered from the analysis of gases trapped in bubbles found in ice cores.

Developments

How will forecasting improve over the next few years? There has been a steady increase in the accuracy of forecasts produced by mathematical/computational models being 'fed' by data from atmospheric measurements, and an even greater increase where they are used in conjunction with human intervention (which I return to later). The accuracy of the 72-hour forecast now (measured in terms of root mean square error of the surface pressure) is about the same as the 24-hour forecast less than 15 years ago. It is expected that the present 24-hour forecast error (of about 2 hpa) will be reduced by at least 10% over the next 5 years (Figure 2).

There are three main reasons why further improvements will come about; firstly, research is leading to new insights into atmospheric processes and their representations in numerical models, and into the best way that data may be inserted into the models. For example, through fluid dynamic studies at turbulent inversion layers, more precise criteria are being developed to determine whether stratocumulus cloud grows in thickness, which leads to rain, and drizzle, or on the other hand, breaks up (because the turbulent eddies gain enough energy by entraining dry air from above the cloud to cause local cooling and thence sink with increasing speed), leading, of course, to clear skies. This fluid mechanics research also leads to a better knowledge of the sensitivity of the forecast, which also has to be communicated! Entrainment processes and up/downdrafts in deep clouds are also of critical importance for modelling their overall structure and internal energetic eddies. Those driven by the cooling of evaporating droplets can contribute significantly to the strength of the gusts at the ground. It is now realized that these may cause the highest gust speeds that produce sudden wind forces on structures, disrupting or destroying surface transport systems; the spatial forms of these cloud-driven gusts tend to be significantly different from those produced by boundary layer shear which we simulated in wind tunnels[11,13].

Once such local processes are understood sufficiently well to be modelled, their net effect has to be averaged or 'parameterized' over the grid boxes in the forecast calculations, an aspect of model development that requires some ingenuity and usually some empirical adjustment to obtain the best results. The modelling of atmospheric flow over terrain and its effect on the terrain drag on the flow over a grid box is an active area of research[14]. Recent fluid dynamics research on turbulent flow over undulations and on stably stratified flow is now being incorporated into forecast models. An important development is to combine different types within one grid box; precipitating ice cloud above hill stratus can greatly increase the rainfall rate compared to stratus alone.

The effectiveness of such changes for the performance of the models has to be examined carefully with statistical techniques, as described by Hollingsworth[15]. Only if the sizes of the grid boxes are reduced below the scale of the characteristic motions can the processes be modelled explicitly. That is not yet practical. For small reductions in the size of the grid box, the parameterizations appropriate for each process have to be adapted to the new size because the physical processes, such as lee waves over mountains, have their own particular length scales.

Since forecasts require, in principle, updates of data in every grid box, the second way to improve forecasts is by providing data in those grid boxes where data is currently unavailable, especially 3 to 30 km above the ground at the altitude of the dominant dynamical processes. Remote sounding instruments on geostationary (at 36,000 km above the earth) and polar orbiting satellites (of which there are two at any time, each pass overhead twice a day at an altitude 850 km) measure radiation in the visible, infra-red and microwave frequency bands.

In 1993 the European experimental polar orbiting satellite ERS-1 produced global data of near surface wind speeds, by measuring scattered microwave radiation from ocean waves; the variation of the wind over several kilometres is related to the wind structure above the surface layer and has contributed to a 10% improvement in the model's accuracy over data sparse areas such as the Southern Pacific.

An excellent example of the use of satellite images in combination with computers and human operation is the forecasting of the trajectories of tropical cyclones.

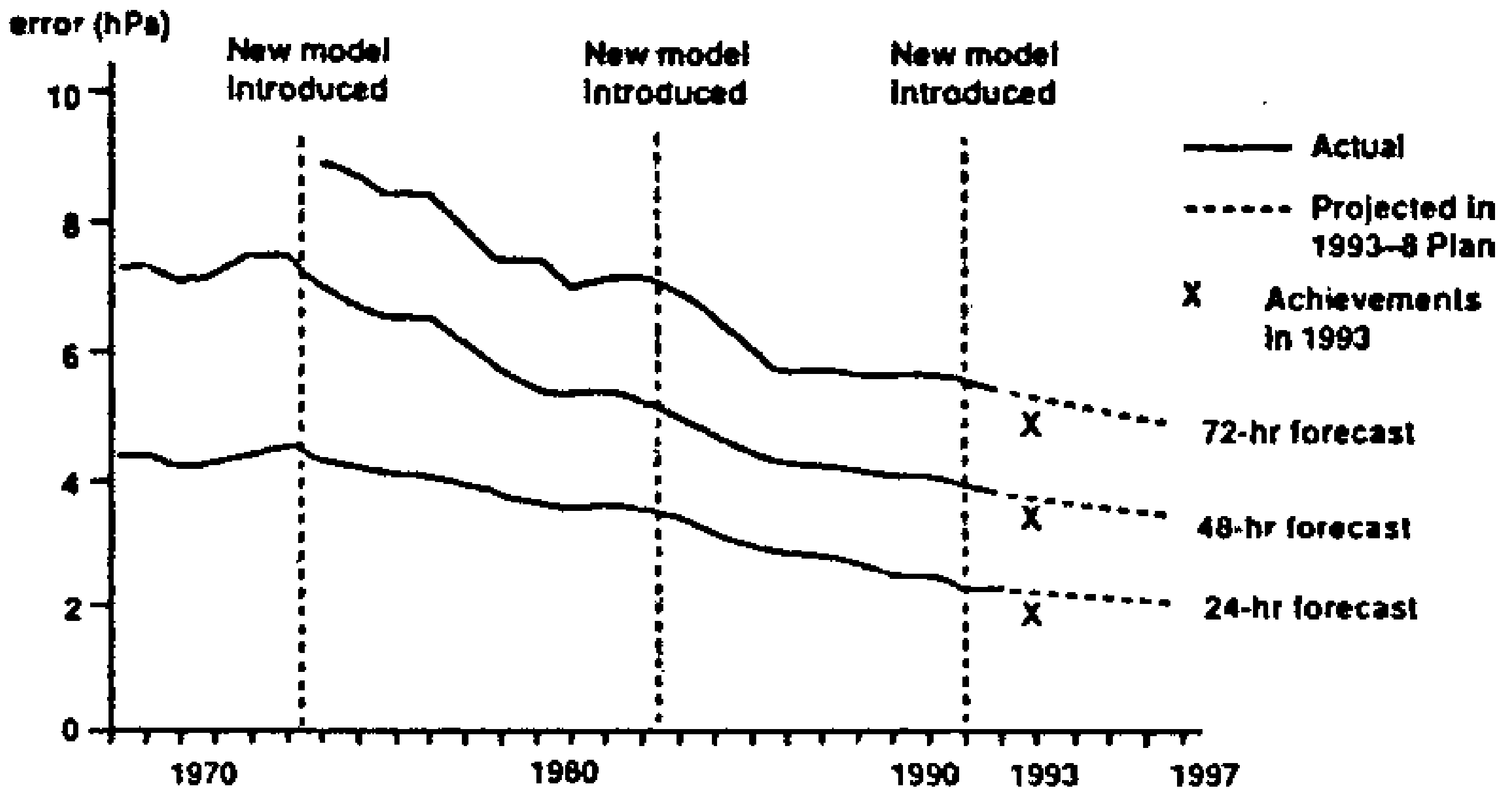


Figure 2. Forecast errors: 1967–1992, actual; 1993–1997, projected.

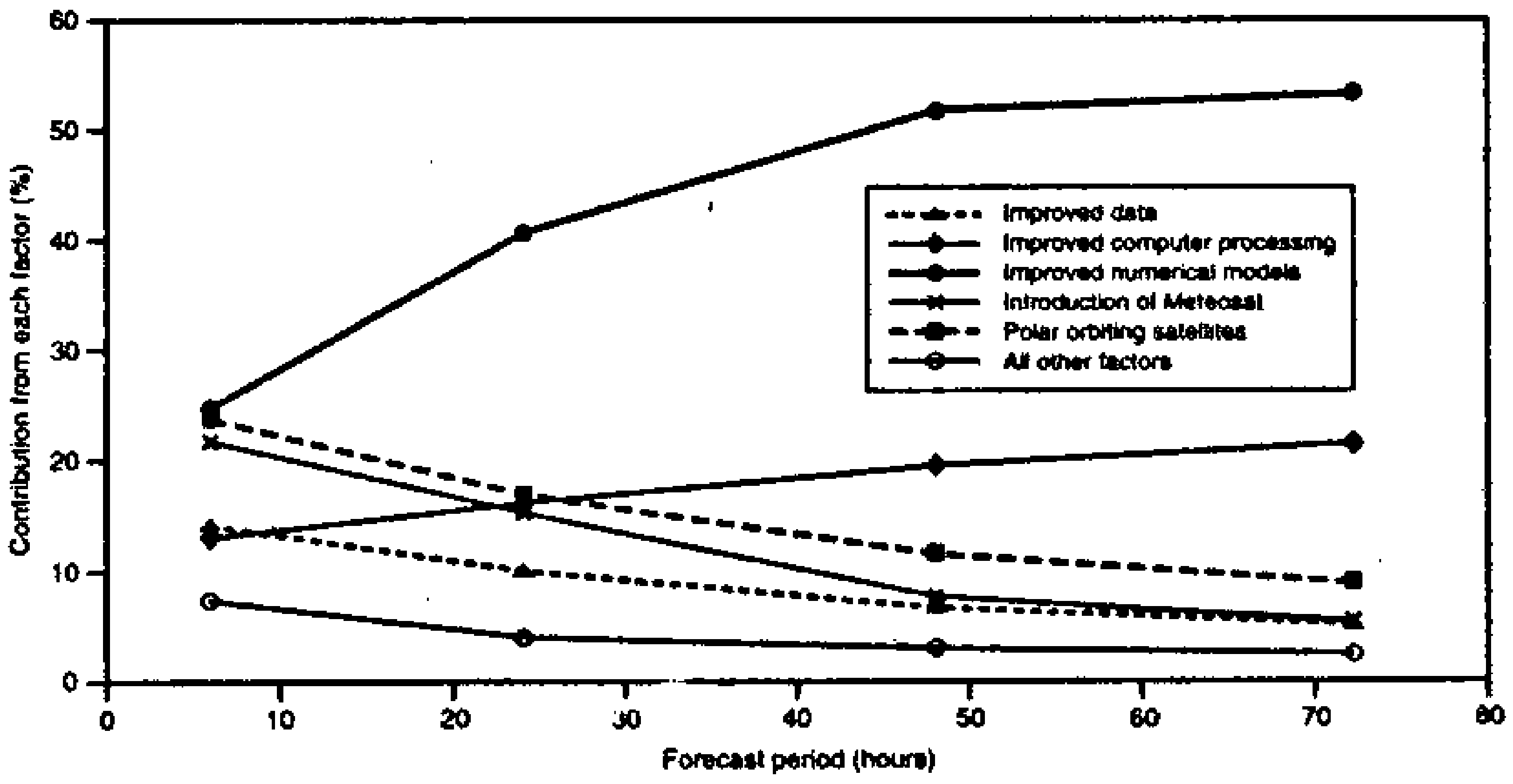


Figure 3. Estimates of the contribution of different scientific and technological factors to the improvement in forecast accuracy.

Many of these cyclones form in remote areas where no other measurements are available, and are only detected once they have been become strong enough to organize clouds into patterns that are visible via satellites. They are not always well predicted by the computer models because initially they are too small, their diameter (about 100 km) being similar to the size of the grid box of the model. After spotting a cyclone, or perhaps learning about it from other sources, a special technique is currently necessary. The human, or 'intervention', forecaster introduces into the numerical code a simple mathematical representation of the vortex to represent the central regions of the cyclone. Then its track is computed[16], a particularly critical task because its direction often changes by 90° in 24 hours. A significant (30%–40%) reduction in the errors in these forecasts has recently resulted from improving the model of the 'vortex' to allow for its asymmetry and history[17]. More elaborate models are now under development, especially in the USA, to represent on small grids moving with the cyclone the detailed winds and precipitation within them, and thence to reduce the errors of freak forecasts. Because of the devastating effects of the cyclones, warnings based on meteorological forecasts are widely publicized on TV and other media. Actions based on these warnings by the emergency services and the public are now saving thousands of lives annually around the world.

The third element in the improvement of forecasts is the provision of greater computer capacity. In the UK Meteorological Office there has been an increased speed of calculation, from around 2000 Floating Point operations per second in 1960 on the Mercury computer to around 6 gigaflops on the current CRAY C90. Every ten years over the past 40 years the power of the computer has increased by a factor of 60, even though the individual processor elements have increased by a smaller factor (of about 10) (ref. 18). At the same time smaller 'workstations' (about 1/100 of the power of the large systems) have improved by a factor of 30 over the past decade, so that these can now be used for many of the research studies and, even local forecasts. Additional power will continue to result from increasing the number of integrated circuits within each silicon 'chip', and from steady improvements in how these chips are connected, housed and cooled within the computers – i.e. its 'architecture'.

In the conventional vector-processing computers only a few calculations (about 8 on the CRAY YMP-8) can be performed simultaneously, and all data are stored in a central shared memory. The next major step in computer architecture in meteorological forecasting has been the introduction in 1995 of massively parallel processors (MPP). A key feature of MPPs is that memory is distributed with the processors. For the first time the architecture of the computer will correspond more closely to the nature of the processes in the atmosphere. Massively parallel computers will allow calculations to be performed at many grid points (about 100 or more) in the computer simultaneously. This MPP architecture (which is less expensive than conventional vector processors for a given level of power) should permit continued refinement of present forecast models for several further generations of computers. Although the most efficient use of this approach requires programs to be adapted specifically for this new architecture, the form of these new programmes is common to many scientific disciplines (e.g. meteorology, aeronautics, hydraulics, etc). Extensive collaboration is now under way across Europe in all these different fields of application of computational methods.

Two different advanced features of numerical weather prediction will be helped by these improvements in computers. First, instead of simply updating the calculation as new data arrives (or 'nudging' the solution), there will be greater emphasis on repeating the original calculations to fit the subsequent data more smoothly[8]. There will be many iterative cycles of calculation in this 'data assimilation' procedure which will give improved predictions by making better use of the previous data. Secondly, there will be time for the calculation of ensembles of different atmospheric states to provide the basis for the mixed dynamical and statistical methods of longer range forecasts, and to estimate their reliability.

So far there has been little discussion of the present and future role of the human forecaster. Until recently, s/he has been interpreting measurements and qualitative observations very much along the lines developed by V & J Bjerknes' Bergen School[19], firstly identifying typical synoptic features and types of air mass, and then with the aid of Sutcliffe's[20] concepts, estimating their movement and development by inspection. These and more recent conceptual developments (e.g. the use of potential vorticity at different levels) aid the understanding and the correction of the numerical models. Interpretation of the computer output is a *scientific procedure* in which hypotheses are made and subsequently, of course, tested. It is based on a knowledge of the data that was introduced into the model calculations and of the characteristics of the one or more models that are available to the particular forecaster. It is found that skillful intervention by the forecaster often leads to a better result for the customer than is obtained by relying on the prediction of any one model, especially in those situations when the various model predictions differ. In some synoptic situations, numerical models are very sensitive to small perturbations. A classic case, that is repeated every few months, is the 'extending frontal trough', which may or may not disrupt into cut-off low pressure systems. The forecaster has to use and interpret all the extra evidence available to him/her that is not in the model (e.g. details of cloud types, detailed humidity profiles, potential vorticity plots, etc.) to make a prediction. The forecaster has to make best use of his/her experience, including making an assessment of how the different models work in the particular synoptic conditions, and give emphasis to different aspects according to the special needs of the various 'customers' of the forecasts.

Some aspects of the human forecaster's contribution could be supplanted by 'knowledge-based' systems developed from the human experience. However, to replace the continual learning by the forecaster would first require the development of a complex self-learning 'neural-network' system. Although no one has yet attempted to do this at the synoptic level, this approach is being adopted for very short range forecasts (less than 3 hours) based mainly on interpreting radar and satellite images. In general, the human forecaster's contribution, although no longer dominant, will remain very important for the foreseeable future.

The number of users and uses of meteorological forecasts are steadily increasing. For example, forecasts are being used for an ever wider range of activities by members of the public, while aviation forecasts, which continue to be vital for the safety of those flying, are now required with greater precision for economical flight planning. Then there are the many specialized uses of forecasts in the retail industry, the oil industry, the public utilities and so on. See, for example, ref. 21. Forecasts are also needed in scientific studies of the atmosphere, and particularly in field experiments in the rapidly growing activity of environmental forecasting. The latter include the dispersion of pollution, wind forces affecting structural safety, wind energy, generation of sea waves, precipitation and flooding, environmental transport problems, and changes in the chemical composition of the atmosphere. Each of these uses requires different information about the atmosphere. As Bjerknes, who began as a fluid dynamicist, found when he was developing his ideas, new applications play a valuable role in testing and improving all aspects of meteorological and climate forecasting.

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