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The work of the Meteorological Office Maintenance Organization

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Summary

This article describes the origins of the Meteorological Office Maintenance Organization and reviews the scope of its present activities in providing technical support for meteorological offices in the United Kingdom and overseas. It discusses the structure and organization of the network of Maintenance Centres and the team at Headquarters and briefly reviews the more important aspects of maintenance. These include technical training facilities, maintenance policies and the concept of central repair, and the reporting system used to monitor the maintenance function. The article concludes by looking at the future maintenance task and how the Organization may evolve to meet the demand.

Introduction

The Operational Instrumentation Branch (Met O 16) is responsible for the inspection and maintenance of standard Meteorological Office equipment having significant electrical or electronic content. This responsibility is carried out by means of the Meteorological Office Maintenance Organization (Met O M O), which seeks to provide a wide measure of technical support for offices and equipment concerned with the Deputy Directorates of Observational Services, Forecasting Services, and Communications and Computing. The scope of the maintenance task involves regular support for some 1200 meteorological instruments and sets of communications equipment, located at 340 widely scattered installations. To discharge this responsibility effectively, the Maintenance Organization requires suitably trained staff who are properly equipped to carry out their function and located as close as possible to the area of work. The objective of Met O M O is to ensure a satisfactory level of support for local meteorological offices, seeking at all times to achieve a balance between the results obtained and the cost of the effort expended.

History

Before 1939 virtually all Meteorological Office instrumentation in general use was non-electrical in design though the first mark of radiosonde was nearing introduction and the initial Sferics (atmospherics) network was being planned. During the Second World War, regular radiosonde soundings were made and upper-air winds were determined by direction-finding by triangulation techniques, using the 28 MHz carrier frequency of radiosonde transmitters. These apart, most of the meteorological instruments in general use were sensors, linked to mechanisms which provided sufficient mechanical advantage to drive indicators or chart recorders. In 1946, 10 cm radars, previously used for gun-laying, were introduced into the Office for wind-finding purposes and technicians were recruited, mainly from the Services, to maintain them. In this way, isolated pockets of electronic expertise were established at radiosonde stations. In addition, a small group was located at Harrow (Instruments Branch) to provide a specialist 'fire brigade' activity to deal with the more complex maintenance problems, to undertake inspections and installations, and to provide training facilities for new entrants. Later, a group concerned almost exclusively with the installation and maintenance of communication and facsimile equipment was established at Dunstable. With the introduction of Bomber Command Fax network, there arose a need for a further centre at Watnall. The introduction of the National Fax network throughout the United Kingdom showed that installation and maintenance could not be carried out satisfactorily or economically from these two centres alone and the radiosonde stations with their technician complements and geographic spacing were obvious candidates as locations for additional maintenance centres. By 1965, an increasing range of electronic and electrical instruments had come into operational use, notably cloud-base recorders, cathode-ray direction-finders (Sferics), and the ground-station instrumentation associated with the radiosonde network (Cintel). It was important to users of these instruments that they operated reliably and were checked regularly (where possible) to ensure accuracy; also in the event of failure there was need for speedy remedial action. It was against this requirement that a field support group known as the Regional Servicing Organization (RSO) was established, with a Headquarters team located initially in the Observations and Communications Branch but later transferred to Met O 16. This Organization sought to combine the various fragmented groups of technicians engaged in maintenance activities into a single cohesive force, with a structured chain of command carrying out unified maintenance policies and employing common technical practices. Prior to this, the groups of maintainers were wholly administered and locally directed by the Meteorological Office Branches on whose stations they were based. With the formation of the RSO, administrative and techical direction passed to Met O 16 and, in 1974, all staff engaged in maintenance activities both at home and overseas were placed within the Met O 16 staff complement. In 1976, technical support for the Ocean Weather Ship Base was provided for the Observational Requirements and Practices Branch (Met O 1) and by 1977 all equipment used by the Deputy Directorates of Observational Services and Forecasting Services and, to a lesser extent, Communications and Computing, was maintained by the Maintenance Organization. To recognise these expanding activities the RSO was redesignated the Meteorological Office Maintenance Organization (Met O M O).

Functions

The primary functions of the Met O M O fall under the following main headings:

(1) To ensure the operational serviceability and performance of all Meteorological Office meteorological instruments for which maintenance responsibility has been accepted by means of regular maintenance visits and inspections.

(2) To provide a technical advisory service for meteorological officers for all matters concerning the operation and status of their equipment or where an appreciation of technical practices is required.

(3) To act as agents for other sections in Met O 16 by providing support in field trials of prototype or pre-production equipment, field calibration of instruments, evaluation of provisional documentation and the installation of portable types of equipment such as facsimile recorders and wind-measuring systems.

(4) To undertake the collection and dissemination of field maintenance data for design, development, management, and maintenance services.

These varied activities take Met O M O technicians into every corner of the United Kingdom (see Fig. 1). Some of the pieces of equipment are located on exposed coastal sites whilst others are installed on elevated sites or remote moorlands in the northern uplands and Scottish Highlands. Many pieces of equipment are mounted on towers reaching heights of 20 m, whilst others are located on top of multi-storey buildings, lighthouses and bridges. Access to these sites can be very difficult, particularly during the winter months, and the regular servicing of these instruments calls for considerable dedication on the part of the maintainer. Travel to the sites is mainly by road and, collectively, technicians drive over 250 000 miles each year. Access to offshore platforms and islands is by helicopter, whilst a variety of small craft, including inflatables, are used to visit buoys. The magnitude of the task continues to expand. Currently, more than 1200 instruments are maintained, comprising some 30 different types which are installed at 340 widely scattered locations. The major equipment networks include: 330 facsimile recorders, of which more than 20 are used for the reception of satellite imagery, 70 cloud-base recorders, 100 temperature-recording systems, 325 wind-measuring systems, 20 radars (weather and wind-finding), 15 sets of radiation data logging equipment, 12 Mk 3 radiosonde ground-stations, and a diverse range of equipment associated with the Ocean Weather Ship service. Another major area of work is that concerned with providing technical support for the Headquarters communications centre. Here maintenance teams provide a full 24-hour cover for the computer-based message switching system AUTOCOM and the facsimile complex. Within the communications centre a large number of electro-mechanical devices are in use. Some are peripheral to the computer system, such as storage disc drives, line-printers and teletypes, while others form part of the facsimile 'store and forward' system. Satisfactory throughput of meteorological data is heavily dependent upon the reliable operation of this equipment and a comprehensive maintenance program is required to ensure that satisfactory performance is obtained. The Meteorological Office is progressively becoming more involved in equipping oil platforms and buoys in the seas around our coasts with instruments and data acquisition systems, and similar equipment is being installed on small remote islands off the north coast of Scotland. An Automatic Weather Station (AWS) has been successfully installed upon Muckle Holm in the Shetland Isles and plans are well advanced to locate a further AWS on Sule Skerry. The technical aspects of maintaining equipment offshore are not more difficult than those associated with land-based systems, but there are problems and hazards in working and, indeed, travelling to these offshore sites which place them in a different category from maintenance activities normally carried out on the mainland. In consequence, it was decided that the work would be carried out most effectively by staff dedicated to the marine maintenance task who need to be good sailors and have an aptitude for work aboard ships and buoys. Maintenance of the buoy moored in deeper water (DB1) located some 137 miles south-west of the Isles of Scilly is especially challenging, involving as it does a 35-hour trip each way in quite small vessels during which sea swells of typically 5–10 metres are experienced.

To carry out successfully the technical and physical tasks required to keep the buoy serviceable, whilst trying to combat the peculiar motion of the buoy, calls for a high degree of commitment to the job. To undertake this work a Marine Maintenance Centre has been established, forming part of the larger Centre maintaining the Ocean Weather Ships at Greenock. From this Centre, staff carry out a regular program of inspections and maintenance on the Ocean Weather Ships and will shortly extend the work to Automatic Weather Stations on oil platforms located in the Beryl and Piper fields in the northern North Sea. As the marine work expands, staff from the Bracknell Maintenance Centre are becoming involved in the support program for meteorological equipment located on oil and gas platforms in the southern North Sea, and the Royal Sovereign light-tower, as well as ships calling into southern ports. In providing this support program for marine activities, close co-operation is maintained with the Port Meteorological Officers and staff in the Marine Division.

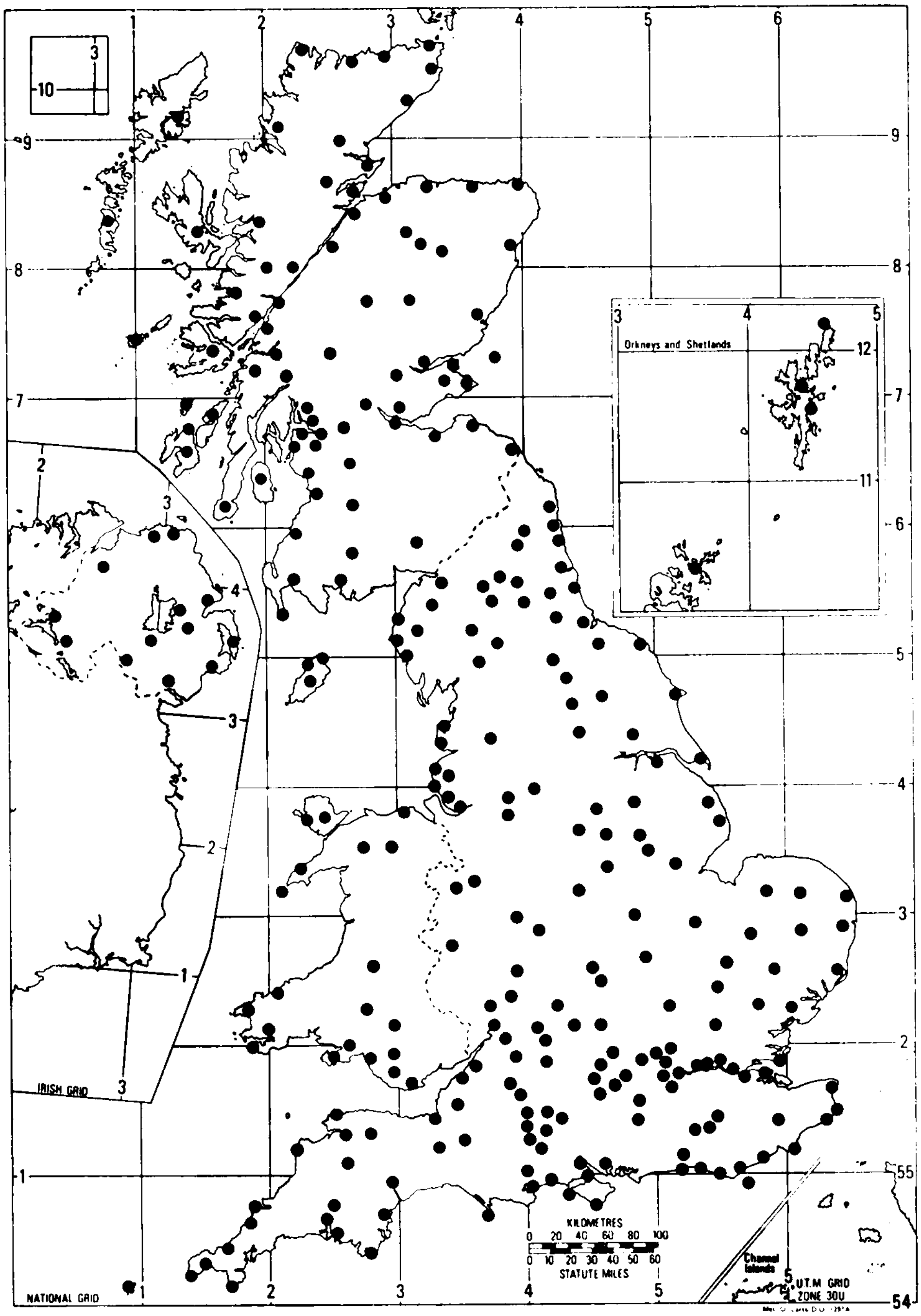

Figure 1. Locations of meteorological offices supported by the Meteorological Office Maintenance Organization.

Organization

Given the widely scattered distribution of meteorological equipment within the United Kingdom and the need to respond quickly to instrument failures, a policy of decentralization has been adopted. At Headquarters a small team comprising a Chief Technical Officer and two Group Technical Officers designated (North) and (South and Overseas) has been established. These control 22 geographically distributed Maintenance Centres, each supervised by an Area Technical Officer and grouped into 5 Regions, each controlled by a Regional Technical Officer. This organization has several advantages:

(a) It allows the Centres to be placed close to the centre of the work-load. This minimizes travel, speeds the time to respond to calls for support and enables the establishment of small but fully employed teams.

(b) It enables close links to be forged between the equipment user and the maintainer with the aim of using the equipment in the most effective manner.

(c) It allows close control of the work to be achieved and improves the efficiency of the maintenance activity.

(d) It increases the maintainer's personal involvement with specific equipment, so that he obtains a deeper insight into local equipment operation and an increased job satisfaction.

The organization chart (Fig. 2) shows the Met O M O infrastructure and the distribution of the 22 Centres in the United Kingdom and the 4 overseas. As stated earlier, there are three levels of direction and responsibility: Headquarters, Regional and Area. At Headquarters, concern is for the overall assessment of the maintenance task and the direction of Met O M O activities. Major functions are:

(a) to partition the work-load and to allocate responsibilities to ensure maximum use of staff and to minimize travel,

(b) to frame maintenance policies for each equipment type (here the appropriate sponsoring Headquarters Branch and the finance branch (Met O 4) are involved closely with the formulation),

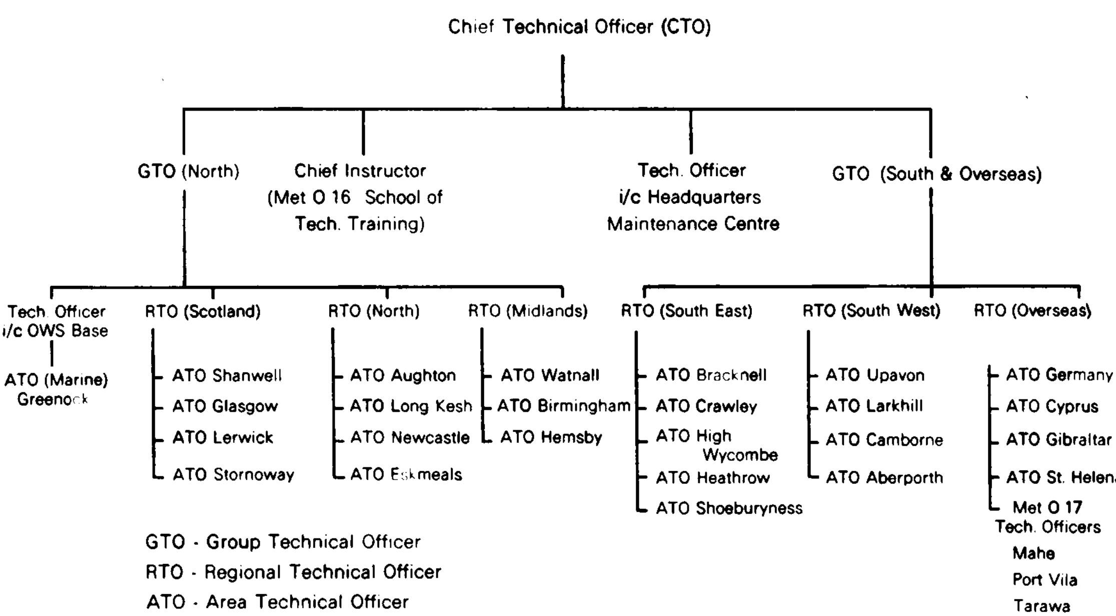

Figure 2. The structure of the Meteorological Office Maintenance Organization.

(c) to co-ordinate the activities of the Area Maintenance Centres (AMCs) by specifying the work to be undertaken through the issue of maintenance instructions and inspection schedules,

(d) to collect servicing data for management, maintenance, development, and logistic purposes,

(e) to make arrangements for servicing at fourth-line level (see Appendix), and

(f) to advise the Personnel Management Branch on technical staff matters and to liaise with other Headquarters Branches on aspects affecting the inspection, calibration, and, where appropriate, the installation of equipment.

In addition, the Headquarters team are called upon to deal with the many elements of work associated with the day-to-day line management, technical, and administrative problems that arise. In particular, close attention is given to all activities concerned with staff reporting, training and career advancement. The Headquarters Maintenance Centre and the 21 AMCs in the United Kingdom are wholly administered and directed by Met O 16 and are located at meteorological offices, radiosonde stations, Weather Centres, and civil airports. This arrangement enables the Centres to take full advantage of local accommodation and communications facilities, and to be sited sensibly, central to the area work-load, this being typically within a radius of 100 miles from the AMC. Locally, each AMC is directed and controlled by an Area Technical Officer (ATO) who leads a small team of technicians, usually not more than three. The distribution of these AMCs and their area of operation is shown in Fig. 3. A substantial amount of responsibility is placed upon the ATO and his technician staff. Staff manning these Centres enjoy a considerable degree of devolved autonomy; each technician has to respond to the varied needs of outstations with the minimum of supervision. Most technicians recognize their job as a challenge and respond positively and, although they are part of a team, there is considerable scope for personal involvement. There is a wide variety of equipment to be maintained and no one technician can expect to gain and retain full comprehension of it all. Specialization amongst members of the teams is encouraged, since this improves the combined performance of the teams and has the added effect of building the individual's confidence in his technical ability. At five of the Centres (Shanwell, Aughton, Watnall, Bracknell, and Upavon), a Regional Technical Officer (RTO) has been established to provide an enhanced level of expertise and experience to enable that Centre to carry out work to third-line level. He also undertakes work of a more exacting nature in the fields of inspection, fault diagnosis and field calibration of equipment employing the newer technology. The RTO is responsible for the direction and control of all AMCs in the Region and also technical control of the entire population of specified instruments. He is expected to establish effective communication with the officers-in-charge of meteorological offices by regular visits and discussion on matters concerning the performance and operation of their equipment and so promote the interchange and feedback of technical information between equipment users and the development and post-design groups in Met O 16 Headquarters.

Overseas

Technical support facilities are provided for overseas stations in a manner similar to that for the United Kingdom. For Royal Air Force Germany, Met O 16 staff are based at Rheindahlen and provide cover for all Meteorological Office equipment in the British Sector of West Germany and also support the facsimile recorders in Gatow (Berlin). Similarly, there are Maintenance Centres at Cyprus, Gibraltar and St Helena. Technical staff overseas are members of the Maintenance Organization and come under the technical direction of Met O 16, but for administrative purposes they are placed under the control of the local Principal Meteorological Officer, since it is for him to decide where local operational equipment priorities lie. Close co-operation on these matters is established between Met O 16 and Met O 6 (Defence Services Branch) as appropriate and no inter-Branch difficulties are experienced in administering these dual responsibilities. The technical activities of these overseas teams are co-ordinated in

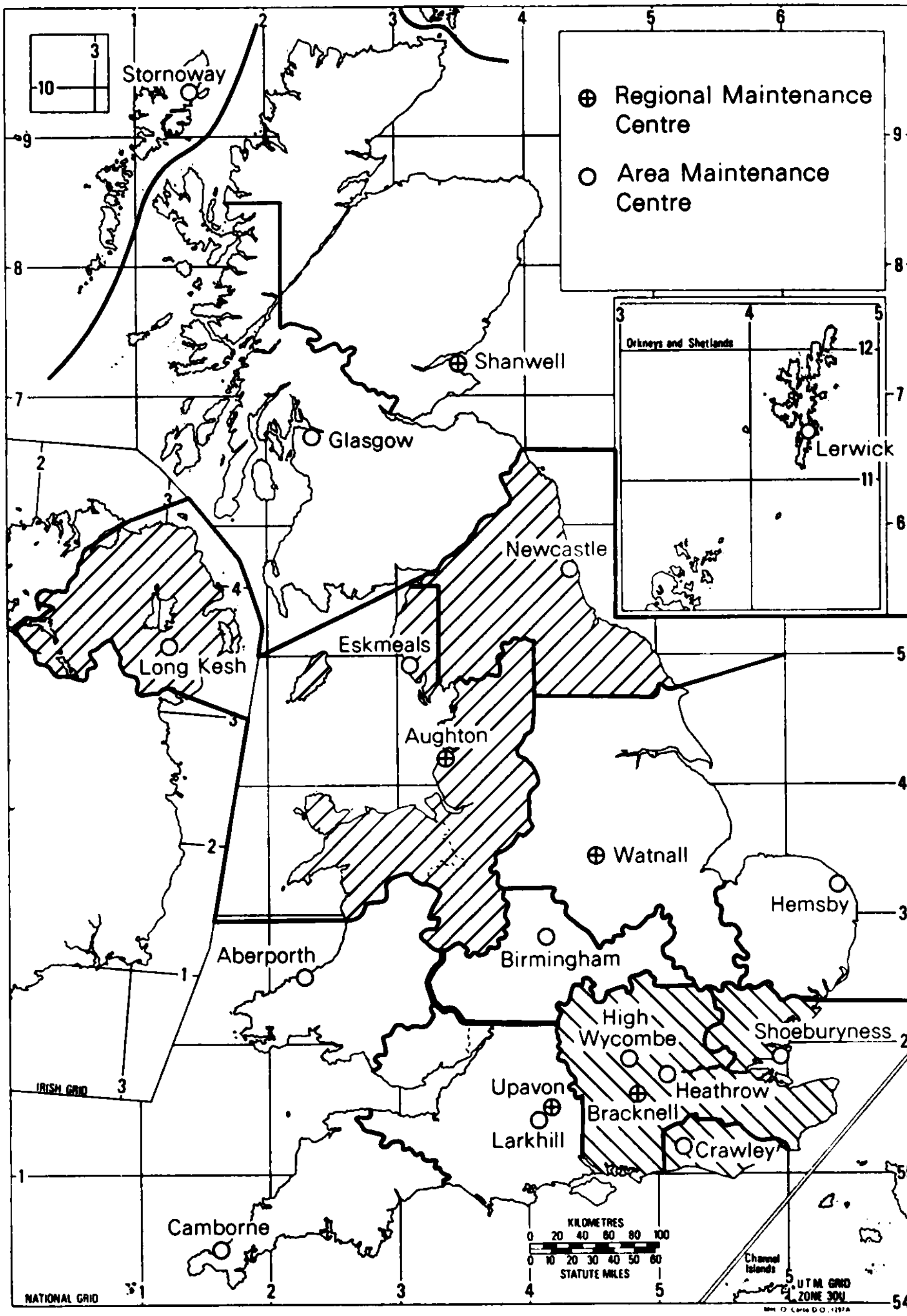

Figure 3. Distribution of Area and Regional Maintenance Centres and their areas of operation.

Met O 16 Headquarters by an Overseas Inspector, RTO(O), who is required to carry out a regular program of inspection and liaison visits. He is also required to provide Headquarters support should an 'emergency' arise and to ensure that the overseas teams are kept fully informed on all technical aspects of the maintenance activity. The Met O M O also acts as an agent for the International and Planning Branch (Met O 17) in providing support for World Weather Watch stations. This service is mainly consultative but, on request, periodical inspections are carried out of radar installations in the Seychelles, Vanuatu, Kiribati and Tuvalu. This latter area of work is being extended to support countries in the continent of Africa.

Maintenance policies

The policy to be adopted for a particular type of equipment is dictated by the operational requirements, its design, construction and complexity, and, to a lesser degree, its location and test requirements. Within the Meteorological Office, equipment falls into three main categories:

(a) Those pieces of equipment which are relatively large, whose construction is non-modular and whose design employs thermionic valves or discrete components not mounted upon printed-circuit boards (PCBs). This category includes wind-finding and weather radars, rotating-beam cloud-base recorders, and Sferics equipment. Most of these are 10–20 years old and for these systems there is no alternative but to maintain and repair them locally down to component level. This demands that a large inventory of spares be held on-site, that the maintainer has a detailed knowledge of the system, has access to a wide range of test equipment, and has been given extensive training. Fortunately, with the advent of PCBs and solid-state devices, many of these problems have been designed out of the new equipment. Nevertheless, these older designs still represent a substantial proportion of the current maintenance work-load.

(b) This category covers all pieces of equipment whose construction is based on modular principles and which use the newer technology. For these more recent designs Met O M O adopts a 'repair by replacement' policy for failed modules and this requires the maintainer only to diagnose the malfunction to one section of the equipment, and to replace the item for subsequent repair at a central workshop. Typical Meteorological Office equipment of this type includes the Mk 3 radiosonde ground-stations, Meteorological Office Weather Observing Stations (MOWOS), Digital Anemograph Logging Equipment (DALE), Continuous Automatic Remote Displays (CARD), and Mk 5 wind-measuring systems.

(c) For small portable instruments such as Magnetic Tape Event Recorders (MTER), Digital Temperature Indicators (DTI) and some wind-measuring systems the policy is to replace the complete instrument when it fails and to return the item to a central repair facility. Here the equipment 'down-time' is limited purely to the response time of the repair team.

The concept of central repair carries with it the commitment to hold locally at AMCs a number of operational 'spares' to support the network of portable equipment and also a full range of modules and PCBs for the more complex systems. Central repair carries with it the following advantages:

(a) The equipment 'mean time to repair' is decreased and hence its availability is much improved.

(b) The level of training and expertise to be acquired by the field maintainer for any one type of equipment is reduced. This enables him to achieve an effective working knowledge of a wider range of instruments.

(c) The local holding of specialized test equipment associated with the more complex equipment such as microprocessors can be reduced, and the inventory of components can be limited at the Maintenance Centres.

On the other hand, there are disadvantages, such as the following:

(a) It may initially prove more costly to support the equipment with spare modules, PCBs, etc.

(b) The central repair time can often be lengthy, particularly if undertaken by an outside agency. Should this be the case then the central base spares would need to be increased to cover the additional turn-round time.

(c) There may be some loss of job satisfaction on the part of the field maintainer.

It is the job of Met O M O to examine the repair policy implications for each type of equipment in conjunction with the equipment sponsor and the finance branch and to attempt to find the most cost-effective option. This mainly involves balancing the cost against the operational requirements. The repair policy is defined at the earliest possible stage so that maintainers and equipment users are well aware of the various implications prior to installation. The successful introduction of equipment into field service depends largely on an adequate logistic support being available.

Various considerations need to be taken into account:

(a) An adequate range of spares must be available where they are most required. If the equipment is remote and 24-hour operation is required, these spares must be held at the parent Maintenance Centre; such items may of course support a number of types of equipment.

(b) The maintainers need to receive an adequate level of training for the work specified and all the relevant documentation must be provided.

(c) Any special-to-type test equipment necessary for the regular maintenance must be made readily available.

(d) Back-up repair facilities have to be organized. These should include:

(1) skilled staff at Headquarters who can travel if necessary to the equipment location at relatively short notice,

(2) a centralized repair facility supplied either 'in-house' or by the manufacturer, perhaps incorporated in a support maintenance contract, and

(3) an adequate pool of main base spares.

When these facilities have been made available (as for systems such as the Cossor wind-finding radar and the Mk 3 radiosonde ground-stations) and the project management has been of a high order, the introduction into field service has been successful.

Maintenance reporting system

If a maintenance activity is to be managed in a realistic way it is necessary that the operation should be monitored effectively so that management decisions can be based on the realities of maintenance, rather than on assumptions. To meet this requirement a fairly comprehensive reporting system has been established based mainly upon equipment servicing reports. These reports detail the equipment worked upon, the number of man-hours expended in both preventive and remedial maintenance, the man-hours expended in travel, and the components used. Such data may be analysed to yield information about the cost-effectiveness of the maintenance system, where the cost reflects the efficient use of resources and the effectiveness of the system is measured by its ability to maintain equipment in working order. The data derived from the reporting system can be used by all management levels for their decision making. The supervisors at Maintenance Centres use the data to schedule and to employ properly the staff assigned to them, whilst at Headquarters these data are used to optimize area work-loads and to identify equipment with poor performance. At a higher management level these data can be used to judge general maintenance effectiveness in relationship to the operational requirements. Additionally, the reports can identify weaknesses in equipment design or the need for intervention by post-design services and the location of maintenance areas where additional training or improved support documentation is required. They can also be used to alert higher management to the need to initiate equipment replacement programs. At present, the use of the reporting system enables effective control of the maintenance activities to be achieved but the effort available for prompt analysis of the reports by manual methods is lacking.

To overcome this problem, work is in hand to try to design an Equipment Information System for Management (EISM) seeking initially to improve the cost-effectiveness of Met O M O. The system will use as source data information culled from the maintenance engineers' report forms which will be processed by automatic means, using 80-character punched cards as input to COSMOS (the main computer system of the Meteorological Office).

Technical training

Technical training is conducted by Met O 16 instructors based at Beaufort Park acting as agents for the Assistant Director (Professional Training). The main source of technician recruitment over the past 10 years has been the Scientific Class under the Assistant Scientific Officer (ASO) to Radio Meteorological Technician (R(M)T) conversion scheme. Selected ASOs are given a sound technical education and this allied to their meteorological background has produced a steady flow of technicians of high calibre. The aim of the ASO/R(M)T course is to provide the minimum technical and practical training to enable the selected trainee to be put to work effectively at the earliest opportunity, leaving him to complete his formal technical education through 'on-the-job' training and external study concessions. This approach enables the technician to gather experience whilst learning his profession and to keep his formal training broadly in line with the requirements of his job specification.

Normally about eight ASOs are selected for training each year and the overall conversion course extends for a period of 15 months. The Electronic Induction Course (seven months) has in the past been held at Royal Air Force Sealand; more recently the training has moved to the REME School of Electronics at Arborfield with the advantage that the facilities (including accommodation) of the Meteorological Office College at Shinfield Park can be fully used. Following successful completion of this first phase, ASOs are promoted to R(M)T (Temp.) and training moves on to the various types of electronic equipment deployed at meteorological offices. Tuition during the remainder of the course is given by instructors from the Met O 16 School of Technical Training and considerable use is made of the equipment located on the trial grounds at Beaufort Park. This second phase, of five months duration, includes a period of eight weeks devoted to practical work in the Met O 16 laboratories and workshops. Finally, a further period of three months is spent at selected Maintenance Centres, where trainees are given 'hands-on' field experience under close supervision, maintaining a wide range of meteorological instrumentation so that they may gain a full appreciation of the duties associated with the technicians' role before taking up their posts as R(M)Ts. The Met O 16 School of Technical Training is not large and has a complement of three full-time instructors. Nevertheless, virtually all the equipment in use within the Deputy Directorates of Observational and Forecasting Services is covered. Additionally, the instructors participate in the instrument maintenance courses for overseas students and special courses have occasionally been mounted abroad under the WMO Voluntary Co-operation Program.

Future services

In the past Met O M O have attempted, whenever possible, to respond to all calls for remedial action within a 24-hour period, whatever the type of equipment involved and wherever it is located, and equipment users have become accustomed to this level of service. With the increasingly tight manning situation that now prevails, and the growing amount of equipment being deployed, staff at Maintenance Centres are becoming fully stretched and this will reflect adversely on their ability to respond to service calls at short notice. It will become necessary to agree with the user Branches the priority to be ascribed to individual equipment types, or even locations, prior to introduction into field service so that an equitable balance may be struck between the operational requirements and the maintenance resources available. For systems which employ suites of sensors, such as the various types of automatic weather stations, some sensors may have less meteorological importance than others, and failures to these may need to await service until a maintenance team is next in the vicinity.

Within the next three or four years the Meteorological Office will be deploying a wide range of new instruments. These will include: synoptic and climatological automatic weather stations, laser-type cloud-base recorders, Digital Anemograph Logging Equipment (DALE), and additional unmanned radars and displays associated with a national weather radar project. Other networks of communication equipment are also scheduled to become operational within the next few years. These include the AUTOPREP systems at Main Meteorological Offices and Speech plus Duplex equipment for the dissemination of teleprinter traffic via facsimile lines to offices receiving MOLFAX. New automatic data processing systems are to be installed at Heathrow and High Wycombe and Met O M O will be much concerned in providing a full range of technical support for these systems. Maintenance policies are being framed for all these networks and consideration is being given to how they may be integrated into the current work-load. Where necessary, new centres may be established and the roles and responsibilities of existing units redefined to determine the most cost-effective combination. Types of equipment employing the newer technology are expected to prove more reliable than many of those currently in service and, where the design is mainly electronic, maintenance activities will be restricted solely to periodic calibrations and remedial work. Some, such as facsimile recorders, are capable of satisfactory operation for periods of up to four months without expert attention, providing a small amount of user maintenance is undertaken. Where this applies, Met O M O technicians will seek the co-operation of meteorological staff to provide this local service, offering such advice and training as may be necessary. Normally, Maintenance Centres have a specified area of operation but working arrangements are quite flexible and Regional and Area boundaries are in no way sacrosanct. To use the available expertise fully, Met O M O will develop specialists for various equipment types who will provide a 'fire brigade' service to deal with the more difficult equipment failures. To provide the same high level of service over the next decade will make considerable demands on the abilities of maintenance staff. There exists at present a high level of commitment to the work and staff have shown a willingness to respond readily to the difficult or dirty jobs that come their way; they are also keen to embrace new technology and to be faced with a generous work-load. To use these qualities to the full, line managers will need to be both flexible and imaginative in directing them, whilst seeking to achieve the most speedy and economic solutions to their problems. I hope that electronic designers can be encouraged to continue to improve the reliability of their equipment so as virtually to eliminate the maintenance activity, but the achievement of this objective seems rather distant at present. Nevertheless, until such time as they are able to make substantial progress towards this goal, I suggest that the future maintenance of Meteorological Office instruments by Met O M O may be viewed with some degree of confidence, and that the Organization will evolve to meet these demands as and when they are made.

Appendix

Ranges of maintenance

The maintenance of equipment is divided into four ranges, first-, second-, third-, and fourth-line, which are defined as follows:

1. *First-line maintenance*

(a) Those tasks which can be carried out by technicians to maintain the equipment in its operational state by means of functional checks, adjustments and servicing by replacement.

(b) The diagnosis of faults and their rectification by replacement units.

2. *Second-line maintenance*

(a) Those tasks which can be carried out within the resources of an Area or Station Maintenance Centre. The actual depth of maintenance carried out at second line will vary widely with different types of equipment. Where large immobile equipment such as radar is installed it will be necessary to carry out a higher level of servicing *in situ*.

(b) The diagnosis of faults in assemblies or sub-assemblies and their rectification by replacement units or replacement of elements within those units.

3. *Third-line maintenance*

(a) Those tasks which are required to maintain equipment in a serviceable condition but which require the resources of a centralized maintenance base. This category of work is appropriate to a Regional Maintenance Centre where more specialized test equipment and a wider range of spares will be accommodated.

(b) The diagnosis of faults in assemblies and sub-assemblies and their rectification by the replacement of elements within these units.

(c) The fabrication or refurbishing of simple mechanical or electrical assemblies.

4. *Fourth-line maintenance*

(a) Those technical processes requiring the use of a main maintenance base with the capacity of undertaking the complete reconditioning of equipment or manufacture of assemblies, or the repair of printed-circuit boards by automatic or manual testing, where the holding of spare components locally is uneconomic.

(b) Testing to an agreed production standard.

(c) Such tasks may be undertaken either at Met O 16 Headquarters or in certain circumstances a contractor may be used.

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Computer story

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Summary
An account is given of the history of electronic computers in the Meteorological Office from 1951 to 1980, with particular reference to numerical weather prediction.

In 1980 so much of the work of the Meteorological Office is inextricably bound up with computers of one sort or another that it is difficult to imagine the Office of only 30 years ago, when pencils, rubbers and 'plonkers'* were by far the most important tools, and slide-rules, desk calculators and Hollerith machines were merely useful adjuncts.

Back in 1948 the Synoptic and Dynamical Research Sub-committee (SC II) of the Meteorological Research Committee discussed the possibilities of using electronic computing machines (as they were then known) in meteorology. Although L. F. Richardson (1922) had put forward his suggestions on numerical weather prediction a quarter of a century earlier, his ideas had not been furthered in the meantime because of lack of computing power. It was now recommended that the Office should recruit one or more mathematicians who were specially qualified in computational methods and also obtain an electric desk-calculator for use in trial computations. Staff of the Forecast Research division spent many a boring hour in later years using the calculator, which did not even have the facility of automatic multiplication.

A big step forward came in the autumn of 1951 when Mr F. H. Bushby (now Director of Services, Meteorological Office) attended a course at Cambridge University on the use of their EDSAC computer, one of the earliest large electronic computers in the country. In a paper published in March 1952 Sawyer gives some of the early history of meteorological computing and also reports that at the colloquium given by Mr Bushby on his return from Cambridge 'there was a lively discussion on the merits of applying the first calculations to the behaviour of a textbook model cyclone rather than to the irregular disturbances of a real synoptic chart; nevertheless all were agreed that numerical methods had a more immediate application to dynamical research than to forecasting'. By the end of 1951, Mr Bushby and I were actively using LEO 1, a copy of EDSAC, which had been built by Messrs J. Lyons, the caterers, at their Cadby Hall headquarters. This machine's storage medium was mercury delay lines, which were housed in large coffin-like wooden boxes covering most of the floor of the computer room. These were very reliable but had very slow access times and were the only form of storage, as there was no backing store. In the early days the only input and output was by paper tape, but later a card reader/punch and a line-printer were installed. Paper tapes were punched on a teleprinter-type hand-perforator with the keys relabelled to the LEO 1 coding and any necessary amendments could be made only with the kind assistance of those with access to a reperforator. All values were stored in the machine in fixed-point binary and careful scaling was necessary if accuracy was not to be lost whilst ensuring that 'overflow' did not lead to wrong answers. There were no counting-registers and movement through the grid of values was done by amending all the relevant instructions after each grid point, and then testing them against the appropriate instruction for the last point in the grid line, or the final point in the grid. The storage was so small that it was essential to overwrite data and intermediate results during the computation. Programming was in a mnemonic assembler-type code.

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* See the glossary at the end of this article.

The first project to be attempted on the computer was the production of charts of the Sutcliffe expression for development. The results were reported in the *Meteorological Magazine* (Bushby and Hinds 1953b) and it is interesting to note that 'the machine took 3 min. to read in the programme and data, 1 min. to perform the calculations and 1½ min. to print the results', compared with manual methods taking 4 to 5 hours.

However, the Sawyer–Bushby atmospheric model equations had now been formulated (Sawyer and Bushby 1953) and interest naturally turned to attempts to solve these equations by computer methods. Programming and numerical methods suitable for high-speed computers were still in their infancy, so it was prudent to advance by fairly small steps. The first of these was the computation of 500 mb geopotential tendencies, using the Liebmann iterative process to solve the Poisson-type differential equation. Bushby and Hinds (1953a) give some details of the computations. The program instructions occupied 480 of the 2048 storage locations in the machine and results were produced for a 12 × 8 grid of points in about 12 minutes, including 40 iterations of the Liebmann process. Intermediate results were printed out in order to compare the different terms in the equation, and the equation was solved with both zero and actual boundary conditions to help assessment of the error due to the use of the former.

The next stage was to solve the Helmholtz-type equation for the 1000–500 mb total thickness and thence obtain a representation of vertical velocity. This program was more complicated than the one for 500 mb tendencies and occupied 757 storage locations, almost half the total storage of the machine. It was suggested that we should subtract the thickness tendencies from the 500 mb tendencies in order to obtain 1000 mb rates of change and with some trepidation we did so, to find an encouraging agreement with observed changes. It was natural to extend this work to the production of numerical forecasts, but this led to organizational problems, as the necessary program and data storage would have exceeded the capacity of the machine. Since the time-stepping was by centred differences, the results of each time-step were punched out from the computer on cards and read in again during the following time-step, together with cards of part of the program which had also been overwritten. There was great pleasure the day that the first 12-hour forecast was produced and actually looked like a synoptic chart and, even more, the right chart. Forecasts were made for an 18 × 14 grid (of grid-length approximately 260 km) covering Europe and the north-western Atlantic Ocean, and a 24-hour forecast took about 4 hours' computing time using 1-hour time-steps. Most of the computing was done during evening sessions at Cadby Hall with assistance from the staff of Messrs J. Lyons both in operating the computer and the provision of supper in the managers' mess.

Cases were mostly chosen from those that had been referred to the Forecasting Research division by the Central Forecasting Office because of errors in their own forecasts, and two of the earliest ones are of particular interest. The east coast floods of 31 January 1953 occurred shortly after the computer forecast program was working and data for 15 GMT on 30 January were quickly read from the chart and punched on paper tape. The results of this forecast (Figs 1–6) show an extraordinarily severe north-north-westerly gale across the British Isles. To quote from Bushby and Hinds (1954b), 'there is no doubt that if these charts had been correct the floods would have been even more calamitous than they actually were'. The other case of interest was a forecast starting from initial data for 15 GMT on 8 January 1951 when a small wave-depression deepened considerably and moved into the south-western approaches. No such development was computed, but on this occasion the forecast produced by conventional methods was very similar to the computed forecast. Data were read from the actual charts for 24 hours later and a hindcast was performed by the simple expedient of reversing the signs in certain instructions in the program. The hindcast suggested that the small depression might have been a more intense feature at 15 GMT on the 8th than originally thought and, in fact, late surface ship reports, which would not have been available when the upper-air charts (from which the computer data were

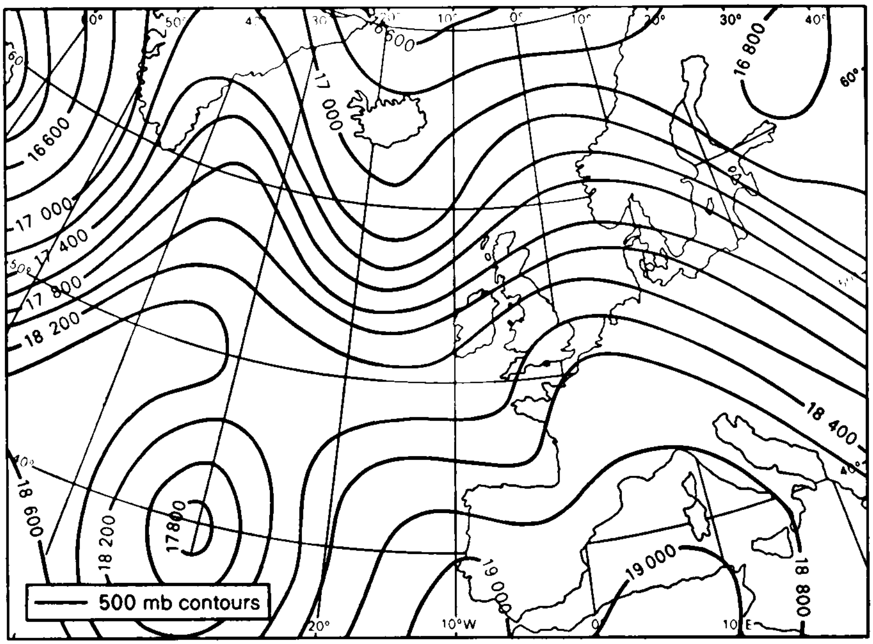

Figure 1. Actual 500 mb chart, 15 GMT, 30 January 1953. (Isopleths in Figs. 1 to 6 are geopotential feet.)

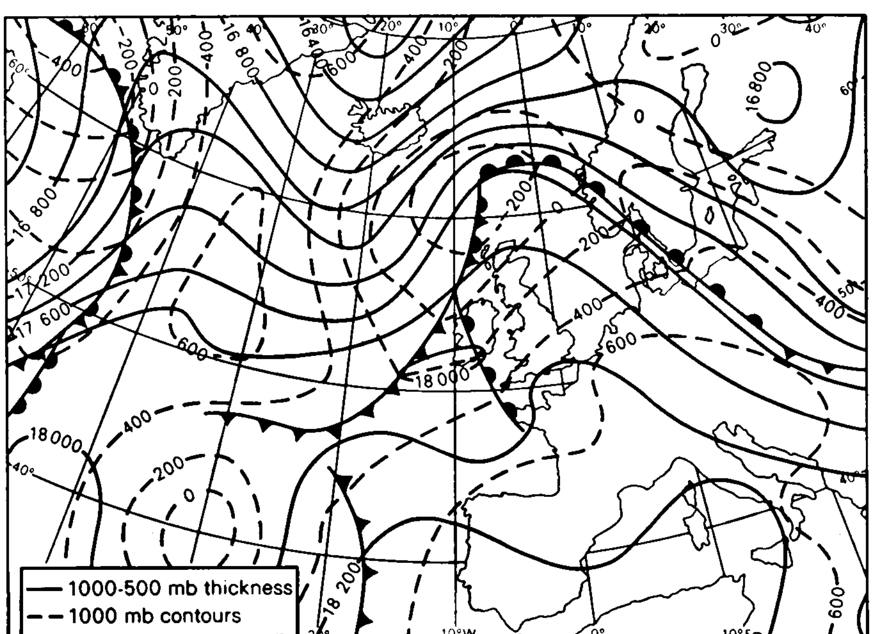

Figure 2. Actual 1000 mb and 1000–500 mb thickness charts, 15 GMT, 30 January 1953.

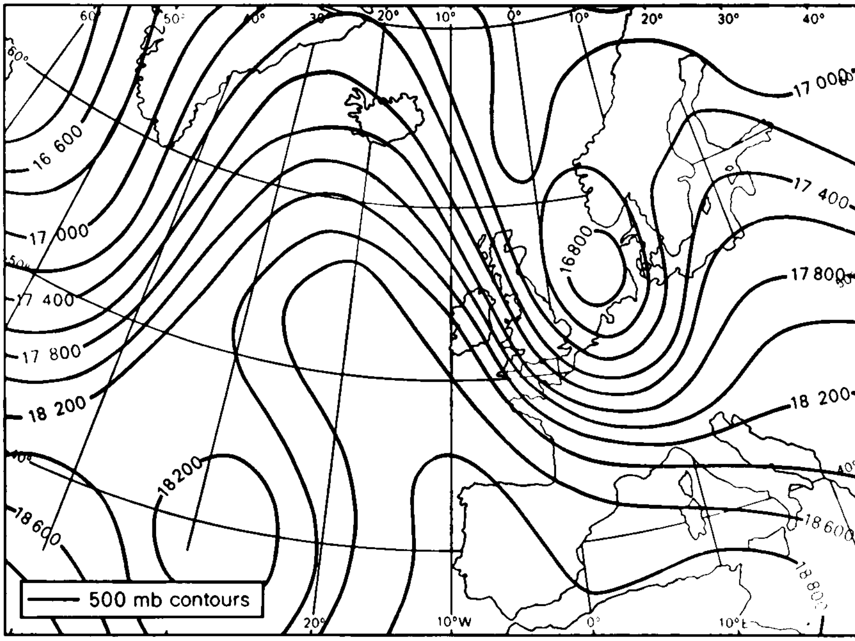

Figure 3. Actual 500 mb chart, 15 GMT, 31 January 1953.

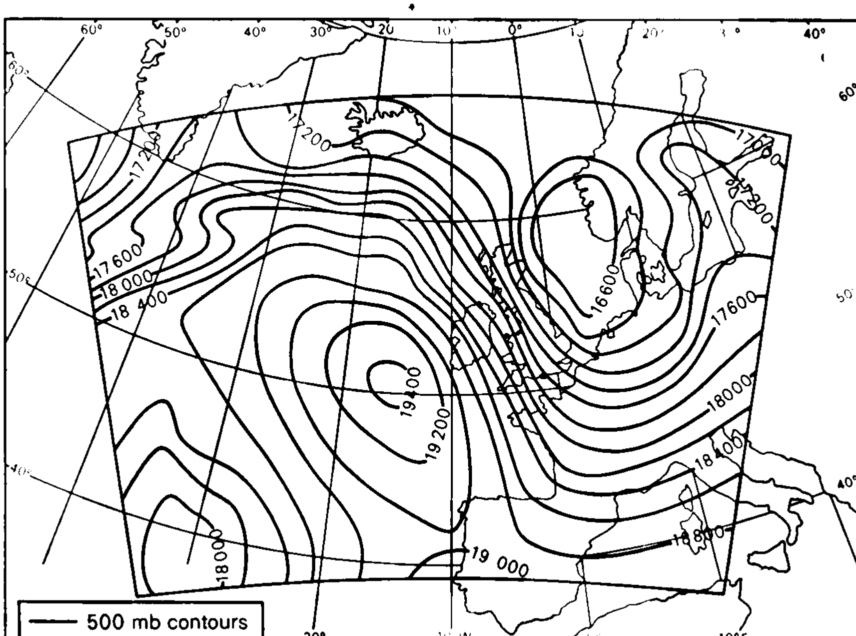

Figure 4. Computed 500 mb chart for 15 GMT, 31 January 1953, using initial data for 15 GMT, 30 January 1953, and the Sawyer–Bushby model.

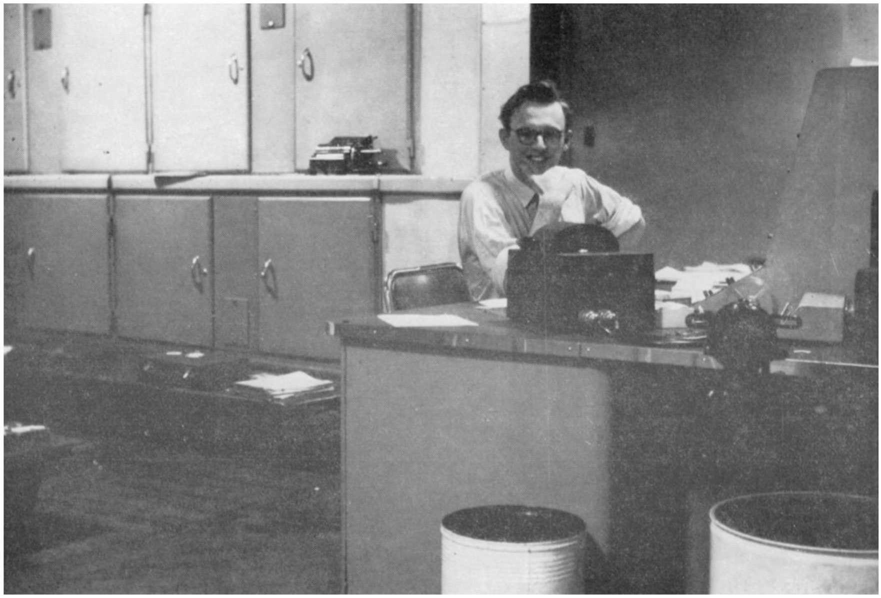

Plate I. Meteorological Office staff using the Ferranti Mark 1 computer at Manchester in the 1950s.

Plate II. The console of the Ferranti Mark 1 computer at Manchester.

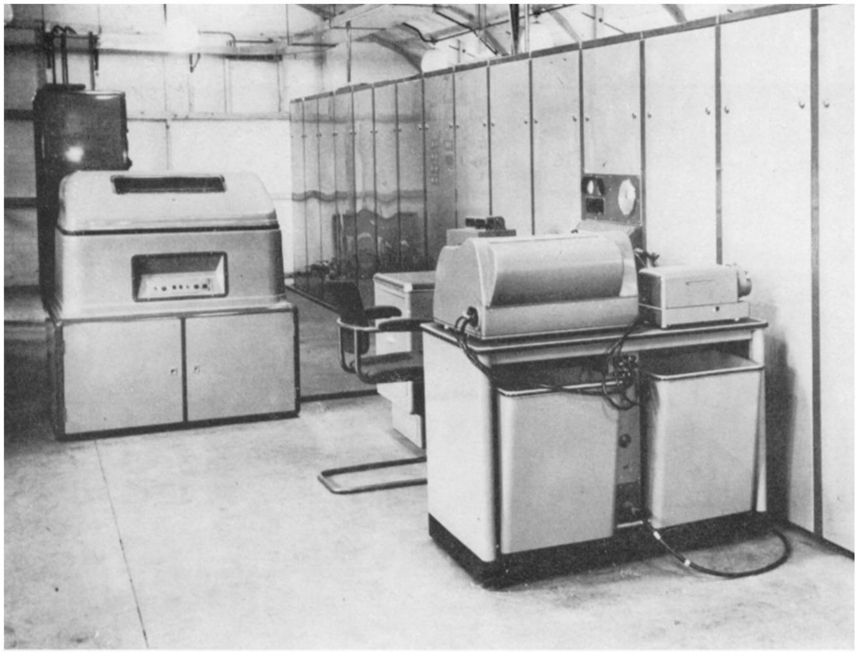

Plate III. Mercury computer at Meteorological Office, Dunstable, showing line-printer.

Plate IV. Mercury computer at Meteorological Office Headquarters, Bracknell, showing console and magnetic drums.

Plate V. KDF9 computer Comet showing console, magnetic tape decks and paper-tape readers.

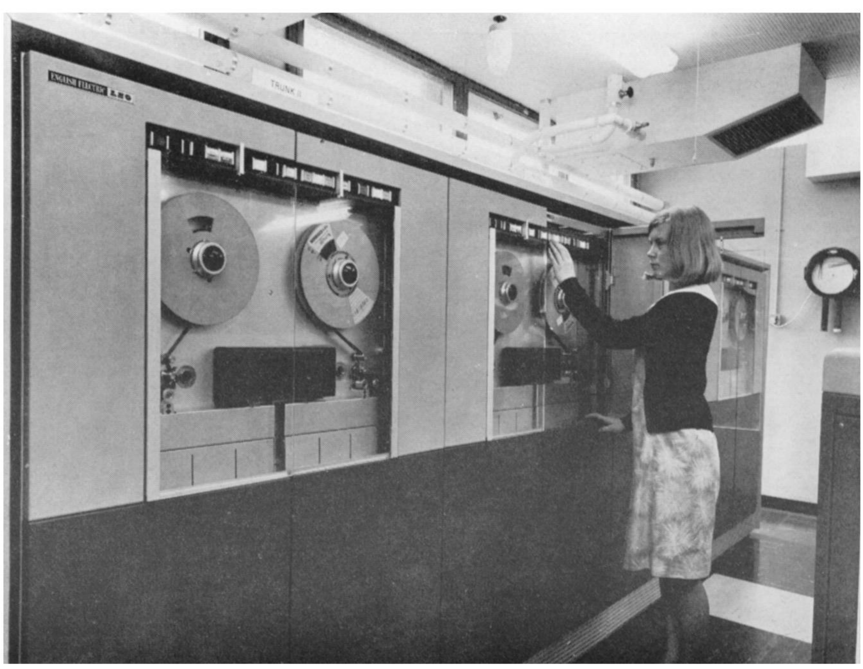

Plate VI. Mounting a magnetic tape on the Comet computer.

Plate VII. IBM 360/195 computer, Bracknell, 1971.

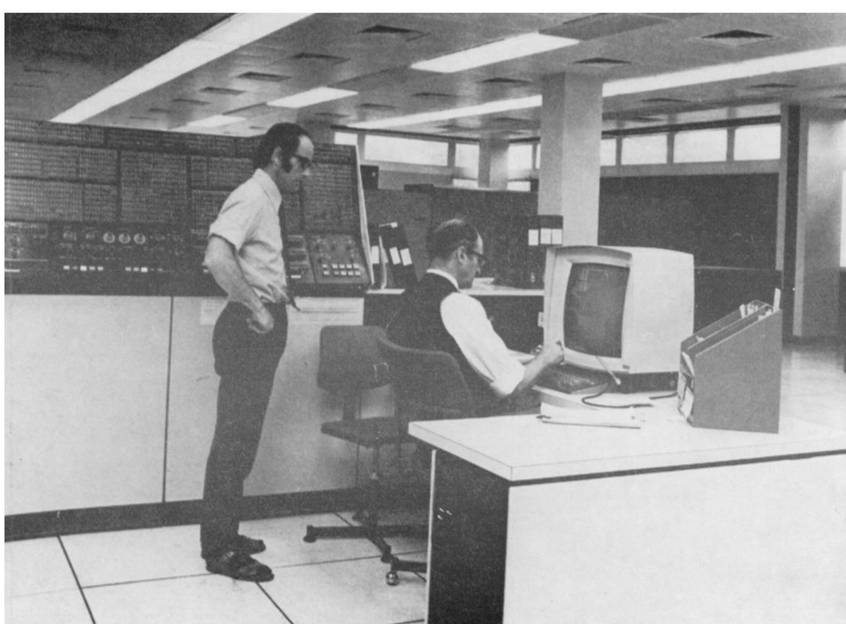

Plate VIII. Master console and video-screen of IBM 360/195 computer at Bracknell.

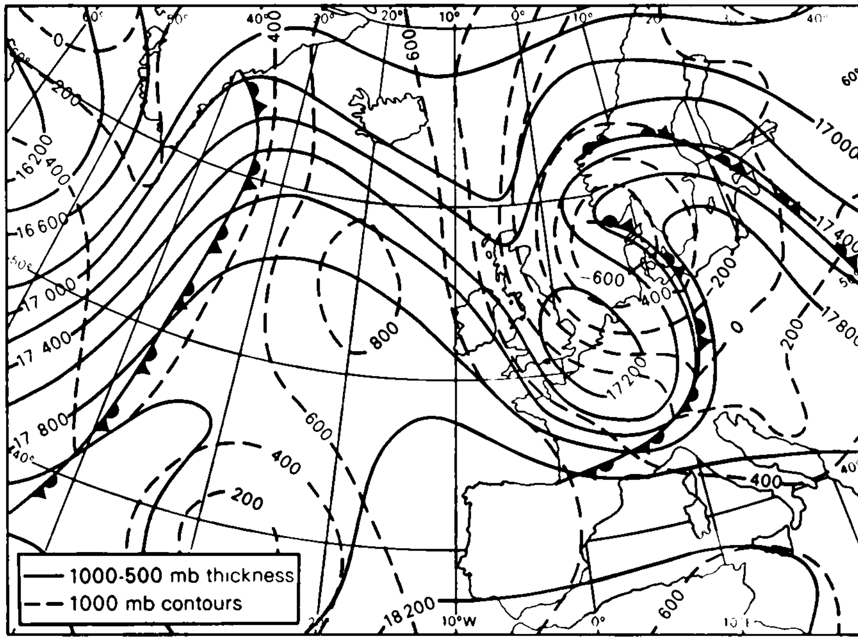

Figure 5. Actual 1000 mb and 1000–500 mb thickness charts, 15 GMT, 31 January 1953.

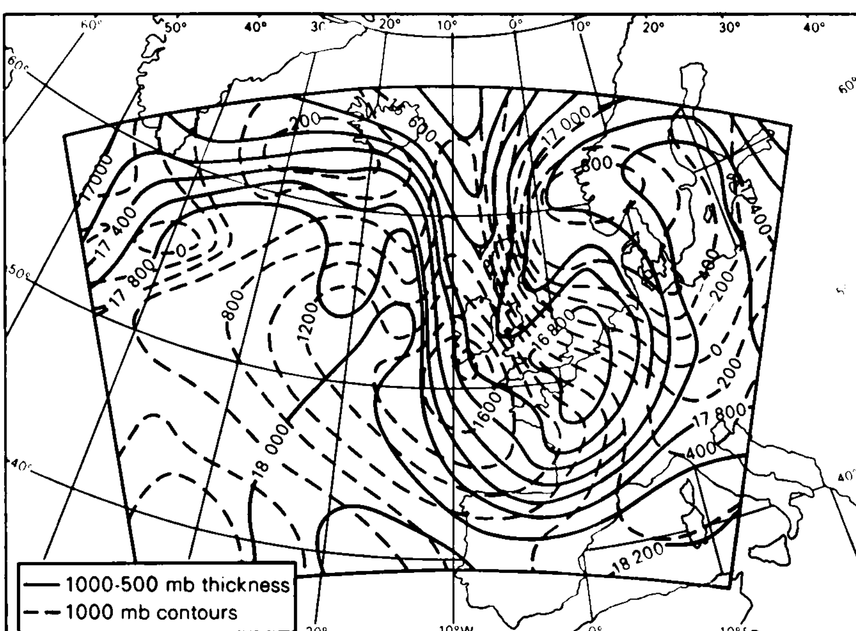

Figure 6. Computed 1000 mb and 1000–500 mb thickness charts for 15 GMT, 31 January 1953, using initial data for 15 GMT, 30 January 1953, and the Sawyer–Bushby model.

extracted) were drawn, indicated that this was probably so. This was a reminder of the importance of a good analysis for producing a reliable forecast.

Another very early computer in this country was the Ferranti Mark 1 machine in the electrical engineering department of Manchester University and, since it seemed likely that more computing would be possible on this machine within the available funds, the decision was made to change over. This machine had cathode-ray-tube storage supplemented by a magnetic-drum backing store. Each binary digit of either program or data was represented by an electrostatic spot on the surface of the cathode-ray tubes and the store could be viewed on monitor tubes on which the 'ones' glowed more brightly than the 'zeros' and the actual data and instructions being currently used glowed more brightly than the rest. Programmers operated the computer themselves (Plates I and II) and with much-used programs they became very familiar with the pattern of 'dancing digits' in each routine of the program. Because of the unreliability of cathode-ray-tube storage each routine was repeated until identical results had been produced twice running. However, since the computer was faster than LEO 1, a 24-hour forecast was still produced in about the same time.

We had no programming course to teach us about this machine and so had to discover everything for ourselves from the large and comprehensive manual without the aid of the team of advisers that was common in later years. The storage of the Ferranti Mark 1 (apart from the backing store) was only 512 words, one-quarter of that of LEO 1, and with our need for large amounts of program and data we had no room for the standard supervisor program, but had to invent our own system. We designated one-quarter of the store (128 words) for program and all routines were arbitrarily made to be of this size, the last instruction obeyed in any routine being the one which overwrote itself with the next routine in the sequence. The remaining 384 words of storage had to suffice, with the aid of backing store, for data, intermediate results and so on. This computer had no compiler, the programs being read in directly from Murray-code teleprinter tape, the holes in the tape corresponding to 'ones' and four rows of holes making up one 20 bit instruction. Tapes were punched on a converted teleprinter/perforator and, since the punching had to be checked from the perforated tapes or from semi-perforated overprinted copy-tapes (because the normal carriage control characters had specific meanings to the computer and could not be used at suitable intervals to produce hard copy), the programmers of that era became expert in Murray code. This had the added bonus of enabling them to recognize the pattern of digits on the cathode-ray tube corresponding to each instruction, a very useful facility for 'debugging'. The paper-tape reader on the Ferranti computer used photoelectric cells in place of the mechanical system of LEO 1 and the coloured self-adhesive tape which was just coming on the market proved to be a boon for last-minute amendments.

Since we needed the computer for several hours at a stretch, most of our usage was at night and for some years we used the machine for two nights each alternate week. We stayed at a nearby commercial hotel, made up of several elderly terraced houses, now happily demolished. Sleeping during the day was made difficult by the shouting of the cleaners and the insistence of the electricity-meter emptier, and if we returned during the night the chorus of snores through the thin walls was unbelievable. Occasionally our time off enabled us to sample the delights of Edale or the Peak, or watch a second-grade film at the local cinema. More readily available treats were the sight of sunrise over Manchester from the roof near the computer room or the exhilaration of coping with an old-fashioned Manchester smog in which the buses were led by a man on foot holding a flare. It was also sometimes necessary to have one member of the party with sufficient athletic prowess to scale the wrought-iron University gate (whilst the others 'kept cave') in order to gain access to the computer building, and several of those who performed this feat have since reached higher directorate level.

The series of forecasts using the Sawyer–Bushby model was continued at Manchester and the encouraging results reported at a 'Monday Discussion' in February 1954 (Meteorological Office 1954) and by

Bushby and Hinds (1954a, 1954b, 1955). By this time the first attempt had been made to include physical processes in the forecasting system by simulating the heating of cold air masses over a warm sea. It had also become clear that with the small grid of 18 × 14 points appreciable errors arose with the use of no-change boundary conditions and in future work with this grid actual boundary changes were incorporated. Preliminary work was now started on objective analysis of data (Johnson 1957) and this was extended to enable the grid-point data required for a numerical forecast to be obtained by least-squares fitting to a quadratic surface at each grid point. Comparison of numerical forecasts based on objectively and subjectively analysed charts (Bushby and Huckle 1957) gave encouragement for the future of automated analyses as well as forecasts.

Meanwhile, in December 1954 SC II of the Meteorological Research Committee had recommended that the Office should have control of an electronic computer for the purpose of continuing research in numerical forecasting. In December 1955 financial approval was given for the purchase of a Ferranti Mercury computer and in the summer of 1956 staff attended the first programming course. The fact that the compiler was being written whilst the course was in progress added some confusion, but also enabled us to influence some of the decisions being taken. Whilst the programmers were busy with their preparations, Mr N. H. Seigne (now of the Operational Instrumentation Branch (Met O 16)) was at the Ferranti factory in Manchester helping to build a Mercury computer as training for his future work as maintenance engineer at Dunstable. The workmen were also busy extending the building and making rainproof that part which would house the computer (a job which had defeated them whilst it was my desk rather than a computer that was at risk). Finally, in the autumn of 1958, pieces of computer started to arrive and in January 1959 it was handed over. In those days the administration of computers was in its infancy and on the Branch inventory 'One Mercury Computer' was entered amongst the slide-rules and desk calculators.

The Mercury computer (named Meteor by the Office) was still a valve machine and input was still 5-hole paper tape, though now in Ferranti code, but in other respects it seemed to be a great leap forward. Floating-point numbers were available, so the old days of careful scaling of all values were at last over. The compiler allowed for 'floating addresses' or labels so that the chore of having to change a great many addresses every time an instruction had to be inserted was also finished with. The instructions were written in a numerical code and translated by the compiler into machine instructions on a one-for-one basis except for 'quickies' which were replaced by in-line routines to perform such functions as sine, square root and reciprocal (there being no hardware division instruction). There was a backing store on magnetic drums and the high-speed store of magnetic cores contained 1024 40-digit floating-point numbers. The first half of the store could also be used for 20-digit instructions or 10-digit fixed-point integers. Output was by paper tape or line-printer. There was also an instruction which sent a pulse to a loudspeaker and, by careful counting of time-wasting instructions between pulses to give the desired frequency, music reminiscent of the bagpipes could be produced. In honour of visiting Soviet meteorologists a data tape for 'The Volga Boatman' was punched. It was fortunate that it was tested before the visitors' arrival, as a punching error led the computer to produce some very embarrassing noises.

By the time that Meteor was available, programs had been written and developed not only for numerical forecasting and objective analysis, but also for the automatic extraction from teleprinter tapes of some upper-air information and the surface synoptic reports from ships. Therefore, two parallel experiments were run using current data, one in which as much of the procedure was automated as possible and one in which only the numerical forecast was done by computer. At 0830 GMT each morning the Frankfurt teleprinter tape was read into the computer and midnight data for 500 mb and 1000–500 mb total thickness were extracted. Missing data were then noted, searched for and manually punched, and at 0945 objective analyses of the 500 mb and 1000–500 mb charts were performed. Just after 1000 the surface data from ships were extracted by the computer from a collective tape produced in the teleprinter room. Following this, the 1000 mb chart was objectively analysed and the results used to amend the 500 mb and total thickness values. The numerical forecast program was then run to produce a 36-hour forecast by 1100 GMT. In parallel with all this activity grid-point data were manually extracted from Central Forecasting Office 500 mb and total thickness charts and punched on paper tape. The forecast based on these data was run at 0845 the following morning whilst the computer was available during the manual search for missing upper-air data. Forecasts by these two methods were then assessed against conventional forecasts and actual events. It was concluded that although numerical and conventional 24-hour forecasts were of similar standard over the British Isles, over a wider area the numerical forecasts were mostly of lower value, for a variety of different reasons.

During the next few years effort was concentrated on research and the production of better methods of numerical forecasting and objective analysis, the results being tested from time to time in real-time experiments. In the first experiment in early 1959 a great deal of manual effort had been found to be necessary for scrutiny of suspected observations and their deletion or correction. Therefore, in the second experiment, from late July to mid-November 1959, an attempt was made to automate this procedure. After an initial objective analysis of all available data, the individual observations (except those from Ocean Weather Ships) were tested in the computer against this first analysis and a second analysis was performed using only those observations which were not suspect. Despite the extra computer time involved, this was found to be a much more satisfactory procedure. The results of these first two experiments are reported by Knighting *et al.* (1961), who concluded that the main errors in the numerical forecasts arose from (a) spurious anticyclogenesis as a result of the geostrophic assumption, (b) boundary conditions, and (c) neglect of the effect of topography.

By early 1960 the two-level Sawyer–Bushby model had been extended to the three-level Bushby–Whitelam model and a version of the two-level numerical forecast program had been developed incorporating a stream function at 600 mb. Therefore, during the spring of that year an extended series of forecasts was run to compare the different available models. The results are reported by Wallington (1962) and Knighting (1961) and the conclusion drawn was that the three-level model was superior to either of the two-level models. As a result of these tests it was decided to mount a full-scale real-time experiment in operational numerical weather prediction in the winter and spring of 1960–61 using the three-level model. The aim was to provide the forecasting staff by 0930 GMT with a forecast for 06 GMT the next day. This necessitated an earlier start than in the previous experiments and the high-quality Frankfurt broadcast that had been used for data extraction was not received in time. Data were therefore extracted and punched manually as they arrived. It was planned to run a 6-hour forecast from 00 GMT data, and then to reanalyse the charts using any available 06 GMT data and continue the forecast for a further 24 hours. In order to obtain as many 06 GMT data as possible, a very close time schedule was planned, and in fact it was only possible to produce the forecast by 0930 GMT on about 35% of occasions. However, it was ready by 0945 GMT on a further 20% of occasions. On about 30% of occasions computer faults caused the delay or abandonment of the forecast, but many of these faults were quickly located and corrected. The results are reported by Knighting *et al.* (1962). The writers concluded that a larger, faster and more reliable computer than Meteor was needed if numerical prediction was to be used operationally. A number of improvements were also needed in the methods used, of which the most important was an increase in accuracy of data-handling.

In June 1961 it was necessary for Meteor to be dismantled so that it could be transported to Bracknell and reassembled on the fifth floor of the Napier Shaw Building (Plates III and IV). Opportunity was taken, with this break in computational facilities, to reorganize and rewrite the experimental operational programs. The biggest change was the production of a comprehensive data-extraction program to obtain the upper-air and surface synoptic observations from paper tapes of the main international teleprinter broadcasts. The three-level forecast program was changed to include the effects of topography and later changed to incorporate a stream function at 600 mb. Arrangements were also made to allow for the use of additional 'bogus' data. Analysis of 06 GMT data was temporarily abandoned so that an earlier start was possible at 0530 GMT and the schedule made it easier to produce the forecast by the appropriate deadline. Real-time testing of numerical forecasting began again in the late summer of 1962 and continued for much of 1963. The extremely cold weather of January 1963 was a considerable trial for the hardware of Meteor and it was found necessary to keep the computer working all night if it was to produce satisfactory results in the early morning. The programmers of the Dynamical Research Branch (Met O 11) took it in turns to 'machine-mind' on those nights when the computer had not been booked for use by another Branch of the Office.

With the acquisition of a computer for the Office in 1958–59 it was obvious that a larger number of staff needed training in computer programming. A small number of courses in Mercury machine code were provided by Met O 11 staff at Dunstable for those who needed a low-level language. However, it was felt to be important to spread a knowledge and understanding of computers much more widely through the Office and, with this in mind, courses were held twice a year in Mercury Autocode, a simple high-level language developed by Dr R. A. Brooker at Manchester University. These courses lasted for three days and by the end of the first day students had written a complete small program, punched it on paper tape, and operated the computer themselves to test it. One course each year was timed to coincide with the end of the Scientific Officer course, so that all new scientists entering the Office received computer training.

Use of the computer spread quickly to spheres other than numerical forecasting and as early as 1961 we find upper-air statistics being routinely computed on Meteor (Dewar 1961). Since Meteor was operated by the programmers themselves and only one program could be in it at a time, a complicated timetable for computer usage had to be drawn up each week in Met O 11. There were several 'development' periods each day when staff could queue up for very short test runs of their programs, but mostly it was necessary for them to book the computer for periods of a quarter of an hour or longer. Those needing several hours of computer time would be expected to use the machine during the late evening or even overnight.

The time was now rapidly approaching for numerical forecasts to become fully operational. For this to be practicable it was necessary for them to cover a much wider area of the globe in an appreciably shorter computing time and for the computer to be more reliable than was possible with a valve machine like Meteor. The decision was therefore taken to purchase an English Electric Leo KDF9. Staff training was started in the summer of 1963 and the computer was in use in an enlarged computer room on the fifth floor in the summer of 1965. Meteor was dismantled by our own engineers and reinstalled at Porton Down, where its useful life extended till 1971.

The KDF9 computer, known in the Office as Comet (Plates V and VI) and, like its predecessor, designed and made in Britain, included quite a number of considerably more advanced features than those of machines of the previous generation. Thermionic valves had gone, and transistors and plug-in circuits had come, and the designers were ahead of their time with the concept of a very fast access 'nesting store'. This consisted of 16 words used on a 'first in, last out' basis. All the arithmetic was actually performed on the top few words of the nesting store, the transfers to and from the store being done in separate instructions. With careful thought it was therefore possible to perform some functions, for instance evaluating a polynomial, at extremely high speeds and in many circumstances it was possible to cut the number of store accesses quite considerably by leaving values in the nesting store.

Fetching and storing could also take place in parallel with arithmetic, so a careful arrangement of instructions could cut the total time taken by the program. Up to four programs could reside in the store at the same time, the one with highest priority having control till it was held up, for instance by the need for input/output. As each program was completed, those remaining would move to either end of the store, leaving all the available space in one block in the centre for a further program to be read in. Control of the store and arrangement of program-switching was performed by the Time-sharing Director. Because of the multi-programming system, for the first time in the Office separate staff (from Met O 18c (Support Services), later Met O 12 (Data Processing)) were set aside to operate the machine on a shift-working basis, in 1965 from 0530 to 2200 GMT seven days a week and from autumn 1966 covering 24 hours a day.

The low-level language was the very simple and easily remembered Usercode in which, for instance, +; ×; were fixed-point addition and multiplication and +F; ×F; their floating-point counterparts. Algol was available as a high-level language. Table I (from Sumner 1964) gives some idea of the size, speed and input/output facilities of Comet compared with Meteor. In almost every way it was appreciably larger, faster and more reliable than Meteor and, in particular, had the additional facility of magnetic-tape storage.

Between 1963 and 1965 all the operational programs were rewritten in Usercode. Most of the testing was done at Kidsgrove, near Stoke-on-Trent, either on personal visits or by courtesy of British Railways, paper tapes and computer output being conveyed overnight via Reading in specially adapted tool-boxes. Soon after Comet was handed over, real-time tests were started and the numerical forecast officially became operational on 2 November 1965. There was much publicity for this event in the local and national Press, with photographs of the Director-General looking at output charts and headlines like '£500 000 computer speeds up weather forecasting. Comet feeds on isobars'. From then on the forecast suite of programs was run twice a day, starting at 0530 and 1730 GMT. The use of the computer for climatological and research purposes increased rapidly and before long there was a backlog of jobs waiting to be run which was cleared only at weekends.

Meanwhile, Met O 11 were already using the larger and faster Atlas computer, first at Manchester and later at the Rutherford Laboratory, for developing the Bushby–Timpson 10-level model. Atlas again was a British-designed and British-built machine and was far ahead of its time in incorporating such features as virtual storage (a system in which parts of the main store not in current use are parked temporarily in the backing store). This computer was also used by the Dynamical Climatology Branch (Met O 20) for research into the general circulation, work which had been started in a very tentative manner at Manchester in the 1950s.

However, by the time that it was appropriate for Comet to be replaced, the IBM 360/195 had become available and this computer was estimated on numerical forecasting work to be 20 times faster than Atlas and 80 times faster than Comet. Programmer training for the IBM 360 started in early 1970 and later that year and for much of 1971 program-testing took place at Croydon and at Poughkeepsie (New York State). Late in 1971 the present IBM 360/195 was installed in the COSMOS computing laboratory in the new Richardson Wing (Plates VII and VIII). KDF9 programs could be run on the IBM machine using a 'KDF9 simulator' and, in fact, the operational three-level model was run in this manner for a while, but Comet continued to operate in the fifth-floor computing room until March 1973.

As would be expected, the IBM 360/195 included a number of new features, apart from the fact that the basic machine cycle was much faster than that of Comet. There was a small, very high-speed buffer store which saved considerably on access times to the main store and the central processing unit was organized so that it could look ahead through the instructions and be decoding and obeying a number of them at the same time. Input/output was improved by the addition of discs for backing store and

Table I. *KDF9 and Meteor compared*

Item	KDF9 Number	KDF9	Meteor Number	Meteor
Internal storage				
Main store		12 288 48-bit words		1 024 40-bit words
Magnetic drum		40 960 48-bit words		16 384 40-bit words
Operating speeds		*microseconds*		*microseconds*
Access to main store		2–12 (average 7)		120
Addition and subtraction—fixed-point		1		–
—floating-point		7–12		180*
Multiplication—fixed-point		15		–
—floating-point		15–19		300*
Division—fixed- and floating-point		35–40		3800
Input/output equipment	Number	Speed	Number	Speed
Paper-tape readers	3	1000 characters per second	1	300 characters per second
Paper-tape punches	3	110 characters per second	1	33 characters per second
Card readers	1	600 cards per minute	0	
Line printers	1	1000 lines per minute (160 characters per line)	1	150 lines per minute (92 characters per line)
Magnetic tape units	6	40 000 characters per second	0	

*Note: Arithmetic times on Meteor include the time of one transfer from the main store to the arithmetic unit, whereas those for KDF9 do not.

Calcomp microfilm plotters (to replace the flat-bed line-drawer used on KDF9), and by the input/output channels being independent of the main processor. There was an increase in the number of programs operating at the same time and further programs could be read in to await their turn in a job queue. The programs in the queue were classified into different types, thus enabling the computer itself to choose the next job according to the facilities available.

The work which had previously been done on the Atlas computer was transferred to the IBM 360/195 and with the extra computing power available the general circulation and climate modelling by Met O 20 were considerably expanded. Other work also increased, and at the end of 1974 an IBM 370/158 was installed in the COSMOS laboratory to provide facilities for those programs which did not require the computing speed of the 195 and to act as a 'front end', organizing the input, output and job-scheduling for both machines. Still the work-load continued to increase. With parallel automation of telecommunications, synoptic data were able to flow directly from the twin Marconi Myriad computers in the Telecommunications Branch via an IBM System 7 computer directly into COSMOS without the use of teleprinter paper tapes. Charts could be plotted automatically by the computer using the data so received. Climatological data, which used to be punched on cards and processed by Hollerith machines, were keyed directly and processed by computer. Interactive visual display units (Time-sharing Option terminals) were available in different parts of Headquarters to give programmers more direct access to the computers. Data for flight-planning could be sent directly from COSMOS to the British Airways computer. COSMOS not only schedules its own work in a sophisticated fashion, it also provides management statistics for those in authority over it. By 1979 over 1000 jobs a day were being run and 4400 million bytes (or characters) of on-line data were available on COSMOS.

By early 1979 some Branches were already making use of the vector facilities of the CRAY-1 at the European Centre for Medium Range Weather Forecasts at Shinfield Park. Now, as this is being written in late 1980, preparations are in full swing for the installation of the 'number-crunching' Cyber 203E in COSMOS early in 1981.

Gone are the days when it was possible, as in 1966, for a small enthusiastic group of staff to film in the computer room in off-duty hours a computer-age fantasy based on the medieval fable of the Sorcerer's Apprentice. (It failed to win an award because the judges felt that insufficient chaos was depicted.) Now, in the 1980s, the operation of the much more powerful COSMOS computing facilities 24 hours a day requires first-class organization and the co-operation of hundreds of staff—a very far cry from the single electrical desk-calculator with which it all started in about 1950.

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Glossary

Compiler. A computer program whose purpose is to read in to the computer a program written in one of a number of appropriate codes by a user, and to translate that program into machine instructions of the form required by the hardware of the computer.

Fixed-point binary. The representation of a number to the base 2, that is, as a series of noughts and ones. Often this refers to integers only—in other words, the binary point is usually after the last digit.

Floating-point binary. The representation of a number as $a \times b^c$, where b is frequently 2 or 16, c is an integer, and a is in fixed-point binary, sometimes an integer, but more often a fraction. Usually the exponent c is represented by about one-quarter of the digits in a computer word and the other three-quarters represent the mantissa a. The value of b is fixed for any particular computer. The use of floating-point enables a wide range of numbers to be represented in a computer to the same number of significant digits.

High-level language. A code for writing computer programs which is very similar to normal algebra, but far removed from the machine instructions required by the hardware of the computer. Normally a sophisticated compiler is required to translate such a code.

LEO. LEO computers were originally produced by Messrs J. Lyons, the caterers, but this section of their enterprise was later acquired by English Electric.

Low-level language. A code for writing computer programs, which is very closely related to the machine instructions required by the hardware of the computer. The compiler is normally much simpler than for a high-level language, and the programmer has a closer control of the processes inside the computer and therefore can often use the computer more efficiently.

Mercury delay-line. This is a device in which electrical signals are converted into an acoustic wave (piezo-electrical effect), this being delayed by circulation through mercury before being reconstituted into an electrical signal. The speed of sound in mercury is very much slower than the speed of electrical signals in a conductor.

Murray code. Teleprinters can be operated automatically by punched paper tape and Murray code is the code connecting each row of holes on the paper tape with the appropriate character. Trained teleprinter operators can frequently read from Murray code tape as effectively as from a printed text.

'Plonker'. A small plastic scale, usually for measuring geostrophic wind strengths from a chart, which could be placed or 'plonked' on the chart.

Total thickness. The difference between the geopotentials of the 1000 mb and 500 mb surfaces. The total thickness chart was a very useful forecasting tool.

Valve. A thermionic valve (or vacuum tube) was a basic part of the hardware of most radios and computers till the invention of the transistor to perform a similar function.

Correspondence

The heat balance of wet snow

We have received the following letter from Dr Lasse Makkonen:

In the article by A. K. Kemp in the March 1980 *Meteorological Magazine* a mechanism of snow accretion on wires was suggested. According to it the cooling of the snow deposit due to evaporation causes refreezing of wet snowflakes after impact, the wet-bulb temperature thus being an important factor in the occurrence of accretion.

This hypothesis has been tested by Wakahama, Kuroiwa and Gotō (1977) by measuring the temperature changes in the snow deposit in wind-tunnel experiments. They found, however, no evidence indicating the freezing of water in the snow deposit during accretion. On the contrary, the free-water content of the deposit increased considerably during accretion, even in the tests with only 70% relative humidity, and in addition some free water was removed from the leeward side of the snow deposit, just as in the case of rime formation in the wet-growth regime (e.g. Makkonen 1980). Thus, it is concluded that the heat transfer from the moving air to the snow-mass by convection exceeds by far the heat lost by evaporation, at least in the temperature range from +1 °C to +2 °C of the wind-tunnel tests. However, intensive snow accretion on wires has been observed at these temperatures (Shoda 1953, Wakahama, Kuroiwa and Gotō 1977).

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Makkonen, L. 1980 Theoretical estimates of ice accretion intensity on structures. 12th Meeting of Nordic Meteorologists, May 1980, Espoo, Finland.
Shoda, M. 1953 Studies on snow accretion. *Res Snow Ice*, **1**, 50–72.
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Dr Makkonen's letter was referred to Dr P. Ryder of the Meteorological Office, Assistant Director (Cloud Physics), who has sent us these comments:

Kemp (1980) has attempted to explain the formation of ice on electrical conductors during heavy falls of wet snow. Makkonen (above) asserts that this is not in keeping with some wind-tunnel experiments reported by Wakahama, Kuroiwa and Gotō (1977).

It is very difficult to evaluate the heat balance of a mixture of ice and water, on or off a substrate, when sensible heat exchange and transfers of vapour, liquid and solid to and from the mixture are possible. For example, some, but not all, of the terms which should be considered in the accretion of ice on a helicopter rotor blade have been described in Ryder (1978) and references therein.

If, for the moment, accretion, splashing and bouncing phenomena are neglected, the role of wet-bulb temperature can be readily understood as a balance condition between convective heat and water vapour transfer between the mixture and ambient air. If the surface of the mixture is at a temperature T_s, the air temperature is T_a and ambient vapour pressure is e_a, then the rate of convective heat transfer per unit area is $q_c = h(T_a - T_s)$. Here h is the convective heat-transfer coefficient, in general a function of Reynolds number. The equivalent rate of evaporation heat loss is

$$q_c = \frac{0{\cdot}622Lh}{c_p}\left(\frac{e_a - e_s}{p}\right),$$

where the symbols have their usual meanings and e_s is the saturation vapour pressure at temperature T. Note that the convective heat-transfer coefficient enters both equations. Formally, this implies that the Sherwood number is equal to the Nusselt number, a commonly accepted assumption at atmospheric pressure. Qualitatively, both the convective and evaporative heat-transfer rates are expected to be sensitive to the ventilation rate. At equilibrium,

$$\frac{e_s - e_a}{p} = 6{\cdot}46 \times 10^{-4}(T_a - T_s).$$

The psychrometric equation (see *Smithsonian meteorological tables*, page 365, for example) which links the wet-bulb temperature empirically to the appropriate saturation vapour pressure is

$$\frac{e_w - e_a}{p} = A(T_a - T_w), \text{ where } A = 6{\cdot}6 \times 10^{-4}(1 + 1{\cdot}15 \times 10^{-2}\, T_a).$$

As might be expected, the surface temperature is effectively the wet-bulb temperature under these circumstances. It has been derived in this way to emphasize the balance and assumptions that are implied by the concept.

I turn now to Kemp's arguments; his assertion that an increased ventilation rate can increase evaporative cooling but not convective heating is unconvincing for the reasons identified above. He may be correct in drawing attention to ventilation but only in so far as this influences the joint magnitude of the terms. At low ventilation rates these become small and less likely to dominate the heat-balance equation. Snowflakes falling through air of gradually varying wet-bulb temperature may exhibit a discernable temperature lag, for example. Kemp is almost certainly incorrect in suggesting that a train moving into a strong wind is more liable to icing than a train moving with the wind, all other influences being equal. He neglects the effect of dynamic heating which provides a net heat transfer to the exposed surface. An object moving at velocity v will achieve an equilibrium temperature $\triangle T$ °C than when it is at rest, where $\triangle T \simeq v^2/2c_p$. $\triangle T = 0{\cdot}05$ °C at 10 m s^{-1}, 1·2 °C at 50 m s^{-1} and 2·8 °C at 75 m s^{-1}.

Makkonen quotes wind-tunnel experiments in which no signs of refreezing were evident in a mixture of water and ice accreted by a wire. The air temperature was held between +1 °C and +2 °C and ambient relative humidity was stated to be 70%. The wet-bulb temperature under these circumstances varies between −0·8 °C and +0·2 °C. Superficially, some ice growth might have been expected, at least at air temperatures close to 1 °C. However, both he and Kemp neglect the contribution of terms associated with accretion, bouncing, conduction, etc. The wind-tunnel experiments showed that almost 80% of colliding particles rebounded. These must be expected to play a part in the heat-balance equation. If rebounding particles have a higher fractional ice content on average than those impacting, then there is a net transfer of heat to the wire in addition to that implied by the local wet-bulb balance. If fragments being shed by the wire are slightly warmer than those impacting, then there will be a net transfer of heat away from the wire. Similarly, the equilibrium temperature of dry parts of the structure is likely to be controlled by the air temperature. Conduction of heat from there to the cooler, wet regions on which ice is accreting also represents a net warming there. Ohmic heating of a wire carrying an electric current may not be negligible.

It is difficult to disagree with Kemp in his suggestion that a wet-bulb temperature at or just below 0 °C is a necessary condition for the accretion of ice on electrical conductors during heavy falls of wet snow. However, it is not a sufficient condition. The practical balance between significant and no icing is expected to be sensitive also to the processes involved in the collection and shedding of water substance, these being in turn a function of wind velocity, snowfall rate and the variation of wet-bulb and air temperature with height. It is suggested that the empirical results of Kemp, and earlier of Foot (1972), reflect this sensitivity.

P. Ryder

Meteorological Office, Bracknell.

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Kemp, A. K.	1980	The formation of ice on electrical conductors during heavy falls of wet snow. *Meteorol Mag*, **109**, 69–74.
Ryder, P.	1978	The role of meteorology in helicopter icing problems. *Meteorol Mag*, **107**, 140–147.
Wakahama, G., Kuroiwa, D. and Gotō, K.	1977	Snow accretion on electric wires and its prevention. *J Glaciol*, **19**, 479–487.

The author of the original paper, Mr A. K. Kemp, makes the following additional comments:

Makkonen and Ryder make the valid point that convective heating must have an important bearing on the heat balance of wet snow on a conductor. Ryder asserts that other terms are likely to be important also.

In the equation for convective heat transfer given by Ryder, $q_c = h(T_a - T_s)$, increasing the value of T_a will increase q_c, but as $T_a \rightarrow T_s$, $q_c \rightarrow 0$. In the experiment described by Makkonen, T_a was between +1 °C and +2 °C and, therefore, for a mixture of ice and water and assuming equivalent ventilation rates, the convective heating term must have been greater than in the Anglesey storm where T_a at the level of most of the conductors was estimated to have been from 0·5 °C to 0·0 °C.

It would be interesting to see the results of wind-tunnel experiments carried out with wet snow where the air temperature and wet-bulb temperature were controlled at and close to 0 °C.

A. K. Kemp

Meteorological Office, Royal Air Force Valley.

Reviews

Atmospheric physics, by J. V. Iribarne and H.-R. Cho. 240 mm × 160 mm, pp. xii + 212, *illus.* D. Reidel Publishing Company, Dordrecht, Holland. Price Dfl 40.00, US £15.95.

Any attempt to describe the physics of the atmosphere in about 200 pages is certain to be a compromise. The virtue of this book is that its specific, restricted purpose is pursued intelligently and faithfully.

The authors assert that they have produced 'an elementary but comprehensive survey of the terrestrial atmosphere'. Their potential market is clearly identified as second- or third-year university students engaged in a course which is preparing them for a career in atmospheric, geophysical or environmental sciences. The students are presumed to have only elementary mathematical skills 'and such knowledge of physics as should be acquired in most first year general physics courses'. A working knowledge of chemistry, to rather better than 'O' level GCE standard, is also necessary to understand some parts of the syllabus. Curiously, this point is not identified by the book's title or in its preamble.

There are seven chapters in all. Five of these deal with the general structure of the atmosphere and its chemical, radiative, thermodynamic and large-scale dynamical processes. The remaining sections describe the physics of clouds, at least in so far as they are producers of precipitation, and atmospheric electricity. The chapter on atmospheric dynamics is about 40 pages in length; the others occupy between 20 and 30 pages each. Within this framework the authors adopt a distinctive style of presentation to attain their objective. There is little space for the analysis of individual problems in terms of established physical principles so the text is a predominantly factual rather than a reasoned exposition. However, this compromise is not as brutal as it might appear at first sight because each chapter ends with a number of questions and problems for the student. Answers and hints for solutions are provided at the end of the book. It is these problems which should exercise the reasoning powers of the reader. The problems are chosen with some skill and, where possible, emphasize the application of atmospheric physics and chemistry to a number of contemporary concerns. In the end, and despite some misgivings, I believe that this arrangement could be very successful. Obviously, it is essential that full use be made of the questions, perhaps augmented by a tutorial system, if maximum benefit is to be obtained from the book.

The scientific material is quite well presented, although the choice of diagrams is somewhat uninspiring. Even for a cloud physicist, three separate graphical representations of the Clausius–Clapeyron equation in different parts of the book is carrying a good thing too far! Most features of modern atmospheric science are introduced but their treatment is often very superficial. Tropospheric processes receive most attention, but the role of the upper atmosphere as an absorber of short-wave radiation is discussed in the production of the ionosphere and stratospheric ozone. The section on dynamics is exclusively concerned with the troposphere and it stops short of the concept of vorticity. As expected from someone with Dr Iribarne's research background the sections on cloud physics and atmospheric electricity are up to date. A short general bibliography is provided for each chapter but no other guidance is given to the student who seeks more of the red meat which is not available in this *ragoût*.

As suggested at the outset, the book is consistent with its stated objectives as a teaching aid. It is recommended to those setting up or taking part in the described courses. It is not so well suited to the enquiring reader who has an informal interest in the atmosphere and seeks a worthwhile understanding of its fascinating physical and chemical processes.

P. Ryder

The middle atmosphere as observed from balloons, rockets and satellites (A Royal Society discussion arranged by the British National Committee on Space Research and Solar–terrestrial Physics, under the leadership of Sir Harrie Massey, F.R.S., Sir Granville Beynon, F.R.S., J. T. Houghton, F.R.S., and L. Thomas, held on 12 *and* 13 *December* 1978), The Royal Society of London. 290 mm × 200 mm, pp. v + 268, *illus.* The Royal Society, 6 Carlton House Terrace, London SW1Y 5AG, 1980. Price £24.50 (United Kingdom addresses, including packing and postage) and £25.75 (overseas addresses, including packing and postage).

This is a collection of the invited papers presented at a discussion meeting of the Royal Society in December 1978, covering the structure, dynamics and observation techniques of the layer 10–100 km.

The description of the climatology makes full use of satellite data, enabling useful spectral analyses of the large-scale temperature waves to be made, though the description is spoiled a little because zonal-mean winds are plotted only up to 30 km. Diurnal variations are derived from rocket and meteor wind data. As one author succinctly puts it: a sun-synchronous orbit is not a good one for the study of diurnal changes.

A second group of papers is concerned with models of the interaction between photochemistry and dynamics, transfer between troposphere and stratosphere and with a theoretical and philosophical discussion of the propagation of waves of small amplitude. Finally, there are papers concerned with the chemistry of the layer, spectroscopic *in situ* and satellite observation of ozone, other trace gases and temperature. There is no discussion nor, presumably, any uninvited papers.

The papers are quite informative and the reader will find much to enjoy and much that is stimulating. However, I do not think he will find anything that has not already been published elsewhere, nor will he find a comprehensive review. There is not enough continuity or background, and too much jargon for the browser. Unfamiliar topics will need the references for background; familiar topics will need the references for clarification. According to the flyleaf, the volume is intended to help planners. Perhaps that is why it is published expensively, in hard covers. I suspect that the planners will be as baffled as I am by the statement that 'many experimenters have underestimated the precision of their data', astonished to read that spectrometers may be large, heavy and expensive, and cheered by the implication throughout the text that there is now a great deal of undigested data on magnetic tape.

I cannot wholeheartedly recommend this volume to individuals or libraries except for the useful list of references, and suspect that its reading by those 'planners' will not do the subject much good. Anyone who has £25 to spare might care to note that Ludlam's monumental work on clouds and storms costs just this much.

J. S. A. Green

Corrections

In the Letter to the Editor, *Meteorol Mag*, **109**, 1980, 362–363, the date of the hailstorm at Sevenoaks should be 25 June 1980, not 26 June 1980.

In the article by N. Thompson, *Meteorol Mag*, **110**, 1981, page 2, the symbol printed in equation (2) as 'R_a' should be 'r_a'.

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NOTICES

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