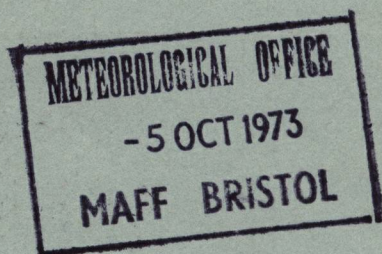


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## BRITISH ARCHITECTS OF THE INTERNATIONAL METEOROLOGICAL SYSTEM

By D. G. HARLEY

In this centenary year of 1973 many things will be written and spoken about the International Meteorological Organization (IMO) and its successor the World Meteorological Organization (WMO). The international system constructed by them is wonderful in its complexity, its flexibility and the methods of its control. Formed of independent national services, which work in continuous daily or hourly contact with each other, it is governed entirely by consensus of the professional heads of those services. Since the beginnings in 1873 the technical developments have been enormous, but the records of the early years show how far-seeing were the men who laid the foundations, and how well designed was the structure that rose on them. What C.-G. Rossby wrote in 1956 fits well the early leaders of IMO: 'During the last decades the technological development has time after time shown the dreams of a visionary mind to be closer to reality than the commonsense judgement of the realists'.

The IMO, which began in Europe, was naturally strongly influenced by European meteorology, as indeed WMO still is. It is not surprising then that although no permanent seats have ever been reserved for any person or country, certain founder countries have nearly always been represented in the governing body. Of these the only one with unbroken continuity from 1873 until today is the United Kingdom. In these one hundred years a great many British meteorologists have played important parts in the developing scene, but during the 78 years of IMO's existence four in particular played leading roles. Those four were R. H. Scott, Napier Shaw, Ernest Gold and Nelson Johnson.

**R. H. Scott and the early years.** The development of electric telegraph services in Europe stimulated the growth of meteorological services, and soon the mutual exchange of reports was begun. Even before this stage the first step in international meteorology was taken, when Maury of the U.S.A. and Quetelet of Belgium organized a conference of 10 countries in Brussels in 1853 on maritime meteorology. The main object of this conference was to achieve a uniform system of meteorological observations at sea.

By 1872 many meteorologists were convinced of the need for uniformity of practice and for international co-operation on a large scale, so 52 directors of meteorological services and a number of other scientists met in Leipzig to plan a formal intergovernmental conference to take place in the following

year. Immediately there arose the problem of who should be invited, as many eminent meteorologists were not directors of their country's central services, and some countries indeed had several institutions of similar standing. Thus early began 'political meteorology', that inescapable incubus of international action.

Governments agreed, and in September 1873 there assembled the first International Meteorological Congress in Vienna, whose centenary will be celebrated in the same place in September 1973. The Congress was a great success, took a number of important technical decisions, and chose a Permanent Meteorological Committee (PMC) to see to their implementation and to call another Congress in a few years. The PMC met immediately, and elected as its President Buys Ballot of the Netherlands who had been the moving spirit and leader of events, and as its Secretary Dr R. H. Scott of the U.K.

Scott, a Dubliner, had become in 1867 Secretary of the Meteorological Committee of the Royal Society, and Director of the Meteorological Office. The Office was then a very small body — its total budget for the year 1874–75 was £11 68s 10s 6d — and in low repute scientifically. In 1866 the issue of forecasts had been suspended as being scientifically unjustified, but the public outcry was such that by May 1867 the Board of Trade asked the Meteorological Committee to resume giving some intimation of storms. At first this was done by merely repeating actual reports, but before 1876 a storm warning system had again been developed. It is difficult now to realize just how little information was available; no ship reports, British reports for one hour in the morning and one hour in the evening (many of the latter came only with the next morning's message) and, gradually, some reports once daily from neighbouring countries. But these messages contained no cloud reports, no pressure tendency, and there was little uniformity of units. Even the hours of observation differed from country to country, a problem that took many decades to resolve.

From the start the vision of meteorologists saw far beyond these handicaps. Indeed, before Scott arrived, the Meteorological Committee went on record in 1866 as 'looking forward to international co-operation in the indication of the causes of meteorological changes over the greater part of the globe'. Thus in 1873 Scott was named with Alexander Buchan, Secretary of the Scottish Meteorological Society, to represent the United Kingdom at the Vienna Conference, with strict instructions 'to abstain from pledging Her Majesty's Government in any way'. He was in the event able to report back that no decisions had been taken involving expenditure.

Scott seems to have been a good organization man, a cautious and sound science administrator rather than a research scientist, although he was also a Fellow of the Royal Society, whereas Buchan from his less official position spoke more independently as a scientist. For example, when the Vienna Congress discussed the units to be used for observations and the universal use of the metric system was urged, Buchan was all for it, but Scott felt bound to say that his Government was now not so keen and was not likely to be able to accept the proposal.

The PMC had seven members initially, this number being increased to eight in 1878 when the French felt able to accept an invitation. They had been absent from the Congress, no doubt as a consequence of the Franco-Prussian war of 1870, the first of the painful effects of war on the continuity

of meteorological co-operation. The second Congress which met in Rome in 1879 elected in its stead an International Meteorological Committee (IMC) to function until another Congress, and this system continued throughout the life of IMO. The PMC and the IMC met frequently from 1874 onwards, generally every two or three years. There was no other organization for continuity, no Secretariat until 1926, no permanent offices or officers. Even the name International Meteorological Organization only appears thus with capital letters in the 1920s when at last a permanent Secretariat was set up. Between the meetings of the IMC the President and Secretary carried on the business by correspondence. Scott was continuously Secretary until he retired in 1900 from the Meteorological Office. In more lowly affairs one might be tempted to suspect that perhaps a Secretary stayed so long because no one else would take on the job, but in this work there were many strong, active and indeed brilliant men, and one can but conclude that Scott was that most useful of men, the industrious reliable continuity man, who underpins the work of his enterprising colleagues.

To one used to today's large organizations for supporting international activities, some features of the early IMO are surprising, such as the publication of reports, language problems and finances. Finance was managed by each country paying its own way, e.g. in 1874 Scott asked the Meteorological Committee for £20 as a contribution to the Permanent Meteorological Committee. There is little or no mention in any of the early reports of the problems of language, whereas nowadays simultaneous interpretation seems indispensable. Yet large agendas were disposed of in meetings of a few days only. Publication of the reports of meetings was done by courtesy of various governments. Scott evidently persuaded his Meteorological Committee at home to support the work, and until the 1920s all the main reports of IMO were published in English by HMSO 'by Authority of the Meteorological Committee'. French and German editions were likewise published by other governments, for the general good. There being no Organization there was no book of rules, but there were the accumulated resolutions and decisions of the various meetings. Only in 1909 was there finally published in London a codex of such resolutions, drawn up by Hildebrandsson of Uppsala and Hellman of Berlin, at the request of the IMC. Until then personal experience and continuity saved the day. The 1896 Paris Conference noted Scott's knowledge of previous decisions and his pressure for consistency. By that time he was one of the only two active survivors of the 1873 Congress, Professor Mohn of Norway being the other (Mohn served from 1873 to 1913!). The Conference accepted Scott's advice that earlier decisions made for good reasons should be adhered to.

After the Rome Congress of 1879 which was, as before, intergovernmental, it gradually became clear that governments did not want any more such Congresses, apparently because the decisions were mainly technical and did not justify the use of such ponderous diplomatic procedures. For several years the IMC could not see clearly how to proceed. Eventually in 1888 it concluded that, as its agenda was finished and it could not call a Congress, its work was finished and it should dissolve itself. It asked its ex-officers President Wild of Russia (who had succeeded Buys Ballot in 1879) and Secretary Scott of the U.K., to carry on and call together the representatives of meteorological services to decide what should be done. So a Conference

of Directors was convened to meet in Munich in 1891, many of them uncertain what could usefully be done in their semi-private capacity. However they soon found that they could do useful work, elected a new IMC, and so in practice things went on much as before. Before the next Conference in Paris Wild fell ill and Scott carried on all the preparations alone, because the rules did not then permit a new appointment to be made.

By this time the organization had spread far beyond Europe. From the beginning the U.S.A. had been involved to some degree, and from time to time participants from India, China, Argentina, Australia and Mauritius came to meetings. In the reports of the 1873 Congress and its Permanent Committee there are recorded discussions on the meteorological problems of Samoa, South America and the Congo among others. To the Paris Conference in 1896 which Scott called and opened single-handed, directors from most parts of the globe were invited, although in the event Asia, South America and the West Indies were not represented.

Until the first Conference of Directors in 1891 there were no subsidiary bodies to the IMC, although *ad hoc* conferences on special subjects had been called from time to time. Such were the private Conference on Maritime Meteorology called by Scott in London in 1874 to update the great work of Maury's Brussels Conference of 1853, and the special Polar Meteorology Conference in Hamburg in 1879. There were no Regional Associations until 1935 although Australasian intercolonial meteorological conferences met in Sydney, N.S.W., as early as 1879 and 1881. The first permanent Commission, forerunner of today's Technical Commissions, was established in 1891, and two more in 1896. At this time the long process of laying firm foundations and a good understanding began to allow real development of the science and practice of meteorology. But not until radio-telegraphy allowed services to escape from the limitations and heavy costs of telegrams, and to collect synoptic data from the oceans, and not until user demand from aviation opened the money bags, could meteorology really begin to take off.

In 1900 Scott retired, and was succeeded by Napier Shaw. The IMC thanked him for his 'unfailing zeal' during his long service. Scott died in 1916, before the rapid growth of meteorology had really got under way. It is sad to find that in the two obituary notices of him in the *Quarterly Journal of the Royal Meteorological Society* there is not one mention of all his international activities over so many years. Elsewhere however, someone recorded that Scott had been 'the architect of the international system'.

**Sir Napier Shaw as President.** Napier Shaw was a physicist of renown at Cambridge, and some were surprised that he took on Scott's job. However his subordinate position as Secretary of the Meteorological Council (imposed on Scott in 1877) was soon changed, and he became Director of the Meteorological Office. Instead of being controlled by the fortnightly meetings of the Meteorological Council of the Royal Society, he now became Chairman of a Meteorological Committee which met only every two months to advise him. The Royal Society and the Treasury were represented on this Committee. Shaw found the means to bring into the Office first-class young scientists and thus set it on a course from which it has never since looked back. Among these new men were Ernest Gold and R. G. K. Lempfert, whose names began to appear on scientific papers which had great influence. Shaw himself led



this work enthusiastically and for the rest of his long life produced many writings on meteorology culminating in his four-volume *Manual of meteorology*, written mostly after his retirement in 1920. Shaw was given the place on the IMC vacated by Scott, and Hildebrandsson of Sweden took over as Secretary. Mascart of France had succeeded Wild as President of IMC, but in 1907 he was seriously ill and had to resign. The IMC, then in session, came to his bedside where Shaw, who had been chosen to succeed Mascart, spoke movingly of the task before them and quoted a French saying to the effect that 'the most terrifying difficulties are those that do not really exist'.

By this time, 1907, radio had begun to be fitted on ships, and the IMC had already been quick to pursue ways of getting synoptic reports from ships at sea. Several meteorological services tried to collect radio messages, but in the early years the results were disappointing, partly because someone had to pay for the messages, largely because of the long delays before the messages reached the forecast offices. In 1907 the British and German services reported that in a 2-month experiment less than 18 per cent of messages arrived within 24 hours and less than 50 per cent within 48 hours! Although the system has gradually improved since then some of these problems are still with us.

To meteorologists of the 1970s, used to floods of data from around the world, it is surprising to discover how long it was before synoptic reports were available in Europe from the Atlantic islands and from North America. Cables across the Atlantic began to work properly in the 1870s, and then extended rapidly throughout the world wherever the traffic appeared to justify it, but cablegrams were expensive and reports from North America were of little use in Europe with none from the 3000 miles of ocean in between. From the Azores three telegrams a day began when a cable there was completed in 1893, and a much improved service direct to the U.S.A. and Britain began in 1901 when new cables were completed. This new service resulted from a generous offer from Colonel F. H. Chaves, Portuguese Director in the Azores, and a quick response from the IMC urged on by Napier Shaw. A cable to Iceland was repeatedly suggested in those years but the financial support could never be organized. As the data collection system developed, the inadequacy of the code form agreed in 1874 became more and more apparent, but just how it should be improved took much labour to decide, and much basic work such as the classification of clouds and preparation of a cloud atlas had to be done first. This was done by the Commission for the Study of Clouds set up in 1891. The Commission for Weather Telegraphy made some progress but the old code remained until 1919.

With these growing demands and opportunities, and 30 years' experience of working together, meteorologists recognized that the system of unofficial Conferences of Directors had advantages, and settled down to plan their future development. The 1905 Conference of Directors at Innsbruck asked the IMC to prepare a regular scheme for regulating international meteorological organization, taking account of historical development and the resolutions of past Conferences, IMCs and Commissions. The Conference also agreed that there should continue to be Commissions appointed for special subjects, and especially to organize collective researches. From this time on the fact of the IMO may be said to have been recognized, although it was not so named until later. Also from this time began the rapid acceleration of development which still continues today.

It is worth noticing here some other historical links between IMO and the WMO of today. The IMC, unlike the Executive Committee of WMO, was the only continuing body, and was completely responsible for action between Congresses and Conferences. Later on as the volume of work continued to grow, a smaller Executive Council of five members was set up in 1929 within the IMC. Neither the Executive Council nor the IMC corresponds exactly to the Executive Committee of today. As to the Conferences of Directors, the informality and possibility of direct inter-service working agreements were soon found to be useful, and political difficulties were reduced by the informality of the system. The formality of the intergovernmental Congresses had had the advantage of settling the question of representation. Necessarily there had had to be one principal delegate, although others from the same country might be of equal or greater scientific eminence, and the Conferences of Directors maintained that convention. The institution of Commissions, readily arranged in so informal a meeting, provided the means and opportunity for the scientists and experts to play their full part. When later the inconveniences of being unofficial became apparent, for example the lack of status of IMO decisions *vis-à-vis* those of intergovernmental bodies, there was much reluctance to lose the now accustomed freedom of association and work. In consequence the WMO Convention has firmly built into it to the greatest extent practicable these methods of representation, work and organization devised by IMO. One of the most valuable legacies of IMO to WMO, as noted by President Viaut in 1960, is 'the principle of effective and constant participation by the meteorological services of Members in the life processes of the Organization'.

Under Napier Shaw the IMO was working up steadily and energetically when catastrophe struck the world with the outbreak of the first World War. During the war meteorology, radio and aviation all developed enormously, and by 1919 a new situation faced the survivors. Shaw as President of IMC summoned a meeting in London of six members, and representatives of others, and a new Conference of Directors was summoned in October of the same year in Paris to set the new course. Not only were there new demands from the customers, new systems of observing and reporting, and new scientific methods to absorb, but there were new organizations to cope with. On the one hand the new International Commission for Air Navigation (ICAN), a fully intergovernmental body, had its own subcommission for meteorology, and on the other was the establishment also in 1919 of the non-governmental body of scientists called the International Association for Meteorology. The latter body freed IMO to concentrate on practical matters, of which it now had more than enough to cope with. The former body was a potential rival with whom to come to terms.

Under Shaw's vigorous leadership, the 1919 Extraordinary Conference took firm grip of the situation and established nine Commissions (the IMC set up three more in 1921) nearly all on urgent practical matters. Shaw was selected as President of the new IMC, and although he retired as Director of the Meteorological Office in 1920, he was maintained as President until the next Conference in 1923, when he was made an Honorary Member of the IMC and so remained until his death in 1945. For several years from 1921 he was also President of the Commission for the Study of Clouds, and of the Commission for the Investigation of the Upper Air, which has since become



WMO's Commission for Atmospheric Sciences. Until 1919 Shaw had for twelve years been President of both the Commission for Storm Warnings and Maritime Meteorology, and of the Commission for Weather Telegraphy.

**Ernest Gold and the development of synoptic meteorology.** In this last Shaw was succeeded in 1919 by Colonel E. Gold, one of those he had brought into meteorology a dozen years before. The Commission soon changed its name to Commission for Synoptic Weather Information, and under the pressure of circumstances and the qualities of its President it became the focus of developments in international meteorology. Gold remained President until 1947, during which turbulent time the world-wide meteorological system now known as World Weather Watch grew into much of its present form. He then retired but is fortunately still with us. In 1958 he was awarded the third IMO Prize, the first of three British meteorologists to be so honoured.

When Gold took over the Commission for Weather Telegraphy the need for urgent action was unmistakable. Not only had the pre-war system of exchanges of telegrams been disrupted, but under the pressure of military needs meteorological services were using a variety of codes including new elements, had greatly increased both the frequency of reports and the numbers of stations, and had developed the use of radio. There was no question of return to the pre-war poverty of data, but the immediate problems were to bring international order to the riot of national arrangements. Nor could the defeated Central Powers be left out of the new plans, as meteorology was now clearly more international than ever. Gold set up two permanent sub-commissions, one on codes and specifications directed by himself, and one on radio transmissions of weather reports under Delcambre of France, and also developed working arrangements with the Commissions serving aviation and marine meteorology. The 1874 code was replaced immediately by one drawing largely on British and Allied experience, and successive revisions based on experiments culminated in the classic SYNOP code adopted in Copenhagen in 1929 for world-wide use, together with all its variants and associated codes. Aviation codes were included and were adopted by ICAN, which thus acknowledged IMO's primacy in meteorological affairs. This was not altogether surprising, because Gold was also President of ICAN's sub-commission of aviation meteorology! Starting from scratch, a whole structure of scheduled national, regional and continental radio transmissions was developed enabling any station to receive all its data needs, using only two radio operators in the daytime (one by night) on a standard set of frequencies. This process of forming a single comprehensive and uniform world-wide system for exchanging data from a great number of national systems was an enormous and unprecedented feat of standardization, reached entirely by the free consent of all concerned. From almost the start the meteorological services of the Central European powers were brought into consultation, and from 1923 Austria and Germany were back in IMO. Russia returned to the IMC in 1929, and Japan and India had never left.

As IMO had no Secretariat until 1926 (although the idea was first considered in 1873) voluntary help was the only way of circulating the flood of decisions. The British Meteorological Office publication *Wireless weather messages* was thus for some years the only comprehensive manual of reporting stations, codes and broadcasts and was widely used. Later the new Secretariat was able to take over the task with its *Fascicule* No. 9.

In the twenty years 1919–39 the Commission for Synoptic Weather Information (CSWI), as Gold's Commission became, held 11 sessions. Its membership rose from 16 in 1919 to 59 in 1929 and 80 in 1937, at which time its work was distributed among 11 subcommissions for joint meetings with other Commissions. In 1939 world war again broke out, and again rapid developments left IMO with quite a new situation at its end. In 1946 Gold and the CSWI set about remoulding the structure, with again new and diverse national practices to reconsider and new requirements, mostly from civil aviation, to meet. In the final 3-week session of CSWI at Toronto in 1947 revised world-wide codes and specifications were agreed. In substance these are the ones which are still in use today. These codes were approved by the immediately-following Conference of Directors in Washington, and became known as the Washington codes. It was true then, and is even more true now, that the growing scale of meteorological operations and the variety of purposes served by the codes makes agreement on changes increasingly difficult to achieve.

At the end of the Toronto session of CSWI Gold retired from the Presidency after 28 years, and was succeeded by J. R. Tannehill of the U.S.A. He was himself named Honorary President of CSWI.

**Sir Nelson Johnson and the IMO/WMO transformation.** When N. K. Johnson succeeded Sir George Simpson in 1938 as Director of the Meteorological Office and as member of the IMC and Executive Council, the IMO was already deep in discussion of its future status. The disadvantages of its non-governmental status, as already mentioned, were apparent in the 1920s, when the formation of ICAN in 1919, with its intergovernmental status, had soon caused difficulties for IMO. Agreements affecting meteorology reached in ICAN, and elsewhere as the applications of meteorology developed in many fields, had full governmental backing, whereas those of IMO did not. IMO attempted to meet the ICAN problem by giving its Commission for Aeronautical Meteorology a special official status. This 'cuckoo in the nest' showed the growing absurdity of the situation. The Directors sat in IMO treasuring their informality, while their subordinates sat in the other bodies where the users took the effective decisions. Many Directors decided that the time had come for change so that intergovernmental decisions on meteorology could again be concentrated within the one organization. Progress was made, though slowly, in drafting a new intergovernmental Convention, though with fears that it would endanger the principle that scientific considerations should be the chief basis for any decision.

Came the war, during which the IMO continued in the form of the Secretariat in Lausanne (reduced to Dr Cannegieter and two others). Throughout the war the Secretariat maintained contact with the members of the Executive Council and with the President, Dr Th. Hesselberg, in Oslo. At the end of the war, as in 1919, all had to be rebuilt, and London again seemed a good place to start. An Extraordinary Conference of Directors gathered in London in the spring of 1946, but without the representatives of the defeated countries. The address of welcome given by the Under Secretary of State described meteorology as the 'key science of the world'. The Conference re-established the Commissions and put them to work, elected a new International Meteorological Committee of 20 members, and charged it with

finalizing the new Convention. Dr Hesselberg stepped down from the Presidency and Sir Nelson Johnson was elected in his place. The new IMC met the same July in Paris, and 14 months later a new Conference of Directors assembled in Washington. This session was preceded by simultaneous sessions in Toronto of the 10 Technical Commissions, from which emerged several hundred resolutions for the consideration of the Conference. The agenda also included the reports of four Regional Associations (three had met in the previous year) and such major matters as relations with the new United Nations Organization and with the new International Civil Aviation Organization. Above all there was the new Convention to be considered and, if all went well, decided on. The Conference, in 31 sessions during three weeks, adopted 220 resolutions and finished the new Convention. The struggles over the Convention were long and of great difficulty. Under the President's patient guidance all the crises over equality of rights, membership, the worldwide character of the organization, and professional representation as distinct from political, were successfully overcome. In the final meeting of the Conference the new Convention of the World Meteorological Organization (WMO) was signed. This was a most remarkable feat by all concerned, and speaks much for the reality of the international spirit of meteorology and of meteorologists.

Sir Nelson Johnson remained as President until IMO met for the last time in 1951, to die and be immediately reborn as the new WMO. The final Extraordinary Conference of Directors lasted three days and was followed directly by the first Congress of WMO. Sir Nelson Johnson opened the new Congress, and was elected President for its duration. He was then succeeded by Dr Reichelderfer of the U.S.A. as President of WMO. The final action of that Congress was to pass by acclamation a resolution proposed by Dr Reichelderfer. That resolution recognized how much the accomplishments of Congress were due to the 'experience, insight, skill, careful planning, and patient perseverance of its President', and expressed its lasting appreciation to Sir Nelson Johnson 'for his unselfish service and devotion to the aims of the Organization and for his distinguished services in launching the new WMO'. Sir Nelson Johnson retired in 1953 but did not long survive.

The twenty months of intense IMO activity, from London in the spring of 1946 to Washington in the autumn of 1947, bore heavily on all concerned, but especially on the President on whom lay the burden of leadership. Sir Nelson as Director, and Ernest Gold, President of CSWI, as Deputy Director of the Meteorological Office, had at the same time to rebuild the Office for post-war tasks as the flood of wartime staff receded. Their international labours at this time completed the structure, built by so many hands, which was bequeathed to WMO by the International Meteorological Organization.

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## SOME CURRENT WORK ON METEOROLOGICAL SATELLITES

By G. P. CARRUTHERS, B. R. MAY, D. E. MILLER and K. H. STEWART

**Summary.** The Meteorological Office is developing an instrument to measure temperatures in the stratosphere from a satellite; it will be included in the TIROS N series of operational satellites to be launched by the U.S.A. from 1977 onwards. The Office is also co-operating in the European project to provide a geostationary cloud-observing satellite. Work on these projects and on the analysis of the data that will flow from them is described.

**Introduction.** This report deals with work being done by the High Atmosphere Branch of the Meteorological Office in connection with two meteorological satellites, the low-polar-orbit satellite TIROS N being developed by the U.S.A. for launch in 1976-77 and the geostationary METEOSAT being developed by the European Space Research Organization (ESRO) for launch at about the same time. In each of these projects almost all the work of instrument development is being done outside the Office; the main work of the Office is in project definition, organization and management, and in preparations for dealing with the data when received.

### TIROS N

**History.** Meteorological satellites of the U.S.A. fall into two classes; the NIMBUS and Applications Technology Satellite (ATS) (geostationary) series are research and development satellites intended to try out new instruments and techniques of observation, while the TIROS and GOES\* are operational series intended to provide a continuous service of observations from well-tried instruments.

The present operational satellites, based on the TIROS M design, will continue in use until 1976-77, when it is intended to replace them by a more advanced design known as TIROS N. When the broad specifications for this design were drawn up in the U.S.A. two years ago it was decided that the three main components of the payload should be a multi-channel imaging system, a location and data-collecting system and a temperature-sounding system. The temperature sounder was to be based on instruments developed in the NIMBUS programme, measuring the radiation emitted by the atmosphere at various well-defined wavelengths in the infra-red. About 14 channels were required for sounding the troposphere (including water-vapour and 'window' channels) and the wavelength selection for these channels could be done by narrow-band filters. In addition, it was decided that measurements in three or four channels in the 15- $\mu$ m band of CO<sub>2</sub> should be made by using the selective chopping principle, as used by the Oxford and Reading (later Oxford and Heriot-Watt) universities in experiments on NIMBUS D and NIMBUS E.

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\* Names are very confusing. TIROS originally meant Television and Infra Red Observation Satellite and nine satellites bore this name with a number. The name is now used for the series of satellites providing similar observations; a letter is added to denote classes of spacecraft within this series, in particular the first of any class (e.g. TIROS M, TIROS N) but individual spacecraft within a class may have different names (e.g. ITOS D in the TIROS M class) and may then be renamed after successful launch (ITOS D became NOAA 2). The Geostationary Operational Environmental Satellites (GOES), whose first two models are also called Synchronous Meteorological Satellites (SMS) are a planned operational series developed from ATS.



The measurements will provide estimates of temperatures in the stratosphere, in the 1–30-mb region. It was agreed that the instruments for these stratospheric measurements should be provided by the Meteorological Office, while the instruments for the tropospheric sounding would be provided by the National Environmental Satellite Service (NESS) of the U.S.A. Preliminary specifications defining the instruments and their interface with the spacecraft were drawn up in May 1972 and have gradually been made more definite over the past year. It is expected that a formal agreement between the National Oceanic and Atmospheric Administration (NOAA) and the Meteorological Office will be signed during 1973.

A contract for the first stages of design and development work on the instrument was placed with Marconi Space and Defence Systems (MSDS) Limited in June 1972 and this has recently been completed with the production of a design report and a plan of work for the next stage.

**Requirements.** The proposed British contribution to the sounding system is now known as the Stratospheric Sounding Unit (SSU). It is required to make measurements of radiance similar to those provided by the three selectively-chopped channels of the Oxford-Heriot-Watt instrument on NIMBUS E, that is to say with weighting functions peaking at three heights in the 1–20-mb region. (The weighting function measures the relative contribution to radiation leaving the top of the atmosphere which originates at different heights and the region where the weighting function is at a maximum is the region whose temperature is effectively measured by the instrument.) In comparison with the NIMBUS E instrument, the SSU has many fewer channels but is required to make measurements at eight angles across the satellite track instead of only vertically downwards. Its accuracy (noise level and systematic errors) must be much improved and above all it must be designed and made as an 'operational' and not an experimental instrument, with great emphasis on reliable performance.

**Design.** Three possible design configurations were studied (by the Heriot-Watt group under subcontract to MSDS Ltd) based on the variants of the selective chopping method used respectively in NIMBUS D, E and F. The choice between the three methods was difficult because the F-method was clearly superior in principle but was at an earlier stage of development and therefore involved more risk. Despite this, the F-method was chosen and so far there is no reason to regret the choice.

The principle of the F-method (suggested and developed at Oxford) is that of pressure modulation. The radiation to be measured passes through a cell containing carbon dioxide whose pressure can be varied cyclically ( $\approx 40$  Hz). This varies the strength and width of the  $\text{CO}_2$  absorption lines and hence modulates the radiation selectively at the  $\text{CO}_2$  absorption wavelengths. It can be shown<sup>1</sup> that the weighting function for the modulated component of radiation passing through such a cell has its peak at a pressure-height in the atmosphere proportional to the mean pressure of gas in the cell, so that by using cells filled to different pressures, weighting functions peaking at different heights can be obtained.

Because the wavelength selection and chopping are done by the gas itself, the pressure-modulation system is inherently independent of changes in filters, windows and choppers which affect other systems. The most critical part

of the design is the pressure modulation itself. This is done by connecting the absorption cell to the head of a sealed cylinder in which a close-fitting piston oscillates. The clearance between piston and cylinder ( $1/1000$  inch) is sufficient to avoid contact, wear and friction but is small enough to prevent any serious leakage of gas in the period of one oscillation. The piston is mounted on springs and driven by a moving-coil loudspeaker-type system at its natural resonant frequency, which is largely determined by the mean gas pressure in the cylinder. The simplified diagram (Figure 1) shows the basic components of one channel of the SSU; three such channels are combined to form a complete SSU (the mirror and black body being common to all three).

The optical system is very simple. A plane mirror at  $45^\circ$  to the optical axis (which is horizontal, along the direction of flight) can be rotated to direct radiation into the system from different fields of view on the earth, across the sub-satellite track, or from space or from a calibrating black-body target in the instrument itself. The radiation passes through the absorption cell, whose front window is the objective lens of the system, and the filter to a field lens and light pipe which condense the radiation on to the detector. The detector is an uncooled pyroelectric one (tri-glycine sulphate) of the type used in the NIMBUS E and NIMBUS F instruments and the electronic design also follows the principles used in those instruments.

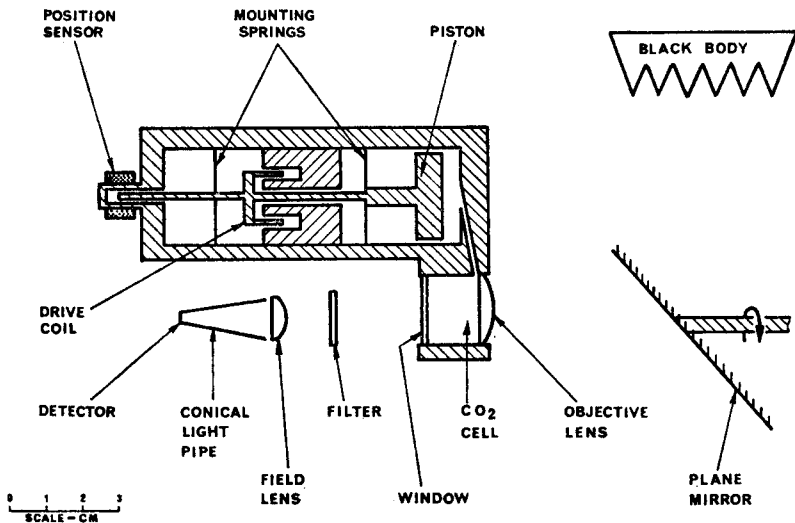


FIGURE 1—SIMPLIFIED DIAGRAM SHOWING ONE CHANNEL OF SSU

**Development.** Two pressure modulator units have been made to the design just outlined. Tests so far have concentrated on two aspects, the mechanics of the pressure modulation process and the performance as a

radiation-measuring device. In the first set of tests the resonant frequency, the sharpness of resonance (which served as a measure of energy loss) and the displacement of the centre of oscillation of the piston were measured as functions of gas pressure. The behaviour is quite complicated, but satisfactory theoretical interpretations of all the phenomena have been found and it has been shown that pressure modulation of stable amplitude can readily be maintained. It has been shown that some increase in the piston-cylinder clearance (1/1000 inch) could be tolerated, which would ease some manufacturing problems.

In the radiometric tests (carried out under subcontract by Oxford University) a modulator unit was assembled with light pipe and detector and was used to measure radiation from black-body targets at various temperatures. The sensitivity and noise level were close to those predicted and appear to meet the agreed SSU specification. A major doubt in adopting the pressure modulation system for the SSU had been whether a predicted but unwanted component in the output signal would be sufficiently stable. This component arises from adiabatic heating and cooling of the gas in the pressure modulation cycle. The heated gas itself emits radiation which the detector receives as a signal of the same frequency as the radiation from the target chopped by the pressure variations in the cell — the wanted signal. Although there was no reason to think that the unwanted signal (which is comparable in amplitude to the wanted one) would not be perfectly steady so that it could be treated as a simple zero offset, it is very satisfactory that the radiometric tests have verified its steadiness and given confidence that the system behaves as predicted.

**Future work.** The design and development work just described was presented by the contractors to Meteorological Office and American representatives at a Design Review in mid March 1973. It was agreed that progress was generally satisfactory and that the work done formed a good basis for the next stage of development. This must be aimed at delivering the first model of the instrument in its final form to America in about two years' time, after completing all tests in this country. Before then it is envisaged that one or more development models will be made and that further tests will be made on the units already produced. Much of the work will be concerned with the details of design and manufacturing procedures needed to ensure extreme reliability but three general points which are fundamental to the success of the instrument will also require much attention and are listed below :

*Weighting functions.* Although the weighting functions for the SSU have been predicted fairly closely from theory and by comparison with those measured for basically similar instruments (NIMBUS D, E and F, in satellite and balloon-borne versions) they have not yet been measured directly. It is important that they should be determined more closely, both by more-detailed theoretical calculations and by measurement, because the optimization of many points in design depends on a good knowledge of these functions. Measurements are currently being made on one of the existing units at Oxford and work is in hand in the Office to undertake the computation of weighting functions, using computer programs provided by Dr Rodgers of Oxford.

*Radiometric errors and calibration.* All radiometers respond to some extent to radiation from outside their nominal field of view and outside their nominal spectral pass-band. The quality of their measurements depends on the extent to which these 'strays' can be eliminated, or allowed for by calibration. A start on this work has been made in the tests already done at Oxford, but it will need to be continued and expanded as development proceeds.

*Gas absorption and desorption.* Each pressure modulator unit contains about 20 ml of carbon dioxide at pressures of a few tens of millibars and is required to have a total life of about five years. A change of 1 per cent in gas pressure would be serious and a 20 per cent change would probably constitute failure, so great care will have to be taken to find, test and use constructional materials that neither absorb nor give off carbon dioxide in the conditions existing inside the SSU.

**Use of data.** The data from a temperature-sounding radiometer consist of a set of radiance measurements made in different spectral intervals and representing a weighted average of the temperature of different layers of the atmosphere — the weights being determined by the weighting function for each channel. In order that the data may be used they must be 'inverted' or 'deconvoluted' to obtain estimates of the temperature profiles which produce them. The inversion problem is a difficult one and many possible methods of solution have been suggested. No one method is clearly the best in all circumstances; the best method depends, among other things, on the nature of the radiometer data (the number and narrowness of the spectral intervals, the size of the field of view and the noise and other errors in the data), the use to which they are to be put and the nature and amount of other information which is available about the temperature profiles being observed. To ensure that the Office makes best use of the SSU data and also of data from the rest of the sounding equipment on TIROS N (and, indeed, on other satellites), studies on inversion methods have been started. The main work so far has been to gain familiarity with several possible inversion methods by applying them to real data samples from NIMBUS satellites and also to simulated SSU data. This will lead to selection of the method or combination of methods best adapted to the nature and use of SSU data. It will also have to be decided whether the temperature profiles provided by the National Environmental Satellite Service by inversion of its own radiometer data enable the Meteorological Office to get maximum benefit from the data or whether we should develop methods — perhaps better suited to our own forecast schemes — of handling the raw radiance data from instruments sounding the troposphere as well as methods for handling the SSU data.

Two investigations with a bearing on the instrument design have already been carried out. The first was a study of the optimum size and spacing of the fields of view of the instrument, taking into account the fact that the accuracy of measurement decreases with the size of the field of view while the accuracy with which the temperature field can be reproduced clearly improves as the number of samples increases — the rate of improvement depending on the space spectrum of the temperature variations. The outcome of the study is that the parameters provisionally selected are not far from optimum; a slight increase in the number of samples would apparently



be beneficial but in view of the greater mechanical complexity and the rather inadequate data on which the theoretical study is based, it is not proposed to make any change.

The other study has been on the optimum location (in height) of the weighting functions to be chosen for the three SSU channels. Here again the conclusion is that the preliminary choice is not far from optimum, but since a final choice need not be made for some time yet, this work can be refined and extended as new data become available.

### *METEOSAT*

**History.** For a long time European meteorologists and technologists have wished to produce a European contribution to space meteorology. Many projects have been discussed and one, for a satellite very similar to TIROS N, reached a fairly advanced stage of definition. In 1971, however, it was decided that this project represented an unnecessary duplication of American effort and that a far more useful contribution to the world observing system would be a geostationary satellite to provide frequent pictures of clouds and so allow wind velocities to be deduced. This decision, by Directors of Meteorological Services, more or less coincided with a decision by the Council of the European Space Research Organization that they should undertake an 'applications' programme with meteorology as one of its three main elements, and with a decision by France to attempt to 'europeanize' her project to develop a geostationary meteorological satellite, METEOSAT. The outcome has been that ESRO has begun development of METEOSAT, under the direction of a Programme Board, on which Directors of Meteorological Services as well as Ministers of Technology are represented. Although the general design is already fairly closely determined by the work previously carried out in France, project definition studies are in progress by two industrial consortia and it is expected that contracts for the full development phase will be placed during the second half of 1973.

**Outline of project.** It is intended that METEOSAT shall be launched by the end of 1976 and that it shall form one of a chain of four or five (U.S.A., Japan, U.S.S.R.) similar geostationary satellites which will provide complete coverage of low and middle latitudes. It will be a spinning satellite (100 rev/min) with axis parallel to that of the earth and its main sensor will be a telescope scanning the earth from west to east by virtue of the spin and from north to south through a mechanism that slowly tilts a mirror. The telescope will provide a 5000-line picture of the earth's disc at visible wavelengths and a 2500-line one in the infra-red window (11  $\mu\text{m}$ ) every half-hour. The resolution at the sub-satellite point will be about 2.5 km and 5 km for the two channels, respectively. The pictures will be transmitted at low power and high data-rate to a well-equipped central station (near Darmstadt in West Germany). This station, and in particular the part known as the Meteorological Information Extraction Centre (MIEC), will process the data to obtain estimates of sea surface temperature, cloud amount and height and, most difficult, wind velocity by observing the motion of clouds from one picture to the next. These reduced data will be disseminated by ordinary meteorological telecommunications. In addition the central station will re-transmit to the satellite a selection of the pictures received, after adding calibration and location data and after suitable changes of format. These

pictures will be broadcast by the satellite (at relatively high power) and can be received by two classes of station known as Principal and Secondary Data Users' Stations (PDUS and SDUS). PDUS will be capable of receiving data at higher rates and with better definition than the much cheaper SDUS. It is expected that pictures received at the PDUS and SDUS will be used qualitatively in forecasting in the same way as APT pictures from polar satellites are now used, but some countries plan to use data received at their PDUS in more quantitative fashion.

The other main function of METEOSAT is to collect and send to the central station data transmitted from 'Data Collection Platforms' (DCP), probably mainly in remote or inaccessible locations, but also including stations in ships and on buoys or balloons. This system will operate in the 400-460-MHz band and is being designed to be compatible with similar systems in the other geostationary satellites.

**Development of satellite.** As already stated, the main features of the design are already fixed. Various modifications have been introduced as a result of pressure from meteorologists, notably an increase in transmitter capacity to allow more pictures to be broadcast and a change in frequency in the DCP system in the interests of international compatibility. Several options are now under discussion. The first is the choice of the exact wavelength range for the visible channel (to achieve the best balance of contrast between clouds and different types of surface). The second is the possible addition to the telescope of a channel sensitive in the water-vapour absorption region at  $6.3\ \mu\text{m}$ ; this would provide some indication of air movement in regions where visible clouds were absent. Another possible addition, on an experimental basis, is a receiver to allow METEOSAT to relay data from polar satellites such as TIROS N or the Russian METEOR. Finally, it has been proposed that the French station at Lannion (in Brittany) might receive pictures from the American geostationary satellite (at  $70^\circ\text{W}$ ) and re-broadcast them through METEOSAT.

**Development of ground facilities.** In all discussions on METEOSAT the British representatives have urged the importance of providing adequate ground facilities and this has been followed up by providing a member of the ESRO working group that laid down the general requirements for the ground station, with particular emphasis on the MIEC.<sup>2</sup> This work has been continued by a group that is now drawing up specifications for the computer software needed in the MIEC, particularly for the determination of winds from cloud movements. It is expected that responsibility for this work will soon be taken over by ESRO and that the need for meteorological participation may decrease for a time, but there will obviously be a continuing requirement for close contact with the work to ensure that both hardware and software are fully adapted to meteorological requirements.

**Conclusions.** Satellite observations will play a vital role in the First GARP Global Experiment and in the World Weather Watch programme.<sup>3</sup> The satellite system envisaged<sup>4</sup> comprises two components, a set of four or five geostationary satellites above the equator and a smaller number of satellites in fairly low quasi-polar orbits. It is satisfactory that, through the work described above, the Office is making a substantial contribution to

both components of the world system. However, the making of observations is not an end in itself, and to get proper benefit from our contribution we must learn to make full use of the data flowing from satellites, not only the data that will come from our own future instruments but also the data available now and in the future from instruments provided by others.

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## THE ESTIMATION OF WHEAT AND BARLEY ACREAGES IN ENGLAND BY REFERENCE TO THE WEATHER OF THE PREVIOUS SUMMER

By L. P. SMITH, J. COCHRANE and V. BAILEY

**Summary.** The proportion of cereal land in England sown to wheat in any one year bears a close relationship to the mean estimated soil moisture deficit in such land at the end of the previous September.

**Introduction.** The greater part of the English wheat crop is sown in the autumn. The extent to which this can be done depends on the speed of clearance of the previous crop and the time available for the cultivation of the fields and the sowing of the wheat. The controlling environmental factors are the state of the soil and the soil moisture content.

Many more days are available for autumn work on the land if the soil has a moisture deficit and has not yet returned to field capacity. Once the return date has been reached and the drains are running, any subsequent rainfall occasions delay while the excess water is drained away before cultivation can be undertaken without damage to soil structure.

It has already been shown by L. P. Smith<sup>1</sup> that the average return-to-capacity date in an area bears a close relationship to the proportion of neighbouring farmland sown to wheat. A further paper<sup>2</sup> showed that in two specimen areas in Warwickshire and Worcestershire, the annual wheat acreage varied in accordance with the changes in return date. This concept was extended in later work<sup>3</sup> to relate the national mean return date to the total English acreages of wheat, barley and fallow. It is therefore possible to form an estimate of future cereal areas once the return dates are known.

Some advantage would be gained if an earlier estimate were possible, and as the return date depends on two factors, namely the soil moisture deficit at the end of summer and the subsequent rainfall, an attempt was made to establish a forecasting method using the first variable only.

**Available data.** Following the procedures explained in Ministry of Agriculture, Fisheries and Food *Technical Bulletins* No. 16<sup>4</sup> and No. 24,<sup>5</sup> both of which were prepared in the Meteorological Office, and using the details

available in the *Daily Weather Report* of the Meteorological Office, a daily check on soil moisture deficits at 24 stations is already made for other purposes.

Some 14 of these stations were taken to represent the cereal growing area of England, and a mean soil moisture deficit at the end of September was obtained by weighting the value at each individual station with the wheat acreage in the area for which it was taken as a sample. Since the stations were chosen because of their presence in the *Daily Weather Report*, (*D.W.R.*) and for no other reason, they cannot be claimed to be truly representative of the areas with which they are associated.

The allocation, together with the farming details for 1969, was as follows :

<i>D.W.R.</i> station	Counties	Total farmland thousands of acres*	Percentage in cereals
Leeming	Northumberland; Durham; North Riding	1702	33
Ringway	Lancashire; Cheshire; Derbyshire	1417	19
Finningley	Nottinghamshire; Kesteven; West Riding	1702	42
Kilnsea	East Riding; Lindsey	1454	57
Shawbury	Shropshire; Staffordshire; Herefordshire	1618	26
Elmdon	Warwickshire; Worcestershire; Leicestershire	1187	37
Wittering	Holland; Huntingdonshire; Northamptonshire; Rutland	1059	50
Honington	Cambridge; Essex	1106	59
Wattisham	Norfolk; Suffolk	1713	57
Filton	Somerset; Oxfordshire; Gloucestershire	1744	28
Boscombe Down	Wiltshire; Berkshire	935	45
Cardington	Bedfordshire; Hertfordshire; Buckinghamshire	835	50
Hurn	Dorset; Hampshire	985	38
Gatwick	Surrey; Sussex; Kent	1292	35

Cumberland, Westmorland, Devon and Cornwall, which grow little wheat, were omitted.

Data concerning the English acreages of wheat, barley, oats, mixed corn, rye and fallow were taken from the annual volumes of *Agricultural statistics*<sup>6</sup> prepared by the Ministry of Agriculture, Fisheries and Food, and these figures can now be examined in relation to the weighted mean deficits, namely

1959	1960	1961	1962	1963	1964	1965	1966	1967	1968
5.0 in*	2.3 in	4.1 in	2.6 in	3.1 in	4.5 in	0.7 in	2.5 in	3.1 in	0.1 in

**Percentage of cereal land in wheat.** It was found that the correlation between the wheat percentage of total cereal land in England and the weighted mean soil moisture deficit at the end of September was 0.92, and the percentage could be estimated from the formula

$$24.4 + 1.54d$$

where  $d$  is the mean deficit in inches.

\* 1000 acres = 404.686 hectares; 1 inch = 25.4 millimetres.



TABLE I—ACTUAL AND ESTIMATED PERCENTAGES OF LAND IN WHEAT

Harvest	Actual	Estimated percentage	Error
1960	31·4	32·1	+ 0·7
1961	27·3	27·9	+ 0·6
1962	32·6	30·7	— 1·9
1963	27·2	28·4	+ 1·2
1964	29·5	29·2	— 0·3
1965	31·8	31·3	— 0·5
1966	26·9	25·5	— 1·4
1967	27·4	28·2	+ 0·8
1968	28·8	29·2	+ 0·4
1969	24·4	24·6	+ 0·2
Mean error (ignoring signs)			0·8

The diagram (Figure 1) shows the actual percentage of wheat and the mean soil moisture deficit for the previous autumn.

**Estimation of wheat acreage.** In 1960 and 1961 the total cereal area in England was about 6 million acres; during the years 1966–69 it was about 8 million acres. The increase took place almost uniformly between 1961 and 1966 and was probably partly due to the fact that many farmers went out of dairying in those areas of England which were climatically unsuited to the growth of grass. To a great extent the growing of barley took the place

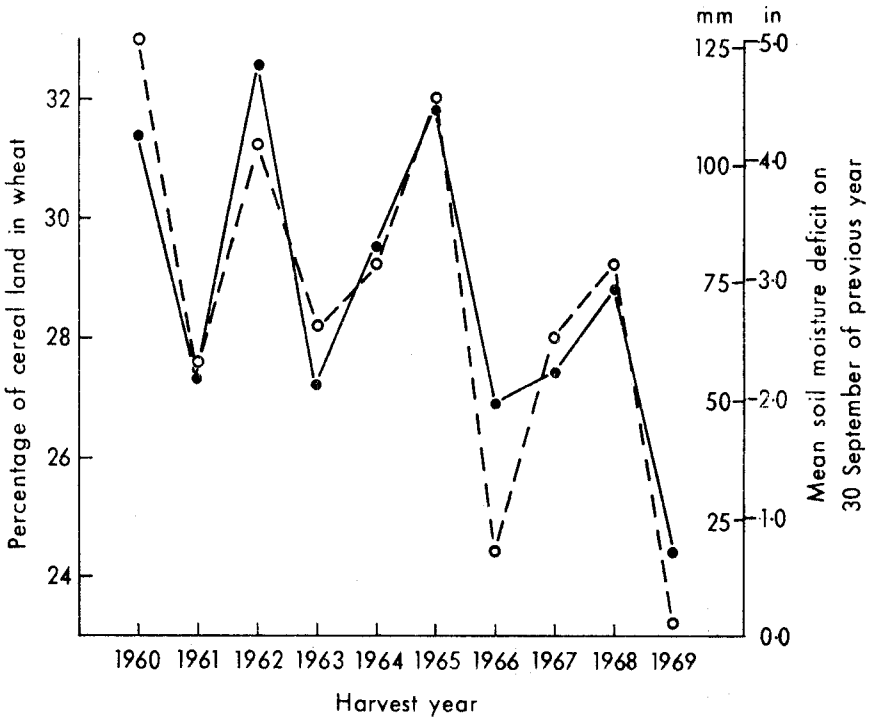


FIGURE 1—COMPARISON BETWEEN THE PERCENTAGE OF CEREAL LAND IN WHEAT AND THE MEAN SOIL MOISTURE DEFICIT ON 30 SEPTEMBER OF THE PREVIOUS YEAR  
● — — — ● Actual percentage of wheat  
○ — — — ○ Mean soil moisture deficit for previous autumn

of milk production in the Midlands and in eastern England, while dairy herds increased in size (but not in total number) in the western counties.

To allow for this change of intent, a second independent variable must be introduced, namely  $n$ , the number of years after 1961, with a maximum of 5. The correlation between wheat acreage and the mean deficit is 0.30; between wheat acreage and  $n$ , 0.61; between the deficit  $d$  and  $n$ , -0.52. From these figures the derived partial correlations are

Between wheat acres and deficit 0.91

Between wheat acres and  $n$  0.94

and the regression equation is

$$\text{Wheat acres} = 1435 + 125d + 100n.$$

TABLE II—ACTUAL AND ESTIMATED ACREAGES OF WHEAT

Harvest	Actual	Estimated	Error
	<i>thousands of acres</i>		
1960	1987	2060	+73
1961	1715	1722	+7
1962	2127	2048	-79
1963	1823	1960	+137
1964	2093	2122	+29
1965	2409	2397	-12
1966	2150	2022	-128
1967	2200	2247	+47
1968	2306	2322	+16
1969	1947	1947	0
	Mean error (ignoring signs) 53		

The multiple correlation coefficient is 0.94.

**Estimation of barley acreage.** As the bulk of the barley is sown in spring, it might be thought that autumn weather would not affect the acreage, nevertheless if conditions prevent the sowing of winter wheat, more barley tends to be sown in the spring as an alternative to spring wheat.

As land unsown in spring will remain in fallow, the dependent variable was taken as the sum of the barley and the fallow acreages. The independent variables were the same as those used with wheat, and it was found that the correlations between the barley and fallow acreage and the mean deficit at 30 September was -0.66, and with  $n$  0.98; the correlation between the deficit and  $n$  was -0.52. The partial correlation coefficients calculated from these values were between barley and fallow acres and autumn deficit -0.91 and between barley and fallow acres and  $n$  0.99. The regression equation was

$$\text{Barley and fallow acres} = 3805 - 110d + 357n.$$

TABLE III—ACTUAL AND ESTIMATED ACREAGES OF BARLEY AND FALLOW

	Actual	Estimated	Error
	<i>thousands of acres</i>		
1960	3200	3255	+55
1961	3631	3552	-79
1962	3600	3691	+91
1963	4271	4193	-78
1964	4465	4475	+10
1965	4684	4658	-26
1966	5396	5413	+17
1967	5304	5215	-39
1968	5139	5149	+10
1969	5389	5479	+90
	Mean error (ignoring signs) 54		

**Discussion.** It is undoubtedly true that the closeness of fit, both for wheat and barley, obtained through the use of these regression equations is largely due to the fact that the increase in acreage between 1961 and 1966 took place in a linear manner. Nevertheless, the high partial correlation coefficients between the cereal acreages and the soil moisture conditions at the end of the previous summer suggest that useful forecasts of future cropping can be made some eight months in advance (the official statistics are based on returns made in June).

Such forecasts would be likely to go astray when a wet autumn follows a dry summer, or when a dry autumn succeeds a wet summer; extreme late-winter conditions, as in 1963, will also affect accuracy.

A further conclusion can be drawn; if end-of-summer deficits tend to decrease in future decades, or more particularly, if return-to-capacity dates become earlier owing to wetter autumns, then there will be a significant change in the wheat/barley ratio of cropping.

**Independent check on formulae.** In 1970, the mean soil moisture deficit, weighted with respect to the 1969 acreage, was 3.9 inches. The formulae would indicate

30.4 per cent of cereal acreage in wheat

2 422 000 acres of wheat

5 061 000 acres of barley and fallow.

The actual values were 30.2 per cent, 2 376 000 acres and 4 833 000 acres respectively.

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## UPPER TROPOSPHERIC DISTURBANCES OF THE EQUATORIAL ATMOSPHERE AND THEIR INFLUENCE ON RAINFALL NEAR THE EQUATOR

By F. E. LUMB

(lately Editor, *Meteorological Magazine*, now WMO Lecturer at the Regional Meteorological Training Centre, Lagos, Nigeria)

**Summary.** Disturbances of the upper troposphere of the equatorial atmosphere by troughs in the subtropical westerlies and their influence on rainfall at and near the equator are discussed.

**Introduction.** Sawyer<sup>1</sup> has concluded that 'a very useful approach to the dynamics of the equatorial atmosphere might prove to be through the investigation of the disturbance initiated in the equatorial belt by distortions of the subtropical jet stream and other changes of the circulation around

latitudes 25 to 30 degrees from the equator'. In support of this statement, it is well known to meteorologists in East Africa that such distortions can have important effects on the weather even at the equator, especially during the 'rainy' seasons. The linkage between the distortions and the occurrence of dry and wet spells within the 'rainy' seasons can be explained in terms of horizontal accelerations and the resulting horizontal divergence, in the upper troposphere of the equatorial atmosphere. By way of example, two well-marked changes of synoptic type which are known to be favourable for wet spells during the 'rainy' seasons are

- (a) change from Duct\* to Bridge\*
- (b) change from Duct to Drift\*.

**Change from Duct to Bridge.** This change of type occurs when upper troughs (say at 300 and 200 mb) penetrate into low latitudes from both hemispheres, at approximately the same longitude, sufficiently to split the subtropical-high cells. Both the duct and bridge patterns are associated with quasi-geostrophic flow almost to the equator. It therefore follows from the well-known relation between the acceleration and the ageostrophic component of the wind that increasing easterly winds on both sides of the equator are associated with horizontal convergence, and decreasing easterly winds with horizontal divergence (see Figure 1). The change from Duct to Bridge in the upper troposphere changes the winds near the equator from easterly to westerly, and is therefore associated with upper divergence. Provided this is accompanied by convergence or simply non-divergence in the lower troposphere (which is usually the case in the 'rainy' seasons) continuity demands upward motion through most of the troposphere. This explains the tendency for increased rainfall. The upward motion feeds moisture into the upper troposphere, and

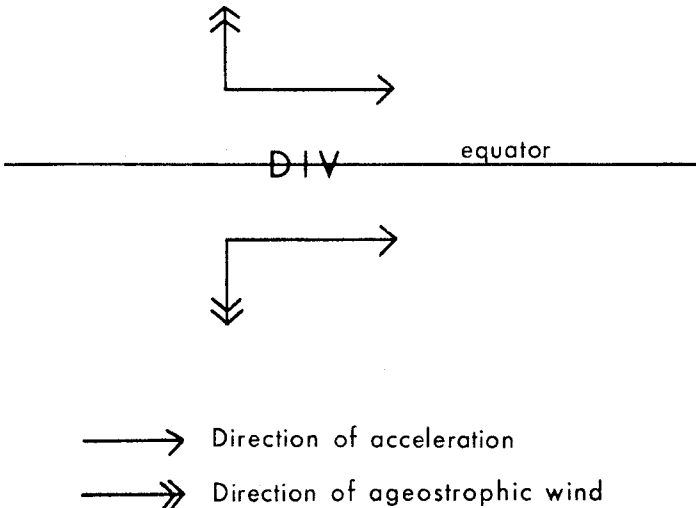


FIGURE 1—DIVERGENCE ASSOCIATED WITH DECREASING EAST WINDS IN BOTH HEMISPHERES NEAR THE EQUATOR

\* The terms Duct, Bridge, Drift used in this paper are explained in reference 2.

solar heating then ensures deep convection, which feeds further moisture into the upper troposphere, resulting in a rainy spell which will last several days if the troughs are slow to relax.

Conversely, as the troughs relax and the split subtropical-high cells gradually amalgamate, upper-level convergence results in a damping down and eventual reversal of the upward motion (at least in the upper troposphere), a marked drying of the upper troposphere, and a reduction of rainfall.

**Change from Duct to Drift.** If a trough penetrates equatorwards and splits the subtropical-high cell in one hemisphere only (see Figure 2), there is still likely to be divergence at and near the equator. It occurs at A where there is marked diffuence between the quasi-geostrophic easterly current and the transequatorial current (Drift); also from A through B to C where the air is being accelerated down the pressure gradient which is seen in Figure 2 to be directed from north to south across the equator.

Hence this change is also likely to be accompanied during the 'rainy' seasons by a marked increase of rainfall. Johnson<sup>3</sup> has discussed the widespread rainfall of 20-21 March 1960 over East Africa, and has mentioned the presence of a small-scale distortion in the 700-mb Drift flow (from northern to southern hemisphere) as a probable explanation of the far northward spread of the rain. However, the 200-mb chart for 21 March 1960 included in the paper by Johnson<sup>3</sup> shows a well-developed drift flow over East Africa (from southern to northern hemisphere), so that upper divergence probably also contributed to the widespread occurrence of the rain.

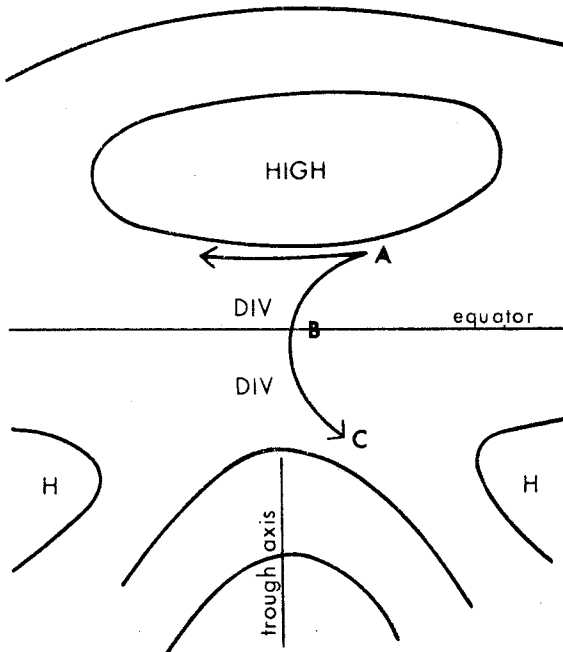


FIGURE 2—TRANSEQUATORIAL FLOW ACCELERATING INTO UPPER TROUGH IN SOUTHERN HEMISPHERE

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## NUMBER OF DAYS OF AIR FROST IN THE WINTER MONTHS IN SCOTLAND IN RELATION TO THE MEAN AIR TEMPERATURE — ON A PERIOD-AVERAGE BASIS, AND FOR INDIVIDUAL YEARS AT SELECTED STATIONS

By R. W. GLOYNE and ELIZABETH A. McKERRELL  
(Meteorological Office, Edinburgh)

**Summary.** The relationships between mean daily temperature ( $\bar{T}$ ) averaged over the winter months (December, January and February) and the corresponding number of air frosts ( $N$ ) were examined

- (a) on a period-average basis, mainly 1960/61 to 1969/70, for 19 stations in Scotland, and
- (b) on a winter-by-winter basis for two stations, Edinburgh (Blackford Hill) and Eskdalemuir Observatory (Dumfriesshire) for up to 30 years.

For case (a) the least-squares best fit valid over the range  $0^{\circ}\text{C} < \bar{T} < 5^{\circ}\text{C}$  and also the best second-degree curve for the range  $-7^{\circ}\text{C} < \bar{T} < 5^{\circ}\text{C}$  were determined, and for case (b) linear regressions were computed.

**Introduction.** Place-to-place comparisons, interpolation and extrapolation in time and space, can be rendered more reliable if statistical relationships between allied series of data can be appealed to.

A long-term average of mean daily temperature (on a monthly basis) can now be estimated for *any* site in Scotland with some confidence; the corresponding estimate of days with frost deduced directly from frost frequencies reported from other stations entails a greater degree of uncertainty. This contribution deals with the numerical relationship between frost frequency in winter and the corresponding mean daily temperature.

Attention was concentrated upon the winter period, namely December, January and February, the data assembled being :

- (a) period averages (as far as possible for the 10 winters 1960/61 to 1969/70 of mean daily temperature and mean number of air frosts for 19 stations in Scotland);
- (b) similar data, but for individual winters for Eskdalemuir Observatory and Edinburgh (Blackford Hill).

Clearly any result will be affected by the magnitude of the mean diurnal range and hence can only be valid for areas in which the mean diurnal fluctuation is sensibly uniform.

### Analysis.

#### (a) Period-average results.

In Figure 1 period-average data (mainly for the winters of 1960/61 to 1969/70) of mean daily air temperature and mean number of air frosts for 19 stations (these are listed below) are plotted together with the best-fitting first- and second-degree curves.

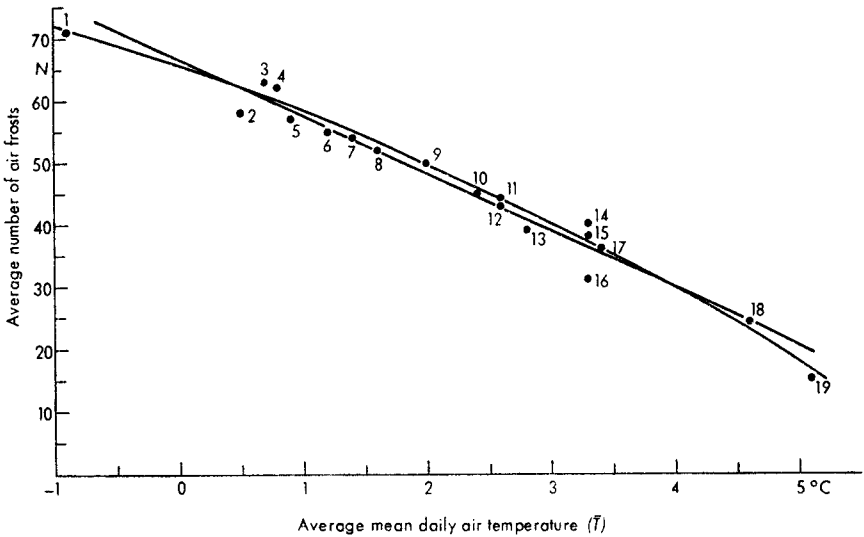


FIGURE 1—RELATIONSHIP BETWEEN AVERAGE NUMBER OF AIR FROSTS AND AVERAGE MEAN DAILY AIR TEMPERATURE FOR THE WINTER MONTHS (DECEMBER—FEBRUARY INCLUSIVE)

For identification of stations, see below.

No.	Station	Height above mean sea level metres	Period
1	Coire Cas (Cairngorms near Aviemore)	762	5 years within 1963/64 – 1969/70
2	Braemar	339	1960/61 – 1969/70
3	Glenmore Lodge	341	9 years within 1960/61 – 1969/70
4	Grantown-on-Spey	229	7 years within 1960/61 – 1969/70
5	Dalwhinnie	358	1956/57 – 1960/61
6	Carnwath (near Carstairs, Lanarkshire)	208	1960/61 – 1969/70
7	West Linton (Peeblesshire)	244	1960/61 – 1969/70
8	Eskdalemuir Observatory (Dumfriesshire)	242	1960/61 – 1969/70
9	Faskally (Pitlochry)	94	1960/61 – 1969/70
10	Perth	23	1960/61 – 1969/70
11	Dyce (Aberdeen)	58	1960/61 – 1969/70
12	Mylnefield (near Dundee)	30	1960/61 – 1969/70
13	Nairn	6	1961/62 – 1969/70
14	Edinburgh (Royal Botanic Garden)	26	1956/57 – 1969/70
15	Renfrew (Glasgow)	8	1960/61 – 1969/70
16	Wick	36	1960/61 – 1969/70
17	Auchincruive (near Ayr)	45	1960/61 – 1969/70
18	Benbecula (Outer Hebrides)	6	1960/61 – 1969/70
19	Tiree	9	1960/61 – 1969/70

Obviously the maximum possible number of days with frost in any winter (ignoring for convenience leap years) is 90 ( $31 + 31 + 28$ ) and the straight line cannot be extrapolated to temperatures lower than about  $-1^{\circ}\text{C}$ ; furthermore the curve must reach its apex of 90 days at some mean temperature well below  $0^{\circ}\text{C}$  and thereafter remain at 90 days.



If

$N$  = average number of days of frost per winter

$\overline{T}$  = average mean daily air temperature (in degrees Celsius)

then

$$N = 66.8 - 9.18\overline{T} \quad (\text{best straight line})$$

$$N = 65.5 - 7.00\overline{T} - 0.499T^2 \quad (\text{best second-degree curve})$$

with, respectively, a linear correlation coefficient of  $-0.981$  and a multiple correlation coefficient of  $0.985$ .

The apex of the parabola reaches  $89.8$  ( $\approx 90$ ) at a temperature of  $-7.0^\circ\text{C}$ . This suggests that if mean daily temperature during the winter is below about  $-7^\circ\text{C}$  every winter night will be one with air frost.

As an independent test for the equations, data for some nine stations in Iceland (i.e. a region subject to a maritime climate) were extracted. The results listed below show that the parabola predicts the frost frequency to within an error of at most one unit.

Station	Latitude	Longitude	Mean 'winter' temperature $^\circ\text{C}$	Mean number of days with frost	
				<i>predicted</i>	<i>actual</i>
Blönduós	$65^\circ 40' \text{N}$	$20^\circ 18' \text{W}$	$-1.5$	74.7	74
Húsavík	$66^\circ 02' \text{N}$	$17^\circ 21' \text{W}$	$-0.9$	71.2	71
Hlaðhamar	$65^\circ 16' \text{N}$	$21^\circ 10' \text{W}$	$-2.0$	77.3	77
Nautabú	$65^\circ 27' \text{N}$	$19^\circ 22' \text{W}$	$-2.4$	79.1	79
Reykjahlið	$65^\circ 39' \text{N}$	$16^\circ 55' \text{W}$	$-3.7$	84.5	84
Grímsstaðir	$65^\circ 38' \text{N}$	$16^\circ 07' \text{W}$	$-4.4$	86.4	86
Möðrudalur	$65^\circ 22' \text{N}$	$15^\circ 53' \text{W}$	$-5.9$	89.3	90
Gunnhildargerði	$65^\circ 33' \text{N}$	$14^\circ 23' \text{W}$	$-1.8$	76.3	76
Thingvellir	$64^\circ 15' \text{N}$	$21^\circ 07' \text{W}$	$-1.9$	76.7	76

(b) *Individual winters at Eskdalemuir and Edinburgh and three other stations in southern Scotland.*

The data and best straight line for Eskdalemuir and Edinburgh are set out in Figures 2 and 3. For the latter station the complete series 1940/41 to 1970/71 has been split into two sub-series, namely 1940/41 to 1954/55 and 1955/56 to 1970/71; the Eskdalemuir data are for the later period only.

Clearly from the scatter diagram all the observations lie within the range for which a linear relationship can be accepted. Expressing the relationship in the form

$$N = a + b\overline{T},$$

where  $N$  = number of frosts and  $\overline{T}$  = mean winter temperature, then the statistical parameters for the several straight lines are as follows :

Place	Period	$a$	$b$	$r$ (correlation coefficient)
Edinburgh (Blackford Hill)	1940/41 to 1954/55	68.9	$-9.29$	$-0.946$
	1955/56 to 1970/71	70.9	$-10.63$	$-0.869$
	1940/41 to 1970/71	68.8	$-9.68$	$-0.899$
	1955/56 to 1970/71	63.8	$-7.88$	$-0.891$
	1955/56 to 1970/71			
Eskdalemuir	1955/56 to 1970/71			

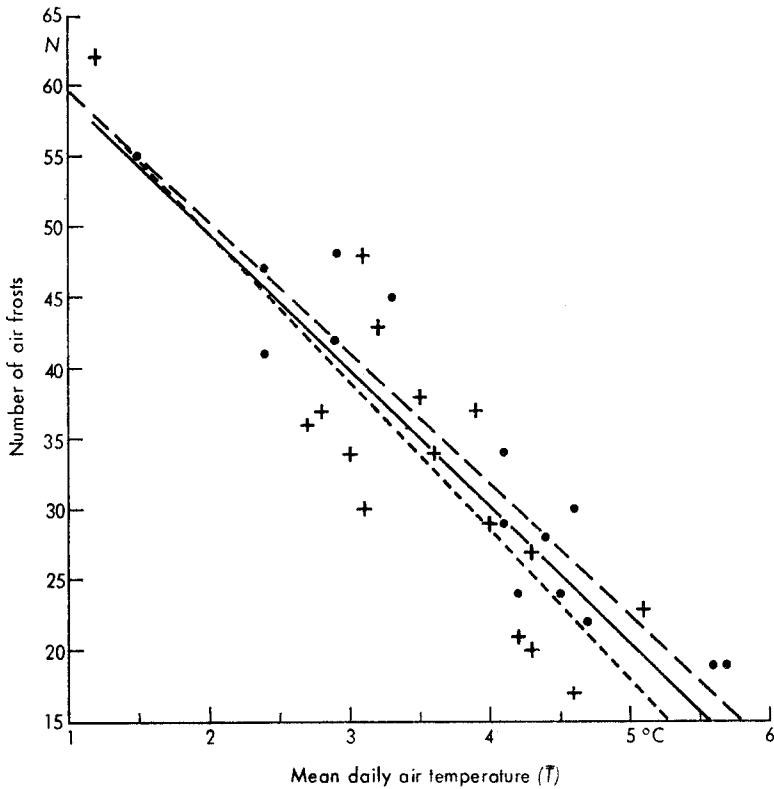


FIGURE 2—NUMBER OF AIR FROSTS AGAINST MEAN DAILY AIR TEMPERATURE FOR THE WINTER MONTHS (DECEMBER–FEBRUARY INCLUSIVE) AND BEST-FITTING LINEAR RELATIONSHIPS FOR EDINBURGH (BLACKFORD HILL)

● ——— 1940/41 to 1954/55; + - - - - 1955/56 to 1970/71; — · — · — 1940/41 to 1970/71.

On the long-period average basis discussed in (a) above the respective coefficients were 66·8 and — 9·18.

When all the straight lines are plotted together, they are found to occupy a narrow band. To the extent that the lines are judged identical it can be stated that, in respect of winter frosts, the area is homogeneous as regards variations in space and in time.

As expected the errors of estimate of data relating to individual winters exhibit a greater degree of scatter than for the long-period values. The standard errors of estimate are :

(a) long-period average data (see Figure 1): 2·7 days.

(b) individual winters

Edinburgh (Blackford Hill) (see Figure 2)

1940/41 to 1954/55 : 3·7 days

1955/56 to 1970/71 : 5·5 days

1940/41 to 1970/71 : 4·9 days

Eskdalemuir (see Figure 3)

1955/56 to 1970/71 : 4·4 days.

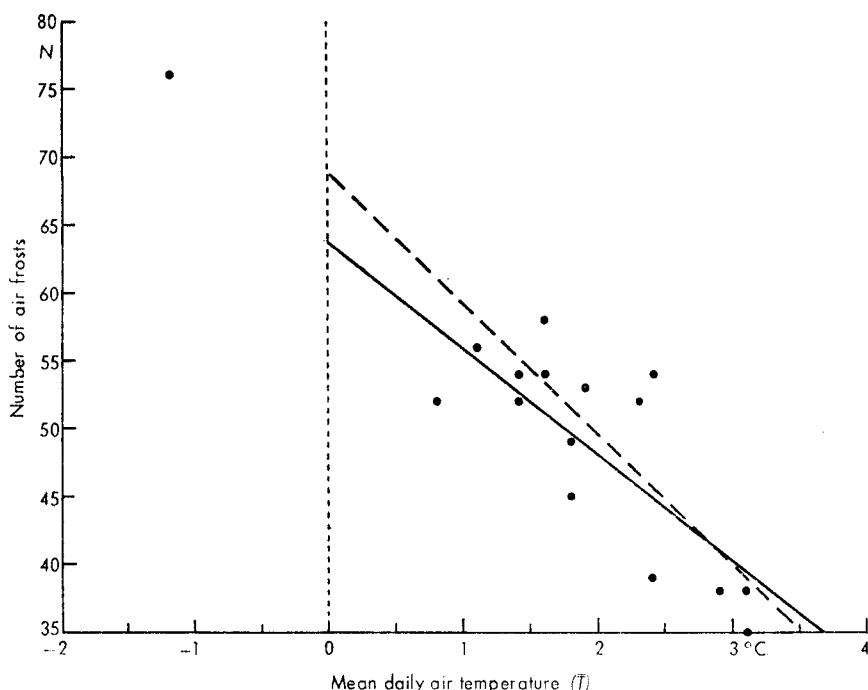


FIGURE 3—NUMBER OF AIR FROSTS AGAINST MEAN DAILY AIR TEMPERATURE FOR THE WINTER MONTHS (DECEMBER–FEBRUARY INCLUSIVE) AND BEST-FITTING LINEAR RELATIONSHIP FOR ESKDALEMUIR OBSERVATORY 1955/56 TO 1970/71; AND, FOR COMPARISON, LINEAR REGRESSION FOR EDINBURGH

● 1955/56 to 1970/71 Eskdalemuir  
 — line of best fit for Eskdalemuir  
 - - - line of best fit for Edinburgh 1940/41 to 1970/71

For a selection of individual winters, the errors (i.e. estimated minus actual) are given below. Rather surprisingly the largest errors in the 10 winters 1960/61 to 1969/70 are for Blackford Hill in spite of the fact that the linear regression was based upon data for the same station (though for the 31 winters from 1940/41 to 1970/71). Table I indicates the magnitude of the errors.

For individual winters therefore, an error of estimate of up to  $\pm 10$  days in frost frequency can occur although most discrepancies will lie within the range  $\pm 5$  days. For the period-average analysis based upon the linear regression, an error as great as  $\pm 5$  days is exceptional.

A more detailed scrutiny of the data at least suggests that stations could be rationally grouped into :

- (a) those at markedly maritime sites or freely exposed on hillsides;
- (b) those which are surrounded by rather higher land, even at a considerable distance, and whose site may be judged to tend to have some of the characteristics of a frost hollow.

In the latter case there are, on a period-average basis, more frosts during the winter for a given average mean temperature than for case (a) — this is physically acceptable: a difference of between 5 and 10 days could be provisionally suggested.

TABLE 1—DIFFERENCES FROM ACTUAL FROST FREQUENCIES DURING THE WINTER, OF ESTIMATES BASED UPON MEAN TEMPERATURE FOR THE SAME PERIOD; DERIVED FROM LINEAR REGRESSION BASED UPON DATA FOR EDINBURGH (BLACKFORD HILL) FOR 1940/41 TO 1970/71, FOR SELECTED STATIONS AND FOR THE PERIOD 1960/61 TO 1969/70

	1960- 61	1961- 62	1962- 63	1963- 64	1964- 65	1965- 66	1966- 67	1967- 68	1968- 69	1969- 70
	<i>days</i>									
Edinburgh (Blackford Hill)	0	0	-4	+7	+9	+6	+7	-5	+6	+5
Edinburgh (Royal Botanic Garden)	-5	-4	0	+1	+3	-1	+2	-9	0	+2
Mylnefield (Dundee)	-3	+1	0	+5	-4	+2	+8	-6	-1	+1
Abbotsinch (Glasgow)	-5	0	-2	-3	-6	+1	0	-8	+4	+1

## REVIEW

*Meteorology and climatology for sixth forms and beyond, 4th edition*, by E. S. Gates. 250 mm × 190 mm, pp. 293, *illus.*, G. G. Harrap and Co. Ltd, 182-184 High Holborn, London WC1V 7AX, 1972. Price: £2.75.

A review of the first edition of this book appeared in the *Meteorological Magazine* for October 1961 and much of what was said then is still true. In this fourth edition the author states that he has revised his book to take account of the successful development of satellites for meteorological purposes and that all units have been rationalized according to the *Système International d'Unités*.

The new Chapter 13 'Weather watchers in space' describes the various satellite systems and the equipment carried very well, but no effort is made to explain for example how temperature profiles are measured. Even though the book is designed primarily for geographers, surely an intelligent sixth-former would want to know some of the underlying physical principles. What a pity too that so few satellite pictures and nephanalyses have been added to the many excellent plates and diagrams. The section on fronts and depressions for example could have been brought alive by the judicious use of such pictures.

A major criticism of the whole book must be that it shows signs of age, both in approach and format. Wing Commander Gates who is Head of the Department of Liberal Studies at the Royal Air Force School of Technical Training, Halton, is on the fringe of meteorology with limited access to the current literature. Had he been in the main stream of the science in its present exciting development phase one feels sure he would have considered a

completely fresh approach based on sound physical principles. His bibliography too would have been revised, for many of the books and papers mentioned have been superseded by later texts which are readily available in libraries. Nor can the book escape criticism in matters of detail. For example on page 97, talking of the mature stage of thunderstorms, we read 'the cloud now assumes a vertical thickness in excess of 6 000 metres, the last few hundred metres being below freezing point'.

Where the book deals with facts it is still of value to the adult amateur of meteorology. The purchaser must not expect it to satisfy him for very many years though.

P. D. BORRETT

## NOTES AND NEWS

### THE BRACKNELL METEOROLOGICAL OFFICE COMPUTER

The KDF9 computer which was installed in 1965 was operated continuously for several years and was used as the main operational computer at HQ Bracknell until 30 April 1972 when the IBM 360/195 took over that role. Hours of operation of the KDF9 computer were subsequently progressively reduced and the installation was finally closed down on 30 March 1973. The serviceability of the KDF9 had been maintained at a high level throughout its period of use. Almost all the computer tasks have been transferred to the 360/195 and arrangements have been made for running a few residual tasks on other KDF9 computers which are still in use at government establishments near Bracknell.

### NOTE ON ACCUMULATED RAINFALL DEFICIT

Special summaries of the accumulated deficit of rainfall have been produced by the Meteorological Office, each month, since March 1973, as guidance in policy-making and planning in water management. The average rainfall over England and Wales from July 1972 onwards was compared with corresponding totals in the past. At the end of March 1973 the 9-month total was the lowest since 1750 and at the end of April, after some rainfall, the 10-month total was the lowest since 1854. May 1973 was a wet month over England and Wales, with 137 per cent of the average monthly rainfall, and the 11-month total was the lowest since 1956. Even so, since 1800, only 1955-56, 1933-34 and 1854-55 had less rainfall in the 11-month period than 1972-73.

### TELEMETERING BUOY

The Office's first telemetering buoy — OBOE I (Offshore Buoy Observing Equipment) has now completed two successful sea trials. In the first, it was on station for three months in the Irish Sea, off Aberporth, from June to August 1972; in the second, it was on station for three months in the Thames Estuary, off Shoeburyness, from February to April 1973. The data recovery rate rose from about 90 per cent in the first trial to over 95 per cent in the second trial.

The buoy provides half-hourly observations of wind speed, air and sea temperature, humidity and pressure. Its purpose is to provide a real-time facility for monitoring the performance of marine sensors, and control observations made in the course of the second trial at the end of Southend Pier have shown that the data are of high quality.

### **Mr R. Dixon — Special merit promotion to Senior Principal Scientific Officer**

It is highly gratifying to announce the promotion of Mr R. Dixon to SPSO under the scheme for the promotion of scientists in the Civil Service who have shown outstanding research ability. Mr Dixon is particularly well known throughout the Office as a result of the considerable periods he spent on roster duties first at the Principal Forecasting Office at London/Heathrow Airport and then in the Central Forecasting Office at Headquarters in Bracknell.

Mr Dixon's mathematical equipment is wide-ranging and powerful. Since 1967 he has been engaged on the development of 3-dimensional and 4-dimensional techniques for the objective analysis of meteorological data for direct application to numerical weather forecasting. Furthermore Mr Dixon has made considerable improvements to the numerical (grid-point) analysis systems in current use in the Central Forecasting Office. The new techniques, which are approaching operational status, involve the fitting of a set of orthogonal polynomials to all the relevant data covering the northern hemisphere. By means of these methods all data can be utilized, whether synoptic or non-synoptic, whether or not at standard pressure levels. This is a very notable advance which is particularly important at this time as satellites are beginning to provide a vast increase in the volume of temperature sounding data which, of course, will be non-synoptic.

The potentialities of Mr Dixon's work are widely recognized not only in this country but also among leading meteorologists in countries such as the U.S.A., Australia and Japan.

P.J.M.

551.593.63

### **LETTER TO THE EDITOR**

#### **Halo display at RAF Gütersloh**

On 19 May 1973 between 0830 and 0930 GMT at RAF Gütersloh, West Germany ( $51^{\circ} 56' \text{N}$ ,  $08^{\circ} 19' \text{E}$ ), I observed a particularly fine halo display (see attached diagram). The following points are of particular interest :

- (a) The parhelic circle. This was seen in its entirety and appeared as a well-defined white band.
- (b) The anthelion at P. This was particularly bright, with the two oblique arcs, N and R, showing brilliant white.
- (c) The arc of contact to the  $46^{\circ}$  halo at V. This was not very bright, but bright enough to show that it was coloured. The halo itself was not visible.







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## NOTICES

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