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Retirement of Mr A. Gilchrist

Mr Andrew Gilchrist retired in January 1989 from the position of Director of Research after a lifetime's career within the Meteorological Office. It began in 1951 when Mr Gilchrist joined the Office after taking a first class honours mathematics degree at the University of Glasgow. He very soon became involved in the Office's research programme, and his career has been in the research branches of the Office apart from the period 1957–63 during which he spent two years as a forecaster in the Central Forecasting Office, two years on secondment to the Nigerian meteorological department for research into tropical forecasting and two years as Scientific Assistant to Sir Graham Sutton the then Director-General. A comment from Sir Graham at that time identified Mr Gilchrist as the best Senior Scientific Officer who had occupied that post.

Mr Gilchrist has always taken a very pragmatic view of dynamical meteorology, and has not thought much of dynamical studies which have little impact on practical problems. The leadership which he has provided has done a great deal to keep the Meteorological Office in the forefront of dynamical meteorology. In particular he has played a key role in the development of numerical modelling within the Office.

One of his early research projects in the late 1950s was to investigate whether atmospheric motion could be usefully represented in terms of spherical harmonic functions. Most people would have considered the results of the research to be highly promising, but Mr Gilchrist was unenthusiastic (the work remained unpublished) because the technique, whilst mathematically viable, failed to map readily on to the observed behaviour of the atmosphere; the wave-like appearance of large-scale atmospheric flow should not be permitted to divert attention from the features which are most important (the influence of the continents and oceans, mountains, tropical convection, clouds and rainfall, fronts and individual depressions), and which do not readily fit into the spherical harmonic mould. Even after it was shown, several years later, that the computational expense could be greatly reduced by the use of fast Fourier transforms, he argued against the Office's jumping on the spectral modelling bandwagon because the technique obscured what was really going on and added nothing to the model's ability to represent the physics more accurately.

With George Corby, he was a founder member of the Dynamical Climatology Branch in 1963. Together, they led the development of the first Meteorological Office model of the general circulation, the 5-layer model, which was the basis of the present 11-layer model developed some years later. They designed finitedifference schemes possessing conservative properties and which avoided large truncation errors, especially those associated with the calculation of horizontal pressure gradients on the sigma coordinate system. He was particularly interested in the development of schemes for the representation of surface exchange and boundary-layer processes in the model. One of his personal projects was to develop a technique for representing the atmospheric boundary layer with an explicit top; it was a disappointment that numerical problems defeated attempts to introduce the scheme despite its well-founded physical basis.

Mr Gilchrist paid special attention to the need for models to display meteorologically realistic results; in a memorable presentation to the summer meeting of the Royal Meteorological Society in 1970, he demonstrated how a depression, which formed many days after the starting point of a 5-layer model run, showed many of the features observed in the life cycle of depressions, including frontal formation, occlusion and decay.

Mr Gilchrist took a full part in the task of writing computer code, though his rather personal programming style did not suit everybody — he could never understand why colleagues objected to his subroutines containing sequences of self-modifying assembler instructions.

His time as head of the Dynamical Climatology Branch ('amongst the happiest of my life') saw the expansion of the use of dynamical models for research into climate change. Indeed, the reputation of the Office now has in the field of research into the climatic impact of increasing atmospheric concentrations of carbon dioxide owes much to his foresight in encouraging the initiation of the work in the late 1970s. His contributions and incisive, critical observations on the subject have continued to be extremely valuable despite the diversions of higher administrative posts. He has written, lectured and given advice extensively on the development of general circulation models and their use for climate studies. Nevertheless, he has retained a realistic awareness of the limitations of the work to the extent of stating that 'all model results should carry a health warning'.

The 1970s also saw Mr Gilchrist's increasing interest in the effective use of atmospheric observations. He gave much encouragement to the use of data obtained in 1974 during the GATE experiment for developing convection parametrizations. He initiated work on Observing System Simulation Experiments for investigating the optimum design of the global observing system; his advocacy of observing-system experiments has continued to the present day with his chairmanship of the scientific steering group for OWSE-NA (Operational WWW Systems Evaluation for the North Atlantic). He was especially keen on encouraging the development of data assimilation schemes based on repeated correction of a forecasting model; he saw this as one of the most practical ways of coping with the increasing quantities of asynoptic data that would become available from satellites and other automatic instrumentation. An early version of such a scheme was used to produce analyses in near real time during the 1978/79 Global Weather Experiment, and a later version is now used for data analysis for the Office's operational numerical weather prediction system.

Soon after becoming Deputy Director, Dynamical Research, he was faced with the decision to stop the public issue of long-range weather forecasts and with increasing pressure to agree to the closure of the Synoptic Climatology Branch. His strong arguments against this and in favour of continuing both the routine preparation of monthly forecasts as a research exercise, and the use of past observations to investigate climate variability and change have borne fruit in the high international regard that is now held for the work of the branch. His advocacy of the use of numerical models for extended-range forecasting has enabled the Office to retain its place amongst the leaders in the subject.

From 1984 to 1986, Andrew Gilchrist was President of the Royal Meteorological Society, to which he gave strong scientific leadership — his Presidential address in 1985 on long-range forecasting is a masterpiece of well-judged exposition of a difficult and controversial subject.

In recent years, Andrew has played an increasing part in international programmes and committees. His thorough knowledge of dynamical meteorology, where he has few equals, and his lively and critical mind have ensured that his contributions at international meetings were always significant and appreciated. His membership (and chairmanship) of an international working group on numerical experimentation since 1982 has been particularly notable.

Andrew's contributions to the scientific literature have, by some standards, been sparse. Quality has always been of more importance to him than quantity. He has, however, contributed to the science and practice of meteorology not only through his writings but also through his style of leadership where the most dominant features have been his high standards and critical mind. Nothing weak or slipshod would pass his desk. No concession would be given to popularity — the points of view of others would be subjected to the most rigorous examination. This ruthless attention to quality has particularly paid off since 1985 during his period as Director of Research, when the idea of research and of its value have been increasingly under attack, and the provision of resources for research under threat.

As he retires, with his wife, back to his native Scotland, he will no doubt continue to follow, more remotely but just as critically as ever, the performance of the Office's products. We wish Andrew and Jean many years of happy retirement.

J.T. Houghton and P.W. White

Expert systems and weather forecasting

B.J. Conway
Meteorological Office, Bracknell

Summary

Expert systems are computer programs that perform high-level reasoning and judgemental processes within narrow specialist fields, rivalling the performance of human experts. They are being developed for weather forecasting applications in many countries and, at the Meteorological Office, Bracknell, pilot projects on nowcasting precipitation and forecasting thunderstorms using these systems have been started.

1. Introduction

Expert systems are a branch of artificial intelligence and a way of using computers to perform tasks normally requiring human judgement. They have been applied successfully in a variety of fields of significant importance and difficulty, including medical diagnosis, mineral prospecting, chemical analysis and configuring computer systems. Experiments are now under way in many parts of the world to apply expert systems to weather forecasting.

This paper explains what expert systems are and how they differ from conventional computer programs. It looks at the special demands weather forecasting makes on such systems and outlines the work which has started in the Meteorological Office to apply expert systems to short-period weather forecasting.

It has not been possible to do more here than touch on the main features of expert systems, with some inevitable over-simplifications. More comprehensive introductions to expert systems are to be found in Jackson (1986) and Hayes-Roth *et al.* (1982), and to artificial intelligence in general in Winston (1984). As with any specialism, expert systems work abounds with jargon. Some of the more common terms are introduced in this paper (where they appear first in italics) to show their meaning.

2. What is an 'Expert System'?

2.1 Definition

'An expert system is a computer program which, within some specified field, emulates the performance of a human expert.'

What do we mean when we describe someone as an 'expert'? We apply the term to someone who has developed a high level of skill in a particular area and from whom others seek advice; we should probably also expect certain specific characteristics as follows:

(a) The expert will have an extensive knowledge of his subject, and that subject will involve a significant level of difficulty.

(b) Some of the knowledge used will be in the form of *heuristics* (empirical rules-of-thumb) which the expert has gained through experience and which he may even use without recognizing explicitly. The use of heuristics is important — it enables the expert to pick out significant information from a mass of confusing material, and distinguishes his performance from that of a well-informed novice.

(c) The expert, though usually able to proceed quickly and efficiently to an outline solution, may have to resort to calculations or external references to fill in the details.

(d) The expert should be able to justify his conclusions and explain his reasoning, at least to the extent of indicating which pieces of evidence he considered important and how they were related.

(e) The enquirer is (usually) free to reject the expert's advice.

(f) The expert will sometimes be wrong.

These characteristics (including the last) are also found in expert systems.

The term 'expert' embodies the concept of 'reasoning': the selection, weighing and connection of appropriate ideas and evidence to arrive at useful conclusions. It is not simply the ability to perform a well-defined, repetitive task quickly and accurately. This is why conventional computer programs, though performing prodigious amounts of arithmetic or data manipulation, are not 'experts' any more than is a machine that, quickly and accurately, fills cans with baked beans.

The other important idea in our definition of an expert system is that of expertise being within a specific field or *domain*. An expert system is characterized by the knowledge it contains and that knowledge is specific to the narrow domain in which the system is designed to perform.

Human experts also operate within narrow specialisms outside which they may have no more than average capabilities — a neurologist will not necessarily be able to mend a television set. However, whereas a human expert has a wealth of general knowledge, enabling him to function in everyday life, present-day expert systems are profoundly ignorant outside their domains.

2.2 Structure

The structure of an expert system is illustrated in simplified form in Fig. 1. The two principal elements are the *knowledge base* and the *inference engine*. It is tempting to regard these as analogous to the database and application program in conventional computing, but there are important differences, as we shall see.

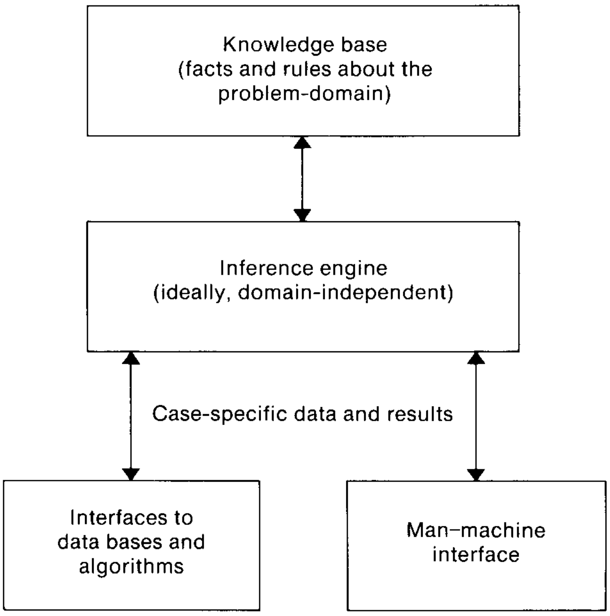

Figure 1. Main components of an expert system.

The most important part of any expert system, the part which ultimately sets a limit to the effectiveness of the system, is the knowledge base, and expert systems are often referred to as *Intelligent Knowledge-Based Systems (IKBS)*. The knowledge base is an explicit representation of the available knowledge about the problem domain; much of this will be provided by human experts in the domain, though some may be derived automatically from collections of examples. It includes established facts and relations, rules-of-thumb and, sometimes, references to algorithms. It holds the relations which are believed to be true within that domain and which are used selectively, as they appear relevant, during the course of solving a problem.

Various formalisms exist for representing the knowledge. Perhaps the most easily understood is the use of *production rules* in the form of IF...THEN... relations. Note that these are not the procedural IF statements of programming languages like Fortran or BASIC (e.g. IF A=B THEN GOTO 100), but rather they assert that IF a condition is satisfied THEN a conclusion follows (e.g. IF it is a Bank Holiday THEN it will rain). Rules may take the form IF...AND...AND... ... THEN..., the left-hand side containing several conditions to be satisfied concurrently.

Rules can also express general relations which are applied to specific instances at execution time. A simple example might be a persistence forecasting rule — 'IF the weather today is X THEN the weather tomorrow will be X', where X is filled in or *instantiated* with the weather prevailing at run time.

A knowledge base may contain hundreds or even thousands of such rules. Each rule is self-contained; it does not direct the next step in the program and rules can appear in the knowledge base in any order. The programmer does not predefine the sequence in which the rules will be processed. The expert system functions by comparing the IF conditions in its knowledge base with what it is told about the problem it is tackling. When a match occurs, that rule *fires* and the THEN part is assumed to hold and is available for comparison with other IF conditions. The system repeatedly goes through its collection of rules and the evolving set of established conditions until a path to a final conclusion or *goal* is established (or shown not to exist). On the way it may ask for specific information that was not initially provided about the problem. It does this in a selective way which depends upon its line of 'reasoning' and the answers obtained to earlier questions.

The inference engine is the program that processes the knowledge base. In principle the inference engine may be completely independent of the problem domain. The domain is then defined entirely by the contents of the knowledge base, not by the details of the inference engine. From this has emerged the concept of an expert system *shell*, an inference engine plus an empty knowledge base, together with a knowledge-base editor and some input/output facilities, ready to be applied to any chosen domain. Many such shells are available for personal computers (PCs) at prices of a few hundred pounds, though more complex products at correspondingly higher prices are available for larger machines. Simple shells can be a cheap and relatively easy way of experimenting with expert systems, but they also have disadvantages compared with purpose-built expert systems. The formalism employed by a shell may be unsuited to the chosen application, and the facilities provided for entering data at run-time and for presenting results may be awkward and frustrating.

The inference engine contains mechanisms to control how it will process the knowledge base. Choices must be made about how to search for a path to a goal —whether to pursue one line of reasoning to its end before trying another (*depth-first search*), develop all available paths to the same depth before moving on (*breadth-first search*), or some combination of the two. Trying, without preference, every possible path until one works is usually too inefficient in large knowledge bases or where speed is important. Attempts may be made, at each step of the search, to calculate some measure of the closeness to a goal, and thus select the most promising path, but finding a reliable measure is often difficult. Heuristics gleaned from human domain-experts and built into the system may also be used to direct the search (essentially making intuitive leaps) and may appear in the knowledge base as *meta-rules* (rules about how the knowledge should be processed), supplementing rules about the problem domain itself.

Rules may be processed from left to right, by trying to satisfy the left-hand sides and proceeding by *forward chaining* to a conclusion. However, in some problems, particularly where there are few possible goals but a large range of initial conditions, it may be more efficient to use *backward chaining* — starting from a goal and seeking to establish the conditions that would lead to it.

Not all ideas can be conveniently expressed as production rules, and other formalisms are also used. *Frames* (Minsky 1975) are data structures which facilitate *inheritance* of properties within a class of objects. In such a representation 'cumulonimbus' might be a member of a 'convective clouds' class which in turn would be a member of the top-level class 'clouds'. A member automatically inherits the properties of higher levels in the structure except where it has specific values that distinguish it from other members. Some problems are best expressed as statements in formal logic, as implemented for example in the programming language Prolog (Clocksin and Mellish 1987). More than one formalism is sometimes used within a single expert system in order to express different aspects of the problem (e.g. Elio *et al.* 1987).

Nearly all practical systems also contain a 'Man–Machine Interface' (MMI) and many can connect to conventional databases and programs; real-time systems may incorporate interfaces to physical sensors. An important function of the MMI is to provide explanation facilities. In the face of a pronouncement from an expert system (particularly if the question or conclusion is unexpected) the user will often want reassurance in the form of an explanation of the reasoning involved, and facilities for this are provided via the MMI. Explanation facilities are widely regarded as an essential attribute of expert systems, even if implemented as no more than a trace of which rules fired during the reasoning process.

2.3 Differences between expert systems and conventional programs

Two important concepts in expert systems are (a) the use of *symbolic reasoning* and (b) *the separation of the knowledge base* (an explicit description of the problem domain) *from the inference engine* (the means of processing the information). From these concepts come most of the important practical characteristics of expert systems.

2.3.1 Symbolic reasoning

Expert systems manipulate representations of ideas, whereas conventional programs are usually concerned with numerical operations on items of data. Fig. 2 illustrates the difference. A surface analysis can be represented by arrays of numbers giving values of parameters, such as pressure and temperature, at regularly spaced grid-points. The same analysis can be represented as a pattern of meteorologically significant features — anticyclones, depressions, troughs, fronts, etc. Both views of the analysis are valid. Grid-point values are convenient for applying physical equations locally in a numerical model while the other, symbolic, representation enables the forecaster to summarize the situation very economically and to concentrate attention on regions of greatest interest.

Symbolic reasoning (considering the problem in terms of named conceptual features) does not preclude numerical processes, but uses them to fill in details within a broad picture or to answer specific questions thrown up by higher-level reasoning, such as 'Is that low

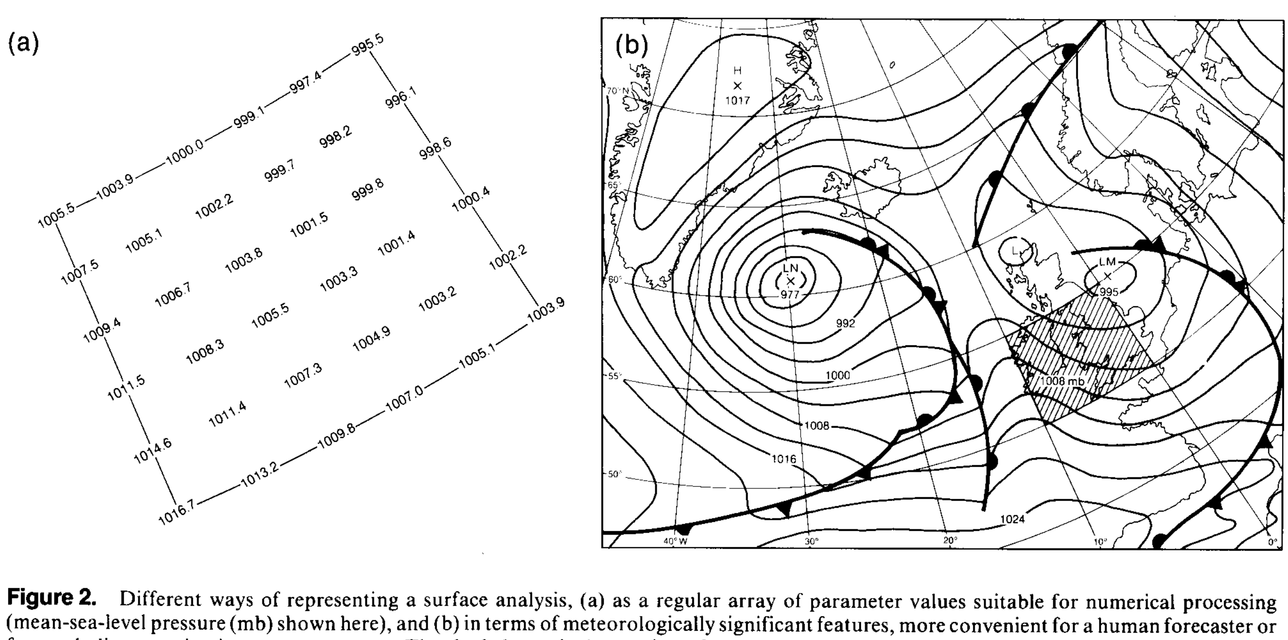

Figure 2. Different ways of representing a surface analysis, (a) as a regular array of parameter values suitable for numerical processing (mean-sea-level pressure (mb) shown here), and (b) in terms of meteorologically significant features, more convenient for a human forecaster or for symbolic reasoning in an expert system. The shaded area is the portion of the chart shown alternatively in (a).

still deepening?' or 'How fast is the pressure changing at Culdrose?' A meteorological expert system would access conventional routines, including pattern-recognition algorithms, to handle numerical operations and supply results which could then be reasoned about at the symbolic level.

2.3.2 Separation of the knowledge base and inference engine

In conventional programming we start with a user who wishes to do some job. This is the 'real world' problem. An analyst (who may also be the programmer and the user) examines what is wanted and constructs an idealized model of the problem. The programmer works out how this idealized problem might be solved and then writes a program, a series of step-by-step instructions for a computer to obey, to implement the chosen solution. The important point here is that the program describes the solution, not the original problem or even the idealized problem. It may well be possible to solve the problem in different ways and the corresponding programs, though ultimately doing the same job, might look completely different. Knowledge about the problem itself — how the user would describe it — does not appear explicitly. It was used by the programmer to translate from the problem to his solution and it is now therefore implicit in the structure of the program, inextricably mixed up with how the program operates.

In developing an expert system we start with the real-world problem as before. The analyst is now called a *knowledge engineer* and has the job of constructing the knowledge base from the user's understanding of the problem. Although some idealization must occur in any process like this, the object is to fill the knowledge base with a description of the problem domain as far as possible in the user's own terms and in a form that the user can understand. What is being produced is a description of the domain — a collection of facts, rules and assumptions which the user (the expert in that domain) uses in his work. There is no attempt to devise a solution and to program it as a set of sequential instructions. Programming the expert system for a particular domain consists of constructing as accurate and complete a description as possible in the knowledge base. The knowledge therefore remains explicit and accessible to the original user, and separate from the mechanisms directing the program's sequence of operations.

These structural and functional differences lead to the main strengths and weaknesses of expert systems compared with conventional programs:

(a) An expert system can often start to function and to produce useful results before the knowledge base is complete, and then evolve in a gradual way as further knowledge is added, just as a human expert continues to learn, and to refine his knowledge. By contrast, a conventional program represents a solution which is implemented complete, and it usually evolves in a series of large, discrete upgrades rather than by small increments.

(b) Because the knowledge base is a description of the problem area as far as possible in the user's own terms, the user is in a good position to understand it, check its correctness and propose modifications. In a conventional program, which relates to a solution rather than to the problem, the operation of the program may be obscure, not only to the user but to other programmers. The effort that goes into structuring and documenting programs is a recognition of this difficulty.

(c) The close correspondence between the problem and the knowledge base makes it easier to modify the expert system to reflect changes in the problem. With a conventional program such modifications are often difficult, because the program represents a solution, and the implications for that solution of even a small change in the problem may be considerable. Indeed, the particular problem-change may have been implicitly excluded as a possibility when the original solution was devised.

(d) Because an unavoidable step in conventional programming is to devise a solution to the problem, the program is not written unless a means of solution appears to exist. With an expert system, however, being able to describe the problem in the knowledge base does not guarantee that a solution to that problem can be found.

(e) The search strategies and inferencing mechanisms in an expert system are more difficult to optimize for speed and efficiency than the sequential instructions that form a conventional program.

3. Expert systems in weather forecasting

3.1 Requirements

Weather forecasting is a promising application for expert systems. In spite of advances in observing systems and numerical weather prediction (NWP) models, the production of forecasts, particularly short-period local forecasts of specific weather events, tailored to the needs of customers, depends to a large extent on the skill and experience of human forecasters. The forecaster must recognize and compensate for errors and biases in the numerical products, identify the sub-grid-scale phenomena that are likely to be present in different synoptic situations but not represented explicitly in the model, and also take account of local conditions, such as topography or a coastal location, which will modify larger-scale patterns. By storing and applying some of the forecaster's knowledge, expert systems should be able to act as useful advisory tools in forecast offices, continuously monitoring information about the weather situation and alerting the forecaster to the likelihood of severe or significant weather events.

Weather forecasting carries a combination of difficulties however, which must be overcome in any expert system designed to help the forecaster in real operational situations. The main challenges (discussed below) are pattern recognition problems, missing and conflicting data, and the need for convenience and speed.

Weather information comes from a variety of sources with widely different spatial and temporal characteristics. Only by recognizing and understanding the current weather pattern, fitting individual observations into coherent conceptual models (Browning 1986), can we reconcile apparently conflicting information and go on to predict the evolution of the pattern and consequent changes in local parameters like temperature and rainfall.

An important observational source, particularly for short-range forecasting, is remotely sensed imagery (Conway and Browning 1988). Much is often made of the difficulties of automatically recognizing patterns in images (e.g. McIntyre 1988) but in some cases the problem can be reduced to a search, made in the light of other evidence, for well-defined observational signatures associated with particular weather phenomena, as for example in the work by Campbell and Olsen (1987) on Doppler radar. The problem then becomes much less daunting than, say, the relatively unconstrained vision-analysis task involved in driving a car. One of the important functions of an expert system will be to use other meteorological knowledge and evidence to focus and constrain the pattern-recognition task, and avoid getting bogged down in huge amounts of low-level image-processing.

In most cases the observational data will be incomplete and contain errors and inconsistencies. This is a common feature of expert-system applications, and is normally tackled by assigning weights and probabilities to evidence and hypotheses. As humans we do not normally reason in numerical terms but prefer vaguer notions of things being 'probable' or 'likely', so the appropriate assignment of probabilities is one of the main difficulties of encoding human expertise in the form of rules. How best to deal with 'reasoning under uncertainty' is a subject of continuing research in the expert systems community (Mamdani *et al.* 1985).

A system which adds to the work-load of the forecaster and slows him down is no use in a forecasting office, however good its eventual pronouncements may be. This means that the amount of information entered manually must be minimized, and the sort of tedious dialogue via screen and keyboard, found in many simple, shell-based systems, must be avoided. The system must have direct access to current meteorological data so that it can work unattended as far as possible, reducing the need for manual data-entry and being ready to display results either when requested by the forecaster or when predetermined criteria are met. The expert system cannot 'look out of the window', so some input by the forecaster, either prompted or volunteered, may be unavoidable, but this must be kept to a minimum.

These are demanding but not impossible requirements and are found individually in many expert-system applications. Their combination here means that expert systems for weather forecasting have more in common with those for battlefield analysis (IKBS in Defence 1984) and industrial process-control (e.g. Paterson *et al.* 1985) than with those for administrative applications such as credit authorization and social security claims.

3.2 Progress in meteorological expert systems

Expert systems for weather forecasting are being developed in many parts of the world, and some of the work is already well advanced. The 1987 AIRIES conference (reported in Dyer and Moninger 1988) highlighted developments at various centres in North America. In a survey presented at the conference, these authors listed some 39 meteorological expert systems and related studies addressing a wide variety of forecasting and diagnostic tasks, including convective storms, precipitation, visibility, low cloud and wind. The systems were at various stages of development, from initial studies to real-time trials. Most activity was in the USA, but Canada, Europe and Australia were also represented. However, while giving a useful impression of the range of work being done, the survey did not claim to be exhaustive; other systems are being developed and applied elsewhere, for example in China, where they are being developed to forecast regional heavy rain (Dai *et al.* 1987).

An interesting development is the use of expert systems, not directly as forecasting tools, but to train student meteorologists. This off-line application avoids some of the more stringent demands of operational forecasting and may perhaps be accomplished using low-cost, PC-based shells (Reiss and Hofmann 1988).

The overall picture to emerge is one of vigorous activity and rapid growth, with many independent investigations exploring a diversity of ideas. It is too early to say which of the techniques now being tried will endure, but at least there is sufficient activity to allow useful comparison and cross-fertilization of ideas.

3.3 Developments in the Meteorological Office

In the Meteorological Office at Bracknell the emergence of expert systems for real applications instead of as mere research curiosities, and their possible use in meteorology, was examined by the author in the mid 1980s. Although the techniques appeared to hold promise, there was at that time little published work in the meteorological field and the available tools were mainly either cheap but simple PC-based products, such as shells for building consultation systems, or very expensive, specialized workstations. The affordable systems did not allow ready connection to machinable data or to software written in conventional languages. More immediate tasks precluded the diversion of much effort to investigating expert systems, but some experiments were done with cheap shells and artificial problems. These showed that the constraints imposed by such shells, in terms of the dialogue with the user and the internal representation of knowledge and uncertainty, would be quite unacceptable in even the simplest tasks in operational weather forecasting. The concepts embodied in expert systems were not invalidated, but these crude implementations fell well short of what was needed.

In August 1988, the Nowcasting and Satellite Applications Branch of the Meteorological Office was formed, bringing together existing research groups concerned with the processing, interpretation and use of remotely sensed images from satellites and weather radars. Experience of interactively processing remotely sensed imagery in near real time in the FRONTIERS project (Conway and Browning 1988) had by then shown the desirability of being able to transfer some of the higher-level judgemental tasks from the man to the machine. Meanwhile, the environment for developing expert systems had become more favourable — the availability of workstations and artificial intelligence software tools had improved, and the establishment of a data network linking together the Meteorological Office's main computers offered access to a full range of meteorological data. Accordingly, one of the tasks set for the new Branch was to investigate the application of expert systems to short-period forecasting and to do this by building and testing experimental systems for specific forecasting tasks.

Two pilot projects have been defined. One is the automation of the forecast stage in FRONTIERS, the other is thunderstorm forecasting.

In the FRONTIERS system (Conway 1987) image data from the UK weather radar network and from Meteosat are combined to produce analyses and nowcasts (forecasts for 3 hours or so ahead) of precipitation. The nowcasts are prepared by a forecaster who uses an interactive display system to view the recent movement of the rainfall pattern, identify separate clusters within the pattern and assign them velocities so that their movement can be extrapolated. Although this gives a somewhat crude representation of a complex evolving pattern it can often produce successful forecasts in the nowcast period, particularly for frontal rain.

The FRONTIERS forecaster works to a very demanding half-hourly cycle and, despite recent improvements in the efficiency of the software, in active weather situations he has difficulty in completing all his tasks on time. Planned extensions to the UK weather radar network will increase his work-load, so ways of lightening the burden by automating some of his tasks are needed.

The existing FRONTIERS forecast method is well-suited to an interactive system controlled by a forecaster, but automation allows other techniques to be considered. Thus a convenient way of automatically estimating the short-period movement of the rainfall pattern is to use trajectories derived from NWP model winds, in this case from the Office's mesoscale model (Golding 1987). This method offers a way of combining realistic, physically based trajectories with the better resolution and timeliness of the remotely sensed observations. One problem is to decide the heights of the 'steering winds' for different parts of the pattern (in which embedded convective cells may move with different speeds from the overall pattern) and to recognize those situations in which none of the winds corresponds to the movement of the rainfall pattern (e.g. because the rainfall is tied to topographic features or because the model output is wrong). Where the model wind fields are unsuitable it will be necessary to use other techniques to derive velocities, such as cross-correlation of successive rainfall fields (Austin and Bellon 1974); more than one method may be needed within a single case.

A multi-layer system is therefore envisaged (Fig. 3). The top levels are occupied by an expert system, which uses evidence from a variety of sources to make decisions about how the movement of the rainfall pattern is governed and, on the basis of these decisions, selectively accesses conventional programs in the lower levels to calculate trajectories, correlations, etc.

Thunderstorm forecasting is attractive as a pilot project because it is an important and non-trivial fore-

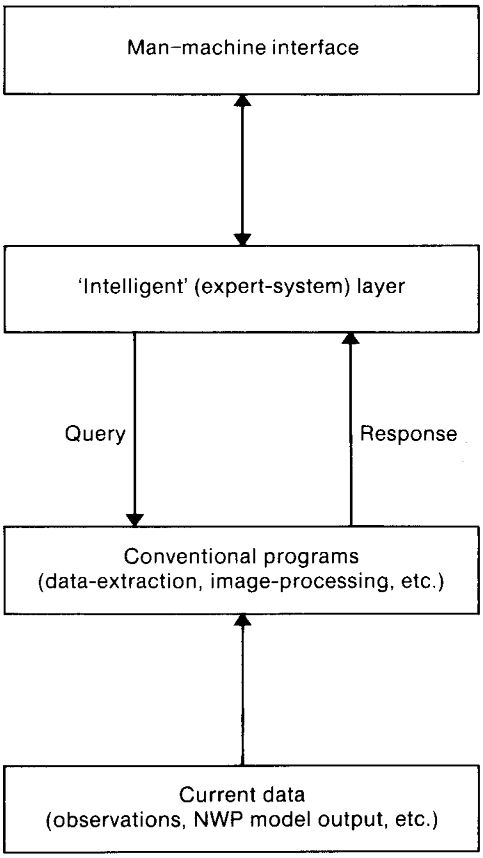

Figure 3. Hybrid structure for operational weather forecasting.

casting task, relevant observational coverage is good and, as a knowledge-engineering project, its problems complement those of automating the FRONTIERS forecast. Although some benefit may be obtainable from experience in North America of developing expert systems for convective storm forecasting (e.g. Elio *et al.* 1987), there are differences in the character of their storms, the local conditions and the observational sources. Thunderstorm activity encompasses a wide range of phenomena (lightning, hail, heavy rain, wind shear, turbulence, etc.) which do not necessarily all occur together and which are individually of importance to different customers. The first task is therefore to review these customer requirements and to limit the task to manageable size by focusing on particular aspects — this is currently under way.

The newly operational, high-resolution ATD (arrival time difference) Sferics system (Lee 1986), images from weather radars and satellites, and conventional surface and upper-air reports, together provide good areal and temporal coverage of ongoing thunderstorm activity and antecedent conditions. Together with forecasts produced by present methods they will form an archive of cases against which experimental systems can be tested during development. Further evaluation of performance must of course be done, preferably in real time, outside this 'training set'.

The experience and co-operation of practising forecasters will be essential in assembling and validating the knowledge base for this system, though other sources (the results of relevant research by groups in the Office and elsewhere) will also be important. The project will thus complement that on FRONTIERS by providing experience in the traditionally difficult process of eliciting and coding the knowledge of human experts (not only their formal knowledge and what they think they do, but also the short cuts and rules of thumb they use without even noticing). It is likely that the compilation of this knowledge will be a worthwhile exercise in its own right, and provide useful insights of practical value, quite apart from its role in developing an expert system. As with the FRONTIERS forecast project it is expected that a hybrid system will emerge, with an 'intelligent' upper layer controlling conventional routines to access and process observational data.

The aim of these projects is to provide experience in constructing expert systems for tasks of real practical value; they will teach us where the main difficulties lie, and demonstrate the strengths and weaknesses of this approach to automation. The first goal will be to show whether expert systems can be applied in these applications to produce successful forecasts when compared with traditional methods in the context of specific customer requirements. If so, work will be directed at making them satisfy the time-critical requirements of operational forecasters, as outlined in section 3.1, and examining other areas where the techniques might be applied.

4. Conclusion

Expert systems offer the prospect of using computers for tasks requiring reasoning (the selection, weighing, reconciliation and connection of evidence and ideas to draw conclusions) in contrast to their traditional 'number-crunching' role.

Weather forecasting, with its strong component of human skill and its basis in known physical laws, is an obvious application for expert systems, though the nature of the task poses some difficult problems and the requirements of operational forecasters will not be easy to satisfy. The development of expert systems in this field is the subject of intensive research by many groups around the world, and in the Meteorological Office two pilot expert-system projects in short-range forecasting have been started.

Expert systems are not an alternative to traditional computing methods but complement them, so that practical systems will be hybrids, with an expert system directing the use of numerical procedures, in the same way that the human being makes use of the calculating power of the computer in interactive systems like FRONTIERS.

Expert systems are certainly not magic ways of performing hitherto impossible tasks. If a task cannot, at least in principle, be done by a human being in ideal conditions (i.e. with access to all the relevant data sources and reference material, means of performing calculations, and no time constraints or distractions) then it cannot be done by an expert system either.

What an expert system can do, within its narrow domain of expertise, is to deliver consistent behaviour and performance. Its conclusions will not always be right, any more than a human expert will always be right, but it will not get tired, or have off-days or panics, or avoid boring or difficult calculations. It will not forget what it has been 'taught', and new knowledge can be added in the light of its mistakes so that it does better next time.

Considerable effort is being put into providing forecasters, at outstations as well as main forecasting centres, with a rich variety of observational data, including increasingly large quantities of remotely sensed images from radars and satellites, derived products and output from NWP models (Cluley and Hills 1988). There is a limit to the rate at which the forecaster can assimilate and use this torrent of information. Interactive computer-based display systems can make it easier to access and manipulate the data, but cannot remove the problem entirely if they rely on the human to do all the thinking. There is the danger that the forecaster, lacking the time to weigh, on each occasion, the relative importance of the full range of products available, will slip into the habit of using some familiar subset of them, so that items of only occasional importance will be ignored. We can alleviate this problem and make better use, both of the forecaster and of the wealth of data becoming available to him, if we can find ways of using machines to help with some of the higher-level judgemental tasks — scanning the data, forming initial conclusions and drawing the forecaster's attention to significant events.

Research into expert systems for weather forecasting is still at an early stage but is proceeding apace. There are many difficulties to be overcome and undoubtedly there will be many false starts, but success will provide a radically new way of using computers to aid the forecasting process.

Acknowledgements

I am grateful to C.G. Collier and Dr K.A. Browning for reading this paper in draft form and making a number of valuable comments and suggestions, and to J. Paterson and C. Wood (formerly of the Systems Development Branch of the Meteorological Office) for their help with experiments on small expert system shells.

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An investigation into the conditions in which air-mass thunderstorms occur at Athens

N.G. Prezerakos
National Meteorological Service, Athens, Greece

Summary

An investigation was carried out into the conditions in which air-mass thunderstorms occur over the Athens region. Consideration is given to temperature and dew-point information from radiosonde ascents, and synoptic charts of the surface, 850 mb and 500 mb levels.

1. Introduction

The forecasting of thunderstorms for a city or relatively small region is a very difficult problem. This may be attributed to the fact that whereas a thunderstorm is a mesoscale phenomenon, synoptic-scale observations are used to forecast them. Summertime air-mass thunderstorms are a welcome relief to Athenians, although the associated heavy rainfall can sometimes be a problem.

The international meteorological literature contained little about thunderstorms until the publication of the remarkable study by Byers and Braham (1948). Since then a considerable number of studies concerning thunderstorms have been published and much has been learned. The improvement in meteorological instruments and the development of new observing methods have contributed to this. Also the development of mesoscale numerical models in conjunction with the increasing power of computers are hopeful signs that further progress can be made in the problem of thunderstorm forecasting. Meanwhile forecasters will have to try to improve forecasting techniques based on a more traditional approach.

A forecaster associates the occurrence of thunderstorms in a region with:

(a) the degree of instability,
(b) the amount of moisture available, and
(c) the presence of a trigger to release the instability.

Normally a thunderstorm occurs when, in a conditionally unstable atmosphere, a trigger forces boundary-layer air up to the level of free convection. However, in a relatively stable atmosphere it is possible for large-scale ascent (e.g. caused by strong convergence or considerable positive vorticity advection at 500 mb) to trigger thunderstorms. This suggests that it is useful to differentiate between air-mass (thermal) thunderstorms and dynamical thunderstorms.

Sometimes the term air-mass thunderstorm is not applied correctly — any thunderstorm which occurs during the afternoon and evening over land in the warm season is usually described as an air-mass thunderstorm. However, even though the surface pressure chart does not show a front and the pressure field is very slack, a dynamical trigger such as positive vorticity advection at 500 mb (often accompanied by cold advection which reduces the stability) could be responsible for the thunderstorms. Consequently, in order to consider just air-mass thunderstorms it is necessary to exclude occasions when there is positive vorticity advection towards the region.

Here, the air-mass thunderstorms which occur at Athens based on observations from Helliniko and Nea Philadelphia (located as in Fig. 1) will be considered.

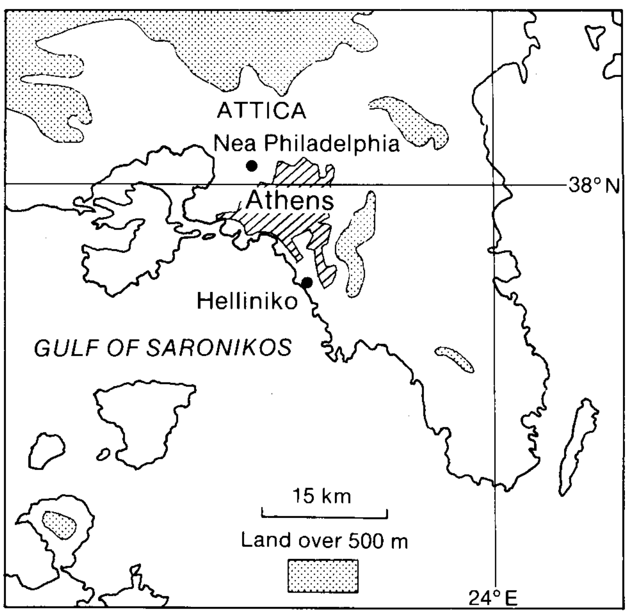

Figure 1. Map of the area under consideration, showing places mentioned in the text.

2. Air-mass thunderstorm days at Athens

According to WMO (1966) a thunderstorm occurs when one or more sudden electrical discharges are manifested by a flash of light and a rumbling sound. A thunderstorm may or may not be accompanied by precipitation. As far as observations are concerned, if thunder occurs without precipitation then a thunderstorm is occurring. However, if lightning is observed without thunder being heard at the station or without precipitation occurring then the event is not considered to be a thunderstorm.

The study described here was based upon days on which thunderstorms occurred in the vicinity of the Helliniko and Nea Philadelphia meteorological stations during the 6-year period 1970–75. These stations were chosen because Athens is located between them and less than 10 km from each (Nea Philadelphia to the north and Helliniko to the south close to the sea). For each station a thunderstorm day was taken to be a day for which at least in one synoptic observation (from the 8 every 24 hours) the present weather was reported as 17, 29 or 91–99, or the past weather was reported as 9. In the cases where the 0000 GMT observation had a past-weather report of 9 but no thunderstorms reported as present weather, the previous day was designated as a thunderstorm day. A thunderstorm day at Athens is taken to be one in which either of the meteorological stations has a thunderstorm day (Metaxas 1972).

After recording all the thunderstorm days at the two stations for May, June, July, August and September for 1970–75, the days in which air-mass thunderstorms occurred were identified. This was done by carefully examining the surface and 500 mb charts and excluding the occasions on which thunderstorms occurred due to:

(a) the passage of a front,
(b) strong cold advection at 500 mb, or
(c) positive vorticity advection at 500 mb.

Also, thunderstorms which occurred during the afternoon with total cloud more than 3 oktas during the morning were excluded. This criterion was imposed in order that any thunderstorms would be purely air-mass produced, and with half cover or more of cloud the insolation would be insufficient to be sure the thunderstorm was thermally produced. The remaining days were judged to be air-mass thunderstorm days — that is days for which the surface temperature exceeded the critical convective temperature and the thermal trigger released the instability and thunderstorms formed.

3. A statistical analysis of the air-mass thunderstorms

The number of air-mass thunderstorm days at Athens (based on the observations at Helliniko and Nea Philadelphia) for each month of the warm season in the 6-year period are given in Table I. Of the 30 days, 23 were thunderstorm days at both Helliniko and Nea Philadelphia, whereas on 4 occasions air-mass thunderstorms only occurred at Helliniko and on 3 occasions they only occurred at Nea Philadelphia. This behaviour was in contrast to what might have been expected (Metaxas 1972 and Mihalopoulos-Nistazaki 1978) but with synoptic experience suggests that this kind of thunderstorm starts over the continental parts of Attica and then develops towards the regions in the vicinity of the coasts of the Saronikos Gulf. It is of course possible that the centre of the released instability is indeed in the continental parts, but as the thunderstorm develops it is carried away by the northerly 700 mb winds which are usually light and so the electrical phenomena start quite far south near Helliniko. Consequently the thunder may not be heard near Nea Philadelphia due to heavy rain and thick cloud. This mainly occurs in winter (Metaxas 1972) but it is not impossible during the summer.

Table I. Number of air-mass thunderstorm days each month during the warm season (May–September) in Athens during the period 1970–75 based on observations from Helliniko and Nea Philadelphia

Year	May	June	July	Aug.	Sept.	Total
1970	0	3	1	0	1	5
1971	1	1	0	0	1	3
1972	1	1	4	1	0	7
1973	1	1	2	0	0	4
1974	0	0	0	1	1	2
1975	4	3	0	1	1	9
Total	7	9	7	3	4	30
Monthly mean	1.16	1.50	1.16	0.50	0.66	

Table I shows that June is the month with the highest number of air-mass thunderstorms. This is due to the large amount of solar radiation during the month and the higher frequency of light winds (the Etesians, the well-known north-easterlies, are more frequent in July and August).

The number of successive air-mass thunderstorm days at Athens is given in Table II. This shows that there are no cases with more than two successive thunderstorm days. Also the number of cases of successive thunderstorm days are so few that it can be concluded that the meteorological conditions which favour the occurrence of air-mass thunderstorms in Athens have a tendency not to persist.

Table II. Number of cases when an air-mass thunderstorm day during the warm season (May–September) in Athens during 1970–75 was not immediately followed by an air-mass thunderstorm day (column I) and the number of cases when air-mass thunderstorm days occurred on two successive days (column II).

Year	May		June		July		Aug.		Sept.		Total	
	I	II	I	II	I	II	I	II	I	II	I	II
1970	0	0	1	1	1	0	0	0	1	0	3	1
1971	1	0	1	0	0	0	0	0	1	0	3	0
1972	1	0	1	0	2	1	1	0	0	0	5	1
1973	1	0	1	0	2	0	0	0	0	0	4	0
1974	0	0	0	0	0	0	1	0	1	0	2	0
1975	2	1	1	1	0	0	2	0	0	0	5	2
Total	5	1	5	2	5	1	4	0	3	0	22	4

4. Conditions in which air-mass thunderstorms occur at Athens

4.1 Use of upper-air soundings

The meteorological parameters $T_{850}-T_{500}$ and $(T-T_d)_{850}+(T-T_d)_{700}$ can be computed from upper-air soundings (T and T_d denote the temperature and dew-point, and the subscript indicates the level in millibars). The first of these quantities provides a measure of the instability of the atmosphere whilst the second indicates the humidity in the lowest levels.

Fig. 2 show plots of $T_{850}-T_{500}$ against $(T-T_d)_{850}+(T-T_d)_{700}$ derived from the 0000 and 1200 GMT ascents at Helliniko for each air-mass thunderstorm day at Athens (each thunderstorm day has been labelled 1 to 30 but some ascents are missing). One immediate result which can be seen from the figure is that in all cases thunderstorms only occurred when $(T-T_d)_{850}+(T-T_d)_{700}$ is smaller than 22 °C and $T_{850}-T_{500}$ greater than 23 °C. This suggests that if the two quantities are outside these limits then the conditions are not at all favourable for the development of air-mass thunderstorms

The plots in Fig. 2 have been divided into three regions based on the characteristics of the thunderstorm days. Region A — severe thunderstorms of long duration with precipitation reported from both stations. Region B — thunderstorms of short duration with precipitation reported from at least one of the stations. Region C — thunderstorms without precipitation reported by either stations. Broadly the regions are determined by the amount of moisture in the lowest layers of the atmosphere.

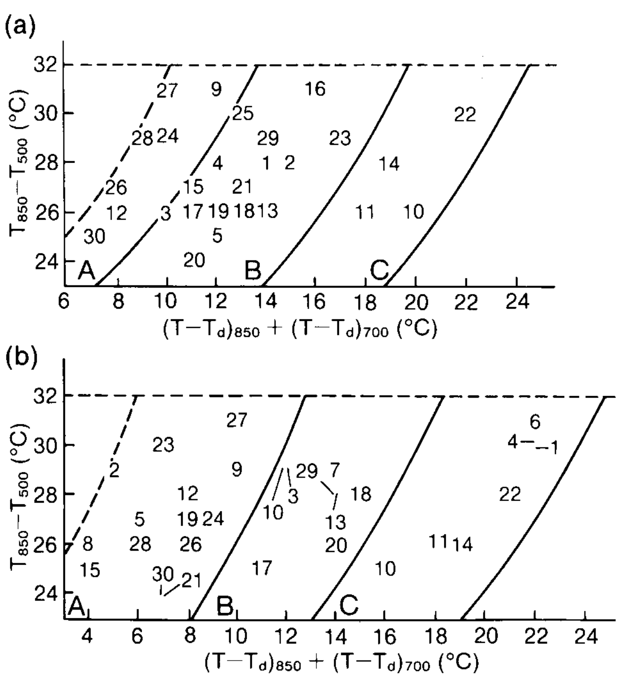

Figure 2. Plots of $(T-T_d)_{850}+(T-T_d)_{700}$ against $T_{850}-T_{500}$ from radiosonde ascents at Helliniko for (a) 1200 GMT and (b) 0000 GMT. The numbers denote the thunderstorm day (i.e. a day when a thunderstorm occurred at Athens). See text for explanation of symbols.

Comparing Figs 2(a) and 2(b) shows that the days in Region A at 1200 GMT (see Fig. 2(a)) are usually in the same region as 12 hours earlier (see Fig. 2(b)). The same applies for regions B and C. This suggests that the values of $T_{850}-T_{500}$ and $(T-T_d)_{850}+(T-T_d)_{700}$ for 0000 GMT can be used to forecast the likelihood and intensity of thunderstorms at Athens and the surrounding region. If these two quantities do not lie within the boundaries of the area in Fig. 2(b) then it is forecast that there is no likelihood of thunderstorms; if they do lie within the boundaries then it is forecast that thunderstorms may occur if the cloud conditions (and other surface synoptic features described in the next section) are suitable.

4.2 Use of synoptic charts

For the air-mass thunderstorm days at Athens the 850 and 500 mb mean charts were prepared for 0000 and 1200 GMT (0300 and 1500 local time) using data from the National Center for Atmospheric Research, Boulder, Colorado. The 500 mb chart is the traditional level at which the contour regime in the Balkans is related to the occurrence of air-mass thunderstorms at Athens. Consequently the difference between the mean height values and the normal values for the summer season (based on the normal monthly values published by the Deutscher Wetterdienst) were computed in order to detect centres of action.

Fig. 3 shows the mean 500 mb contour height and temperature at 0000 and 1200 GMT during the days characterized as air-mass thunderstorm days at Athens. Also shown are the anomaly of the contour height from the normal conditions in the warm season (it is the difficulty of maintaining these features that is responsible for there only being a few occasions on which air-mass thunderstorms occur on successive days). A feature of these charts are the low contour heights and cold air over Greece. Also the anomaly field shows that the contour heights are lower than normal for the summer over the whole of the Balkan region, the eastern Mediterranean and adjacent African coast, while in north-west and central Europe the contour heights are higher than normal. A statistical analysis of the anomaly shows that it is a very regular feature in cases where air-mass thunderstorms occur at Athens.

Fig. 3 also shows that the broad-scale flow associated with thunderstorms at Athens is a blocking anticyclone (Makrogiannis 1976 and Prezerakos 1978) which obstructs the regular eastward movement of the pressure systems. Note that the polar jet over the Atlantic splits and one of its branches passes over the Mediterranean resulting in a fall in the 500 mb heights whilst the subtropical jet retreats southwards. The blocking is a diffluent type and this suggests that the low and the accompanying cold air which occurs on a thunderstorm day comes from the west or north-west. So, for an air-mass thunderstorm to occur over Athens, it is reasonable to assume that a low at 500 mb and an

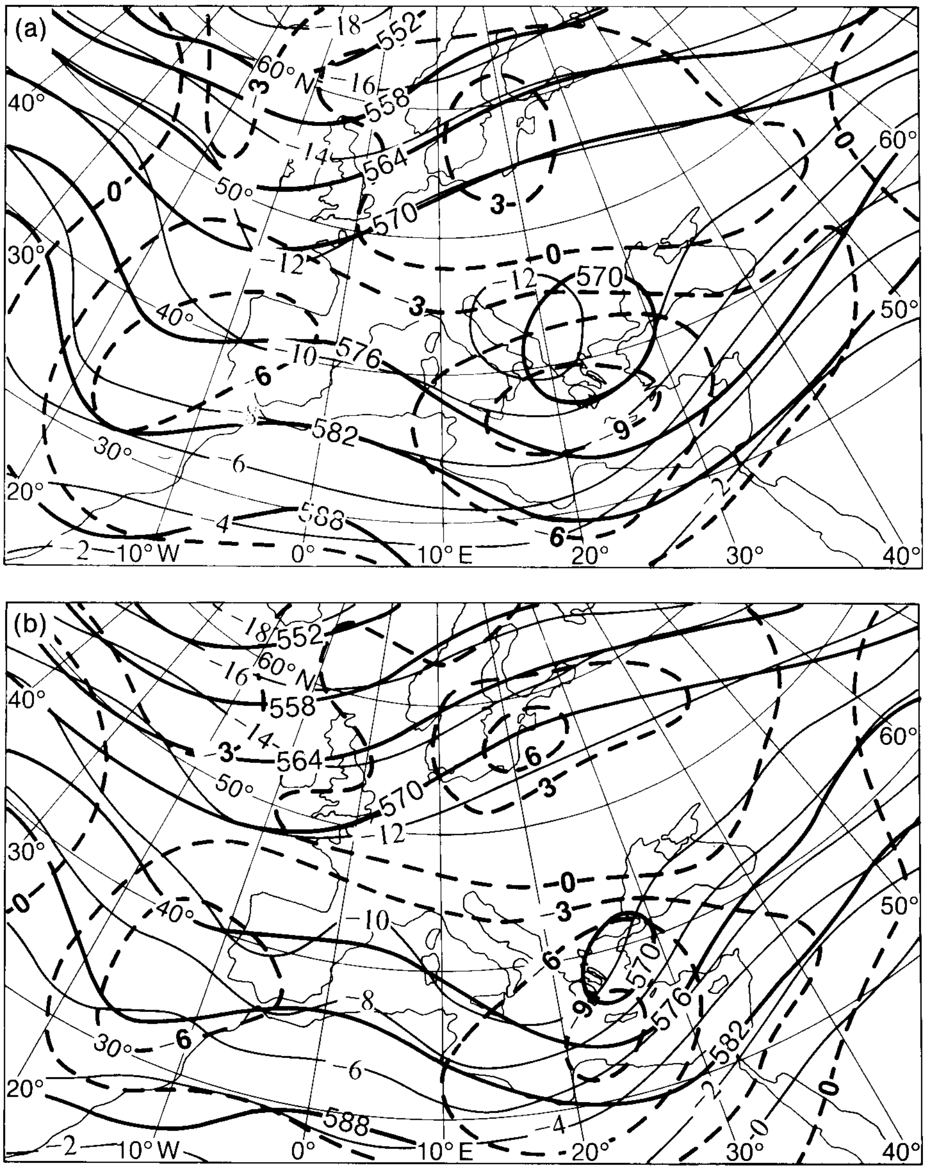

Figure 3. Mean 500 mb contours (dam, thick lines), isotherms (°C, thin lines) and height anomalies (dam, dashed lines) for the 30 air-mass thunderstorm days at Athens at (a) 0000 GMT and (b) 1200 GMT during the period 1970–75.

accompanying cold pool must occur in conjunction with the instability and moist lower troposphere.

At 850 mb the contour height and temperature for the air-mass thunderstorm days have low values in the Balkans and Greece, and high values in the European region north of the Balkans (see Fig. 4). Furthermore the spacing of the contours indicates that on air-mass thunderstorm occasions there are only light winds at 850 mb. This is consistent with the observed 850 mb winds, though there are occasions when the wind exceeded 15 kn (usually in the morning).

The mean-sea-level pressure chart for the air-mass thunderstorm days at Athens has a slack pressure gradient in the vicinity of the Balkans and Mediterranean. The associated calm conditions in the Athens region allows the surface heating to be sufficient to trigger the instability. This means that when the Etesian blows at Athens, thunderstorms are unlikely. Consequently the extension of the permanent thermal low over Cyprus towards Greece and/or the establishment of high pressure in the central Mediterranean, both of which are associated with the Etesian in Greece, are incompatible with air-mass thunderstorms at Athens.

4.3 A quick objective method

From the material presented in the previous two sections it appears that air-mass thunderstorms tend to occur at Athens if the following conditions are satisfied:

(a) In Fig. 2 the quantities $(T-T_d)_{850}+(T-T_d)_{700}$ and $T_{850}-T_{500}$ fall into the regions delineated.

(b) There is less than 4 oktas total cloud before noon.

(c) The 500 and 850 mb fields are similar to those given in Figs 3 and 4 with light winds at 850 mb and the surface.

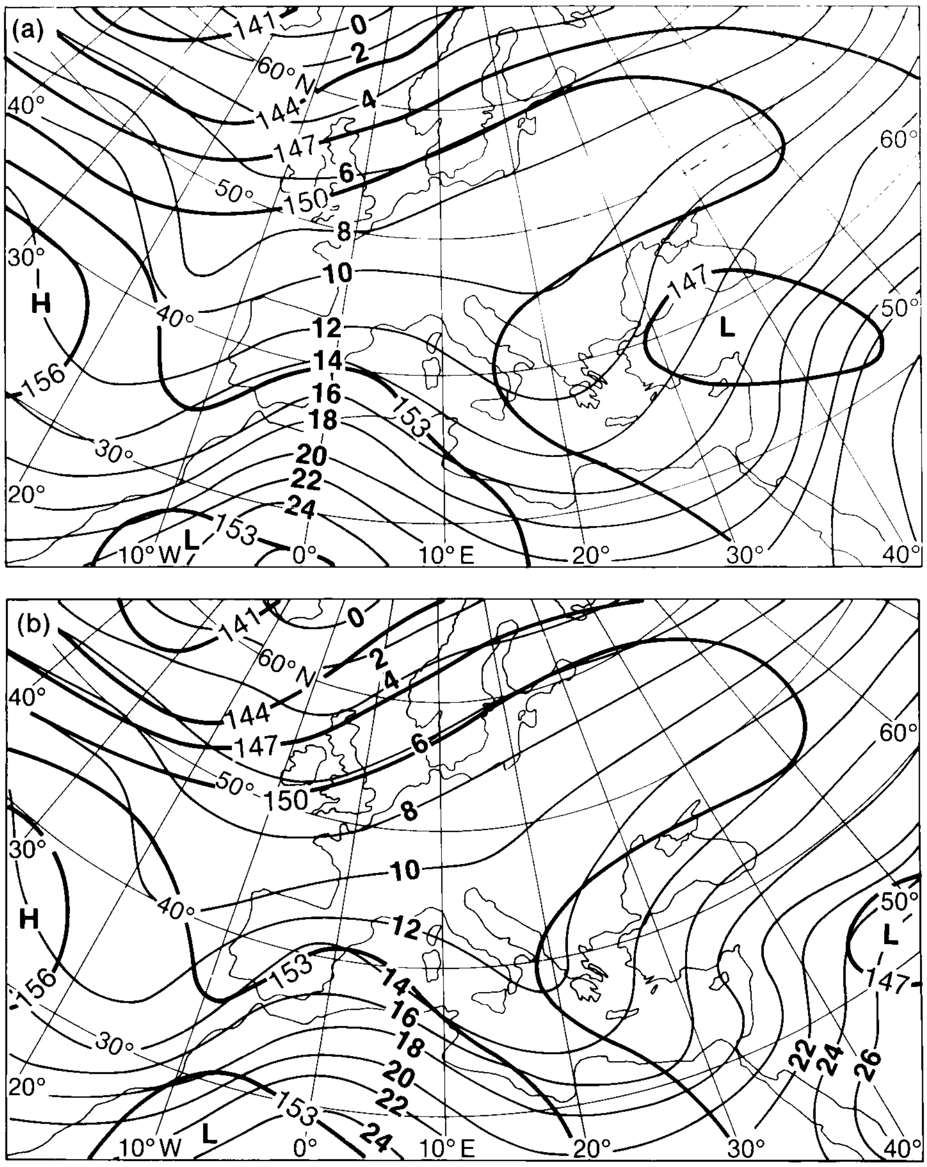

Figure 4. Mean 850 mb contours (dam, thick lines) and isotherms (°C, thin lines) for the 30 air-mass thunderstorm days at Athens at (a) 0000 GMT and (b) 1200 GMT during the period 1970–75.

This forecasting scheme was verified for May–September for the period 1980–82. For each day the humidity, $(T-T_d)_{850}+(T-T_d)_{700}$, and instability, $T_{850}-T_{500}$, parameters were estimated from both the 0000 and 1200 GMT ascents at Helliniko and the dates when these parameters fell within the areas A, B, or C in both Figs 2(a) and 2(b) are recorded. Twenty per cent of all cases were excluded as having more than 3 oktas cloud before noon. The similarity of the 0000 and 1200 GMT 850 and 500 mb charts with those in Figs 3 and 4 was then examined; this guarantees that the passage of a front, strong cold advection at 500 mb or positive vorticity advection at 500 mb did not occur in the afternoon. This eliminated a further 35 per cent of remaining occasions. Ninety-five per cent of the occasions left corresponded to observed air-mass thunderstorm days at Athens. It was not possible to identify any specific reasons for the failure in the residual 5 per cent of cases though more detailed studies may prove valuable.

5. Conclusions

The main conclusions resulting from this study are as follows:

(a) 59 days of thunderstorms (either air-mass or dynamical) occurred in Helliniko and 50 in Nea Philadelphia during the warm season (May–September) of the period 1970–75. From these it was deduced that during the period under consideration there were 30 air-mass thunderstorm days at Athens. Cases of three or more successive air-mass thunderstorm days at Athens were not detected during the 6-year period, and even the number of occasions of two successive days was extremely small.

(b) During the air-mass thunderstorm days at Athens $(T-T_d)_{850}+(T-T_d)_{700}$ is lower than 22 °C and $T_{850}-T_{500}$ is higher than 23 °C. In addition there are light winds at 850 mb and calm at the surface, and at 500 mb strong cold advection or positive vorticity advection do not occur in the afternoon.

(c) For air-mass thunderstorm days there is a 500 mb low in the vicinity of Greece centred to the east of Athens accompanied by a cold pool, and in northern Europe there is an anticyclone associated with a diffluent block. Also the 500 mb heights are much lower than normal with the subtropical jet stream displaced southwards so that the polar jet stream, which is to the north of the diffluent block, crosses Greece. At 850 mb the contour heights and temperatures are lower than usual.

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The effect of a sea surface temperature anomaly on a prediction of the onset of the south-west monsoon over India*

R. Kershaw

Meteorological Office, Bracknell

Summary

At the time of the onset of the monsoon in June 1979 the sea surface temperatures in the eastern Arabian Sea were higher than usual. Experiments carried out with an atmospheric model show that a better prediction of the onset is obtained using the anomalously high temperatures rather than the climatological ones.

1. Introduction

The Global Weather Experiment (also known as the First GARP Global Experiment (FGGE)) carried out in 1979 has provided a wealth of data which have been used in numerous studies of the atmospheric circulation. Many research groups have investigated the ability of models to predict the onset of the south-west monsoon over India. These studies have met with varying degrees of success (Krishnamurti *et al.* 1983), but they are nearly all marked by an inability of the models to predict the formation of a tropical storm (also known as the onset vortex) over the Arabian Sea.

Seetaramayya and Master (1984) pointed out that the sea surface in the eastern Arabian Sea was warmer than normal at the time of the onset of the monsoon in 1979. They also suggested that the development of the tropical storm in this region was aided by the anomalously high surface temperatures. This hypothesis has been tested by making two predictions of the monsoon onset using an atmospheric model with and without the positive temperature anomaly. Here only a brief description of the predictions will be given; a full account of the results and a discussion of the mechanism of onset are given in Kershaw (1988).

2. Experimental details

Experiments were carried out with a global model of the atmosphere, developed by the Dynamical Climatology Branch of the Meteorological Office, which has a horizontal resolution of 2 degrees of latitude and 3 degrees of longitude, and is divided into 11 (unequally spaced) layers in the vertical. The model contains parametrizations of physical processes, including convection, radiation, large-scale precipitation and turbulent mixing in the boundary layer; a complete description may be found in Slingo (1985). The model is not normally used for numerical weather prediction; it is mainly used for the study of the general circulation and climate change.

Both the control and anomaly experiments started from the same atmospheric analysis — the FGGE analysis for 12 GMT on 11 June 1979 produced by the European Centre for Medium-range Weather Forecasts (ECMWF) using all the observations available for that time, collected during the Global Weather Experiment (Lorenc 1981). The analysis had to be horizontally and vertically interpolated from the ECMWF grid to that used in the 11-layer model. After the interpolation no initialization was carried out before running the model.

* An abridged version of a paper by Kershaw (1988) which appeared in the *Quarterly Journal of the Royal Meteorological Society.*

The sea surface temperatures were kept fixed throughout each 8-day prediction. In the control experiment the sea surface temperatures were simply the long-term average values for the appropriate time of year (Fig. 1(a)). The anomaly experiment used the same values as the control, except in the Arabian Sea where the temperatures are based on the analysis of Seetaramayya and Master (1984) (Fig. 1(b)). The difference between the temperatures used in the two experiments (the anomaly) is shown in Fig. 1(c)).

3. Discussion of the experiments

During the onset of the south-west monsoon the atmospheric circulation undergoes a considerable change; a westerly jet becomes established over the Arabian Sea in the lower troposphere and in the upper troposphere an easterly jet forms. At the same time the rainfall increases in south-west India and moves northwards along the west coast. In June 1979 these changes occurred more rapidly and somewhat later than is usual (Pearce and Mohanty 1984).

The developments in the lower troposphere over the Arabian Sea are illustrated by the sequence of 850 mb wind analyses in Fig. 2. At 12 GMT on 11 June the jet over the Arabian Sea had not yet fully developed and the strongest flow was near the Somali peninsula (Fig. 2(a)). By 12 GMT on 15 June (day 4) the Somali jet had strengthened and extended eastwards (Fig. 2(b)); the onset vortex had formed on its northern flank, close to

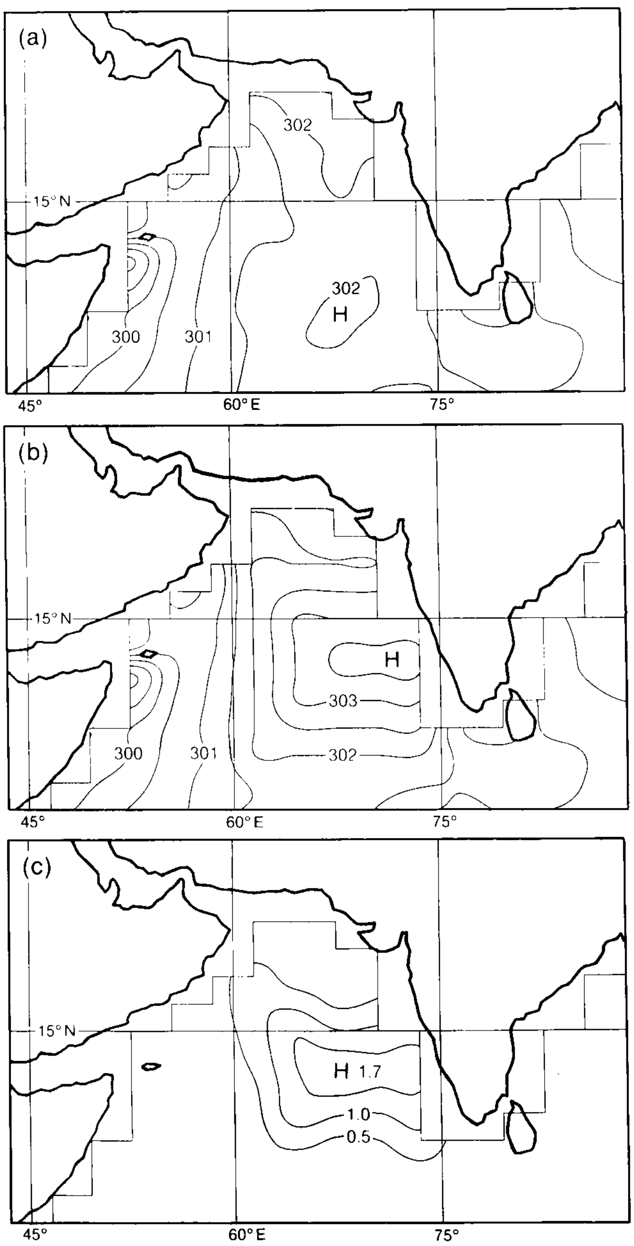

Figure 1. Sea surface temperatures (K) in the Arabian Sea for (a) the control forecast and (b) the anomaly forecast; (c) is the difference between (b) and (a).

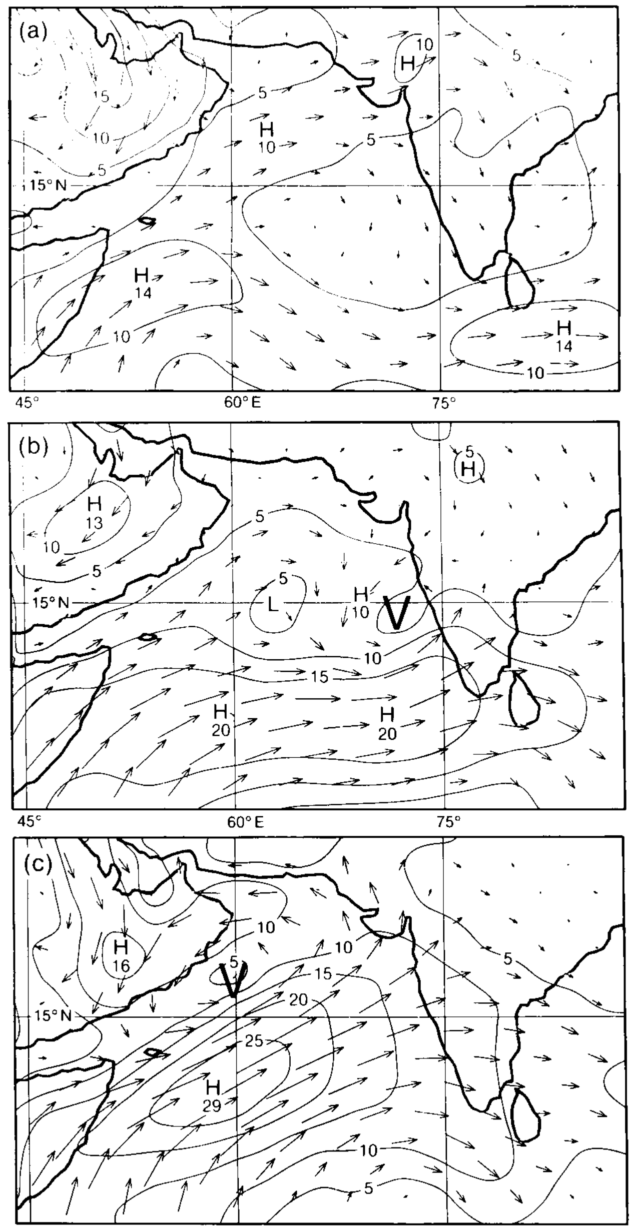

Figure 2. Wind vectors and isotachs (m s^{-1}) at 850 mb from the ECMWF FGGE analyses for (a) 12 GMT on 11 June 1979, (b) 12 GMT on 15 June 1979 (day 4) and (c) 12 GMT on 19 June 1979 (day 8). V marks the position of the vortex.

the Indian coast, and south-westerly winds were affecting southern India. The vortex strengthened and moved north and then west, so that by 12 GMT on 19 June (day 8) it was just a few degrees to the east of the Arabian coast (Fig. 2(c)). Meanwhile the jet strengthened and moved northwards, and strong westerly winds were affecting the entire west coast of India by 19 June.

In the control experiment the Somali jet did not move eastwards quickly enough or attain sufficient strength. By day 4 of the prediction (Fig. 3(a)) no vortex had formed on the north-eastern edge of the jet. During the next 4 days a weak vortex did form, but remained stationary, and the jet attained a maximum speed of only 24 $m s^{-1}$ compared with the analysed speed of 29 $m s^{-1}$ (Fig. 3(b)). Also the strong westerly winds had not moved northwards, so that by day 8 they were only affecting the southern part of India. Clearly the control prediction failed to capture the full intensity of the changes that occurred during the onset of the monsoon.

As shown in Fig. 4, the anomaly experiment produced a much better prediction of the changes. By day 4 (Fig. 4(a)) the low-level jet had extended further eastwards than in the control and the vortex had already formed, and during the next 4 days the vortex strengthened and moved north-westwards (Fig. 4(b)). By this time the jet had attained a maximum speed of 29 $m s^{-1}$, identical to the observed value, and the entire western coast of India was under the influence of the strong winds. The prediction was not perfect but, for an 8-day forecast, the quality was remarkably high. In particular, the forecast of the formation of the onset vortex was very good.

In the upper troposphere, both experiments predicted the strengthening of the easterly jet and the increase in the cross-equatorial flow, though neither experiment predicted the replacement of the weak westerlies by weak easterlies over northern India. However, the anomaly experiment was superior in that it predicted a stronger easterly jet which was more like that observed. The anomaly experiment also produced a more realistic forecast of precipitation over India than the control. Further information about the prediction of precipitation and the upper flow can be found in Kershaw (1988).

4. Conclusions

These results support the initial hypothesis that the sea surface temperature anomaly was instrumental in the development of the onset vortex, and there is evidence (not discussed here) that the main cause of this was the consequential enhancement of the release of latent heat over the Arabian Sea. Moreover, the use of realistic sea surface temperatures improved the prediction of other aspects of the onset of the monsoon. In particular, the strengthening of the Somali jet and the upper-level easterly jet, and the northward movement of the rainfall over India were all predicted more accurately in the anomaly experiment than in the control. This is a very good example of the beneficial

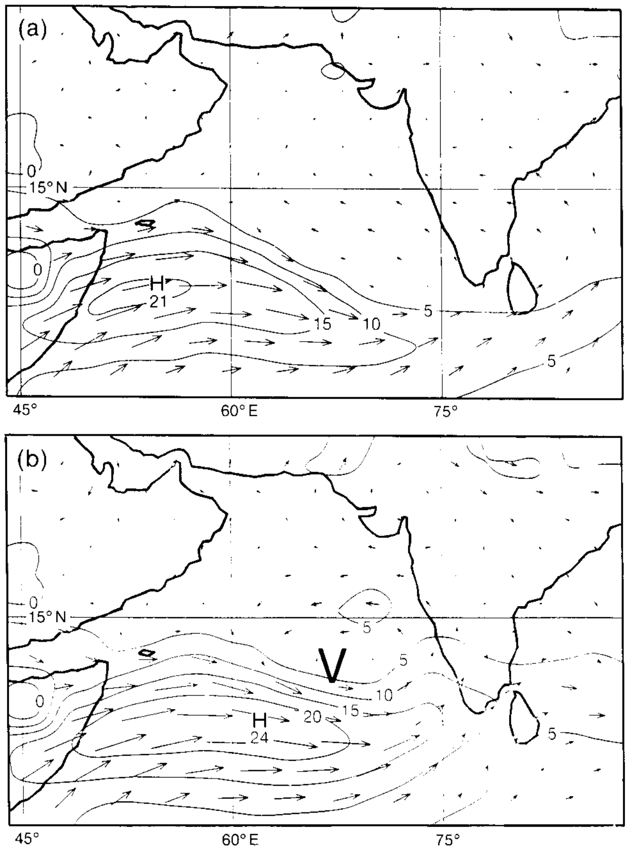

Figure 3. Wind vectors and isotachs ($m s^{-1}$) at 850 mb from the control forecast for (a) 12 GMT on 15 June 1979 (day 4) and (b) 12 GMT on 19 June 1979 (day 8). V marks the position of the vortex.

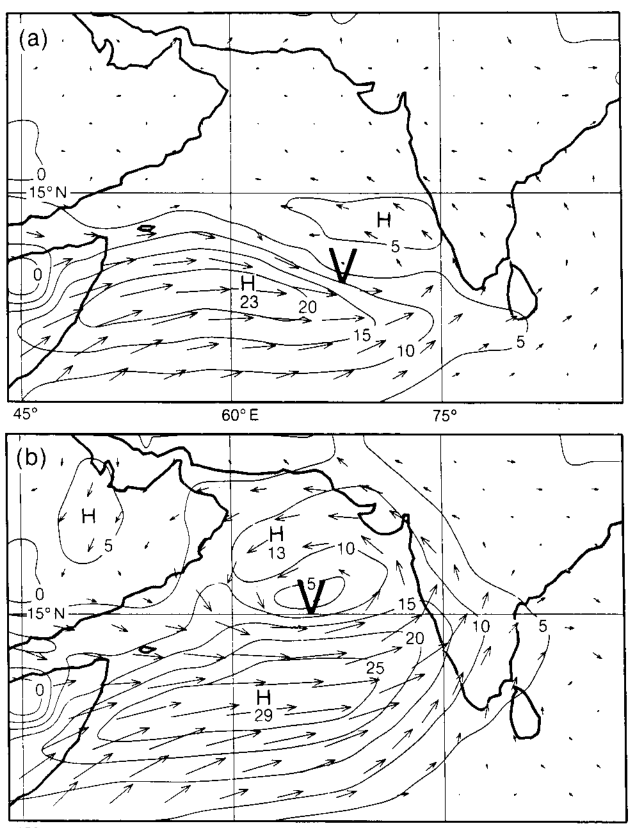

Figure 4. As Fig. 3 but for the anomaly experiment.

impact that the use of observed rather than climatological sea surface temperatures can have on numerical weather prediction in the tropics.

In the tropics a sea surface temperature anomaly will have more influence on the atmospheric circulation when the winds are strong over the anomaly. Therefore, because they develop near the low-level jet, monsoon disturbances are likely to be particularly sensitive to sea surface temperature anomalies. Also, the normal gradient of sea surface temperatures in the Arabian Sea will amplify the impact of an anomaly in the east because the prevailing low-level winds flow up the gradient from cooler to warmer seas. Thus it is likely that the onset of the monsoon in other years will be sensitive to such anomalies.

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The spring of 1988 in the United Kingdom

G.P. Northcott

Meteorological Office, Bracknell

Summary

The spring of 1988 was generally rather wet, but mild in most areas and with average sunshine over the season.

1. The spring as a whole

Mean temperatures were a little above average in most parts of the United Kingdom, apart from some places in the north of Scotland and eastern England where temperatures were just below normal, ranging from 0.4 °C below normal in Shetland to 1.0 °C above normal in parts of south-east England. A very wet March and a showery May helped towards making the spring generally rather wet. Sunshine amounts were about average.

Information about the temperature, rainfall and sunshine during March–May 1988 is given in Fig. 1 and Table I.

2. The individual months

March. Mean monthly temperatures were above normal in all districts except northern Scotland, where they were generally below normal, and ranged from 0.7 °C below normal in northern Scotland to 1.3 °C above normal in parts of the Midlands. In Northern Ireland it was the mildest March since 1983. Monthly rainfall amounts were above normal in most parts of the United Kingdom, reaching about two and a half times the normal in some places in the Midlands and north-west, but slightly below normal in some parts of Northumberland. Silsoe, Bedfordshire reported the wettest March there since 1982, despite having 13 days with no measurable rain. Northern Ireland, where it was the wettest March since 1903, had around twice the normal rainfall for the month. It was a generally dull month with sunshine amounts not reaching even 70% of average on the south coast of England. However, coastal areas of north-eastern England and eastern Scotland, and Orkney and Shetland, had above average sunshine, and just over 130% was reached in the Fife Region of Scotland. At Oxford, where only 85 hours of sunshine was measured during the month, it was the second dullest March since records began and nearly 30 hours less than the long-term mean.

The month started with sleet and snow showers in many places and continued for the next few days with rain or showers, and some snow on the 4th. It remained unsettled with occasional rain or showers for most of the month. The 15th was a windy day in many places especially in the south. Brighter showery weather spread to all but the south-east of England during the 28th. There were further showers over Scotland and Northern Ireland during the closing days of the month, while in England and Wales there was a good deal of sunshine with a few scattered showers. On the 24th there were widespread reports of thunder from southern Scotland to East Anglia; lightning caused structual damage to property at Donington, approximately 13 km south-west of Kirton, Lincolnshire. Hail was reported frequently during the month, widespread at times.

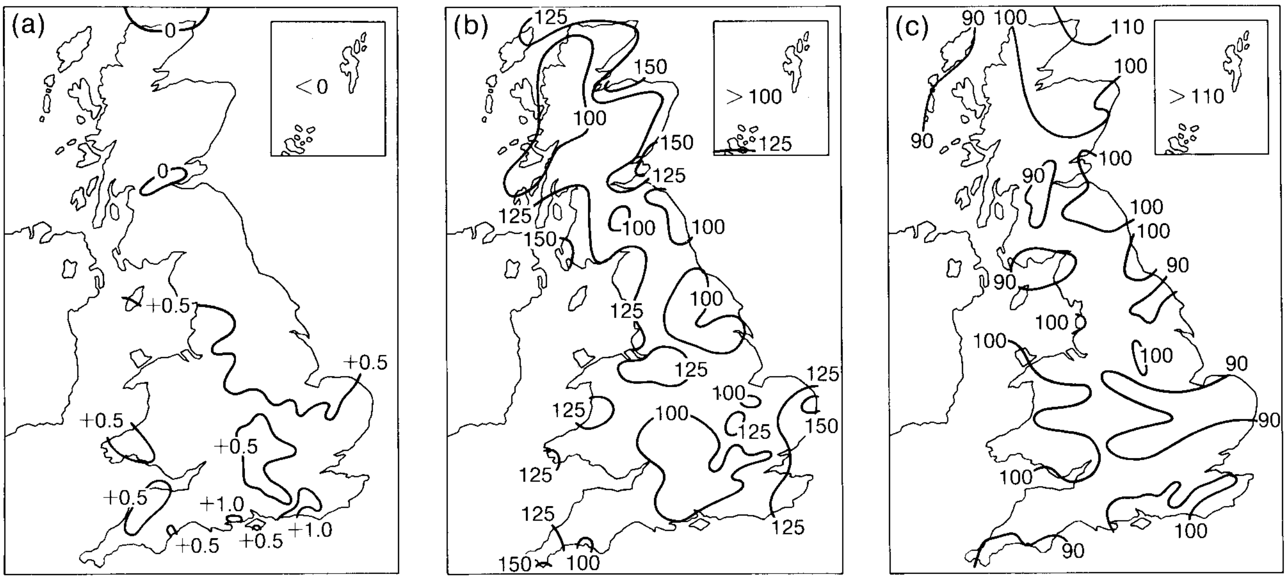

Figure 1. Values of (a) mean temperature difference, (b) rainfall percentage and (c) sunshine percentage for spring 1988 (March–May), relative to 1951–80 averages.

Table I. District values for the period March–May 1988, relative to 1951–80 averages

District	Mean temperature (°C)	Rain-days	Rainfall	Sunshine
	Difference from average		Percentage of average	
Northern Scotland	+0.1	0	100	100
Eastern Scotland	+0.4	0	115	101
Eastern and north-east England	+0.4	+2	99	95
East Anglia	+0.6	+2	118	87
Midland counties	+0.5	+1	100	94
South-east and central southern England	+0.7	+1	98	95
Western Scotland	+0.3	+2	112	89
North-west England and North Wales	+0.6	+2	118	95
South-west England and South Wales	+0.6	+1	112	96
Northern Ireland	+0.6	0	103	89
Scotland	+0.2	+1	110	97
England and Wales	+0.6	+2	108	94

Highest maximum: 26.5 °C in the northern Scotland in May.
Lowest minimum: −10.2 °C in eastern Scotland in March.

April. Mean temperatures were above normal everywhere except for some east-facing coasts in the south and west and the far north of Scotland, where they were below normal, approaching 1 °C below normal in Shetland. Temperatures in Co. Antrim were just over 1 °C above normal. April was the fifth month in succession in which temperatures were above normal nearly everywhere. Monthly rainfall amounts were generally above normal north of a line from about Tyne and Wear to the Isle of Man except for a large part of western Scotland where it remained rather dry. South of the line it was generally rather dry apart from some places in central and south-eastern England and southernmost parts of Cornwall. Rainfall amounts ranged from nearly three times the normal at Arbroath, Tayside Region to less than 40% in Guernsey, Channel Islands. It was the driest April since 1984 in parts of Northern Ireland. Sheffield, Weston Park reported the lowest rainfall amount since 1981. Sunshine amounts were below the average generally, apart from the far north of Scotland, south-east England and South Wales where sunshine was near or just above average, ranging from 115% in East Kent to a rather dull 66% in the Isles of Scilly and the Southern Uplands of Scotland. Sheffield, Weston Park reported the dullest April since 1978.

The weather was changeable with warm and cold spells. There were reports of thunder in the Midlands, notably over Nottinghamshire and Derbyshire, on the 3rd and over a wide area on the 18th, with outbreaks in eastern and southern England from North Yorkshire to the Isle of Wight. Several places in Northern Ireland had thundery outbreaks on the 20th. Further thunder occurred on the 27th over much of central southern and south-west England. Hail was widespread in the north Midlands and in parts of southern England from Kent to Dorset on the 27th.

May. Mean monthly temperatures were above normal nearly everywhere, ranging from 0.3 °C below normal at Finningley, South Yorkshire to 1.5 °C above normal at Gatwick, West Sussex. Coventry (Bablake), Warwickshire reported the warmest May since 1970, the first without any frost in Coventry since 1970, while Hampstead, Greater London had the warmest May since 1976. Monthly rainfall totals were below normal in all districts except East Anglia, and south-west England and South Wales. A dry 52% of normal at Hurn, Dorset contrasted strongly with 128% of normal at Ilfracombe in the neighbouring county of Devon. The first 26 days of the month yielded just half the normal rainfall in the south-east, and across the United Kingdom it was the driest for 6 years. Monthly sunshine amounts were about normal in all areas, ranging from 93% in parts of East Anglia to 135% in eastern Scotland.

It was quite a warm month everywhere apart from the east coast where it was a little cloudier and cooler. The month was also rather showery with thundery outbreaks; warm, moist air from the Continent brought outbreaks of thundery rain to the south-east on the 8th, and some showers were reported in other areas. Generally dry conditions prevailed from the 13th, although some rain was reported at first in eastern Scotland and north-east England, and there were a few thundery showers in central southern England on the 15th. Scattered showers occurred on the 18th and 19th with thunder reported from southern counties of England and Wales on the 19th. The last three days were unsettled; however, much of southern and eastern Scotland escaped rain on the 30th and Wales and southern England soon became mainly dry on the 31st. A severe thunderstorm at Moel-y-Crio, Clwyd on the 1st just after 1300 GMT was accompanied by hailstones 15 mm in diameter that caused considerable damage to fruit trees and hedges in the vicinity; heavy rain caused some local flooding. Reports of coloured dust deposited on the 7th were received from places as far apart as North Yorkshire, Dyfed, Essex and the south coast.

Conference report

Seventh Meteosat Scientific Users' Conference, Madrid, Spain, 27–30 September 1988

The 7th Meteosat Scientific Users' Conference was held in Madrid from 27–30 September 1988. It was jointly organized by the Instituto Nacional de Meteorologia (INM) and Eumetsat. Both organizations are to be complimented for their contributions to a most interesting and rewarding meeting. INM, the local Spanish hosts, made all attendees feel most welcome. The meeting was conducted in English, despite the large contingents from Spain and France and the paucity of native English speakers.

The proceedings were divided into sessions as follows:

(a) Present and future systems — this included a description of aspects of the current system and the forthcoming Meteosat Operational Programme (MOP), and papers on Meteosat Second Generation (MSG). Three papers in this section were of particular interest.

- De Waard (European Space Operations Centre) presented a keynote address on changes that will occur when the MOP series becomes available from April 1989.
- Bonneyfoy (European Space Technical Centre) presented a keynote address on MSG, summarizing the current requirements for instruments. This includes an eight-channel imager with a spatial resolution of 2 km (oversampled by 1.5), a sounder with both infra-red and microwave channels and numerous scientific instruments. However, technology places limitations on these requirements; characteristics of instruments resulting from the compromise between what is needed and what is feasible were presented.
- Bizzari (Italian Meteorological Service) continued the theme with a paper on the spatial resolution of the MSG imager. He showed that the detection of objects of a certain size by an imager was dependent upon the difference between the temperature (or brightness) of the object and that of its background. Plans to extend the function of the imager to provide information on temperature profiles through the judicious selection of spectral channels were also discussed.

(b) Cloud and radiation — one paper of interest was by Borger of The Netherlands and described work in classifying clouds using knowledge-based methods. Another was one by Geneviève Sèze (LMD/Centre National de la Recherche Scientifique) on the spatial and temporal variability of radiance values. Differences between the radiances of pixels as a function of distance were interpreted in terms of scale invariance. Extensions of this type of study to smaller spatial scales, for example using Landsat or SPOT data, could assist in the interpretation of measurements of surface temperature at the coarser scales.

(c) Systems for research and operational environments — this session gave the opportunity for the developers of systems to show off the features of their wares. The main aim seemed to be to produce a cheap receiver and image processor for use by the emerging nations. Systems included one from the University of Bristol that specialized in the detection of precipitation, and one from the University of Bradford that used software from the University of Reading's Department of Meteorology.
(d) Radiation — the temporal resolution of Meteosat has been exploited to gain knowledge of global radiation for use in studies of the radiation budget.
(e) Surface and climate — a large number of papers was presented on these topics. Many were concerned with extracting information about regional variations of surface characteristics, including soil moisture and albedo. Flitcroft (University of Reading) gave an interesting paper on the relationships between point measurements of precipitation and areal averages. The consequences for the Sahel region were discussed.
(f) Precipitation — this session also had a large number of papers, more than half of which described applications to measuring rainfall in Africa. Some of the problems of such applications were discussed by Dugdale (University of Reading); he is forced to use stream-flow measurements combined with a catchment model to derive rainfall in an area devoid of conventional data! Collier's (Meteorological Office, Bracknell) keynote address on the measurement of precipitation from space was delivered by Richard Allam. The paper by Isabelle Jobard again alluded to the variations of precipitation in space and time.
(g) Atmospheric dynamics — Debois' keynote paper reviewed progress in determining winds from the apparent motion of clouds. Anke Eriksson described preliminary results of a new method of extracting wind vectors from water vapour images. The usual slick films sent to the conference by Zick (Free University of Berlin) showed it is possible to give a 'paper' without actually being present in person.
(h) Operational meteorology — this rather mixed session featured presentations from two members of the Nowcasting and Satellite Applications Branch of the Meteorological Office; Geoff Monk on the imagery associated with the October 1987 storm, and Richard Allam on sea-fog monitoring. Interesting papers on forecasting in Spain were also presented, including a case-study in which more than 800 mm of rain (exceeding the annual average) fell on a narrow coastal strip of eastern Spain in 24 hours. A movie loop revealed that a mesoscale convective system remained anchored to topographical features in the area, despite the obvious marked upper flow relative to it.

Four themes seemed to run through the meeting. The first was the extensive use of Meteosat imagery in the monitoring and forecasting of rainfall in arid regions of Africa. The second was the encouraging sign of appropriate research being performed by the African nations themselves, rather than by European countries. The third was the scientific interest in problems associated with the variations of the properties of objects and images at different spatial scales. The fourth was the universal enthusiasm with which scientific work with Meteosat data is conducted, and the optimistic view of future applications with both the MOP and MSG systems.

R.J. Allam

Notes and news

The European Geophysical Society

1. General Information

The European Geophysical Society (EGS) was founded in 1971 to promote both disciplinary and interdisciplinary co-operation among scientists in Europe and throughout the world concerned with the full range of geophysical studies. According to the broad divisions of geophysics, the activities of the Society are organized into three main sections:

Section I — Solid Earth and planets
Section II — Hydrospheres and atmospheres
Section III — Upper atmospheres, ionospheres, magnetospheres and external geophysics.

To promote its aims the EGS organizes annual scientific General Assemblies at different venues in Europe normally held in spring during the second, full working week before Easter; publishes a *Newsletter* to keep members informed about its activities; runs the journal *Annales Geophysicae* (for Sections II and III) and jointly with the American Geophysical Union the journal *Tectonics*, and participates in the running of the *Geophysical Journal* (for Section I) of the Royal Astronomical Society; and co-sponsors appropriate scientific meetings, summer schools, or workshops organized by other bodies.

Membership of the EGS is open to all scientists as individuals or as societies, institutes, laboratories or groups. Members are entitled to subscribe to the EGS journals at greatly reduced concession rates, and to attend the General Assemblies at a reduced registration fee.

2. The 1989 General Assembly

The 14th General Assembly of the EGS is to be held in Barcelona, Spain from 13–17 March 1989.

Many of the topics being discussed in symposia, workshops, open and joint sessions are of interest to meteorologists and climatologists. The following are of particular relevance:

Symposia on: atmospheric and oceanic boundary layers, hydrological and desertification processes at land surfaces, mesoscale precipitation (measurement, modelling and forecasting), prediction, predictability and low frequency variability of the atmosphere, mediterranean weather systems.

Workshops on: the atmospheric boundary layer over non-homogeneous terrain, innovative numerical techniques in atmospheric modelling, Arctic polar ozone.

Joint sessions on: forecasting extreme hazardous events, and stratospheric ozone depletion.

Open session on meteorology and climatology not dealt with elsewhere.

The EGS makes Travel Awards for young scientists (less than 30 years old) to attend the Assemblies to present papers. Although the application deadline for these awards (and attendance generally) at this year's Assembly is now passed it should be noted that the 15th General Assembly is to be held in Copenhagen from 23–27 April 1990. The EGS is currently seeking ideas for topics for the symposia and workshops and names of potential conveners for this next Assembly.

3. Further Information

For further information or to make suggestions and proposals for the forthcoming Assembly contact:

The EGS Office
Max-Planck-Str. 1
Postfach 49
D-3411 Katlenburg-Lindau
Federal Republic of Germany

METARC launched

The first edition of Parts 1 and 2 of the Meteorological Office Archive Catalogue (METARC) has recently been published.

The Meteorological Office has an obligation under the Public Records Acts to produce a catalogue of holdings in the Archives and a limited hand-compiled edition was produced in 1975. In 1984 a feasibility study was made for a computer-based version which indicated that it would be a long job but a start on its compilation was made in early 1986. The Office's Systems Development Branch first produced a 'user-friendly' program for the Archive staff to input to the mainframe computer the details of all main holdings. In 1986 the observation registers for approximately 900 stations in England, Wales and overseas held in the Archives were being moved, sorted, counted and re-shelved and so it was decided that these would be the first to be catalogued. This has taken over two years and has resulted in METARC Part 1 — observation registers from England and Wales, and Part 2, for overseas stations (mainly ex-colonial or wartime airfields).

In this context daily registers of observations usually made at 1-, 3- or 6-hour intervals, should not be confused with registers of once daily observations made by the daily climatological stations.

In both parts the form number of the register is given which usually indicates whether the observations are in SYNOP, AERO or SYRED form, along with the period and times of the observations and remarks about missing data. In Part 1 the entries are arranged in alphabetical order of (pre-1974) county name and then station name with National Grid Reference. In Part 2 the entries are in alphabetical order by continent or ocean and then country or island, and the details are the same as in Part 1 except that the latitude and longitude are given.

METARC may not contain details for more recent registers as these are kept at observing stations (for 25 years for official meteorological offices and 2 years for Auxiliary ones) before being deposited in Archives.

It is hoped to produce further METARC catalogues of observation registers from stations in Scotland and Northern Ireland currently held in the Archives at the Meteorological Offices in Edinburgh and Belfast. Meanwhile progress is being made in the cataloguing of the climatological observations held at Bracknell from approximately 5000 stations, some of which go back to the mid 1850s.

Copies of the METARC Parts 1 and 2 are available on application to the Meteorological Offices and all of the catalogued registers are available for inspection in the Office's Archives at Eastern Road, Bracknell during normal working hours.

Books received

The listing of books under this heading does not preclude a review in the Meteorological Magazine at a later date.

Precipitation, by G. Sumner (Chichester, New York, Brisbane, Toronto, Singapore, John Wiley and Sons, 1988. £45.00) brings together the meteorology, climatology and hydrology of the subject. It provides a link betweeen the subjects of geography, meteorology, hydrology and engineering without assuming knowledge of complex mathematics and physics.

Satellite photograph — 4 December 1988

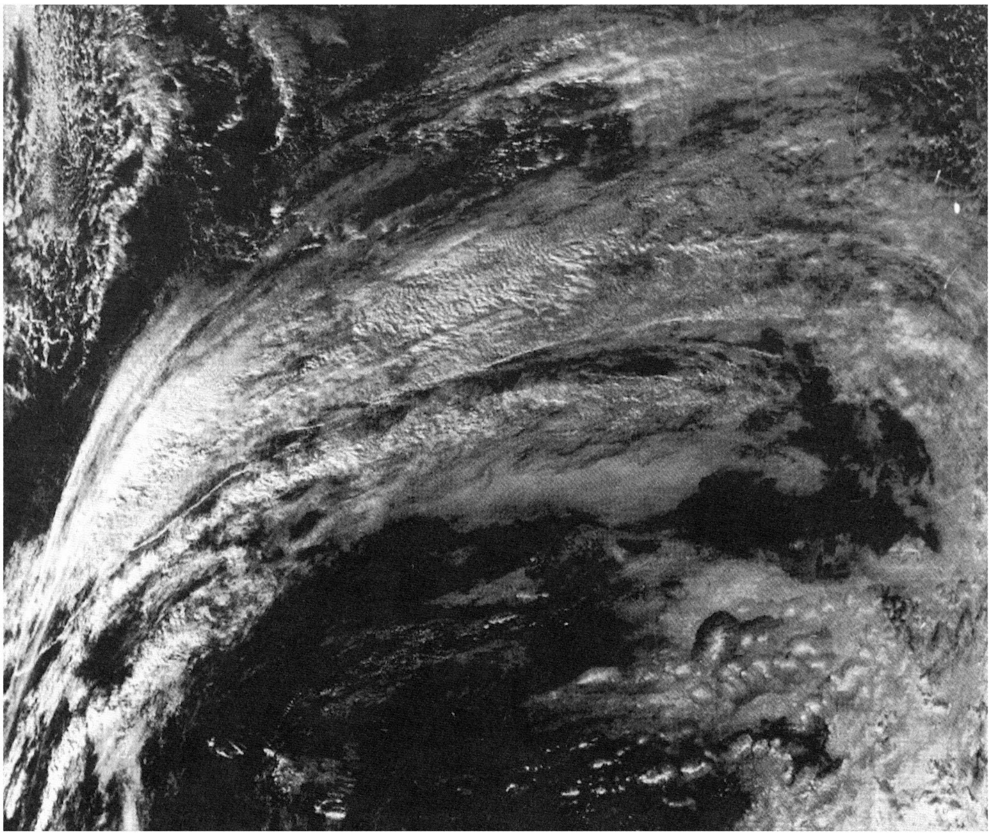

Figure 1. NOAA-11 visible picture for 1445 GMT on 4 December 1988.

This NOAA-11 visible picture illustrates a remarkable cold front in that its surface position can be located by a 'rope' of low cloud over a distance of some 1800 km (see Figs 1 and 2). Just ahead of the cold front (in the warm sector), there is a band of instability and considerable stratocumulus cloud.

Of particular interest is the structure of the cold-frontal zone as implied by the image shown and the corresponding infra-red image. Immediately poleward of the surface front, the broad band of thick cloud is mostly at middle and upper levels, suggestive of a region of slantwise ascent, probably commencing at the surface front (as shown schematically in Fig. 3). Such direct evidence of a classical 'ana' front is not often seen in the eastern Atlantic. More often, the leading portion of the middle or upper cloud 'overhangs' the relatively shallow cloud at the surface front obscuring its position in satellite imagery. Ana (surface) fronts on radar are often marked by line convection. This front was no exception, with radar observations indicating line convection in the English Channel when the front reached the UK weather radar network some 18 hours later.

The portion of the cold front in the western half of the picture lay beneath a very marked jet-entrance region with wind speeds increasing from 60 to 170 kn over only 600 km. The jet stream lay close to and parallel to the poleward edge of the frontal cloudiness. Classical cold fronts are usually located near to and downstream of marked jet-entrance regions and/or confluent troughs.

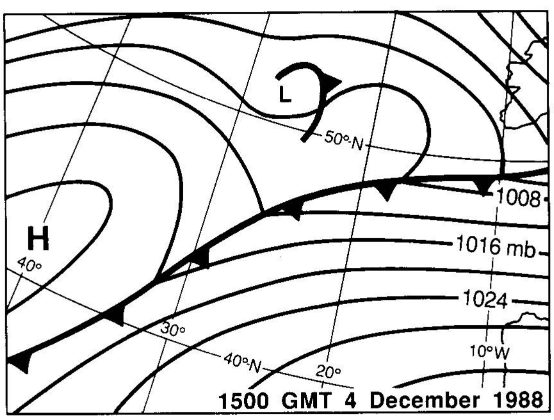

Figure 2. Synoptic chart, interpolated from 1200 GMT data, so as to correspond to the time of the image.

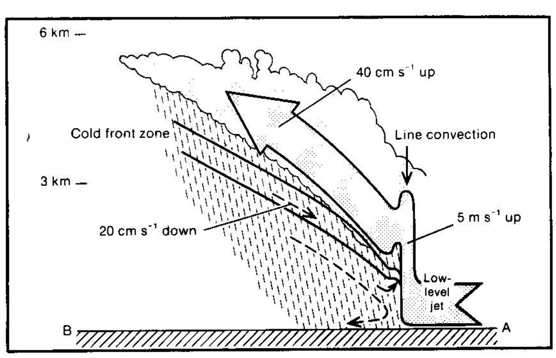

Figure 3. Idealized cross-section across a classical anafront (from Browning, K.A.; Conceptual models of precipitation systems. *Meteorol Mag*, **114**, 1988, 293–319).

Meteorological Magazine

GUIDE TO AUTHORS

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Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary*.

References should be made using the Harvard system (author, date) and full details should be given at the end of the text. If a document referred to is unpublished, details must be given of the library where it may be seen. Documents which are not available to enquirers must not be referred to.

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