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Trajectory and plume analysis in the Meteorological Office Atmospheric Dispersion Group

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Summary

This paper discusses the problems associated with modelling trajectories and outlines the facilities for trajectory and plume analyses available in the Meteorological Office.

1. Introduction

Before describing the trajectory facilities developed using the Meteorological Office numerical weather prediction (NWP) models, it is worth pausing to consider what we understand by the word trajectory. A trajectory is defined as the path followed by a projectile or object moving under the operation of given forces. In our context, it is the path of a passive particle or fluid element being carried along by the ambient wind. An equivalent expression is 'particle path'. A plume needs no definition; an instantaneous plume is the position at a given instant of all the material, previously emitted from a source, which is still in suspension. The source may be simple, multiple or areal. In the real atmosphere the air, with any gaseous or particulate matter suspended within it, is continually being mixed by diffusive motions over a range of scales. The trajectory followed by a molecule of gas in the atmospheric boundary layer (broadly, the 1 km or so adjacent to the earth's surface) is very complicated indeed, although in general it will move along in the direction of the mean wind, where 'mean' is taken to be the wind time-averaged over a period much longer than the time-scale of the turbulent eddies. The mean wind can itself, of course, change significantly

over a few hours, or almost instantaneously across an active weather front. It should be said that, in strictness, what constitutes a mean wind and what constitutes turbulence depends upon the period or volume over which averages are calculated. It is assumed, for purposes of the present paper, that the mean wind is that stored at the grid points of a synoptic-scale NWP, and that by turbulence we mean those motions that are too small in scale or lifetime to be so represented.

There is a requirement for accurate estimates of both 'forward' and 'backward' trajectories for use in a range of scientific and environmental applications. Forward trajectories enable the transport of suspended material emitted from a known source to be traced downwind, while backward trajectories enable material detected in the atmosphere to be traced upwind, usually with a view to identifying the source.

As an aid to visualizing the uncertainties attaching to a horizontal trajectory calculated from NWP data, consider these questions: how quickly do two particles in the real atmosphere, released 1 mm apart, start to lose the 'memory' of their initial velocity and follow diverging paths? What if the particles start 10 m apart?

Or 10 km? The processes operative are discussed in section 2. Assuming they are neutrally buoyant, how would the trajectory of a toy balloon compare with that of a 20 m diameter balloon which ‘integrates’ a greater range of turbulent motions? How serious is the presence of strong horizontal shear, or diffluence, or stagnant regions of the flow? What if a motion system of marked 3-dimensional character is traversed?

The methods we use to compute trajectories from NWP motion fields use the values of the wind components which are stored over a 3-dimensional mesh of grid points — each grid-point value represents a volume average of (commonly) hundreds of cubic kilometres in which the smaller, sub-grid scale, motions are parametrized to give realistic bulk values of the turbulent fluxes. The small-scale motions are not, then, available for computing trajectories (ways of giving effect to turbulence in a statistical sense have, however, been developed, as will be shown later). Clearly a trajectory computed using a NWP model can only follow the model mean wind, i.e. the wind stored at the model’s grid points. This usually necessitates interpolation in both time and space, that is, between grid points and between the available times of analysis or forecast. A particle ‘released’ into the model’s boundary layer, then, behaves like no particle or small fluid element of air in the real atmosphere. It may be argued, however, that it can be taken to represent the centroid of a parcel comprising many particles, which is large compared to the small-scale turbulence. The main influence of the smaller scales of motion on such a parcel is, it may be hoped, to diffuse or ‘expand’ it (within the boundary layer, say) without influencing the position of the centroid too much. A real parcel, however, will be affected by mesoscale motions which a model such as the operational fine-mesh NWP cannot represent; whatever the model resolution there will be a range of eddy sizes too large to be mutually self-cancelling in their effect and too small to be explicitly represented. This all leaves to one side the central problem of the accuracy of the model’s mean wind.

Nonetheless, over regional or continental distances, where a trajectory crosses many model grid squares, and an expanding parcel in reality may engage sufficiently varied sub-grid-scale regimes for the net effect on the centroid not to be too serious, the model mean wind is a useful first approximation to actual long-range transport in the sense that one may infer that there is a high probability that ‘some of the material travelled thus’. How reliable this inference is, over a given distance, is a matter yet to be investigated in any detail. The effect of trajectory error is clearly more significant if the transport of a single puff of pollutant is being simulated than in the case where time-integrated concentrations are used, as in modelling, say, the seasonal exports of sulphur species across a national boundary. A single trajectory gives no information on the total area which might be affected by a release: a sequence of trajectories

may, but it is usually preferable to use puff or plume analysis (of which trajectory analysis is the foundation) for this purpose.

2. Transport and dispersion in the atmosphere

When a pollutant, such as the plume from a factory chimney or the exhaust fumes from a stretch of motorway, is released into the atmosphere, it is dispersed by two processes which act together but are effective over different time-scales. From the moment of its release the material is carried along in the ambient wind and at the same time starts to spread out. This process of diffusion is initiated by the turbulence of the source emission and carried on by the 3-dimensional turbulence of the boundary layer (in which energy is cascaded to successively smaller eddies until it is dissipated at the smallest scales). The diffusion process is effected most vigorously by eddies of similar size to the puff or cloud of material, and, as it diffuses, the puff will engage larger and larger eddies. On a much larger time-scale the wind-field itself (with any suspended material) is undergoing distortion due to the movement and changes in intensity of the weather systems.

These processes account for the slope of the spectral density (kinetic energy per unit wave number) illustrated in the schematic power spectrum of atmospheric wind velocity components in Fig. 1. For wavelengths above about 1000 km the spectrum has a slope proportional to the wave-number, k , raised to the power -3 , which reflects the transfer of eddy enstrophy (root-mean-square vorticity) to motions of smaller wavelength by

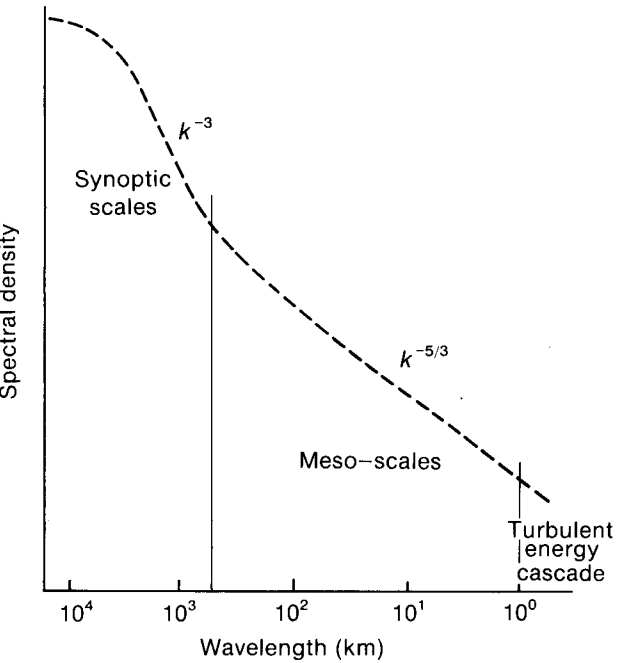


Figure 1. Schematic variance power spectrum for horizontal wind velocity components, based upon spectra in Gage and Nastrom (1986) of data from commercial aircraft (the GASP project). Spectral density is the kinetic energy per unit wave number. Wave number (k) is defined $2\pi/\lambda$, where λ is wavelength.

the relative motions of the velocity field (the ‘enstrophy cascade’; see Tennekes 1978 for a discussion). This is, to an approximation, a 2-dimensional, area conserving process: absolute vorticity is conserved so that the vorticity field becomes more convoluted as the horizontal variations are driven towards smaller scales of motion. Fig. 2 is based upon a dish-pan experiment by Welander (1955) which has been used by Tennekes and others to illustrate the phenomenon; a patch of dye is released, and becomes increasingly contorted by the fluid motion. Material is dispersed in this way by the enstrophy cascade in the atmosphere, but it is a stirring process, not, strictly, a diffusive one. Theory suggests that the rate of separation of particles in the enstrophy cascade can become exponential: this satisfies a criterion for ‘Lagrangian turbulence’, more succinctly known as chaos.

The role of the meso- and sub-synoptic scales between the enstrophy and turbulent energy cascades (through which some authors consider a reversed energy cascade towards larger scales occurs) is less easy to define. A $k^{-5/3}$ slope extends across a wide range of meso-scales into the 3-dimensional turbulence of the boundary layer (Fig. 1); it is easily demonstrated to be appropriate to the turbulent transfer of kinetic energy. Motions initiated by storm systems, orography, breaking gravity waves, it has been suggested, might cascade energy in two ways, 3-dimensional to smaller scales, 2-dimensional to larger. Thus Lilly (1983) analyses the reverse cascade in terms of the decay of 3-dimensional turbulence into ‘stratified’ 2-dimensional turbulence and gravity waves. As far as macro-scale dispersion is concerned the mesoscale motion systems can be considered as contributing to the diffusion process, albeit in ways as yet little studied. The presence of a mesoscale gap in the spectrum of atmospheric velocities has been suggested from time to time, although clear evidence of its existence remains elusive.

In summary: over long time-scales, a plume is distorted by the evolving synoptic pattern and, as a result of the stretching and thinning of the polluted air parcels, the area of contact with clear air is increased, allowing the energy cascade diffusion processes to continue to operate on individual elements of the cloud.

Sometimes the distortion can fold or wrinkle up a plume to form clumps of polluted air, but air concentrations of the pollutant cannot, of course, be increased in this way (some phenomena involving particulates can result in increasing concentrations, but this is not due to the kinematics of the airflow).

3. Practical difficulties in simulating the transport and dispersion of pollutants

An accurate representation of the mean wind is, of course, of first importance when simulating plume transport. Either observations or the wind as resolved on the grid of a NWP model can be used. Observations may require a mass-continuity condition to be imposed (Sherman 1978); they may be sparse in space and/or time, or perturbed by local effects. Modelled winds, strictly grid-volume means, are subject to adjustment and smoothing in the analysis process and perhaps less representative of real terrain and conditions. In either case a good deal of interpolation is usually required. Trajectories may be determined using winds at a single level (e.g. on a pressure surface or a mean boundary-layer wind), or in 3 dimensions, or on isentropic surfaces. Trajectories derived from NWP models can be subject to error of various kinds (section 4), including systematic errors associated with the particular model or resulting from the choice of level used to simulate the trajectory. Most NWP models, as we have noted, fail to represent properly the mesoscale motion systems which can be generated, for example, by land-sea juxtapositions or orography, or indeed changes in surface topography, type and roughness which can influence the transports or the diffusive process. One advantage enjoyed by the long-range modeller, however, is that the effects of surface inhomogeneities and of small-scale motion systems encountered over a track of hundreds or thousands of kilometres will, in ensemble, tend rather to modify the diffusion than to influence the mean path very strongly. The net error due to these influences should accordingly be small, in a simulation, at least in comparison with other sources of error. Where a plume is required it must be so modelled that both the turbulent spread and the effects of synoptic-scale distortion (section 2) are adequately represented.



Figure 2. Four stages in the evolution of a patch of dye on the surface of a pan filled with liquid, illustrating enstrophy cascade dispersion. Based upon Welander (1955).

The mean vertical motion of the air can have a critical effect upon a trajectory, particularly near a region of marked mass ascent, such as a front or active depression. A 2-dimensional trajectory entering such a region of horizontal convergence can 'stagnate' and the apparent concentration of a pollutant in the boundary layer (which might, for example, have been computed using the area of a simulated plume segment as described in section 7) show a spurious increase. Conservation of area can only apply with strictly 2-dimensional motion systems, and certainly not in the real atmosphere.

Plumes can be spread laterally by wind shears in the vertical. Within the boundary layer the turbulent motions will convey parcels up and down so that they experience, ultimately, the motion at all levels — the plume centreline responds to a mean boundary-layer wind — but above the boundary layer, material extended through any significant depth can be fanned out by the shear (this is illustrated in Fig. 6). Should a developing convective boundary layer extend into such a region, material is quickly brought down to what might be a previously unaffected surface — a process analogous to plume 'fumigation'. Material can also be vented out of the boundary layer by convection, e.g. in cumulus clouds, which can 'vacuum up' pollutants, carrying them up into the free troposphere and releasing them through detrainment or in the dissipation stage. Frontal cloud may do this on a large scale.

It is clear from the foregoing that the static stability of the atmosphere, the diurnal changes in the boundary-layer depth, and associated shears (including those due to the 'nocturnal jet' which can develop above the stable night-time boundary layer), all influence the transport and spread of pollutants, their dispersion in depth, or their appearance at the surface. The treatment of these factors requires careful consideration.

There remains the problem of estimating accurately the strength (and sometimes position!) of the source of the pollutant, and its profiles in time and space. Loss processes also have to be parametrized. The latter include the flux of material to the surface in dry air (dry deposition) which may or may not involve gravitational settling, and the removal of pollutants in rainfall. Wet deposition processes are of profound importance — witness the acid-rain problem and the washout of radioactive species following the Chernobyl release. Radioactive decay can be treated as a loss process. (See Smith and Clark 1989.)

4. Techniques for calculating trajectories

Given a wind field stored at the grid points of a rectangular mesh the simplest method of computing a trajectory is to use

$$d\mathbf{x} = \mathbf{u}(\mathbf{x}, t)dt \quad (1)$$

where \mathbf{x} is a position vector, t is time and \mathbf{u} the mean wind vector; \mathbf{u} will, of course, have to be interpolated

from the adjacent grid points and between the time-intervals for which winds are available. If the interval is long (6-hourly NWP output has commonly been used) there is an immediate loss of accuracy. Interpolation is usually linear in time, bilinear in 2-dimensional space, etc. — more sophisticated methods of interpolation can be used but it is debatable whether the generally slight increase in accuracy justifies the additional processing. Maryon and Heasman 1988 (henceforth referred to as MH88 in this paper) look at this question.

Expression (1) can be solved numerically, using finite differences. For example, the solution at time $t + 1$ can be obtained from

$$\mathbf{x}_{t+1} = \mathbf{x}_t + \mathbf{u}(\mathbf{x}_t)\Delta t \quad (2)$$

where Δt is the forward time-step. The accumulated error, however, is proportional to the size of the time-step used. A more reliable technique of integration was originated by Sykes and Hatton (1976) using Runge-Kutta methods. A 5th-order Runge-Kutta-Merson formula is now used, the solution of which is equivalent to the first six terms of a Taylor expansion about \mathbf{x}_t . The truncation error can be estimated; if the error exceeds a chosen small magnitude the time-step Δt is halved, \mathbf{u} re-interpolated, and the calculation repeated. This method has performed so well using 6-hourly data that lengthy trajectories over the domain of the fine-mesh NWP can be reversed in direction to terminate very close to the starting point.

Clearly there are a number of components to the error of a simulated trajectory. These are discussed and compared in MH88. To the numerical errors due to interpolation and forward integration we must add forecast error or, if only NWP analysed fields are used, those due to the differences between the analysed and 'real' wind fields. The numerical errors are not large, if due care is taken, although they will accumulate with the time into integration. Forecast error, however, can be very large — Table II of MH88 shows a mean angular divergence from validation of over 6° after 24 hours when a large sample of trajectories was 'released' at the start of fine-mesh forecasts, increasing to over 10° after 36 hours. For coarse-mesh trajectories not released until the forecast has already run 36 hours the corresponding deviations are no less than 22° and 24° respectively. The validation, however, was against trajectories computed using NWP-analysed and short-period forecast wind fields. Validation against reality is very difficult, and requires the tracking of constant-density balloons (tetroons). MH88 briefly reviewed a number of tetroon experiments and suggest that a mean angular deviation of 12° or more must be expected for trajectories of some hundreds of kilometres computed using the best available analysed fields, although the results are very variable — the statistics are very sensitive to the onset of the stage, which occurs sooner or later, when the divergence of the computed trajectory and the validation

begins to accelerate. This, and the forecast error (as defined above) are not, of course, simply additive, but it does suggest that the forecast errors quoted are the minimum ensemble means to be expected.

Computing a trajectory is only the start of the problem of simulating dispersion in the atmosphere; methods of treating the spread due to vertical shear and boundary-layer turbulence will be described briefly in section 7.

5. Two-dimensional trajectory facilities

The following brief account of the trajectory facilities available will be confined to those developed and maintained by the Atmospheric Dispersion Group of the Boundary Layer and Atmospheric Chemistry Branch (Met O 14) although similar facilities are available elsewhere in the Met. Office, such as the Central Forecast Office (CFO) and the Forecasting Research Branch (for example, 3-dimensional trajectories can be obtained from the operational mesoscale model). The Met O 14 routines are described in more detail in Dickinson (1984a, 1984b), Ephraums and Macari (1987) and Macari (1987a, 1987b). Trajectories may be run from the current print-files of the operational fine- and coarse-mesh models (print-files are the standard data sets containing output from the operational NWP models; each consists of the latest analysed fields and a sequence of forecasts), or from archived data. This archive accumulates, on tape, 3-hourly fine-mesh wind analyses at the 950, 850 and 700 mb levels which are extracted from the operational print-file. The archive is 'rolled over' approximately on a 2-year basis. Routines are available to restore winds for the period and levels required to a direct access data set on disk.

There are five trajectory packages available, which have certain features in common. They all produce 2-dimensional trajectories using winds at the standard output levels of the operational NWP suite. Winds in all cases are linearly interpolated between the available data times, bilinearly interpolated in space from the four surrounding grid points and the trajectories integrated using the 5th-order Kutta-Merson scheme. The trajectories are continued until they reach the edge of the model grid, exhaust the sequence of wind fields available or reach a limiting period (in the case of archived winds, 360 hours). The data are available every 3 hours (fine mesh) or 6 hours (coarse mesh).

The successive trajectory coordinates are transferred from grid values to latitude and longitude, and printed out in tabular form. Alternatively a facility is now available for plotting trajectories directly onto suitable map backgrounds. An example showing two back-trajectories is given in Fig. 3. As each trajectory is calculated it is stored on disk: repeated runs from the current print-files create a sequence of trajectories based upon analysed or forecast wind fields, or both, those with a forecast component being overwritten as time passes. The routines available are:

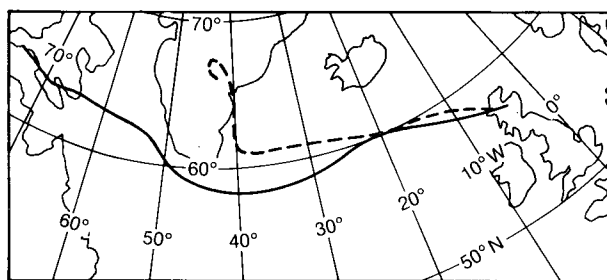


Figure 3. Sample plots of back trajectories released 12 hours apart, 0600 and 1800 GMT on 5 December 1988, computed using the fine-mesh backward trajectory model.

(a) Fine-mesh forward trajectory and rainfall forecast model — this model utilizes fine-mesh forecast print-file data. Trajectories of up to 36 hours (at present) are computed from the forecast wind fields. In addition to the position reached by the trajectory, local dynamical and convective rainfall rates are output. These data are printed every 3 hours. Only one start point is permitted.

(b) Coarse-mesh forward trajectory and rainfall forecast model — this version concatenates fine- and coarse-mesh forecast wind fields, using the former for the first 36 hours of a forecast, the latter for a further 36 hours. Again, the dynamic and convective rainfall rates are plotted, and only one start point is available. With repeated updates, the trajectories are eventually overwritten by revisions based upon fine-mesh analyses.

(c) Fine-mesh backward trajectory model — this version computes back trajectories from archived fine-mesh wind fields using 3- or 6-hourly input data; the resultant trajectory is always defined on a 3-hourly basis. Up to 54 trajectories can be processed concurrently using any combination of start locations and levels, and times of release.

(d) Fine-mesh forward multi-point and multi-time models — these versions compute up to 60 forward trajectories from the archived winds using 3- or 6-hourly input data. One version releases all the trajectories simultaneously, but from different starting positions, as required; the other can compute consecutive trajectories from the same start point.

In addition, isentropic trajectories (paths along surfaces of constant potential temperature) can be produced by the Atmospheric Chemistry Group in Met O 14. These provide more realistic paths through the free atmosphere than 2-dimensional standard-level trajectories, and are particularly useful in the upper troposphere and stratosphere, and in the study of air transports through synoptic weather systems.

6. Applications of trajectory and plume analysis

The tracing of trajectories has a wide range of applications both in the atmospheric sciences and in more practical aspects of pollution control. Atmospheric

chemists need to determine the sources, and simulate the transports and mixing, of reactive species and of substances such as the hydrocarbons and nitrogen oxides which produce oxidants (hydroxyls and ozone) in the presence of sunlight. Oxidants figure prominently in a number of important and indeed urgent ecological investigations, which are currently the subject of intensive study. One of these is the acid-rain problem, where trajectory and plume analysis help to model the transport, intermixing and chemical interaction among species which result in the solution of sulphates and nitrates in rain-water. In this connection MH88 attempted to assess the feasibility of using forecast trajectories for acid precipitation control strategies. Simulation of the dry deposition of gaseous and particulate pollutants to the surface equally requires the employment of trajectories. There are applications in stratospheric photochemistry, where the transports of trace species and coupling of dynamical and photochemical processes are under investigation.

Trajectory analysis has application in acute, as well as chronic, pollution problems. Back trajectories can be used to trace the source of noxious or hazardous materials released into the atmosphere, or forward trajectories to predict their destination. Recent (relatively short range) examples of such contingencies are the chemical fire at Nantes, and the release of ash and asbestos among the combustion products from a conflagration in the north Midlands (Evans and James 1989 describe the tracking of this material using radar). A long-range study was made of the release of volcanic ash from the Mount St Helens eruption (Crabtree and Kitchen 1984). Potentially the most serious of accidental releases is that of radio-nuclides, a subject returned to in section 7. Pollution associated with mesoscale-motion systems can in principle be studied using trajectories from appropriate models; a classic example is the complicated fate which befalls a plume which is entrained into a sea-breeze circulation (Lyons *et al.* 1983).

Other examples requiring back-trajectory studies include the transport of Saharan dust eventually rained out over the United Kingdom and the contamination of Highland or Arctic snow by industrial effluents. No doubt the reader can supply other applications — a few that come to mind are biology (the atmosphere has its plankton!), epidemiology (for example, the foot-and-mouth disease models) and of course navigation — an Atlantic crossing by hot-air balloon would be ill-advised if the fine- and coarse-mesh trajectories projected a diversion to Thule.

7. Plume analysis over long range

Many ways of modelling plume spread close to the source exist, the most widely used for practical purposes being the Gaussian plume (Pasquill and Smith 1983) which in its basic form assumes constant wind speed (without shear), constant diffusivity and a homogeneous

surface for the plume to traverse. This is not the place to analyse the strengths and weaknesses of the Gaussian (or other short range) formulations except to emphasize their complete unsuitability for use over long range, in view of the variable meteorology and terrain that will be encountered by the plume, and the absence of provision in most short-range techniques for all the influences described in section 2.

Another paper of this length would be required to do justice to a description of the variety of techniques developed for long-range transport modelling. Attention will be confined to two models recently developed in Met O 14 for simulating the transport and spread of neutrally buoyant pollutants over continental scales: the Basic and Main Models associated with the national nuclear accident response programme. Both are Lagrangian models — that is, estimates of concentration etc. are made as the material is followed through the domain rather than by solving equations at fixed points (the Eulerian method) — and are accordingly entirely relevant in an article dealing with trajectories. These models will have uses other than nuclear accident response: any large-scale chemical emergency can be handled, while the Main Model in particular could form a 'chassis' for chemical modelling and other research projects.

7.1 The Basic Model

The National Response Plan initiated by the Department of the Environment following the nuclear accident at Chernobyl required the development of a fast-response model capable of simulating the transport, dispersion and deposition of radio-nuclides released into the atmosphere from any European installation. The Radiation Incident Monitoring Co-ordinating Committee (RIMCC) requested that a basic model be produced as quickly as possible, that is, by the end of 1987, while plans were made for a more comprehensive version (now known as the Main Model). The modelling project bears the acronym NAME.

The Basic Model requires a prescribed emission profile. The model can run in forecast or hindcast mode using data from the operational fine-mesh NWP, and the runs updated as time passes. To facilitate this process, an archive has been created by staff of the Forecasting Products Branch which accumulates analysed fields from the fine-mesh print-files and stores them on a 10-day 'roll-over' basis. The plume is initiated with a 2-dimensional, single-point, single-level trajectory with successive points being released at hourly (or longer) intervals, and the plume is expanded empirically about its centre-line to give effect to turbulent diffusion and shear. Winds are linearly interpolated in space and time, and the 5th-order Kutta-Merson integration is used. The young plume is divided across its width into segments by an array of equidistant points so that the full plume is defined by quadrilaterals. With each quadrilateral is associated a mass of material released

during a time-step: initially this mass is distributed across the plume in a Gaussian manner. When they are 24 hours old, the points defining the plume segments are advected individually in the evolving synoptic wind field, and the plume allowed to deform. In fact this technique cannot cope very well with the deformation beyond a couple of days, and further refinements would be necessary to prolong its usefulness. An example of the output is shown in Fig. 4.

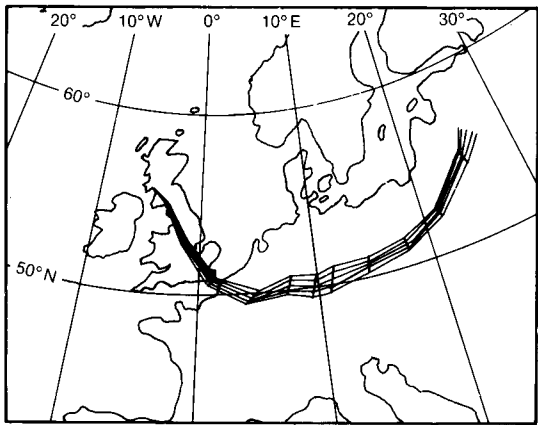


Figure 4. The NAME Basic Model: the 950 mb plume at 0000 GMT on 20 December 1988 following a notional release of a pollutant from an arbitrarily chosen location in the south-west of Scotland, starting at midday on 18 December. In this run the plume was divided into 3-hourly segments.

The boundary layer is dealt with in a simple fashion; an initial depth, and upper and lower limiting values are prescribed, and a conservation of volume principle applied to prevent unwarranted changes in pollutant concentration resulting from convergent/divergent 2-dimensional flows. With strong horizontal divergence the pollutant can be diluted to allow for boundary-layer entrainment, while in the case of marked convergence a proportion of the material is vented from the boundary layer in response to the associated (but unrepresented) vertical motion. Boundary-layer concentrations of the pollutant are computed by projecting the plume segments (Fig. 4) onto the fine-mesh grid, and assessing the contribution to each grid-square from each overlapping segment. The accumulated dry deposition and time-integrated dosage are also computed for up to four radio-nuclides, after allowing for radioactive decay.

7.2 The Main Model

In view of the difficulties involved in representing 3-dimensional motion fields with 2-dimensional techniques, a completely different approach has been adopted for the Main Model. A 'random walk' or 'Monte Carlo' formulation is used: the plume is simulated by releasing a large number of particles at the source (in batches at hourly intervals, reflecting the emission profile in time and space) and allowing them to be transported by 3-dimensional winds taken from the fine-mesh forecast print-files or the roll-over archive. A time-step of 15 minutes is used (an appropriate eddy turnover time in

the convective boundary layer) and at each step a random perturbation is added to the horizontal displacements to account for turbulent diffusion, giving

$$\mathbf{x}_{i+1} = \mathbf{x}_i + \mathbf{u}(\mathbf{x}_i)\Delta t + \mathbf{A}r, \tag{3}$$

where Δt is the timestep, r a random number from the standard normal distribution and \mathbf{A} a coefficient which can be identified with $\sqrt{2\Delta t K}$ in conventional parametrizations of diffusion (K being the horizontal diffusivity). In addition, the particles in the boundary layer are randomly re-assigned in the vertical so that over a period of time each particle will sample the mean wind at each level within the boundary layer. The effect of vertical wind shears above the boundary layer can be allowed for, to some extent, by 'stacking' the particles in the vertical when they are released.

The model is multi-level, with a realistically evolving boundary layer and several layers above (currently up to 700 mb). The boundary-layer depth is diagnosed from the fine-mesh wind and temperature profiles using a gradient Richardson number. This depth, taken with the positions and vertical velocities of the particles, automatically if rather simplistically allows for entrainment and detrainment through the inversion (although the venting effects of deep convection are yet to be parametrized).

A mass of pollutant or quantity of radioactivity is associated with each particle at the outset, and concentrations in air are calculated simply by counting the particles in each grid volume. Of course, statistical reliability requires the release of large numbers of particles, and this technique is much more expensive computationally than the Basic Model. However, given adequate resolution and sufficient particles it is far more realistic in that any 3-dimensional motion system can, in principle, be handled. There is no question of using a sophisticated integration scheme in this case — apart from the overriding problem of computational expense, the random fluctuations would blur the slight differences, given that there are no systematic errors.

At this stage, the output diagnostics are similar to those of the Basic Model. Two major components of the (as yet incomplete) Main Model are the real-time, high-resolution rainfall archive now under development by staff of the Nowcasting and Satellite Applications Branch to underpin the crucial wet deposition parametrization, and the radiological package being planned at the Safety and Reliability Directorate of the United Kingdom Atomic Energy Authority, which will enable observed radiation from any future accident to be used to modify the model assumptions and products. Examples of recent output from the current version are given in Figs 5–9. Fig. 10 shows an application of the Main Model to the release of radio-nuclides from Chernobyl. The particles in Figs 5, 7 and 10 represent material suspended in the atmospheric boundary layer; those in Fig. 6 material in the 850–700 mb layer.

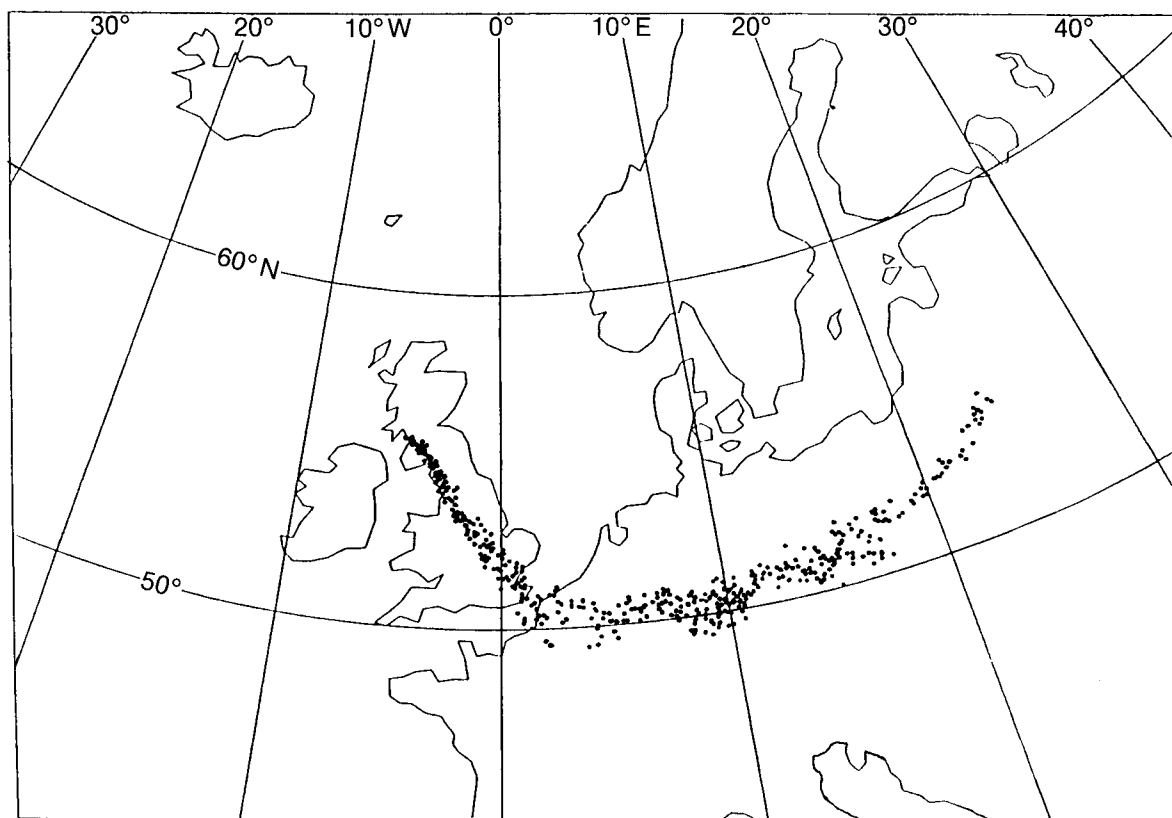


Figure 5. The NAME Main Model: multiple particle boundary-layer plume corresponding to Fig. 4. Note that the 950 mb wind used in the Basic Model carried the plume a little further than the full profile of boundary-layer winds used here.

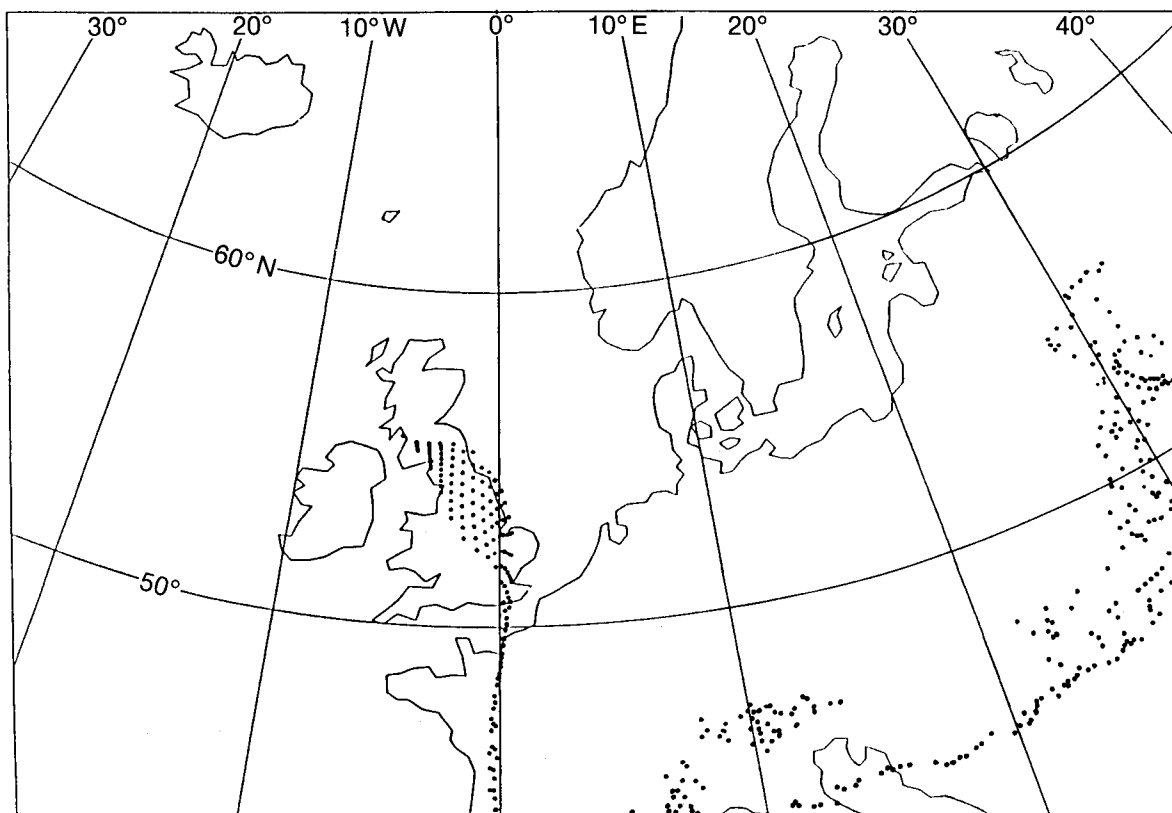


Figure 6. The 850–700 mb plume 12 hours later than Fig. 5 at 1200 GMT on 20 December 1988. No random perturbations have been applied at this height, but the particles released 'stacked' in the vertical. Note the effects of wind shear over northern England. Some of the particles have been lifted to this level in ascending air.

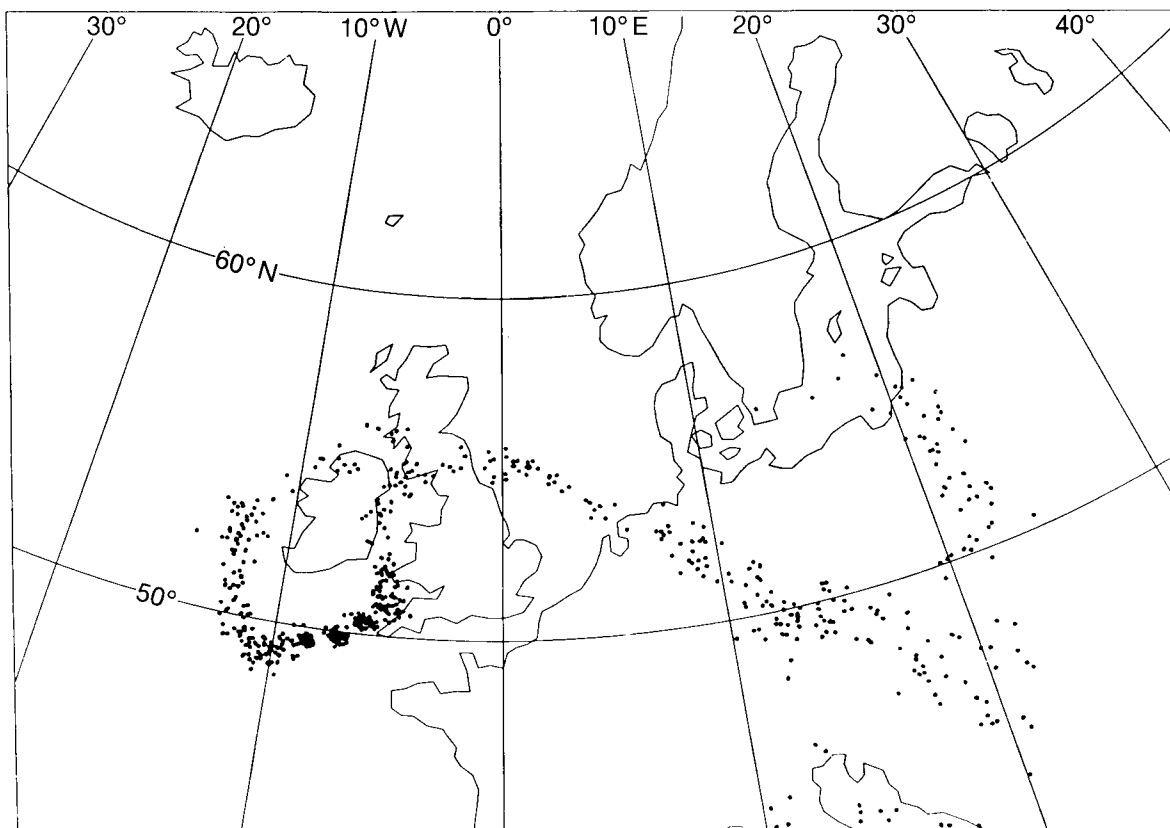


Figure 7. The NAME Main Model: boundary-layer plume at 0000 GMT on 3 March 1989 from an imaginary source at 50° N, 10° W starting 1200 GMT on 28 February. This interesting case shows some of the material spiralling back around Ireland to merge with fresh emissions at the source.

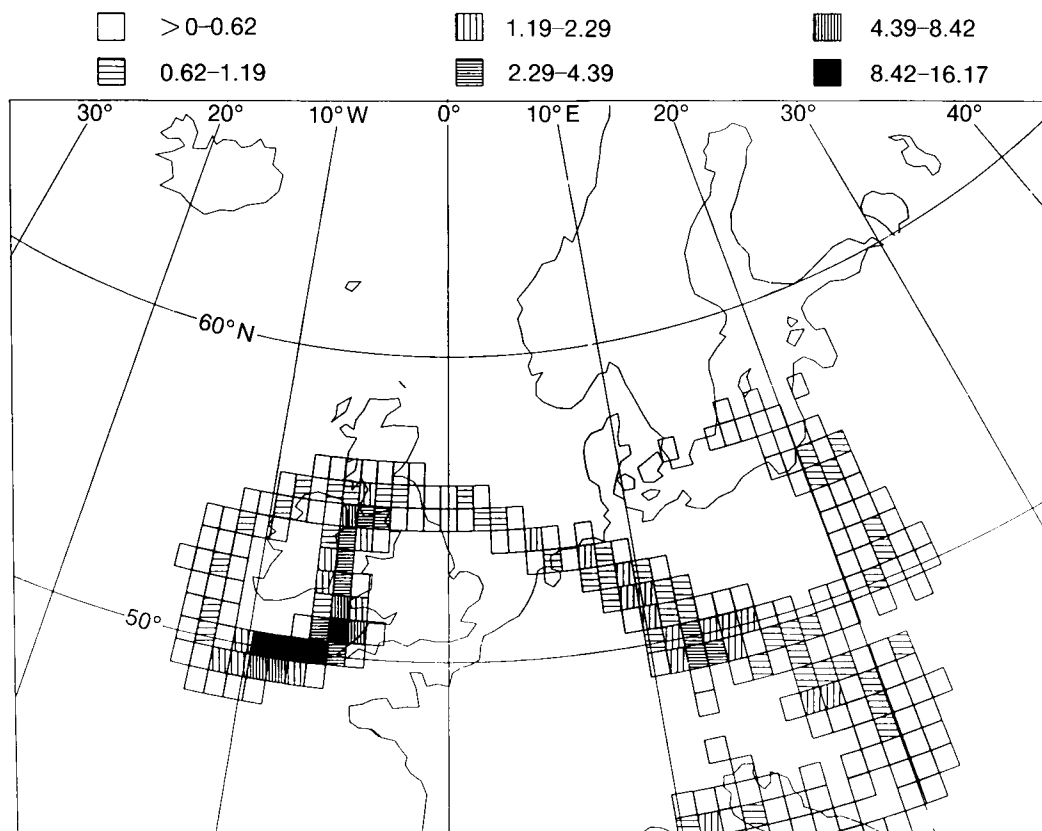


Figure 8. Boundary-layer air concentrations (Bq m⁻³) of the pollutant corresponding to the plume in Fig. 7, assuming a release strength of 100 TBq h⁻¹.

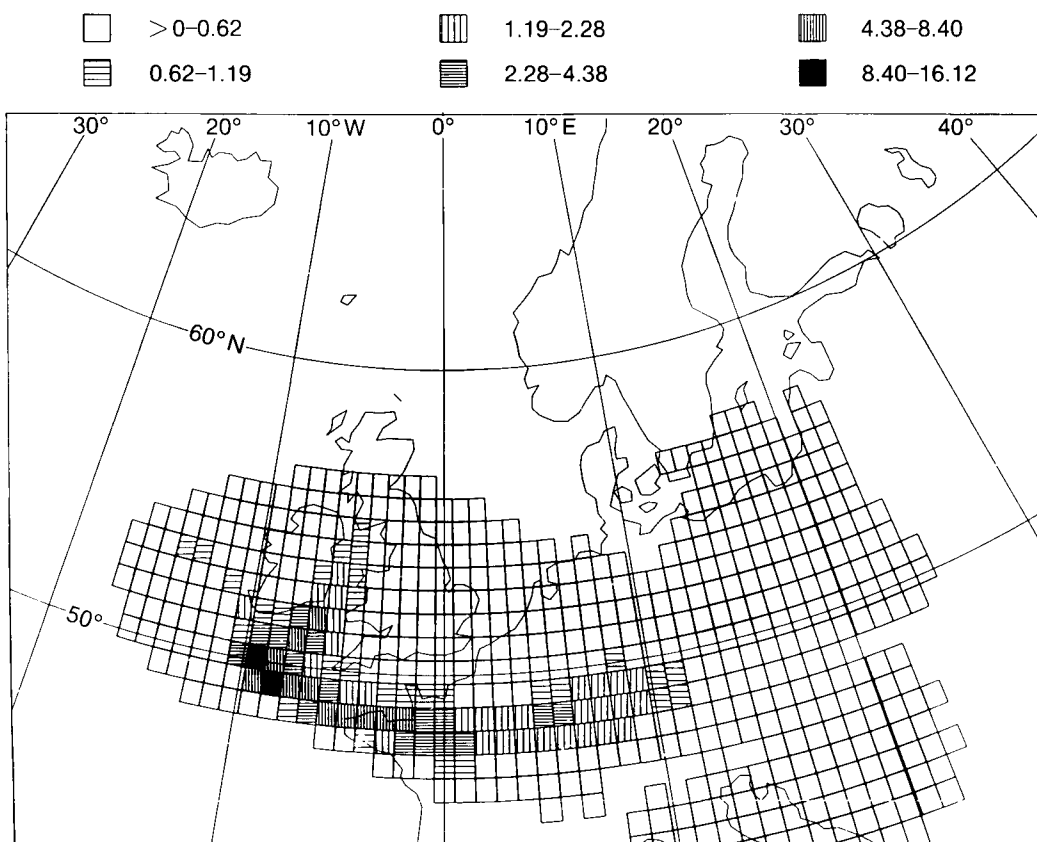


Figure 9. Accumulated dry deposition (kBq m^{-2}) of the pollutant by 0000 GMT on 3 March 1989.

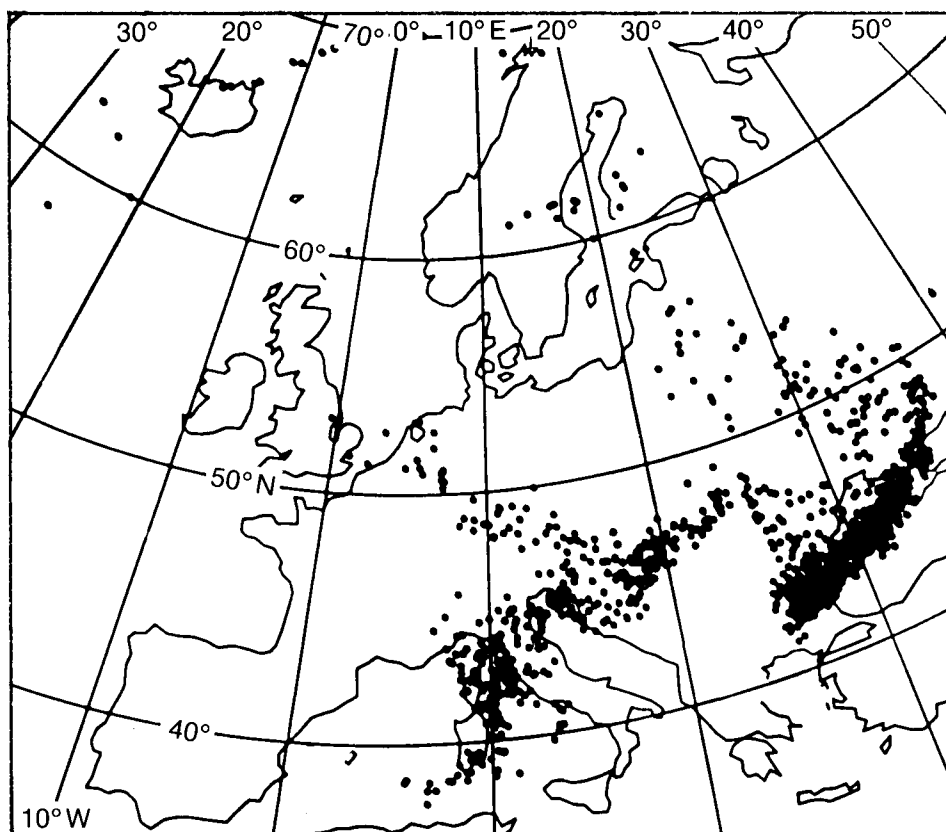


Figure 10. Airborne material from the first day's release from Chernobyl (2123 GMT on 26 April 1986 to 0000 GMT on 27 April 1986) at 1200 GMT on Friday 2 May. Again, the boundary-layer plume is reproduced.

Considerations of economy prevented the release of sufficient particles to give a statistically significant pattern over the United Kingdom in Fig. 10, but the arrival of material from Chernobyl on 2 May 1986 and the presence of the plume over eastern England by midday were quite well indicated.

8. Conclusions

The difficulty in conceptualizing precisely what is being simulated when boundary-layer trajectories are derived from NWP wind fields does not prevent their frequent use in a range of applications. Most importantly, trajectories are the foundation of plume analysis, which is extensively employed in current ecological and pollution studies. Of the various sources of error that may be associated with trajectory analysis, those due to numerical and sub-grid-scale effects are considered to be of less importance to the long-range modeller than forecast error (which can be severe) and error in the mean wind (as analysed). Such errors can be systematic, depending upon the model and the method used to calculate the trajectory. In the case of analysed winds, error magnitude is difficult to determine with any accuracy — such measurements as are available show wide variation but suggest that the difference between 'real' and analysed trajectories (over some hundreds of kilometres) averages at around 12° of arc. The utility of trajectory analysis has, however, been demonstrated in many contexts.

A necessarily brief account has been given of the Atmospheric Dispersion Group's trajectory facilities and of recent work on long-range plume modelling, which is associated with the national nuclear accident response programme (but should have other applications). All of the facilities described in this paper, with their comprehensive operational databases, are available to the wider scientific community.

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Observed climatic change, and the greenhouse effect

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Summary

The observational evidence is reviewed for the possible past and present impact of changing atmospheric concentration of carbon dioxide, and other greenhouse gases, on climate.

1. Introduction

Since the early nineteenth century, atmospheric carbon dioxide (CO₂) concentration has increased from about 280 parts per million (ppm) to 350 ppm in recent times (Fig. 1) as a result of deforestation and the burning of fossil fuels. Because of increasing concentrations of other greenhouse gases such as methane and chlorofluorocarbons, the overall radiative effect is equivalent to an increase of 40% in the CO₂ concentration, at least half of which has taken place in the last 30 years. The annual cycle in Fig. 1 results from the seasonal growth and decay of the vegetation of the northern hemisphere, which dominates the global land biosphere. The trend in Fig. 1 is a potential cause of global climatic warming.

There are already observational precedents for relationships between atmospheric CO₂ and climate. The pre-industrial atmospheric CO₂ concentration ranged between 250 and 310 ppm in the Holocene (since the last ice age, i.e. about the last 10 000 years) and in the previous interglacial, but was about 200 ppm at the peaks of the last two major glaciations (Barnola *et al.* 1987, Neftel *et al.* 1988, Webster 1985). The changes in atmospheric CO₂ concentration accompanied or slightly lagged the glacial-interglacial periods, so they did not cause them, but they were of the correct sign to have amplified them. They may also have forced the observed synchronism of glaciations in the opposite hemispheres (Broccoli and Manabe 1987), which cannot be explained in terms of

the Earth's orbital changes believed to underlie the Pleistocene ice ages, because these changes result in largely interhemispheric redistributions of a fixed annual total supply of solar radiation.

Numerical models indicate that, in equilibrium with doubled atmospheric CO₂, the following broadscale changes of climate are likely (see Schlesinger and Mitchell 1987):

- (a) A global mean surface warming of about 3–4 °C, and more confidently between 1.5 and 4.5 °C. Most of the larger warmings are obtained by the more recent models, and are likely to have resulted from the more comprehensive treatments of clouds which appear to induce a positive feedback in addition to that from increased atmospheric water vapour.
- (b) A stratospheric cooling of between 3 and 5 °C.
- (c) An increase in warming with height in the tropical troposphere. In the models, the magnitude of this feature depends on the convective parametrization scheme.
- (d) Enhanced warming at the surface in high latitudes in winter. In the models, the magnitude of this feature depends on the treatment of sea-ice and albedo, and the resulting feedbacks.
- (e) Generally greater precipitation in equatorial regions and in middle and high latitudes, and a tendency to decreased precipitation in the tropics away from the equator. Regional details are very uncertain.

In practice, the thermal capacity of the oceans will delay the development of these changes — the lag may be of the order of half a century (Spelman and Manabe 1984). Also, natural fluctuations of the climate system will continue, and constitute 'noise' above which the greenhouse-gas induced 'signal' must be detected. For temperature, the natural fluctuations are greatest at high latitudes (Jones and Kelly 1983) so (d) above may be obscured. The signal to be sought has to be assumed to be that defined by the numerical models, with the uncertainties specified above. Observations made since the mid-nineteenth century, and particularly in the past few decades, have been analysed with the above considerations in mind.

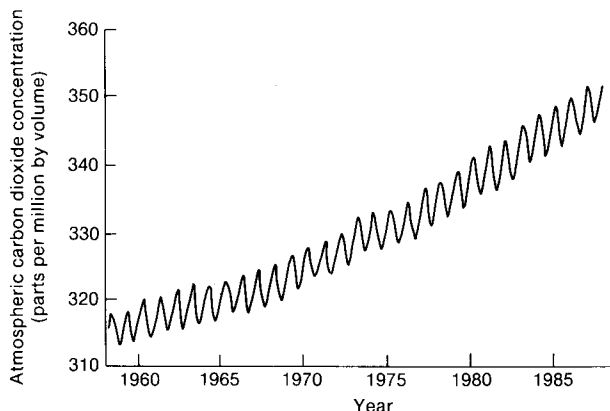


Figure 1. Atmospheric carbon dioxide concentration at Mauna Loa Observatory, Hawaii. All the data were obtained from C.D. Heeling (Scripps Institute of Oceanography).

2. Analysis of air and sea temperatures

After independent adjustment for systematic biases in the data, sea surface and marine air temperatures show very similar global trends since the mid-nineteenth century (Fig. 2). The corrections to sea surface temperature were made using a numerical model of an uninsulated canvas bucket and succeeded in removing the spurious annual cycles in pre-World War II data (Folland and Parker 1988) which had been caused by the enhancement of heat transfers from uninsulated buckets in winter. The corrections to marine air temperatures compensated for long-term trends in deck elevation and for non-standard observing procedures during World War II. Night-time marine air temperatures were used, in order to avoid spurious on-deck heating. The corrected oceanic temperatures are in fair agreement with island station data (Fig. 3) but land areas as a whole were

relatively colder in the nineteenth century except, apparently, in summer in the northern hemisphere (Fig. 4). Urban heating may have slightly accentuated the trends measured over land (Hansen and Lebedeff 1987, Karl *et al.* 1988).

The twentieth century global surface warming has been a little less than 0.5 °C but much of this was before 1940 (Figs 5 and 6) when the enhancement of greenhouse gases was small. The more recent surface temperature trends agree with tropospheric trends derived from radiosonde data (Angell 1988). The most recent warming does not, however, show the enhancement expected in winter at high latitudes (Jones 1988), or the anticipated amplification in the tropical upper troposphere (Angell 1988, Parker 1985b). Also, lower-stratospheric cooling has only been evident since the early 1980s (Angell 1988), and even this may reflect the recent depletion of stratospheric ozone. Furthermore the radiosonde data may be affected by changes in instrumentation (Parker 1985a), which tend to involve improved shielding from radiation, leading to lower observed temperatures. The global surface and tropospheric warming since the early 1980s (Fig. 5) can be partly ascribed to the two strong El Niño events of 1982–83 and 1986–88. El Niño events warm the tropical surface and troposphere in particular for a year or two (Pan and Oort 1983, Parker 1985b).

Since the 1950s, there has been a warming of the southern, relative to the northern hemisphere, especially over the oceans (Figs 2, 4 and 6: see also Fig. 6 of Parker and Folland 1988). This is not an anticipated result of increasing atmospheric greenhouse gases, and appears to involve natural modes of oscillation of the atmosphere and ocean, associated with major changes of atmospheric circulation in the tropics, and marked fluctuations of rainfall in sub-Saharan Africa (Folland *et al.* 1986). The world-wide precipitation changes expected by the models with enhanced atmospheric CO₂ have not yet been unambiguously identified in the observations, which may have been affected by changes in gauge design (Bradley *et al.* 1987).

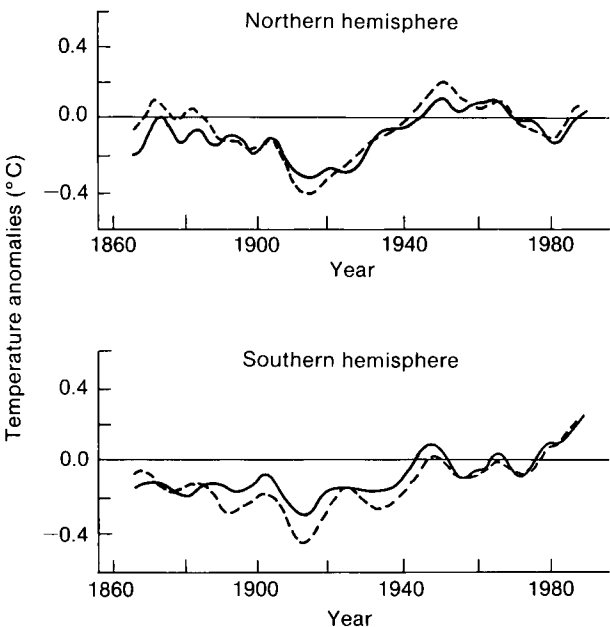


Figure 2. Corrected sea surface temperature (solid) and night-time marine air temperature anomalies (relative to the means for 1951–80). The data are plotted against the end-date of a 10-year triangular smoothing filter.

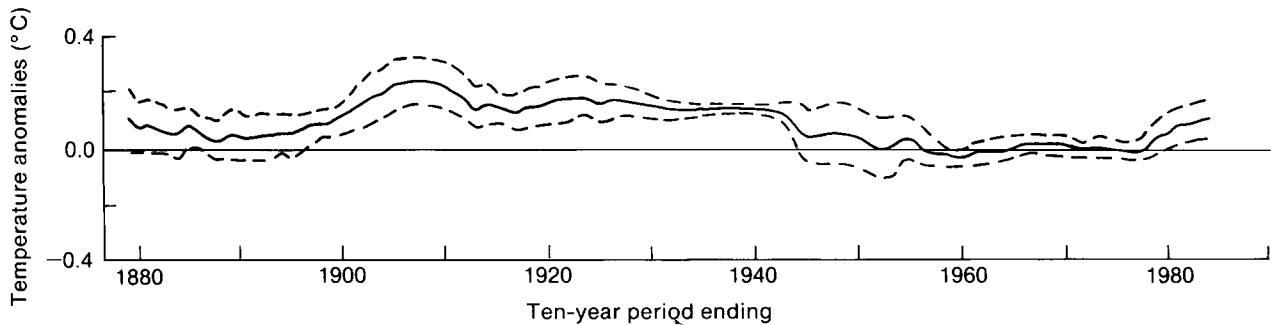


Figure 3. Average differences (solid line), and plus and minus twice the standard errors, between decadal averages of island air temperature and nearby corrected sea surface temperature. Land air temperature data were provided by P.D. Jones (University of East Anglia).

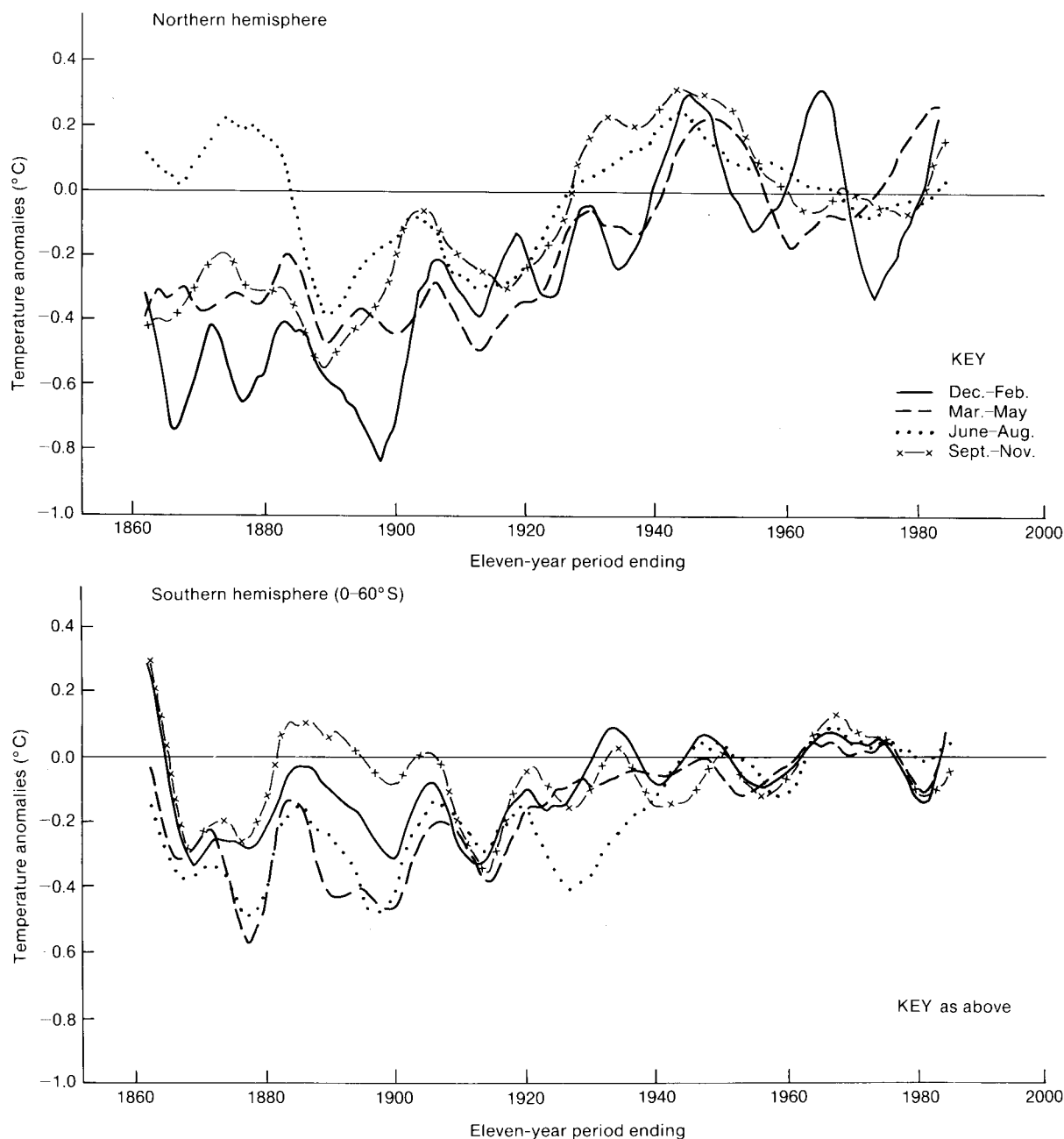


Figure 4. Seasonal land surface air temperature anomalies (relative to means for 1951–80) plotted against the end-date of an 11-year triangular smoothing filter. Data provided as in Fig. 3.

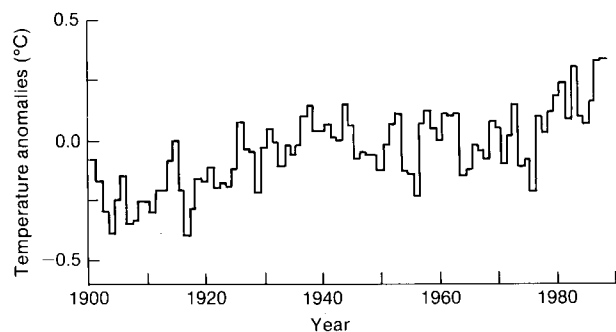


Figure 5. Anomalies of global surface temperature, 1901–88. Data are combined land air temperatures and sea surface temperatures. Land air temperature data provided as in Fig. 3, and sea surface temperatures were adjusted as in Jones *et al.* (1986).

3. Conclusion

There is growing evidence for the importance of the role of variations of atmospheric CO₂ concentration in the climatic changes of the late Pleistocene and early Holocene. The broad-scale atmospheric and oceanic effects to be expected as a result of the recent increase of greenhouse gases are becoming more clearly understood as numerical modelling studies develop, but regional details and the time-scale of the response of the ocean remain uncertain. Observational evidence corroborates the anticipated climatic changes to some extent, but may yet be ascribed to other, natural causes.

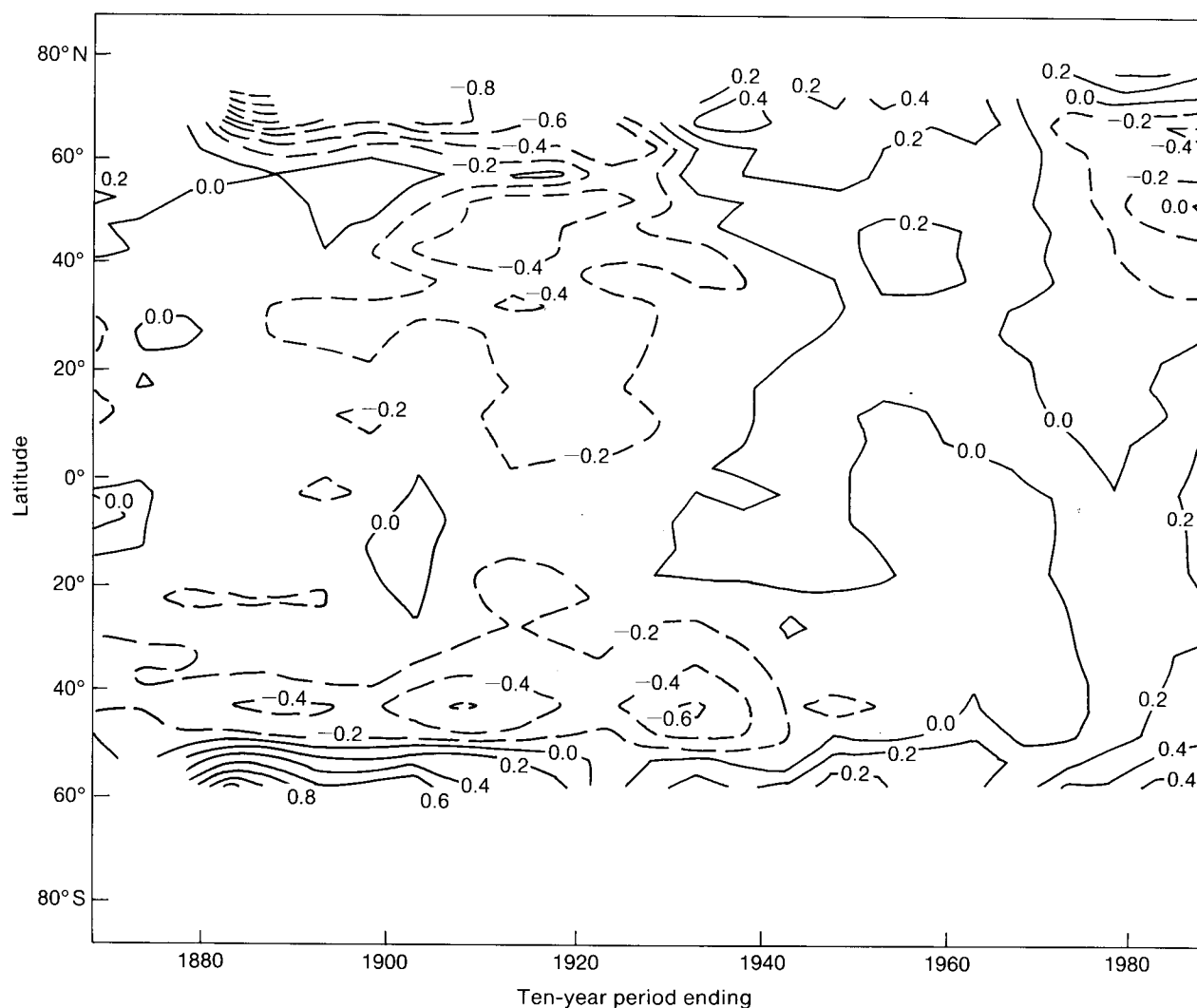


Figure 6. Zonally averaged decadal mean sea-surface temperature anomalies ($^{\circ}\text{C}$) relative to means for 1951–80. The anomalies are updated every 5 years from 1859–68 to 1979–88. Values are calculated for every 5° of latitude, and at least 10% of the ocean of a zone had to be covered for a value to be plotted.

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Trials use of a weighing tipping-bucket rain-gauge

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Summary

This article explains the need for a state-of-the-art rainfall rate recorder for use in trials of modern weapon systems and describes a weighing tipping-bucket rain-gauge (WTBR) which has been developed by the Operational Instrumentation Branch of the Meteorological Office. Measurements made by the new instrument and by a nearby standard tilting-syphon rain recorder, obtained during evaluation trials, are compared.

1. Introduction

All modern weapon systems pass through an extensive programme of testing under field conditions during their development. As part of this, it is required that some trials are carried out in rain. There are several aspects where rainfall affects the operation of weapon systems — two of the more important are the effect of rain on the target detection and tracking systems, and its effect on the actual firing mechanism (the fuse).

The various target detection and tracking devices now used operate over a wide range of electromagnetic frequencies. For example, heat-seeking thermal sensors detect electromagnetic radiation at frequencies within the atmospheric window. Also, targets may be illuminated by infra-red lasers with sensors detecting the reflected laser energy. Such electro-optic devices are adversely affected by the presence of water in the atmosphere, and their use is particularly restricted in rainfall.

Modern fuses are more sophisticated than those of the past. The long-standing impact fuse operates on physical contact with the target and when this occurs the fuse is triggered, causing the detonator to ignite the main explosive. Some ultra-sensitive modern impact fuses can be triggered when passing through heavy rain, which creates a risk to the operator of the system, particularly when the munition is fired from an aircraft as it may subsequently fly through the debris left by the round. Modern larger missiles often also carry a second (proximity) fuse which is designed to identify a near-miss situation and to initiate a detonation without actually making contact with the target. This type of fuse monitors the strength of the emissions of electromagnetic radiation from the target and is designed to trigger at a predetermined level, or when the strength of the emissions has peaked, e.g. as the missile or shell flies past the target. The presence of rainfall can cause a reduction in the strength of the emissions received and so can lead to premature detonation. Clearly, in the testing of modern weapon systems, these effects need to be simulated in trials, and this requires accurate monitoring of the rainfall.

2. Earlier rainfall monitoring devices.

In the past, various devices for rainfall monitoring have been used in trials of military equipment. Some early and ingenious techniques include one in which discs of blotting paper were exposed to rainfall for a short period of time. These discs were impregnated with potassium permanganate dust; impacting raindrops left a clear mark, and the rainfall rate was determined by counting and sizing the impact signatures. Other instruments were developed to make a direct record of the rainfall. These include the 'Jardi', which used a float suspended in a cylinder attached by levers to a pen arm, and the Meteorological Office instrument which consisted of a funnel with a constricted exit so that the channelled raindrops operated a counter switch. The disadvantage of both of these instruments was that only a narrow range of rainfall rates could be measured.

This limitation is largely overcome by the rain-gauges currently in use at most observing sites. The current instruments are the tipping-bucket rain-gauge which registers each 0.2 mm fall of rain, and the tilting-syphon rain recorder which produces a trace for manual post-event analysis. These devices are, however, still unable to meet the requirements for monitoring rainfall in the trials of modern weapon systems, which are:

- (a) The accurate measurement of rainfall rate, for all intensities between drizzle and heavy rain, with a sampling period of as short as 10 seconds, and
- (b) a real-time read-out facility, so that the actual weapon firing can be made at a particular rainfall intensity.

3. The standard tipping-bucket rain-gauge

Most meteorological observing sites are currently equipped with either a Mk.3 or Mk.5 tipping-bucket rain-gauge (TBR). These gauges consist of a collector in the shape of a funnel, with an internal rim diameter of 309 mm providing a collecting area of 750 cm². The collected rain then passes through the funnel tube and into a stainless steel bucket with two identical compartments which is mounted on a spindle. When 15 cm³ of

rainwater (equivalent to 0.2 mm of rainfall) has been collected in one compartment, the bucket tips and the rainfall is then directed into the other compartment. Each time the bucket tips a magnet actuates a reed switch. In addition, the Mk.5 incorporates a second magnet and reed switch providing two outputs.

The outputs from the reed switches are usually fed to one of two types of counter, namely an electromagnetic counter or a solid-state event recorder. The electromagnetic counter simply consists of a four- or five-digit counter which increments by one each time a reed switch is closed by the bucket mechanism. Solid state recorders are now often used as they store the number of tips and the time of their occurrence on a data cartridge.

Obviously, the output from the standard TBR gives information on the time taken between successive increments of 0.2 mm of rainfall or the mean rainfall rate over this time. This duration is usually from about 1 minute or longer (mean rainfall rate 12 mm h^{-1} or less) but at the largest rates the TBR can lose accuracy due to water splashing out of the buckets. In any case, with the TBR changes of rainfall rate within the time between bucket tips cannot be detected. This restriction is overcome with the weighing tipping-bucket rain-gauge.

4. The weighing tipping-bucket rain-gauge

A detailed description of the weighing tipping-bucket rain-gauge (WTBR) is given by Pettifer *et al.* (1980) and Molyneux (1984) and so only a brief summary will be given here. A schematic diagram is shown in Fig. 1. The device is based on a Mk.5 TBR and maintains continuity with the current standard. However, the tipping-bucket mechanism is now suspended from a back plate by a strain wire between the poles of a magnet. This wire is

excited electrically at its resonant frequency, which is dependent upon the tension in the wire due to the mass of the tipping-bucket mechanism. As rain-water from the collector enters the bucket, the tension in the wire increases and the resonant frequency of the wire increases. As the rate of change of mass of the tipping-bucket mechanism is proportional to the rate of change of frequency, by measuring the change in the resonant frequency of the wire, the rate of rain-water accumulation in the bucket can be calculated. The sharp reductions in frequency which occur when the bucket tips are taken into account in the rainfall rate calculations.

The instrument used in these trials is a prototype. It is anticipated that refinements in both hardware and software, which are currently nearing completion, will mean that the instrument will be suitable for more widespread use in the near future.

5. Comparison of results with an open-scale tilting-syphon rain recorder

To illustrate the performance of the instrument, some results comparing the rainfall rates obtained from the prototype WTBR with a standard tilting-syphon rain recorder are shown in Fig. 2(a). Here, 1-minute averaged rainfall rates from the WTBR have been plotted together with 3-minute averages estimated from the tilting-syphon chart for the period 0710–0730 GMT on 30 July 1986 near Aberporth. Both instruments show similar results, with a steady increase in the rainfall rate to 0720, followed by a sharp decrease, then remaining fairly steady at about 2 mm h^{-1} . From 0710 to 0730 the WTBR collected 1.57 mm of rain, which was in reasonable agreement with that estimated from the tilting-syphon chart, which was 1.7 mm. Analysis of

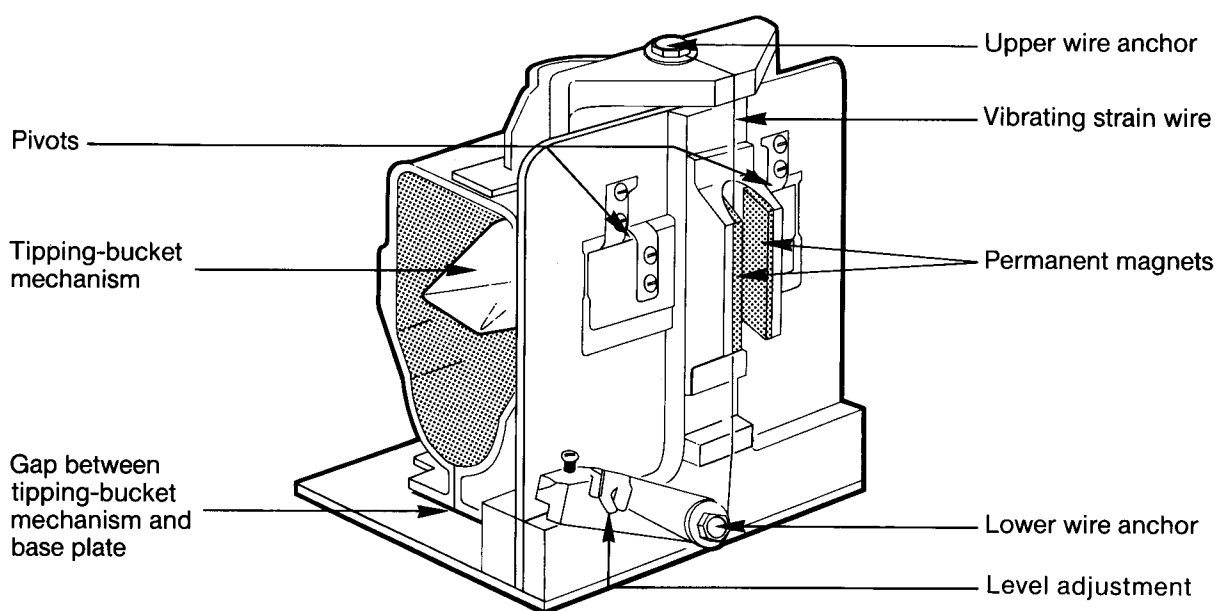


Figure 1. Schematic diagram showing the construction of the weighing tipping-bucket rain-gauge.

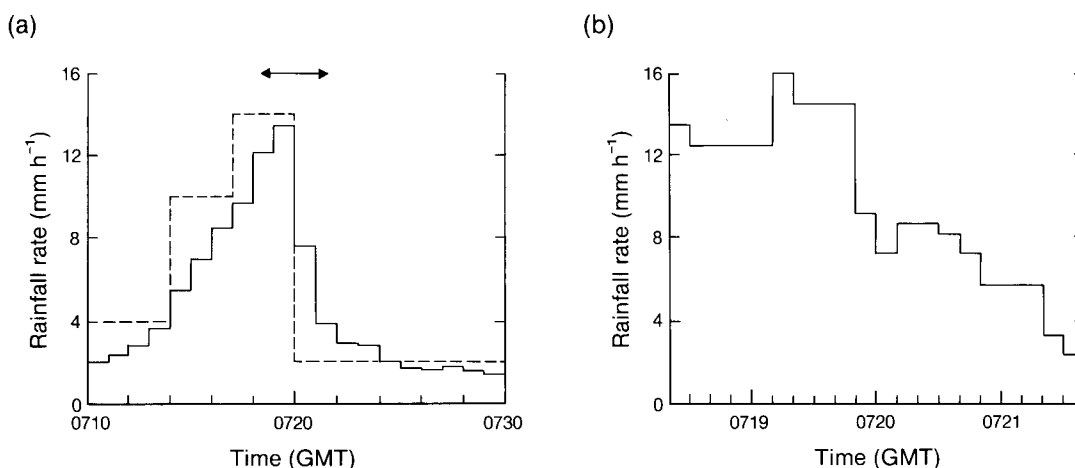


Figure 2. (a) Comparison of rainfall rates derived from the weighing tipping-bucket rain-gauge (solid bars, 1-minute averages) with those from a standard tilting-syphon rain recorder (dashed bars, 3-minute averages) for 0710–0730 GMT on 30 July 1986, and (b) expanded section of the WTBR rainfall-rate record around 0720, indicated by the arrow in (a), with 10-second averaged rainfall rates.

data on other occasions have also shown similar agreement between the two instruments.

Fig. 2(b) shows an expanded section from around 0720, denoted by the horizontal arrow in Fig. 2(a), where the 10-second rainfall rates from the WTBR are plotted. This shows the detailed structure of the rainfall rates, with a peak value of 15.8 mm h^{-1} being recorded.

6. Conclusions

The prototype instrument offers, for the first time, the facility to monitor rainfall rates in real time. This is essential for trials which have to be conducted specifically in predetermined rates of rainfall. Whilst there is an increased degree of error in the 10-second values, experience suggests that it is not excessive. Also, in practice, most trials specify a range of rainfall rates within which the firing must take place, so this is not a problem.

Practical considerations of conducting trials in rain suggest that conclusions drawn from point sampling of the rain at the firing point should be treated with care. In frontal conditions the measured rainfall rate is probably representative for small ammunition with a range of 100–200 m. However, shell ranges from artillery are typically 5000 m upwards, whilst air-to-air and ground-to-air missiles have a range up to several tens of kilometres. The spatial and temporal variations in rainfall rate over these distances are likely to be very significant. As a result, developments in this field of trials support are moving towards the use of weather radar data, combined with the WTBR for local real-time calibration, to define the rainfall over the longer trajectories.

In the future it is likely that weapon target detection and tracking systems will need to be able to select the optimum of several available electro-optic sensors, depending upon the weather conditions, to enable the detection of the target at maximum range. Even with the specialized instrumentation described here, the challenge to forecasters participating in these types of trials is daunting. An accurate assessment of the time of onset of suitable rainfall is needed, not just at the firing point, but along the trajectory. Also required are estimates of the likely duration and short-term changes within a time-scale of minutes. Such weapon systems will also require forecasts of cloud base, wind strength and visibility, so that their performance can be evaluated. This will require forecast products from many sources, e.g. output from sophisticated numerical models and real-time on-site interpretation of weather radar and satellite data.

Acknowledgements

Thanks are due to the Surface Instrument Development Group of the Operational Instrumentation Branch of the Meteorological Office who designed and built the modified instrument.

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Awards

L.G. Groves Memorial Prizes and Awards for 1987

The memory of Sergeant Louis Grimble Groves, RAFVR, who was killed in September 1945 while serving as an Air Meteorological Observer with 517 Squadron Coastal Command, is perpetuated through the endowment of the annual L.G. Groves Memorial Prizes and Awards by his parents, Major and Mrs Keith Groves. The 1987 awards were presented by Air Marshal Sir Kenneth Hayr, CB, CBE, AFC, RAF on 25 November 1988 at HQ Strike Command (High Wycombe), and the citations were read by the Inspector of Flight Safety Air Commodore G.R. Profit, OBE, AFC, RAF. The ceremony was attended by representatives of the RAF and the Meteorological Office, and by the wives of the award winners, but, sadly, no members of the Groves family were able to be present at this, the 41st anniversary of the awards.

Meteorology Prize — Dr A.P. Cluley, Mr T.S. Hills

The citation for this award was:

'By the early 1980s there was extensive use of computing to support forecasters in large offices such as the Central Forecasting Office at Bracknell and the Principal Forecasting Office, HQSTC, but small offices on RAF stations were wholly reliant on teleprinter and facsimile channels for the receipt of meteorological data. A long-term strategy, which came to be known as Weather Information System (WIS), was conceived whereby these channels would be replaced by an advanced digital communications network, and the reams of paper by a small computer in each office. This latter element of WIS was called the Outstation Display System (ODS) and its purpose was to hold a database of observations and processed data from which the forecaster could retrieve information in a variety of formats. The ODS concept was refined using a prototype during 1984/85 and the first batch of 15 systems was procured and installed at 8 key RAF stations early in 1987. Subsequently, a second batch of ODS equipment has been installed early in 1988 extending the coverage to a further 8 RAF stations plus HQSTC, Met O College and Manchester Weather Centre.

ODS is the result of much teamwork, but two individuals stand out. First, Dr A.P. Cluley was the project manager from the inception until the first batch of systems were operational. His leadership and energy were vital ingredients in driving the project through the stages of requirement specification, prototyping, procurement, initial systems development and installation. He overcame many technical and administrative problems and achieved installation of the first batch on schedule. Second, Mr T.S. Hills, now project manager, was responsible for the software design. The high quality of



Dr A.P. Cluley and Mrs Cluley on the left, Mr T.S. Hills on the right and Air Marshal Sir Kenneth Hayr.

his own work and his success in blending together the contributions of his team of programmers have resulted in a system which meets the requirement, is very reliable and is, above all, a model of 'user-friendliness'. The design shows real understanding of the working environment of the forecaster serving military aviation.'

This award was made to Paul Cluley for work undertaken whilst in the Systems Development Branch of the Meteorological Office, a period from 1983 to 1987. His career in the Meteorological Office started in 1972 and he worked in the Meteorological Research Flight (MRF) at Farnborough from 1973 to 1978. After a short spell at Headquarters, he was promoted to Principal Scientific Officer in 1980 and spent three years at Heathrow Airport as Deputy Chief Meteorological Officer. In August 1987 he was promoted to Grade 6 and appointed as Assistant Director for Data Processing.

Trevor Hills joined the Meteorological Office in 1976 and worked on computer modelling of the world climate until 1983. His work in this field varied from examining the effect of varying the model's grid resolution in polar regions to automating the long-running programs required for climate modelling. He was one of the first Meteorological Office staff to use the Cyber 205 supercomputer, visiting the USA to gain experience with the machine while it was still in the factory. After a short spell at the forecasting bench he spent a year working in the IBM mainframe operating system team. In 1985 he was posted to the Systems Development Branch where he worked with Dr Cluley to specify the hardware and develop the software for the ODS project. In 1987 he took over full responsibility for ODS and for other computer systems to support outstations.

Award for Meteorological Observation —Mr K.J. Dewey

The citation for this award was:

'During 1987 the aircraft of the Meteorological Research Flight (MRF) took part in two highly successful major international experiments. The success of these experiments relied heavily upon the dedication and professionalism of all the air observers, of which Mr Dewey (HSO) is singled out for his particular contributions both to instrument development and to flying duties. During the two years prior to the experiments, Mr Dewey was responsible for solving the mechanical, electronic, data processing and environmental problems of adapting a 16-channel radiometer for deployment on the aircraft. This radiometer was originally designed as a prototype satellite instrument, and is considerably more complex to maintain and operate than most scientific equipment installed on the aircraft. The radiometer was crucial to the success of MRF participation in the first international experiment, and was operated successfully, often under stress, by Mr Dewey on all 14 flights of that experiment. During the second experiment (for which the radiometer was not required) and during other, home-based operations, Mr Dewey participated regularly in flight duties, and, as a flight leader, has earned the respect of everyone who has worked with him. Much of this work involved long hours including some weekend and night flying.'

Ken Dewey joined the Office in 1961 as an Assistant at Uxbridge. He made the most of his opportunities to travel and between 1964 and 1969 he was posted to Labuan, in Borneo, Gan and Bahrain. After a spell at Gloucester he retrained as an R(M)T and subsequently was posted to Crawley radiosonde station until promotion required a move to Beaufort Park. The lure of the tropics was still strong though and at the first opportunity he went off to Tarawa in the Gilbert Islands (now Kiribati). On his return he joined the Cloud Physics Branch working on the cloud physics and



Mr K.J. Dewey flanked by Mrs Dewey and Air Marshal Sir Kenneth Hayr.

dropsonde instrumentation as fitted to the MRF Hercules aircraft. A promotion to HSO produced another move, this time to the Radar Research Laboratory at Malvern for a short period before joining the MRF at Farnborough in 1985 where he has been mainly involved with the Multi-Channel Radiometer and as a flight leader on the aircraft. This has enabled him to satisfy his continued wanderlust in allowing detachments to places as far afield as San Diego, Dakar and Machrihanish.

Air Safety Prize and Ground Safety Award

This year the Air Safety Prize was won by a five-man team from HQSTC — Wing Commander A.J. Thorpe and Squadron Leaders A. Melville-Jackson, B.C. Holding, D.L. Warner and P.J. Bonsall — who produced a series of videos promoting flight safety. The Ground Safety Award was given to Chief Technician D.F. O'Reilly of RAF Cottesmore for devising a set of blanks to protect Tornado GR1 systems when the aircraft is on the ground.

Notes and news

The death of Sir Harold Jeffreys

The death is noted, at the age of 97, of Professor Sir Harold Jeffreys, who as far as is known, was the last surviving link with Sir Napier Shaw, the Director of the Meteorological Office from 1905 to 1918 and from 1919 to 1920. Harold Jeffreys D.Sc. became an 'Assistant' on the secretarial staff of Sir Napier Shaw during the year ending March 1918. By the time of the Annual Report of March 1920 he had gained an MA and had become a 'Professional Assistant'. The Annual Report of March 1921 reveals that by then both Shaw and Jeffreys had left the Office to pursue more academic careers. Ultimately Sir Harold became Emeritus Professor of Astronomy and Experimental Philosophy at Cambridge. Included in his writings were several papers related to meteorology, and copies of them are lodged in the National Meteorological Library at Bracknell. One of his many books, *The Earth; its origin, history and physical constitution*, was first published in 1924, revised by himself through six editions over 52 years, and is still in print. In the early days of the 1960s, when artificial earth satellites were still novel, the Editor (as a young and inexperienced scientist) had the honour to serve with Sir Harold on the Satellite Orbital Analysis Working Group of the British National Committee on Space Research. He is recalled as being very much a classical geophysicist but nevertheless having a keen appreciation of the potential impact on geodetics of studies of the effect of gravitational perturbations on satellite orbits. An obituary of Sir Harold appeared in the *Daily Telegraph* on 21 March 1989 and an appreciation of him written by Dr Raymond Hide was published in the April 1989 issue of the *Quarterly Journal of the Royal Meteorological Society*.

Reviews

Long and short term variability of climates, edited by H. Wanner and U. Siegenthaler. 164mm×242mm, pp. 175, *illus.* Berlin, Heidelberg, New York, London, Paris, Tokyo, Hong Kong, Springer-Verlag, 1988. Price DM 48.00

For a number of years, the Climatic Research Unit at the University of East Anglia has been involved in teaching a third-year undergraduate optional course on Climatic Change. The course falls naturally into three segments: evidence, causes and impacts. In the past, it has never been possible to recommend a set book for the course that would cover more than one of the three components to the required depth. This fact, combined

with the impecunious state of the student body, has meant that we have opted to dispense with a set book, and have relied instead on journal papers. As all lecturers will be aware, this approach has certain disadvantages — some students will take it as a licence to read nothing at all, some will attempt to read everything, and inevitably, by the end of the academic year, most of the journals will have gone missing anyway. With a good set book, on the other hand, a certain minimum body of knowledge should be within the reach of every course participant. Here we have such a book, covering at least two aspects of our course, evidence and causes, both thoroughly and in a most up-to-date manner.

The book is the sixteenth in a series called Lecture Notes in Earth Sciences. Whereas others in the series have been primarily concerned with geology and geomorphology, this is the first to deal with atmospheric sciences. It contains eight papers by a number of eminent European scientists, divided under the loose headings 'Observational Studies' and 'Modelling Studies'. Papers on evidence and causes are included under both headings. Thus, under 'Observational Studies' there are contributions on the detection of climatic change in the instrumental record (Jones and Kelly), on tree growth rings (Schweingruber) and on documentary records of, for example, harvest dates (Pfister). Papers on causes are by Fröhlich (on the variability of the solar constant) and by Duplessy, Labeyrie and Blanc (on variations in Norwegian Sea deep water over the last climatic cycle). Under 'Modelling Studies' there is a general essay by Grassl on numerical models — how they work, what their inherent errors are and how they can be used for detection studies. The following papers are on forcing by the orbital parameters (Tricot and Berger) and a very comprehensive study of the causes and effects of carbon dioxide variations in glacial-interglacial cycles (Siegenthaler).

The book is softback and the text is camera-ready. As such, the price (which is not available to me) should be reasonable and within the reach of students. This is a good thing, as the text is clearly aimed at the later years of undergraduate study and/or the postgraduate market. The book is very successful at achieving this aim. However, for three reasons it deserves to be more widely read as a reference text by scientists working in the field of climatic change. Firstly, the articles are written by scientists working at the forefront of their field in countries where, with one exception (Jones and Kelly) English is not the mother tongue. As such, it presents a European view of the science of climatic change to English-speaking researchers accustomed to the North American or British stance. Secondly, camera-ready production has meant that the book has appeared very quickly, and therefore the essays are all state-of-the-art. Thirdly, most of the papers are accompanied by extensive, and very useful, reference lists.

The real strength of the book is in bringing together a collection of up-to-date papers on research on the frontiers of the science of climatic change. In this and other aspects, the book is most timely and most valuable. My only regret is that, without a section on climate impacts, it is not the perfect teaching textbook. I can only hope for a second edition.

J.P. Palutikof

How to write and publish a scientific paper, third edition, by R.A. Day. 155 mm × 235 mm, pp. xi+212, *illus.* Cambridge University Press, 1989. Price £7.95 (paperback), £20.00 (hardback).

This book, written in Anglicized American, is a joy to behold. The author describes it as a 'cookbook', not for cooking results but for providing recipes for success in scientific writing — it should sell like hot cakes. Every question the reader has ever wondered about asking in this subject appears to have an answer provided. Practical advice is given generously in all areas, without necessarily expecting it to be taken, but at the same time challenging and encouraging the reader, from an experienced position, to think of something better, if possible. The language and presentation are very clear and succinct while at the same time being amusing, anecdotal and eminently readable — open at any page and one is captured.

The book commences with a definition of scientific writing, its history and then a definition of a scientific paper. Each chapter has its pithy, italic quote for starters, something which I always enjoy in a book. The title of the book is slightly off-putting if one thinks that one will never aspire to write a scientific paper, but other forms of writing science, such as conference reports and reviews are covered — the latter read avidly by this reviewer, with this result.

In following chapters, the scientific paper is dissected into nine component parts which are considered separately. Incidentally, dissection is an appropriate term, the slant if anything being on biology, but this does nothing to detract from the book's general application to science. The few illustrations are medical/biological, but are mainly used to give advice on whether diagrams or tables should be used for various topics, or that often a sentence of text can be better than either. Beside the crackling text, the Peanuts cartoons, although a good idea, appear pedestrian. In most publications they provide the comic relief.

Further chapters, on associated information, deal with editors, proofs, where and how to submit, ethics (including copyright), use of English, etc., the last being a potential minefield for English purists. More useful information is provided by six appendices, a glossary and references; the index is interesting and varied, and is headed by an acknowledgement to the compiler, which is rare but thoughtful, because a good index is a labour of love.

For less than £8 (in paperback), this is a bargain for anyone with the vital task of setting science, in its many forms, on the printed page. It represents a saving akin to the author's example of spending a lot of money on a piece of equipment and then 'saving' by not spending a little to have it drawn properly for your scientific report on it. One wonders how scientists have managed without it, but since it is the third edition ('larger and better') perhaps many authors have been referring to a previous edition for years.

S.H. Barker

A glossary of computing terms, fifth edition, edited by the British Computer Society Committee Glossary Working Party. 147 mm × 209 mm, pp. xii+73, *illus.* Cambridge University Press, 1987. Price £1.95, US\$3.95.

The glossary consists of two parts; in the first part there is an alphabetical index of terms, each with a numeric code of chapter and paragraph, which in turn directs the enquirer to a location containing the relevant definition in the second part of the book. The chapter headings tell the reader what types of definition he will find therein, such as Communications, Documentation, Input and Output, Programming, etc.

Ideally, a book of this type should be independent of any particular manufacturer's wares, and it was a pleasure to read it and find only minimal references to any company names. The book is not really one to be read through from beginning to end, nevertheless it is short enough for that task not to be too arduous. The type-face and lay out are clear, easy to read and up to the usual high standard of the Cambridge University Press, but a few errors have crept in — why is it that, in these days of word processing, there seems to be a school of thought which says that proof reading is no longer necessary? It was at least ineffective for the definition of 3.6 (bit), which appears to have a repetition of the text for 3.7 (block). The use of cross-references by the numeric codes in the main body of the book has resulted in some of the errors, probably caused by insertions of new definitions. Where cross-referencing is necessary, it would be better to use the relevant term and leave the reader to look it up in the index.

The reviewer would take issue with the authors on a few definitions. If Kbyte is defined for computers as 1024 (2 to the power of 10) then surely Mbyte is 1 048 576 (2 to the power of 20). There is also something slightly amiss with the definition of 3.67 (variable record) as one where the number of bits (or characters) is not predetermined. The length of a variable record is contained within a preliminary descriptor word or series of bits, and may well be predetermined. Perhaps a future edition could clarify this under a separate heading 'record type'. A similar treatment has already been given to 2.4 (character codes), but this needs the addition of

ASCII, ANSI and EBCDIC to the index for completeness. As far as 2.2 (baud) is concerned, the authors are at odds with some other reference books in assuming 'for convenience' that it is one bit per second.

Nevertheless, having said all this, it is only fair to point out that there are no more than a dozen errors to be seen in 800 definitions. Despite the above criticisms, this book must be on the shelf of every school and technical college library for quick and easy reference. The authors clearly set out to provide them with an inexpensive *aide-memoire*, and have successfully achieved this, also reaching a much wider audience in the process.

J.W. Prince

The weather journals of a Rutland squire, edited by J. Kington. 185 mm × 245 mm, pp. xii+217, *illus.* Oakham, Rutland Record Society, 1988. Price £15.00.

By bringing together so many of the writings of Thomas Barker of Lyndon Hall and providing also a potted biography of the man, John Kington and the Rutland Record Society have done a good service for the climatology of the eighteenth century. They have clothed the dry records with a sense of the presence of a keen and methodical observer both of the weather and the countryside, whose position allowed him to indulge his interests to the full. That meteorology was one of them is to our benefit.

As a boy Barker met Gilbert White of Selbourne, a friendship which continued and deepened throughout their lives, and reference to the Lyndon Squire and his records occur in many of White's writings. Throughout his long life he maintained his enthusiasm and produced consistent records over a period of more than 60 years. Unfortunately, as with so many similar records and diaries, the manuscripts have suffered through the carelessness of posterity, volumes have been lost and all are scattered. It is a tribute to the editor's energy that so much is made available.

Like all his contemporaries Barker was free to set his own standards and expose his instruments as he desired. For his 'temperature abroad' we only know that the thermometer was 'outdoors in the shade', while his rain cistern is on top of a wall where it meets another at right angle, 7 ft 3 ins on the north side, 8 ft 6 ins on the south-west and 10 ft on the south-east.

But in spite of these limitations the records at Lyndon covering the period 1733–98 have long been accepted as one of the better sources for that period and it is strange

that until now there has been no single volume dealing with them. The Annual Reports which he submitted, through friends, to the Royal Society from 1771–98 have previously only been available in the few remaining copies of the *Philosophical Transactions*. They expand and supplement his own *Meteorological Journal* 1733–95 given in earlier chapters. In all of his records he deals with the effects of weather on nature and on agriculture, and so provides ample material for a social history of the period.

As a contribution to the records of the sadly departed Rutland this book fills an important niche, to a climatologist both the text and bibliography will be of considerable benefit, whilst to the general reader there is much of interest with source material of the 'Coldest/wettest...' type, and all this for a not excessive £15.

F.J. Ayres

Books received

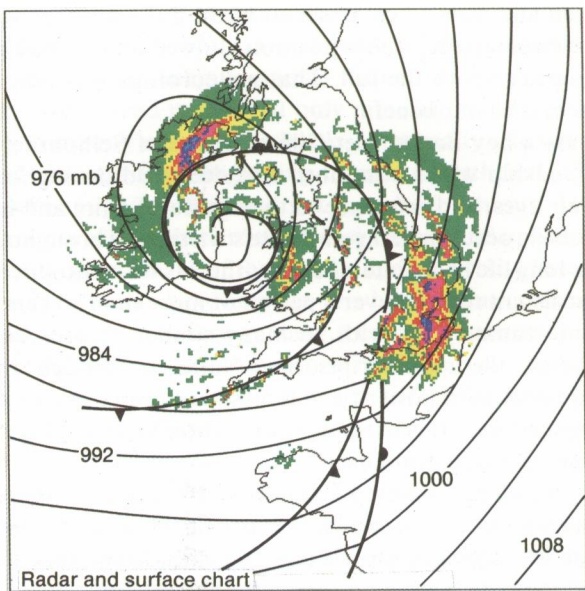
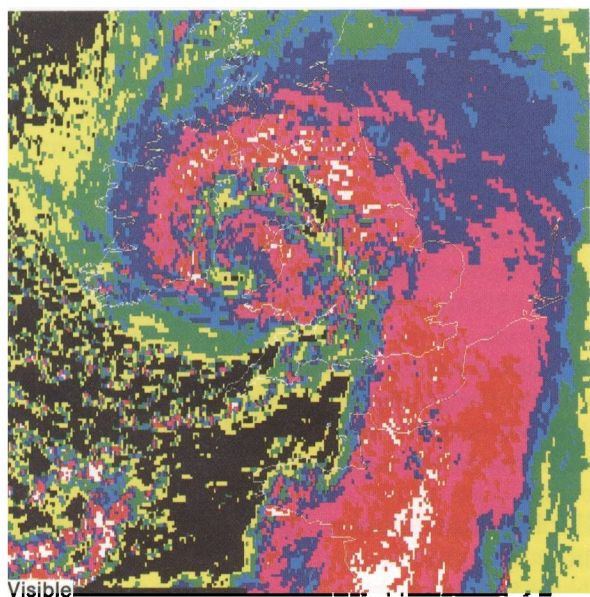
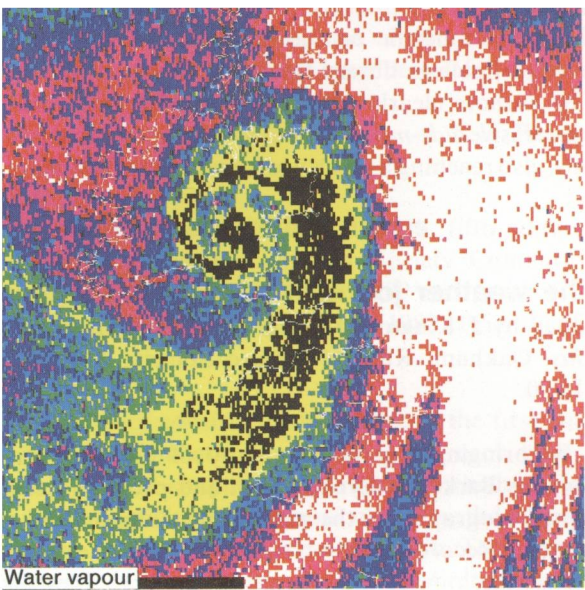
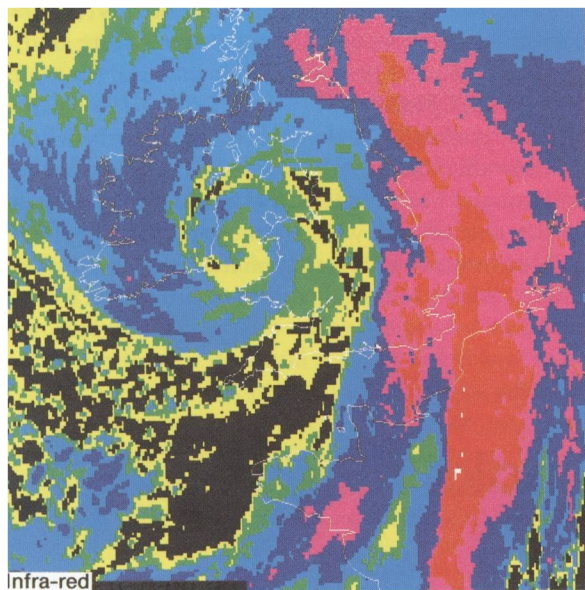
The listing of books under this heading does not preclude a review in the Meteorological Magazine at a later date.

The geostationary applications satellite, by P. Berlin (Cambridge University Press, 1988. £30.00, US\$49.50) gives an overview of the design, construction, launch and orbital flight of the subject, with a section on meteorological payloads. It has been written from a background of practical involvement in a project management team.

Solitons: an introduction, by P.G. Drazin and R.S. Johnson (Cambridge University Press, 1989. £11.95, US\$19.95 (paperback), £32.50, US\$59.50 (hardback)) is a textbook on the theory of solitons and its diverse applications to non-linear systems that arise in physical sciences. The generation and properties of solitons are explained, and the mathematical technique known as the Inverse Scattering Transform is introduced.

Glacier fluctuations and climatic change, edited by J. Oerlemans (Dordrecht, Boston, London, Kluwer Academic Publishers, 1989. Dfl.195.00, US\$109.00, £64.00) contains papers dealing with glacial geology, mass balance studies, snow drift, modelling studies and energy balance and climatology of the glacier surface. Collectively they form a unique book on the central theme of how retreat and advance of glaciers is related to climatic change.

Satellite and radar photographs — 11 April 1989 at 1300 GMT



The Meteosat and UK radar network images portray a remarkably well-defined spiral of cloud, upper tropospheric moisture and precipitation, associated with an intense depression that had deepened explosively over the preceding few hours. The spiral is composed of alternating bands of dry air (where upper cloud and precipitation are largely absent) and moist air (considerable upper cloud and precipitation present). A surface occlusion can be drawn along the rear (or inner) edge of the moist air into the centre of the vortex. Note that on

the radar image, the precipitation gaps within the spiral over southern Scotland and the Celtic Sea are due to poor radar coverage.

In the satellite images (which are slightly mis-registered) the colour sequence: black, yellow, green, cyan, blue, magenta, red and white represents warm to cold in the infra-red, dry to moist in the water vapour and dark to bright in the visible. The radar colour sequence: green, yellow, red, magenta, blue and cyan represents progressively increasing rainfall rates.

GUIDE TO AUTHORS

Content

Articles on all aspects of meteorology are welcomed, particularly those which describe results of research in applied meteorology or the development of practical forecasting techniques.

Preparation and submission of articles

Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately. Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary* (latest edition). Articles prepared on floppy disk (Compucorp or IBM-compatible) can be labour-saving, but only a print-out should be submitted in the first instance.

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

Tables should be numbered consecutively using roman numerals and provided with headings.

Mathematical notation should be written with extreme care. Particular care should be taken to differentiate between Greek letters and Roman letters for which they could be mistaken. Double subscripts and superscripts should be avoided, as they are difficult to typeset and read. Notation should be kept as simple as possible. Guidance is given in BS 1991: Part 1: 1976, and *Quantities, Units and Symbols* published by the Royal Society. SI units, or units approved by the World Meteorological Organization, should be used.

Articles for publication and all other communications for the Editor should be addressed to: The Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ and marked 'For Meteorological Magazine'.

Illustrations

Diagrams must be drawn clearly, preferably in ink, and should not contain any unnecessary or irrelevant details. Explanatory text should not appear on the diagram itself but in the caption. Captions should be typed on a separate sheet of paper and should, as far as possible, explain the meanings of the diagrams without the reader having to refer to the text. The sequential numbering should correspond with the sequential referrals in the text.

Sharp monochrome photographs on glossy paper are preferred; colour prints are acceptable but the use of colour is at the Editor's discretion.

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June 1989

Editor: B.R. May

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Editorial Board: R.J. Allam, R. Kershaw, W.H. Moores, P.R.S. Salter

No. 1403

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