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I think it was Einstein who was a asked what he would say to God when he got to heaven. The great man said he would ask the almighty to explain turbulence, but he did not really expect to understand the answer! This paper does not fully explain turbulence, but you should be able to understand it (the paper that is). So, whatever you may think of the topic you should give the following a try.

Editor

551.551:551.511.6:551.509.313.4

Turbulence simulation in the Meteorological Office

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Summary

Progress in simulating turbulence in the Meteorological Office is described. Applications of the 'large-eddy' model include boundary layers, gravity waves and clouds of various types. In each area there is some evidence of good performance. The technique has considerable potential for increasing our understanding of atmospheric processes and helping to improve forecast model parametrizations. Validation of the model using high-quality observations continues to be very important..

1. Introduction

One of the functions of the Atmospheric Processes Research (APR) Division of the Meteorological Office is to study phenomena which in forecast or climate models need to be 'parametrized', i.e. represented in a simplified way. Such processes are generally 'subgrid-scale', i.e. they occur on scales which are too small for the large-scale model to resolve. The art of parametrization is to represent in a simplified and computationally efficient way the large-scale effects of the process concerned in terms of the resolved variables of the model.

'Atmospheric Processes' include clouds, radiation, turbulence and gravity waves. The first three have been thought of as 'physics' rather than 'dynamics', a classification which is natural for radiation. But turbulence, just like weather systems, obeys laws of fluid dynamics and is not just a branch of statistical physics. Although parametrizations involve predicting turbulence statistics, and fluxes in particular, their derivation requires considerable dynamical understanding. For clouds too, the dynamical circulations can be just as important as the 'physical' processes. Of course the point is that traditional distinctions between 'dynamics' and 'physics' now seem increasingly arbitrary and outdated. There is a significant distinction, on paper at least, between reversible and irreversible processes, but in the real atmosphere the two can never be completely separated.

Turbulence is important first of all because it largely controls the profiles of wind, temperature, humidity and other variables, e.g. pollutant concentration, in the lower atmosphere. We often talk of 'turbulence in the boundary layer' but the depth of the boundary layer is quite variable, and indeed during deep convection the boundary layer may in a sense extend to fill the troposphere. Most clouds are turbulent to some extent, whilst clear-air turbulence is well known to aviators. So the applicability of atmospheric turbulence modelling is rather wide. In terms of climate models or extended-range forecasting the turbulent exchange of heat, momentum, humidity, etc. between the atmosphere and land, sea or other surfaces is particularly important, as is also the turbulent contribution to the dissipation of atmospheric disturbances which arise on much larger scales.

In the Meteorological Office we seek to understand and predict the effects of turbulence in a practical context. It is not enough to gather abstract understanding on its own, indeed making testable predictions is arguably the essence of science. However, we still need reliable and up-to-date theories to help organize our predictions and help analyse any real or apparent discrepancies between forecasts, or hindcasts, and observations. In the important area of climate change for instance, we need models based on a 'firm physical basis with a minimum of adjustable parameters' (Mitchell and Zeng 1991), and not simply on a fit to present-day climatology. This is why the climate issue has stimulated research in almost every area of 'atmospheric processes'.

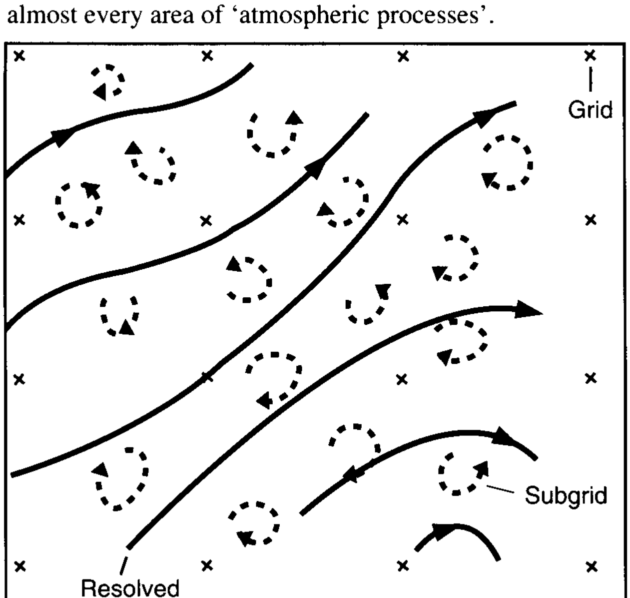

Figure 1. Sketch showing resolved (full lines) and subgrid (dotted) motions. The resolved flow can be represented explicitly in a model by storing the velocity at each grid-point (x): The subgrid motions can not; their effects must be represented statistically.

Amongst the questions we need to answer in detail are: how exactly does turbulence affect clouds? What determines the formation, persistence or break-up of stratocumulus and other layer clouds? Do convective clouds transport momentum significantly? How deep is the boundary layer under various conditions, and how fast does entrainment deepen it? How much drag is carried from topography by gravity waves, and where is it deposited? How much heat and momentum are transported during intermittent turbulence associated with stable nocturnal conditions? ...not to mention many questions relating to pollution dispersion and other practical concerns.

Last, but in some ways most important, how should all these effects be represented in forecast models? Capturing the essential behaviour of the atmosphere in a computationally economical,and therefore usually simplified manner is an art in itself, but good parametrization rests on an accurate knowledge of the true physics. So one aim of research is to provide accurate standards against which parametrizations can be tested.

A dynamical approach to the above questions is essential. Given the complexity of turbulent flows this makes computer modelling an important tool. The models used are similar in principle to forecast models, even though the dynamics of 3-D boundary layer turbulence differ considerably from those of weather systems. In boundary layers, because the time and length scales are smaller, the appropriate Rossby number* is much higher, so the Coriolis effect of the Earth's rotation is less dominant. However, a wide range of significant scales may exist within the same turbulent flow, typically from 1 km to 1 mm. Hence we cannot just compute everything by brute force, and must instead parametrize the small eddies which slip through the computational mesh, but are crucial to the dissipation of turbulent kinetic energy.

In the context of turbulence modelling this procedure is called 'large-eddy simulation' (LES). The 'large eddies' are computed explicitly ('resolved') while the small ones, including their effect on the large eddies, are parametrized ('subgrid') — see Fig. 1. The rationale is that we think we more or less understand the small eddies from 'universal' turbulence theories but the large ones vary more between particular flows, e.g. between stable and unstable conditions. The word 'simulation' implies that the resolved and subgrid motions taken together should statistically mimic atmospheric turbulence, but the timings of transient eddies cannot be taken literally. Compare a 'climate simulation' which may to some extent, depending on resolution, represent weather systems in the next century but cannot predict particular weather on, say, 24 August 2023.

The equations needed for our LES model are not very different from those used in numerical weather prediction or climate models, both being derived from equations describing the dynamics and thermodynamics of air

* See Appendix

in a rotating reference frame. The differences lie in the approximations and idealizations which are made. In synoptic-scale models the hydrostatic assumption is appropriate because vertical accelerations are relatively small when averaged over grid squares typically 100 km square. Such an assumption is clearly inappropriate in a model of horizontal resolution 1 km or less. For 3-D turbulence or convective cloud simulations, the vertical component of acceleration has to be calculated from Newton's 2nd law just like the horizontal components are. Unfortunately the full equations of motion permit sound waves. Sound waves are not thought very important in real atmospheric dynamics, but cause trouble in models, for technical numerical reasons, when their period of oscillation is comparable to or smaller than the model time-step. So steps must be taken to eliminate or control them. In a model confined to the boundary layer, the assumption of incompressibility is an acceptable approximation, but to model deep convection properly we have to allow expansion and contraction due to vertical motion, as atmospheric pressure varies with height. This is done by making the deep anelastic approximation (Lipps and Hemler 1982). Because the domain of the LES model only covers a small portion of the earth's surface we do not have to worry about curvature effects and spherical coordinates: ordinary cartesian coordinates (x, y, z) are good enough.

2. Boundary-layer modelling

In recent years the Meteorological Office, particularly P.J. Mason, has been in the forefront of developing large-eddy simulation, especially in its application to atmospheric flows. However the origins of LES were in America in the 1960s and early 1970s, when meteorologists Smagorinsky, Lilly and Deardorff developed it into a convincing method of turbulence simulation, the first application being the structure of convective boundary layers.

The basic instabilities responsible for convective turbulence are fairly robust and insensitive to subtle details of profiles, boundary conditions or numerical computation method. A superadiabatic layer will support convective instabilities unless the viscous-diffusive terms are large, which they rarely are in the atmosphere. However, detailed flow structures such as shown in Fig. 2 require quite high resolution to be computed accurately. Mason (1989) showed that various subtle but important features of the convective boundary layer, including the 'skewness' of the probability distribution of vertical velocity, were misrepresented by coarse resolutions. This skewness means physically that updraughts tend to be narrow and vigorous, but downdraughts broad and sluggish.

Here by 'convective boundary-layer' we refer to shallow convection occurring when the boundary-layer is unstable but the free troposphere fairly stable. Such convection may be marked by small cumulus. Simulations of deep convection and other clouds are discussed in section 4. There are dynamical similarities between deep and shallow convection, but to model deep convection requires more 'physics'.

Recently Mason (1992) has used LES to release and track 'particles' in a convective simulation both with and without wind-shear. This provides a means of predicting how the dispersion of pollutants changes according to boundary-layer winds and stability.

Convincing simulations of thermally neutral boundary layers, where turbulence is driven by wind-shear, have been possible only fairly recently. Mason and Callen (1986) showed that certain technical problems previously attributed to parametrization errors (laminarization occurred, i.e. turbulence died out, unless the subgrid viscosity was made rather small) were really associated with model resolution. This implies that a fair-sized computer is needed for shear flow simulations! Armed with this knowledge, Mason and Thomson (1987) successfully simulated a neutral boundary layer.

Completely neutral boundary layers are hard to find in nature, because some thermal stability or instability is usually present. Why bother modelling them then? Well, strong-wind situations, especially over the sea, are often 'nearly neutral', with small Richardson numbers*. But also, in testing our simulations initially we need to focus on certain idealized cases which approximately correspond to a reasonable quantity of reliable data. In time one obviously progresses to modelling 'complex situations', and we shall outline in section 5 some ideas for dealing with these. It is simply a matter of learning to walk before trying to run.

Mason and Thomson analyzed many features of the neutral boundary layer, such as the elongation of gust structures along the wind, which is characteristic of shear-driven turbulence. One perhaps surprising conclusion was that the computational domain needs to be very deep, up to 10 km or so, before the effect of the upper boundary becomes negligible. This slightly disquieting result underlines the somewhat unrealistic nature of the strictly neutral boundary layer, as stability effects will become important well below 10 km. Bull and Derbyshire (1990) discussed further the relation between simulations and parametrizations of the neutral boundary layer.

Stable, typically nocturnal, boundary layers remain somewhat enigmatic and inordinately sensitive to influences such as small slopes. It is therefore often hard to interpret stable boundary layer observations. Some datasets seem very complicated, unsteady and sensitive to local effects; others show simplifying features like 'local scaling' (Nieuwstadt 1984) (local scaling or local similarity implies for instance that the turbulent energy balance applies locally, and that certain energy transport terms are small). Idealized simulations are potentially a vital tool in unravelling the structure of stable boundary layers and their various sensitivities, but it had been widely thought that LES of stable boundary layers was

* See Appendix

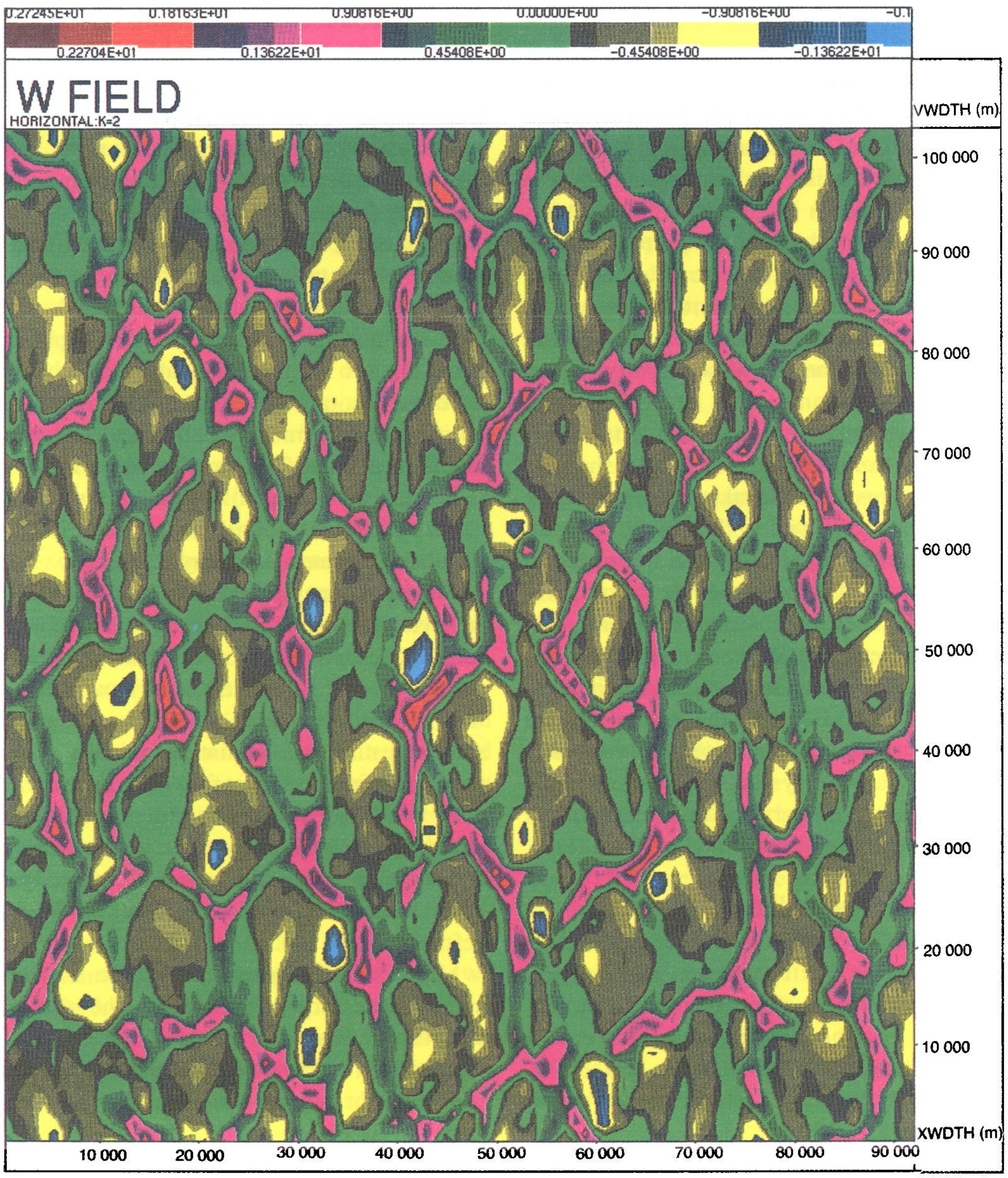

Figure 2. Vertical velocity field on a horizontal slice through a modelled convective boundary layer. Magenta/red = upward motion, yellow/blue = downward motion.

virtually impossible at present. However, Mason and Derbyshire (1990) showed that it could be done, and obtained results which fit well with Nieuwstadt's analysis of observations, and in turn with a theory (Derbyshire 1990) which predicts a limit on the surface heat-flux in terms of the geostrophic wind. There is a lot more to be written on this subject, but it is already clear that simulations can shed considerable light.

The Meteorological Office group, whilst by no means alone in performing boundary layer simulations (see, for example, Nieuwstadt and deValk (1987), Moeng (1984), Schumann (1990)) has shown above all how essentially the same model can handle all three main dry types of boundary layer. Work continues on some important aspects (e.g. Mason and Thomson (1992) show how partial randomization of subgrid parametrization can improve performance in the surface layer), but the overall success of the model and general consistency with the best observations are clear.

3. Gravity waves

Gravity waves are oscillations in which buoyancy provides the vertical restoring force. They are very common in stable regions of the atmosphere and they can transport significant amounts of energy and momentum in the vertical. Mountain lee waves are a familiar example of such oscillations .

Some may be surprised to see gravity waves mentioned in this paper, since even when they occur 'randomly' they are not a form of turbulence. In principle the differences are clear, although making the distinction from observational records is not always easy. Turbulence is chaotic, strongly non-linear and dissipative; gravity waves are predictable, often essentially linear phenomena, and do not dissipate significantly until they 'break' and become turbulent, in a way roughly similar to water waves breaking on a beach.

What then has all this to do with the large-eddy model? First of all, from a very general point of view gravity waves obey the same underlying physical and dynamical equations as turbulence. Secondly, in stably stratified conditions almost any disturbance (including turbulence) can generate gravity waves. Thirdly, various transitions can occur between waves and turbulence, e.g. by wave-breaking or collapse of turbulence. So it is quite important that our model can handle both waves and turbulence, and if it could not we might question its accuracy.

The large-eddy model's handling of both waves and turbulence has recently been demonstrated in 2-D simulations of breaking gravity waves in the lower stratosphere. The model was initialized using real wind and temperature profiles taken from field experiments in the Lake District. In these experiments orographically forced gravity waves were observed using radiosondes .

Even though the LES model contains no orography, such waves can be simulated by imposing a fixed, sinusoidal vertical velocity at the lowest grid-point, imitating the effect of the hills. The domain width (18.8 km) was chosen to satisfy a resonance condition, allowing the waves to build by constructive interference. The top of the domain was at 30 km, with a damping layer above 23 km, and 250 grid-points in each vertical column.

With imposed vertical velocities of amplitude 0.25 m s^{-1} at the surface, waves of maximum amplitude 3 m s^{-1}were simulated, similar to those observed. The vertical resolution was sufficient for wave breaking to be seen in the model (Fig. 3). The heights and some features of the breaking are in reasonable agreement with the observations.

Other results show that:

(a) The large-eddy model accurately conserves energy in long gravity-wave integrations (this is a moderately strict test which revealed imperfections in the original formulation).

(b) Gravity-wave phase speeds match predicted values both in the incompressible and anelastic cases (recall that our dynamical equations can take two slightly different forms).

(c) The model satisfies the generalized Charney–Drazin non-acceleration theorem (Andrews and McIntyre 1976), which says that momentum carried by steady gravity waves is absorbed only in regions of dissipation (this is a significant test of the model's numerics).

An illustration of gravity waves occurring naturally in the model is shown in Fig. 4 where boundary layer convection radiates waves. The momentum transport of these waves can be inferred from the sense of the phase line tilt.

4. Clouds

The simulation of clouds is a particularly important application of the LES model, because of the sensitivity of climate models to the representation of cloud processes. We seek deeper understanding of the processes themselves, with a view to improving their parametrization in larger-scale models. There are two areas of current interest. The first is the study of stratocumulus, and especially of the conditions under which break-up occurs. This is

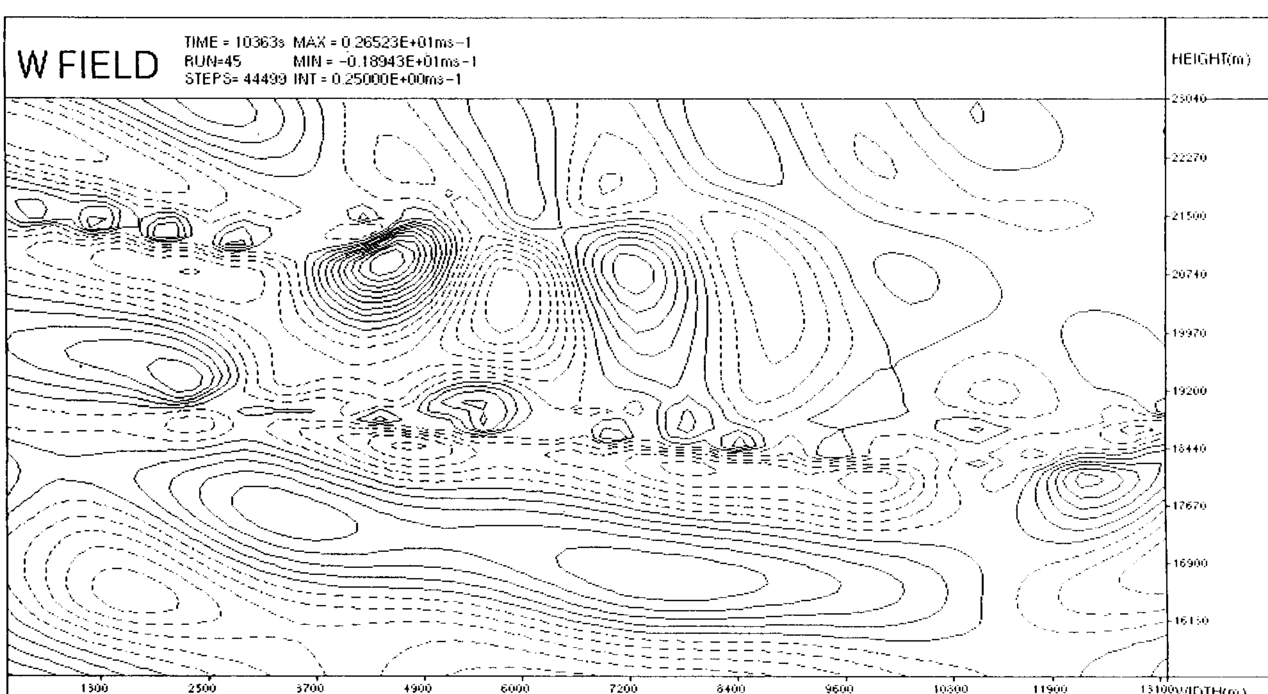

Figure 3. Vertical velocity from a 2-D simulation of gravity waves. Solid contours = upward motion and dashed contours = downward motion. The small-scale features in the centre of the figure and at top left are indications that the waves are breaking.

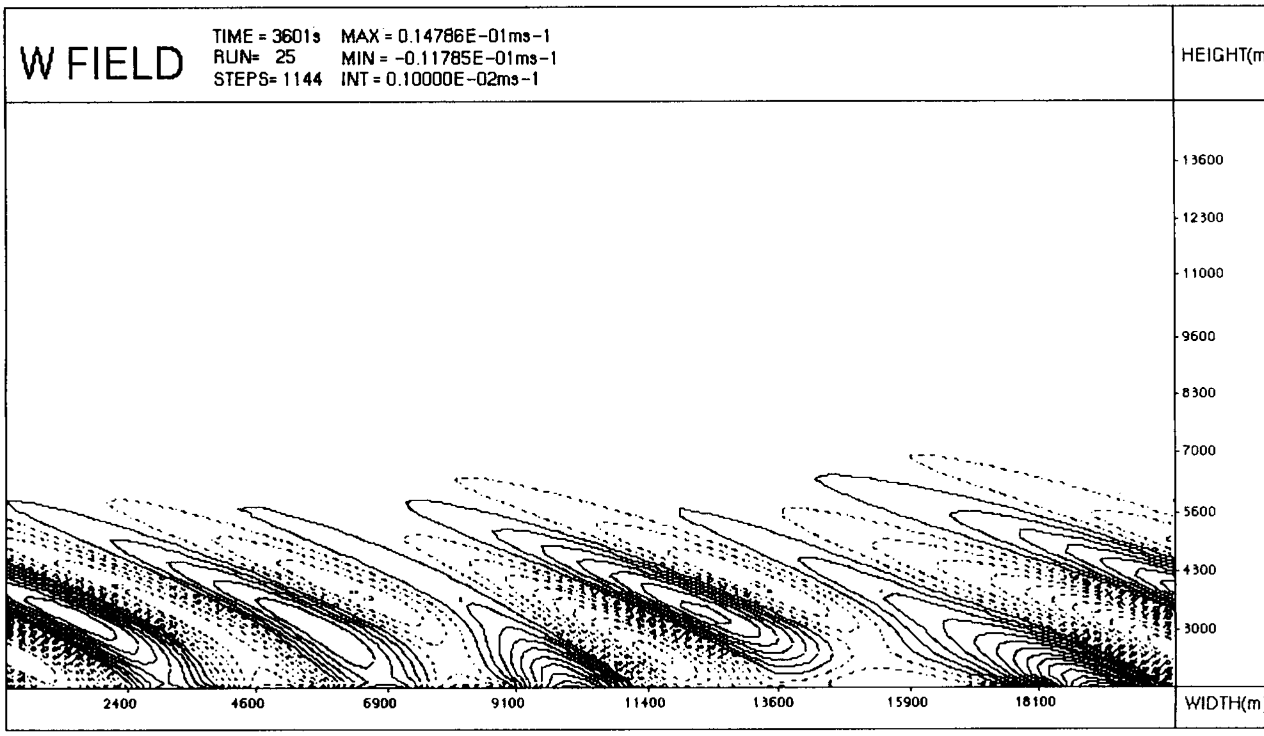

Figure 4. Vertical velocity from a 2-D simulation of an atmosphere heated from below, with strong wind shear near the surface. The shear inhibits convection and gravity waves are generated. Solid contours = upward motion and dashed contours = downward motion.

important because stratocumulus has a major impact on the radiation balance in the atmosphere. Clearance of stratocumulus is also difficult to forecast. The second area is the simulation of deep convection. This process transports substantial quantities of heat, moisture, and (possibly) momentum in the atmosphere, and latent-heat release in convective systems is a major energy source for atmospheric circulations, especially in the tropics.

In order that the LES model might be used to simulate cloud, the code has had to be extended. The minimum extension required to simulate non-precipitating cloud is the inclusion of suitable moist variables. There are various possible choices, but many cloud models use a thermodynamic variable which is conserved even when condensation occurs. Wet-bulb potential temperature (θ_w) is a familiar example of such a variable, though it is not easy to use in a model. The LES model uses liquid water temperature

$$T + gz/c_p - Lq_l/c_p$$

(Shutts 1991), because it proves to be more accurate and computationally convenient than other possible choices for the simulation of deep convection. The moisture content variable is total water mixing ratio (q_t), which comprises vapour and cloud. In the absence of precipitation, this too is a conserved variable.

Simulation of precipitating clouds requires the addition of a rain density variable, together with a parametrization of the microphysical processes of autoconversion (growth of raindrops by condensation), accretion (coalescence of rain and cloud droplets), and evaporation. In the current version of the model, two alternative parametrizations of these 'warm rain' processes have been included, based on the work of Kessler (1974) and Lee (1989). The ice phase is not currently represented, but virtual temperature and water loading effects are. Moist air is less dense than dry air at the same pressure and temperature; cloud and rain droplets exert a drag on the air: these effects modify the buoyancy of convective plumes. Indeed the evaporation and drag due to precipitation generate an important dynamical ingredient of convective storms, the downdraught. Fig. 5 shows the downdraught from our simulation of the Halifax storm (Collinge *et al.* 1990), spreading out as it reaches the ground.

The simulation of the break-up of stratocumulus is a particularly challenging problem because the model needs to resolve dynamical features near the inversion. The scale of these features is comparable with the depth of the cloud-top inversion, which might be only a few metres. However, the domain of the model must be several kilometres deep, to include the whole boundary layer, and several kilometres across, to include the largest eddies. Three-dimensional simulations are not yet feasible at sufficiently high resolution (grid length 5 m or so), but 2-D simulations are. Fig. 6 shows a chart from such a simulation. The moisture gradients are very sharp near the cloud boundaries: the model must use quite sophisticated numerical schemes to simulate accurately the advection of such gradients. To date this modelling work has helped to confirm recent developments in the

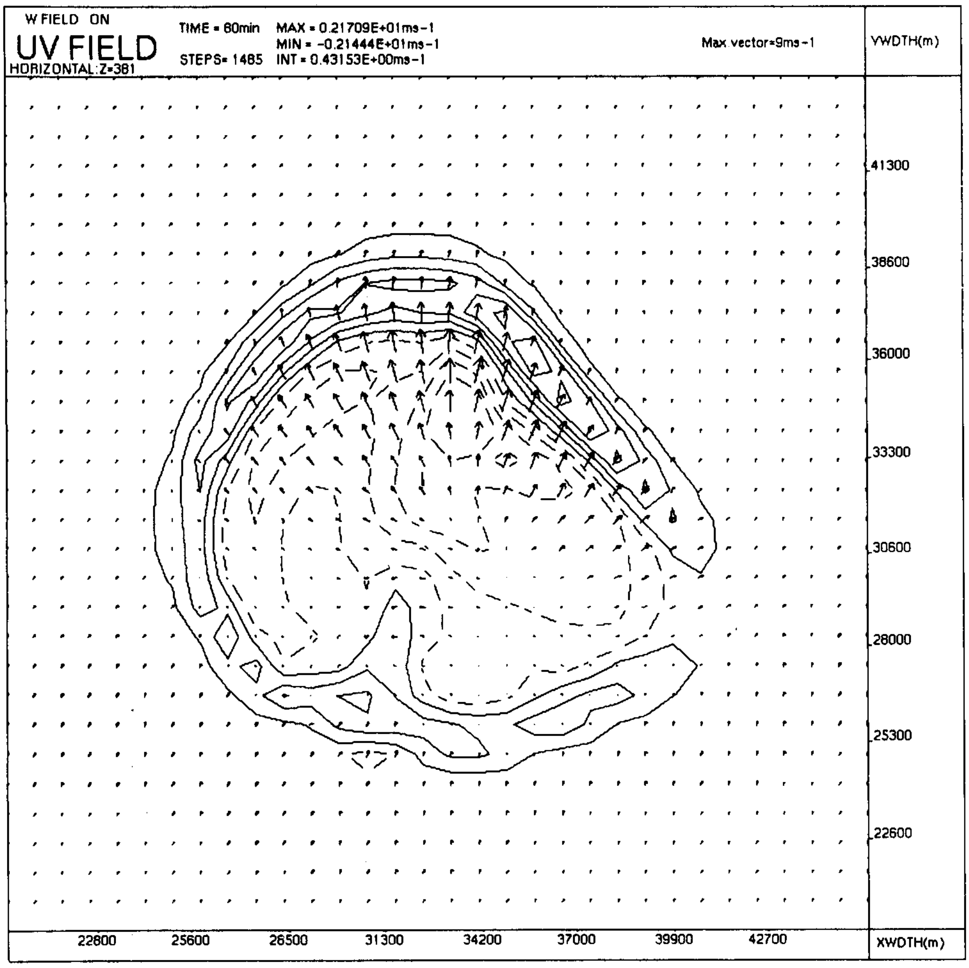

Figure 5. Horizontal slice through simulation of the Halifax storm. Height 380 m. Contours are of vertical velocity (solid = up). Arrows represent horizontal wind vectors.

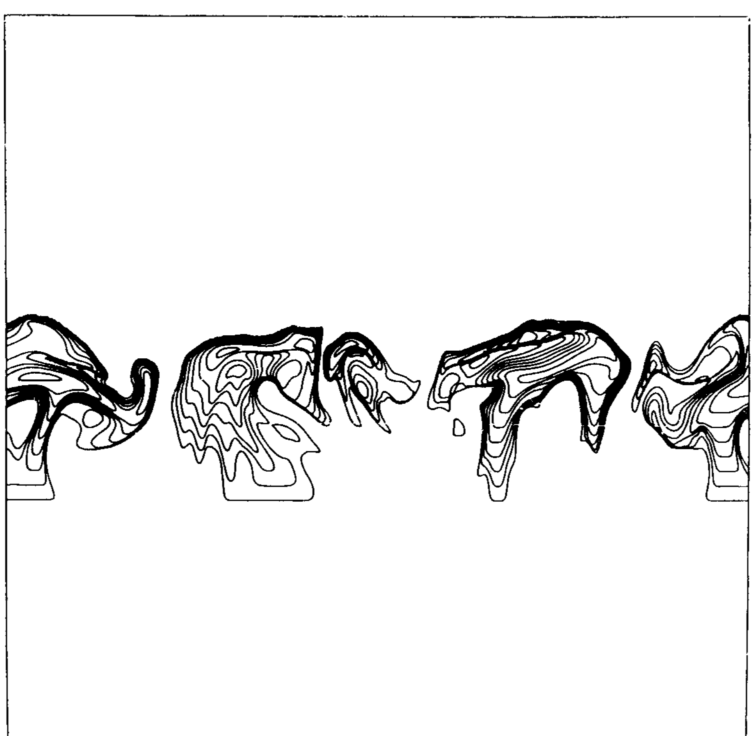

Figure 6. Liquid water content in a 2-D simulation of the break-up of a stratocumulus deck. Contour interval 0.07 g kg^{-1}.

theory of cloud-top entrainment instability. Under certain conditions, mixing and evaporative cooling near the inversion can lead to instability and rapid break-up of the cloud. The model simulations have helped to define these conditions more precisely, and shown that the instability can lead to complete break-up of the cloud deck within one hour or so. See MacVean and Mason (1990) and MacVean (1992) for further details.

The simulation of deep convection is a relatively new application of the LES model. Cumulonimbus models have been used for many years and have been reasonably successful in simulating individual storms, in mid latitudes (e.g. Miller (1978)), and in the tropics (e.g. Tao and Simpson (1989)). Given adequate resolution, and an adequate parametrization of the microphysical processes, such models can represent the dynamical structure of storms, and the vertical profile of latent heat release. This previous work has highlighted, amongst other features: the 3-D nature of convective flows, the importance of the ice phase, and the significance of long-wave cooling near cloud top. Ideally, our model would represent these dynamical, microphysical, and radiative processes accurately.

However, our goal is to simulate not one convective system but many within the model domain, because we seek to quantify the statistical effects of the convection on the large scale. This poses the fundamental difficulty that we need a large domain, to include many systems, and high resolution, to resolve the main dynamical features of the individual storms. For tropical systems, which are organized on scales of 100 km or more, a domain 1000 km square is probably needed, and horizontal and vertical resolution near 100 m would be preferable. This is clearly out of the question: it would need 1000 times more memory than we have on our CRAY-YMP and each time-step, around 1 second, would take approximately 1 day of CPU time! For the foreseeable future, integrations will have to be restricted to smaller domains and/or lower resolutions. With current computing power, integrations with 1 million points and 1 km horizontal resolution are feasible. That should allow us to simulate less-organized systems such as cold air outbreaks in mid to high latitudes, and even for tropical systems we may be able to learn something from the model. With a domain size equal to the grid-length of a climate or weather forecasting model, we can think of the LES model as a means of simulating the unresolved circulations within a single column of the large-scale model. Experiments which compare the diagnosed effects of convection, in the LES model, directly with single column versions of the parametrizations, in the large-scale model, are likely to be a useful area of research.

Available computer power also limits the complexity of the microphysical parametrization which can be used in a cloud ensemble model. A measure of that complexity is the number of cloud physics variables included. A cloud physicist would like to keep track of many different size classes of cloud and precipitation particles, ranging from small droplets to large rain drops, and from ice crystals to graupel, hail and snowflakes. A typical scheme might have 40 variables which have to be advected around, and sources and sinks have to be calculated for each one. For a 3-D model we are unlikely to be able to afford many more than 5 variables, amounts of cloud water, rain, cloud ice, snow or graupel, and hail, for example. The current version of the model only has the first two. Bearing in mind the aims of our modelling to guide parametrizations in larger-scale models, it is important to assess which variables and processes are really important, and which just add the icing on the cake.

5. A look ahead

As a research tool the LES model has many advantages. It is for example simpler in many ways than a climate model: it has no orography, the vertical coordinate is height, it has simple boundary conditions, and it has no physical parametrizations except those we choose to add. This simplicity is an advantage because it enables us to run idealized experiments to isolate, study and understand individual processes. For the simulation of deep convection, more complex physical parametrizations will be necessary; for example the ice phase must be included and so must long-wave cooling. However, it is important to proceed step by step and understand the effects of each addition to the model, since the usefulness of such a research tool rests on three characteristics:

(a) the integrity of the computer code (a 'bug-ridden' code could be worse than useless),

(b) our detailed understanding of the processes within it (a purely 'black box' model would not be much help), and

(c) the facility to redeploy computational resources, e.g. between sophisticated physics and high resolution (so that we can test out the importance of different processes).

The LES model does not attempt to be a forecast model. A forecast or climate model has to some make provision for handling nearly every process that is likely to be important, even when relatively poorly understood. It also has to handle complex terrain, which can be a significant overhead. Many of the overheads in a complex model tend to remain even when one tries to run it in a 'simple' mode, e.g. without orography. Also the overriding need for a forecast model to run fast and efficiently imposes various constraints. So whilst it is useful to be able to run a forecast model in research mode, e.g. the Meteorological Office mesoscale model is both a research and an operational model, there is also an advantage in having a research model which does not have to worry about direct forecasting applications. This is the role of the large-eddy model, for which the flexibility to run all sorts of idealized experiments is a prime consideration.

The development of simulations is at best only a partial substitute for high-quality detailed observations of boundary layers and other processes. The observational database continues to play a vital role in validating many aspects of simulations and pointing up their deficiencies. Models are useful in setting up idealized situations which may act as benchmarks to forecast models, and thus pinpoint any failings of, say, the boundary layer scheme. But comparison with observations always provides a vital check against the real atmosphere, which is far more complex than any model. So work done for example by the Meteorological Research Flight C-130 research aircraft and by the Meteorological Office Research Unit at Cardington is important to the future development and application of the model.

Observational verification of simulations of ensembles of convective clouds is likely to depend on international field experiments, especially for cases of organized convection. Measurements are needed on vastly differing scales: the microphysical scale (μm) for cloud variables, the convective scale (km) for individual up/downdraughts, and the mesoscale (100 km) or even synoptic scale (1000 km) for the large-scale organization. TOGA–COARE (the Tropical Ocean Global Atmosphere–Coupled Ocean Atmosphere Response Experiment) is an example of a forthcoming experiment which will provide useful data. Expensive experiments of this kind can only be run infrequently, and in a limited number of regimes. They are an important means of validation in a subset of the possible atmospheric conditions. One of the advantages of a computer model is that it can be run again and again under different conditions, at far less cost than a large experiment, though with much more simplistic physics than in the real world.

A new possibility which we are only beginning to exploit is to combine simulations and observations directly. It is probably not appropriate here to use the elaborate assimilation schemes developed for blending synoptic (or asynoptic!) data into forecast models. However, relatively simple techniques for nudging simulated profiles towards observed values could help us considerably in comparing real and simulated turbulence levels and fluxes. As an example Lilly and Mason (1990) showed that incorporation 'by hand' of a pronounced mesoscale influence on wind profiles measured during an experiment in eastern Colorado (the influence was presumed to relate to the nearby Rocky Mountains but not completely understood) led to good agreement with observed turbulence structure.

This raises the hope that in complex situations, which we promised earlier to consider, simulations and observations will complement each other to give a full picture from which detailed deductions may be drawn about the performance and possible improvement of forecast models. In summary, the Met. Office has a leading position in meteorological applications of large eddy simulation. The development work has taken several years, but our ability now to simulate all the main types of boundary layer represents something of a breakthrough. One of the most exciting prospects is to be able to represent various types of cloud accurately enough to help parametrization in a significant way.

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Appendix

A Rossby number *Ro* can be defined as a ratio of the Coriolis timescale f^{-1} to the characteristic flow timescale. In textbooks on dynamical meteorology one often takes $Ro = V/fR$ for a circularly symmetric synoptic system where *V* is the wind and *R* the radius. In that case *R*/*V* can be interpreted as the time that a parcel of air would take to circulate an angle of 1 radian around the system, if the pressure system were constant and stationary. Many different characteristic Rossby numbers can be defined for different aspects of flows in a rotating atmosphere. Basically, when *Ro* is small rotation is dominant and the flow will be nearly geostrophic, but when *Ro* is large rotation is relatively unimportant.

The gradient Richardson number *Ri* is the ratio of the static stability to the square of the wind-shear. The static stability is proportional to the rate of change with height of potential temperature, whilst the wind-shear is of course the rate of change of vector wind with height. This number is very important in determining the amount of turbulence in stably-stratified layers. Where it exceeds a certain critical value Ri_C we expect the flow to be laminar, i.e. not turbulent. Clear air turbulence is often thought of in terms of flow instabilities which occur when *Ri* falls below Ri_C.

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Quasi-operational test of a forward scatter visibility meter at Ronaldsway, Isle of Man

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Summary

Assessments of Runway Visual Range (RVR) at Ronaldsway Airport (Isle of Man) are currently made by manual observation but a proposal has been made to install an instrumented (IRVR) system. Whilst the current standard instrument is the transmissometer, in the USA the FAA have recently adopted the forward scatter meter (FSM) for future IRVR applications. An FSM was tested at Ronaldsway during 1991 and this report compares measurements by the instrument with visibility parameters used operationally at the airfield during several periods of low visibility.

1. Introduction

During conditions of low visibility at Ronaldsway (Isle of Man) Airport, assessments of runway visual range (RVR) are currently made by manual observation. A proposal has been made to install an Instrumented RVR (IRVR) system. The current standard IRVR instrument is the transmissometer, which measures the light transmittance of the atmosphere between a light source and detector over a baseline of (usually) some 10 to 200 metres. However, there are some operational problems with the instruments currently in use. The optical alignment is critical, so the bases for the transmitter and receiver must be very stable, which often leads to high installation costs. The optical surfaces must be cleaned frequently, and if maintenance is required (such as lamp replacement) during conditions of poor visibility it is not possible to recalibrate until conditions improve. The Federal Aviation Administration (FAA) of the United States has recently instigated a replacement programme for the transmissometers which have been in use at major US airfields for more than a decade with a new generation of IRVR systems employing forward scatter meters (FSMs) (S. Ammann, *ICAO Journal*, April 1990). The advantages of forward scatter meters are increased reliability and simplified maintenance, reduced overall cost, and the ability to allow calibration in moderately low visibility.

During preliminary discussions, a FSM (manufactured by HSS Inc., Massachusetts, USA) was offered on loan to the Isle of Man Meteorological Office for a practical assessment at Ronaldsway. It was installed for a period from early February to mid-April 1991, and some results from this test are presented here.

2. Principle of operation of the forward scatter meter

Horizontal visibility through the atmosphere is determined by the presence of particles which cause light to be scattered. For light in the visible (and near-visible) part of the spectrum, scattering occurs by suspended particles such as fog droplets, dust and smoke particles, and by precipitating particles such as raindrops, drizzle droplets, snowflakes and hailstones. When viewing a distant object or light-source two processes affect its visibility to the observer. Light travelling from the object or light-source towards the observer is scattered out of the line-of-sight, reducing the intensity reaching the observer directly. Also, stray light from other sources also scattered by the particles can be scattered into the line-of-sight. This added stray light (sometimes called 'air light') has the effect of reducing the apparent contrast between the distant object or light-source and its background, making it less discernible (commonly said to increase 'haziness'). Consequently, visibility is determined by the concentration and type of scattering particles and can be quantified in terms of an atmospheric scattering coefficient. When measured scientifically, this scattering coefficient is called the 'extinction coefficient' (EC). The EC is very low on clear days, but high in mist and fog. Meteorological optical range (MOR) is defined as the length of path through the atmosphere required to attenuate a beam of light to 5% of its original intensity; it approximates to meteorological visibility but it can be measured instrumentally whereas visibility cannot. Koschmieder's Law relates MOR to measurements of EC through the simple relationship:

$$MOR = 3/EC.$$

The forward scatter meter is an instrument which measures values of EC, enabling the calculation of MOR. When the instrument is situated close to the edge of a runway, the MOR determined is considered the best assessment of RVR.

Fig. 1 illustrates a plan view of the instrument, which is around 1.5 m in overall length and mounted on a pole at its mid-point, where there is a junction-box for the electrical connections (covered by a splash-guard to stop rain bouncing into the sample region). A weatherproof box containing the power control unit is also mounted on the pole near the ground. A source of light is mounted at one end of the instrument (actually an infrared source with central wavelength 0.89 μm, modulated at 2000 Hz). The detector mounted at the other end contains a hybrid Si-sensor amplifier. Unlike the transmissometer which has a direct optical path between the source and detector and measures the transmittance of the atmosphere, the FSM detects light scattered out of the source beam in the direction of the detector by particles suspended in or falling through the atmosphere. The sample region is defined by the aperture and acceptance cones of the source and detector respectively. It represents a volume of 3000 ml, covering scattering angles from 27° to 42°. The amount of scattered light received by the detector depends on the type, size and number of scattering particles in the sample volume, and the signal produced enables the EC to be measured. A photograph of the instrument is shown in Fig. 2.

3. Interpretation of data

The instrument was installed at Ronaldsway from early February to mid-April, 1991. Due to the temporary nature of the installation, the only convenient site was situated between runways 18 and 22, as shown in Fig. 3. The site was approximately equidistant from the Meteorological Office (where observations including meteorological visibility are made) and the runway 09 RVR observers' position (ROP), and a little further from the 27 ROP. Information from the sensor was fed back to a computer situated in the Meteorological Office.

During that time, a spell of frequent fog occurred during the second week of March. Fig. 4 shows the development of the synoptic situation between the 11th and 14th of March. The fogs occurred in various wind directions (from NE through E and S to SW), and wind speeds from calm to over 10 kn. A series of four 6-hour periods was selected, for which the MOR measured by the FSM instrument is indicated, together with the visibilities (MV) reported by the meteorological observer and RVR assessments for runways 09 and 27. The sea temperature around the south of the Isle of Man at that time was about 7.2 °C.

In order to interpret the data, it is important to remember the relative positions and elevations from which each visibility measurement was made and to understand something of the physics of the fogs which affect Ronaldsway. Fig. 5 shows schematic tephigram constructions of idealized fog formation.

Figs 5(a)and 5(b) illustrate the classic formation of advection fog, with warm moist air moving over a relatively cooler sea surface. Firstly, stratus forms by turbulent mixing under a low-level inversion (Fig. 5(a)). As cooling of the mixed layer proceeds, the base of the stratus lowers towards the sea surface, eventually producing fog (Fig. 5(b)). This type of fog forms in light to moderate (and occasionally strong) winds, usually from the south to south-west direction (since the Irish Sea is often exposed to warm moist Atlantic air from that direction). Turbulent mixing occurs on a range of scales (from metres to hundreds of metres), leading to large variations in visibility over the airfield. However, due to the limited number of condensation nuclei in maritime air favouring relatively large fog droplets, the lowest visibilities are usually around 200–400 m. Fog depth is often 100–400 m.

Fig. 5(c) shows how fog can develop in warm moist air in calm or very light wind situations. Cooling occurs first near the sea surface, with latent heat release providing small-scale mixing to increase the depth of the fog, usually to around 50–100 m. This type of fog often forms

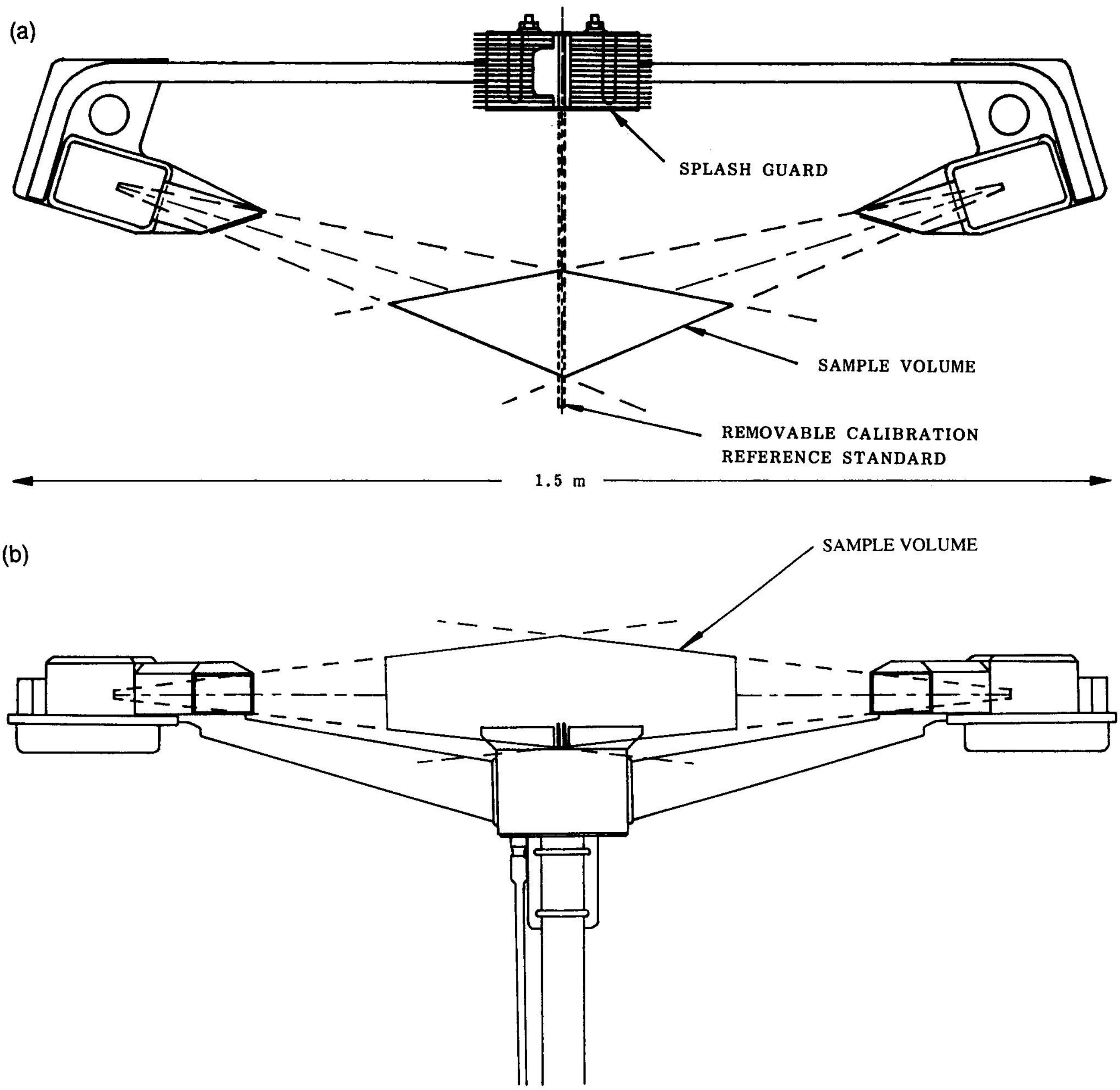


Figure 1. Views of the HSS FSM sensor head. (a) plan view, and (b) elevation. Sample volume is around 3000 ml.

Photograph by courtesy of M. Stephens-Row, BIRAL/HSS.

Figure 2. The HSS forward scatter visibility meter.

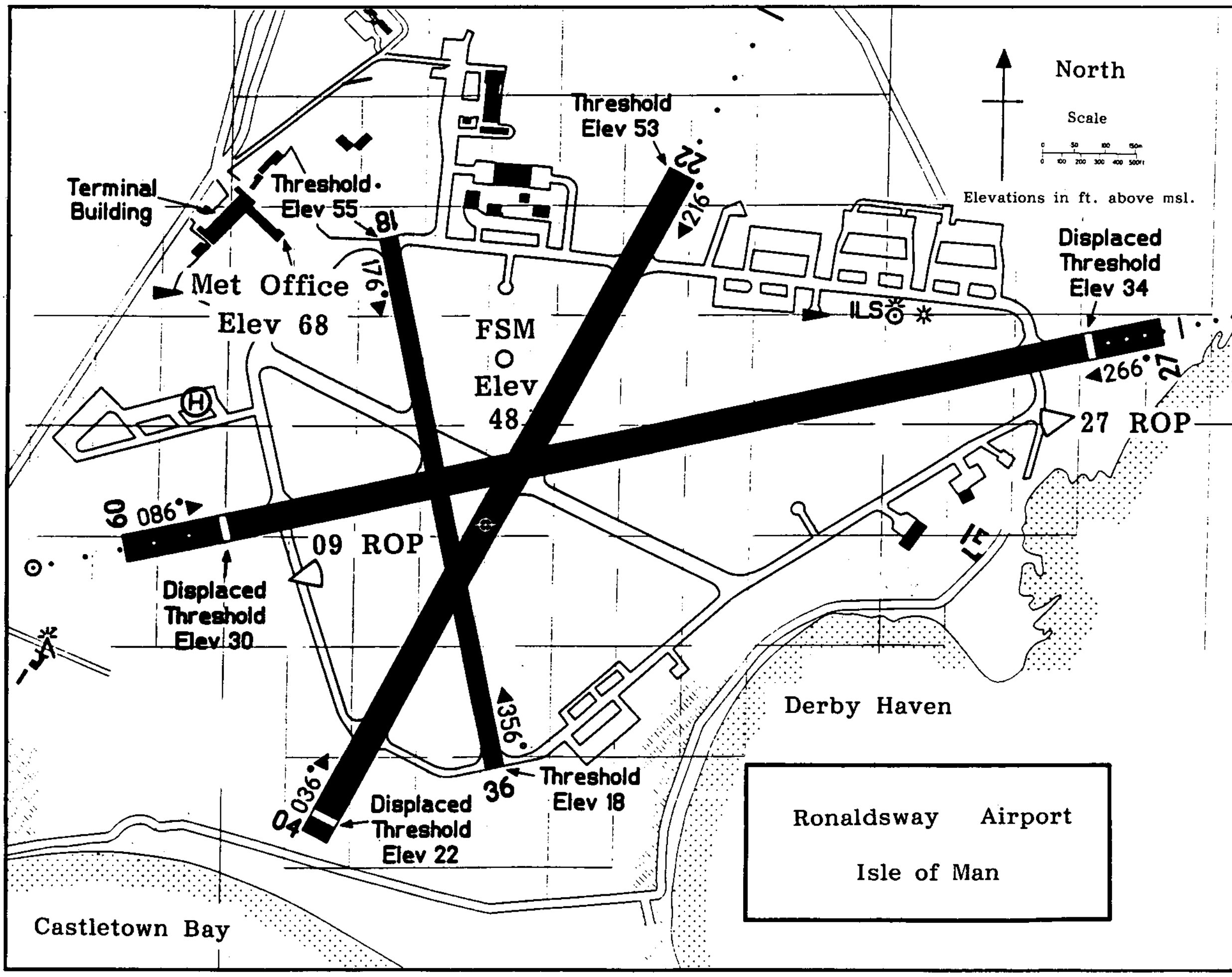


Figure 3. Plan of Ronaldsway Airport, Isle of Man.

or thickens overnight, behaving in some ways like land radiation fog. It can encroach inland as the coastal land temperature falls overnight (unless held back by katabatic drainage) and is sometimes driven inland by light onshore winds developing or by sea breeze circulations in summer. The encroaching fog then cuts off the sea breeze by cooling the land, but the heat thus absorbed can lead to the inland edge of the fog eroding and allowing the sea breeze to develop again. The balance between these competing processes is often reached at Ronaldsway close to the line of the main 09/27 runway! Due to the production of fog droplets occurring at low levels (and sometimes a partly continental history of the air mass providing an abundance of condensation nuclei) the visibility is often around 100 m or less.

Fog can also occur in slow moving cold-frontal zones, due to mixing of the two air masses producing supersaturation. It usually develops from the base of warm-sector stratus descending towards the surface (similar to the advection fog described above) but the visibility can be less than 100 metres and the fog top undefined (merging with frontal cloud above).

Radiation fog is rare and only occurs when there is sufficient synoptic pressure gradient to counteract the katabatic drainage (from high ground to the north) which normally occurs in radiation conditions. When it does occur, visibility can fall below 100 m with fog depth usually less than 50 m.

The physics of real fog is obviously more complicated (often involving a combination of formation processes) but in any case the fogs which affect Ronaldsway usually produce large temporal, spatial and directional variations in visibility.

4. Some results obtained during the period 11–14 March 1991

The graphs in Fig. 6 show data obtained during four 6-hour periods of reduced visibility at Ronaldsway during 11–14 March 1991. In each case, the meteorological visibility assessed by the duty observer is shown for

(a) routine reports completed for SYNOP reports (at 50 minutes past each hour),

(b) METAR reports (at 20 and 50 minutes past each hour during airport opening hours), and

(c) whenever special reports were issued to Air Traffic Control (due to the visibility changing through certain specified values of operational significance).

Values of MOR calculated from measurements of EC by the FSM are plotted at 1-minute intervals. Manual

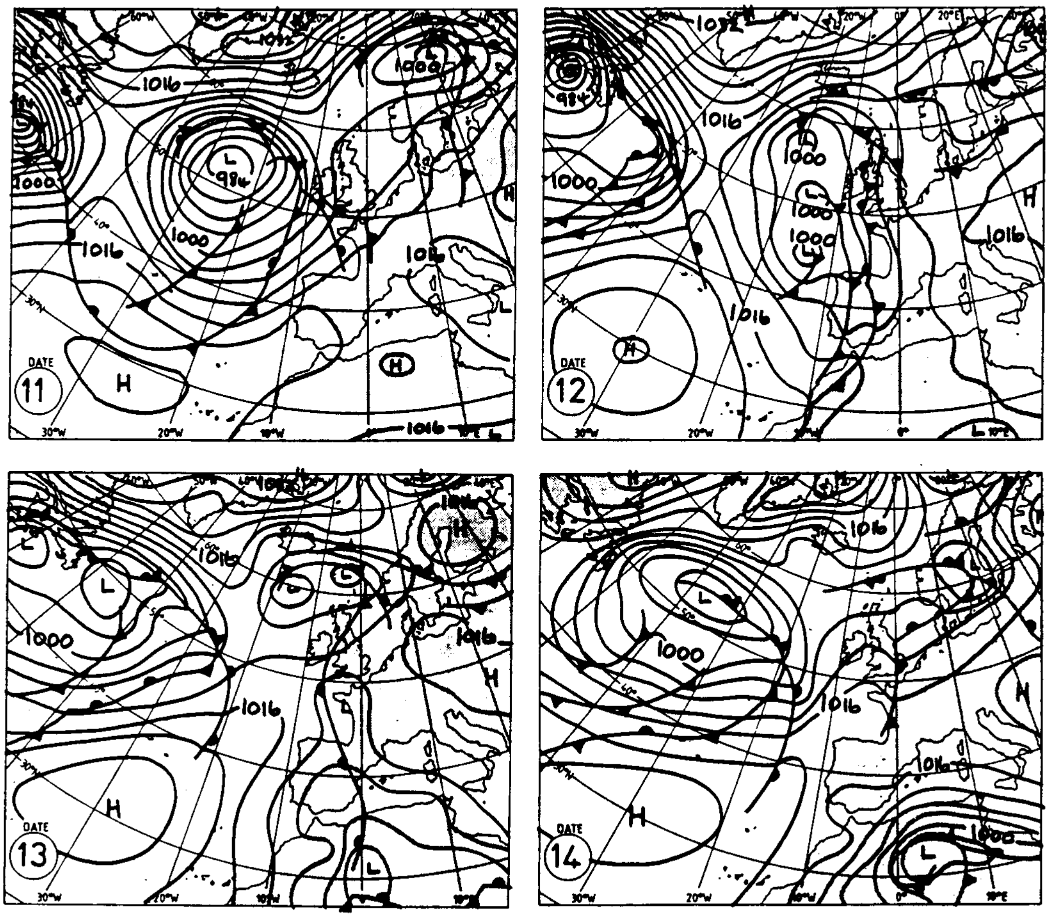


Figure 4. Surface charts for 1200 UTC on 11–14 March 1991. Dates shown in bottom left-hand corner.

assessments of RVR from the ROPs at each end of runway 09/27 are also shown.

Fig. 6(a) shows a comparison of visibility measurements for the period 1700–2300 UTC on 14 March. There was a light moist south-westerly airstream with visibility around 6 km during the afternoon. After 1700 UTC the wind decreased and both the temperature and dew-point dropped, with the relative humidity (RH) rising from 88% towards 100%. At 1748 UTC the visibility was 5000 m, with half cover of stratus developing at base 300 ft. The visibility deteriorated below 1000 m at 1812 UTC, with the cloud base touching the ground in places and generally 100 ft. By 1824 UTC the observer reported a meteorological visibility (MV) of 200 m. Initially, the MV and RVR reported from the 09 ROP were in close agreement. As the fog reached the FSM it gave good agreement with the observer, while RVR reports from the 27 ROP showed the approach of the edge of the fog. For the remainder of the duration of the fog, the FSM and MV remained in remarkably close agreement, with RVR reports around twice the MV. This effect might be due to stratification of the fog, with the ROPs (at elevations around 30 ft AMSL) remaining below the layer of lower visibility which affected the FSM and observer. Alternatively it might be due to the test instrument not having a background luminance meter (which is required for true RVR calculation in darkness) and continuing to measure MOR, thus illustrating the difference between MV (and MOR) and RVR in conditions of darkness. After 2100 UTC the wind fell calm and with little change in the temperature and RH; the visibility increased towards 8 km, with the fog lifting and breaking to patches of stratus at base 600 ft, below overcast stratocumulus with a base of 5000 ft.

Fig. 6b) shows a comparison of visibility measurements for the period 0300–0900 UTC on 13 March. There was a very slow moving frontal zone over the area, with the weak surface front crossing the airfield around 0540 UTC and veering the light easterly wind to south-south-westerly. At 0300 UTC the screen-level temperature was 9.0 °C with RH 100% and complete cover of stratus with base between 50 ft and 200 ft. The temperature fell to 7.9 °C by 0350 UTC, as the cloud lowered to form fog with MV 100 m. Between 0350 and 0450 UTC the temperature and dew-point rose a little (7.9 to 8.2 °C) and the fog became patchy on the surface below a stratus base at 400 ft. This is illustrated by the fluctuating FSM readings, whereas the observer is constrained to report the lowest MV in any direction. After 0620 UTC (with the availability of RVR assessments after airport opening) the situation appears similar to that in Fig. 6(a) with a stratification of visibility, decreasing from the

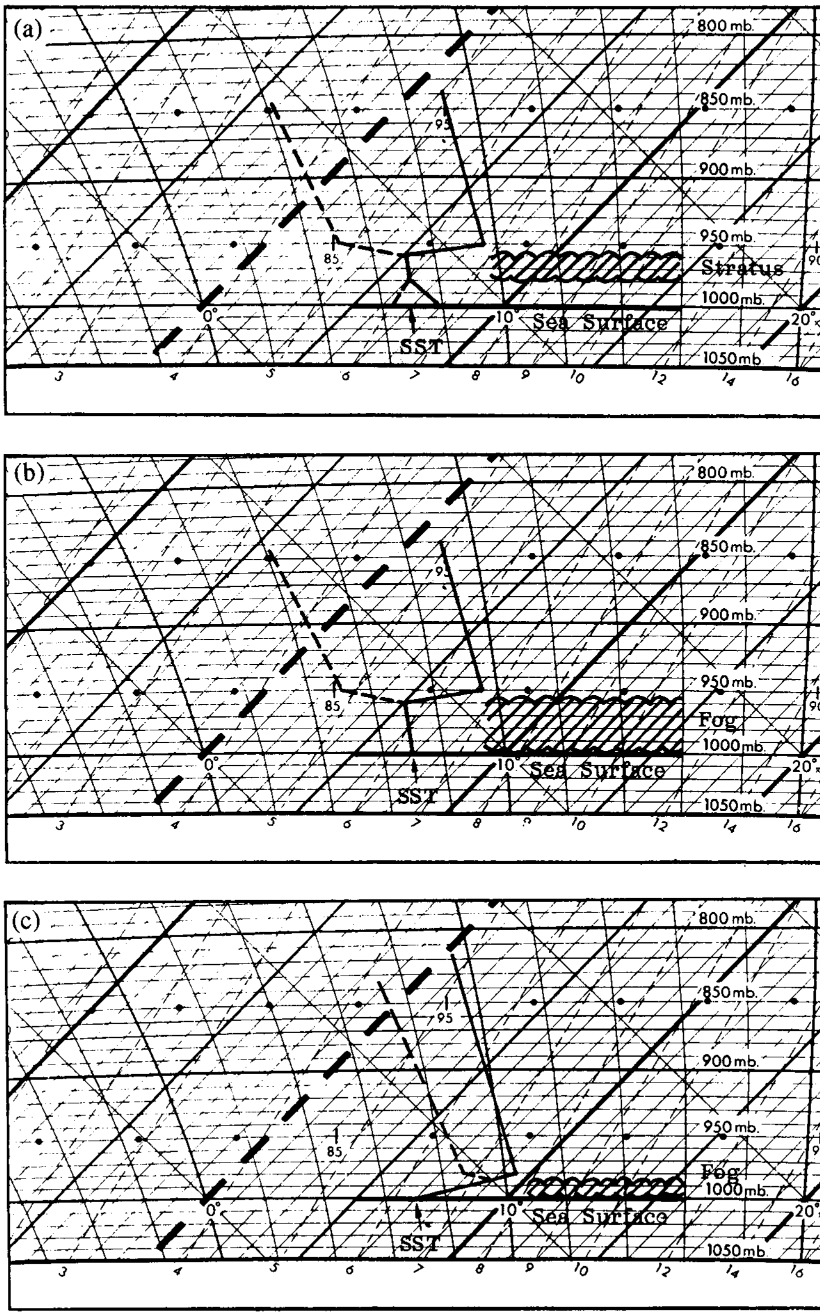
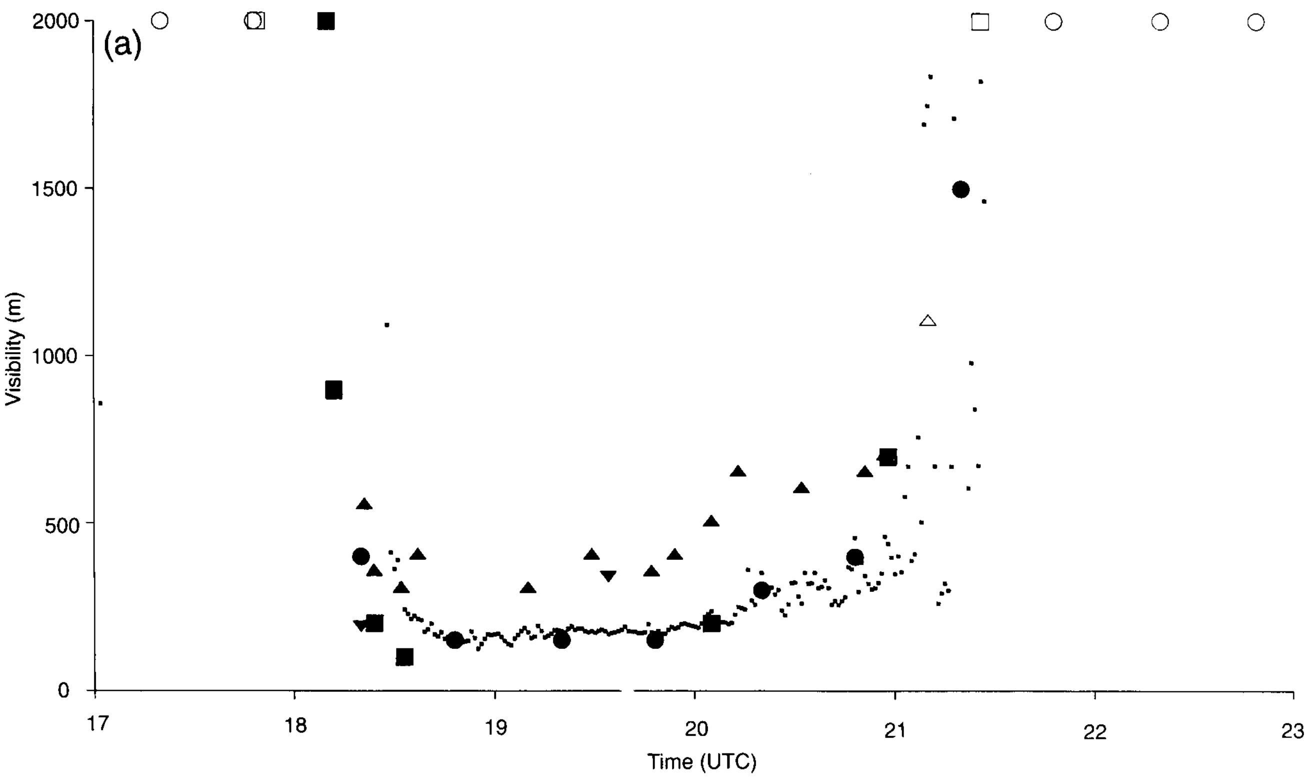


Figure 5. Idealized tephigram constructions showing processes of fog formation. For full details see text.

ROPs (30 ft AMSL) through the FSM readings (48 ft AMSL) to the observer (68 ft AMSL).

Fig. 6(c) shows a comparison of visibility measurements for the period 1200–1800 UTC on 11 March. There was a moist easterly airstream at the surface ahead of a warm front approaching from the south-south-west. The screen temperature of 7.3 °C at 1200 UTC fell abruptly to 5.7 °C (with RH around 93%) by 1220 UTC then gradually increased to 6.7 °C (with RH 100%) by 1650 UTC. Patchy fog around the coast below a stratus base at 100 ft (with inland visibility 15 km at first) became widespread over the airfield for most of the period. The scatter of the results illustrates the variability of visibility around the airfield. However, as long as the FSM could be seen from the Meteorological Office it appeared to respond rapidly to the approach of thicker patches of fog and to the clearances around 1500 and 1700 UTC.

Fig. 6(d) shows a comparison of visibility measurements for the period 0600–1200 UTC on 12 March. The synoptic situation showed a waving cold front near the east coast of Ireland, with a surface easterly wind around 10 kn at Ronaldsway. Light rain and drizzle from 0826 to 1010 UTC gave the lowest visibility, with MV down to 1000 m for a short time around 0850 UTC. The generally good agreement between the observer and FSM indicates that the instrument coped well with the precipitation. The dip in the FSM reading around 0940 UTC was reflected in the 09 RVR assessment but did not meet the criteria for a special report by the observer.



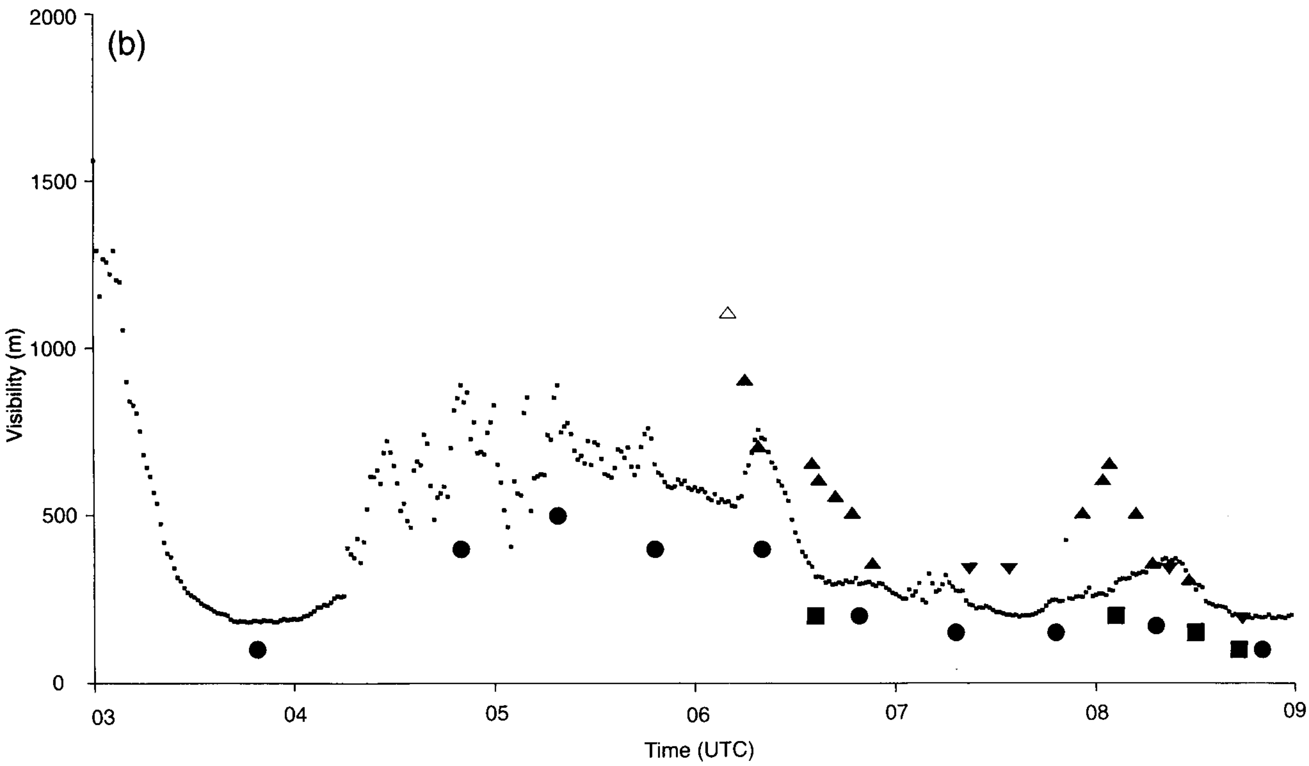
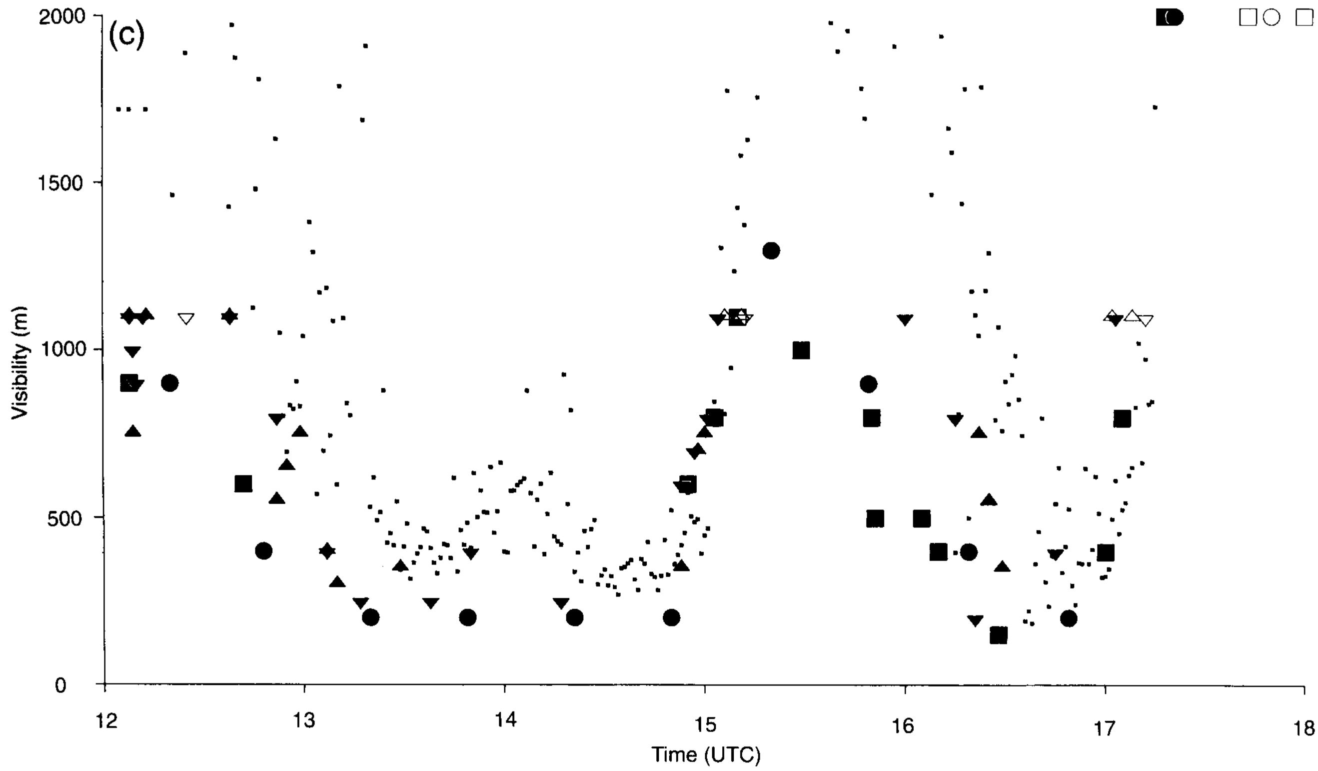


Figure 6. Comparison of visibility assessments and measurements at Ronaldsway. (a) 14 March 1991, 1700–2300 UTC, (b) 13 March 1991, 0300–0900 UTC, (c) 11 March 1991, 1200–1800 UTC, and (d) 12 March 1991, 0600–1200 UTC. Key: ▪ MOR calculated from EC measured by FSM: ● Meteorological visibility estimated by observer in routine reports: ■ meteorological visibility in special reports by the observer to ATC: ▼ manual RVR assessment from 09 ROP: ▲ manual RVR assessment from 27 ROP. Open symbols indicate FSM/observer values >2000 m and RVR values >1100 m.



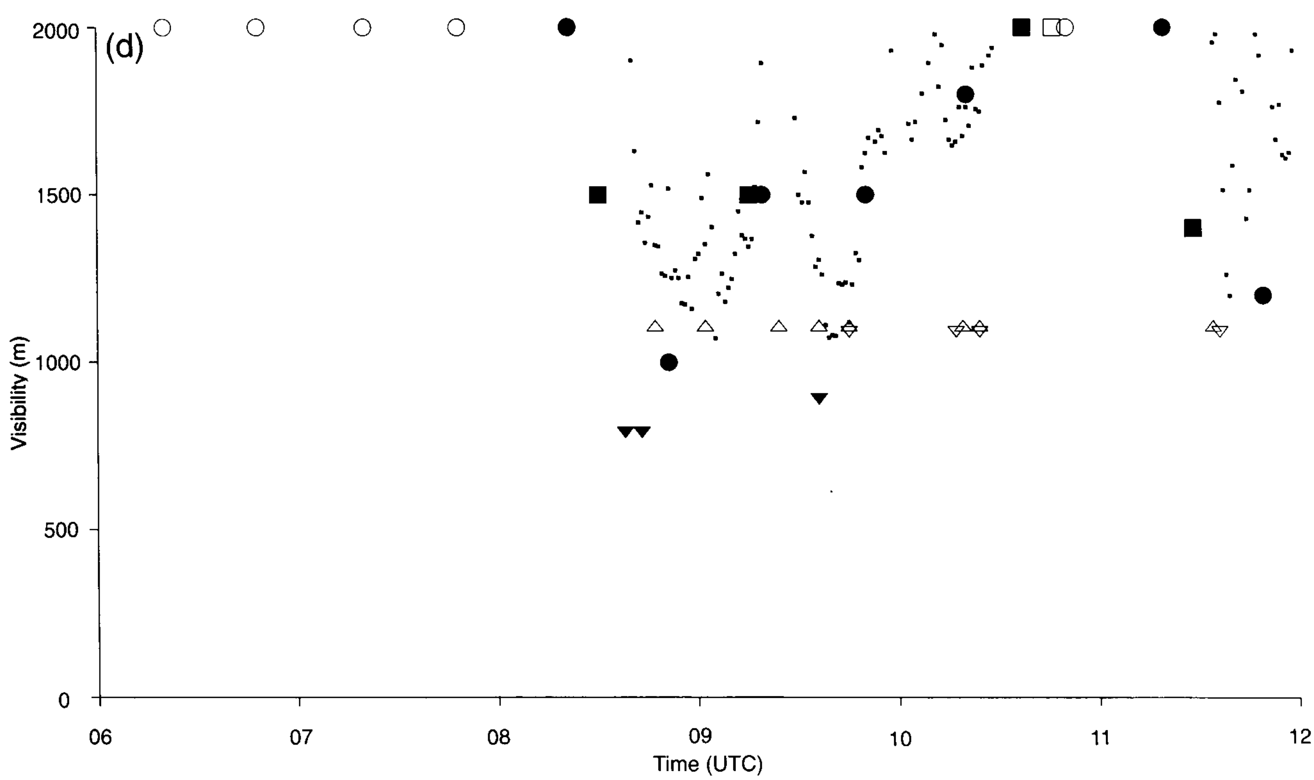


Figure 6. Continued

5. Conclusion

Overall, the variations in assessments and measurements of low visibility during the selected periods can be explained in terms of the physical behaviour of fog at Ronaldsway. Whenever possible the movement of thicker patches of fog around the airfield was observed, in particular as variations occurred in the vicinity of the FSM. Subjective assessment by experienced observers indicated that the FSM was performing very well at all times, and responding quickly to variations in visibility within its sample region. After initial calibration and cleaning of the optical surfaces, no maintenance was required for the duration of the test.

The preliminary report on the First WMO International Intercomparison of Visibility Measurements concluded that 'The useful range of most of the forward-scatter devices is clearly much greater (than transmissometers), although there is some doubt about their accuracy, particularly at low visibilities. However, their general level of serviceability and apparent lack of sensitivity to optical contamination suggest a useful role in remote operation in support of synoptic meteorology.' However, in the results presented for 10 forward-scatter devices employed in the test, the HSS version does appear to perform well at visibilities around and below 1000 m, with deviation from 'standard' generally less than that of the human observer. This would suggest that the discrepancies of some of the other forward-scatter instruments might be reduced by modifying the calibration coefficients (the prototype HSS FSM was calibrated against standard FAA approved transmissometers at the USAF Geophysical Laboratory on Cape Cod, Massachusetts, over an extremely wide range of fog and haze situations).

This test provides further evidence that FSMs can perform reliably in harsh conditions and supports their lack of sensitivity to optical contamination (which is important for a coastal station where airborne salt deposition can be a serious problem) and ease of calibration. The HSS instrument appears to measure visibility in its sample region comparable with the assessment of a human observer, both in daylight and in darkness. Due to the fact that such sensors can be frangibly mounted much closer to the runway edge (near the touchdown zone) than the existing ROPs they would more closely fulfil the aims of RVR measurement as 'the best possible assessment of the range over which the pilot of an aircraft on the centreline of a runway can see the runway surface markings or lights'. However, due to the sensitivity of such instruments to variations in visibility it might be worth considering the application of 2- and/or 10-minute digital averaging to RVR reports (in the manner that ICAO requires averaging of surface wind reports).

Acknowledgements

Thanks are due to Mark Stephens-Row of Bristol Industrial and Research Associates Ltd. for the loan of the instrument, to Andy Roberts for processing the data, to Brian Rae for helpful comments and to many Airport staff for obtaining the non-instrument data and for assistance with the installation.

Appendix

Since there are probably few remaining practising meteorologists who have been involved with manual RVR calibration, it is perhaps worth briefly explaining how RVR assessments are made (in the United Kingdom the responsibility for RVR calibrations now rests with the Civil Aviation Authority).

RVR is defined (ICAO Annex 3) as 'The range over which the pilot of an aircraft on the centreline of a runway can see the runway surface markings or the lights delineating the runway or identifying its centre line'. The Eighth Air Navigation Conference (Montreal, 1974) developed the definition, recommending that 'Since, in practice, the runway visual range cannot be measured directly on the runway and in view of other limitations imposed by observation methods, a runway visual range observation should be the best possible assessment of the range over which the pilot of an aircraft on the centreline of a runway can see the runway surface markings or the lights delineating the runway or identifying its centreline. For this assessment a height of approximately 5 metres should be regarded as corresponding to the average eye level of a pilot in an aircraft.' At Ronaldsway, this is achieved by placing the RVR observer on top of a fire tender (to approximate the 5 m eye level) at a safe distance to one side of the runway (actually around 100 m to the south side of the main east–west runway) as close as possible to the 09 and 27 touchdown points.

Calibrations are normally carried out by meteorological staff every three years, or when changes are made to the runway lighting system or RVR observers' position. The procedure is carried out in darkness in conditions of good visibility (more than 20 km). The runway edge lights (RELs) are fitted with covers and the lighting system turned on. The observer stands on top of a fire tender positioned on the centreline of the runway. Each REL to be used for RVR assessment is uncovered in turn, and the observer uses a Gold visibility meter to measure the apparent brightness of each REL from the centreline position. The readings are used to calculate an equivalent extinction visibility (EEV, the equivalent daylight visibility if the atmospheric transmittance was reduced to the value measured by the meter for the REL to be just visible) for each REL from that position. The observer then moves to the normal ROP and the procedure is repeated to obtain EEVs for each REL from that position. A graph is then plotted of the distance of each REL from the observer against corresponding EEV for both the centreline and ROP readings, from which a table is constructed relating the number of RELs visible from the ROP to the corresponding centre line RVR. In practice, complete calibrations are produced for RELs on the opposite side of the runway to the ROPs only, for intensities set at both 30% and 100%.

In operational use, whenever the visibility falls below (or is forecast to fall below) 1500 m, an observer is positioned at each ROP and counts the number of appropriate RELs visible. This information is passed by radio to Air Traffic Control, where the calibration graphs are used to estimate the corresponding RVR.

There are problems with this system at Ronaldsway due to the fitting of flush lights in the runway intersection area which are unsuitable for use in assessing RVR, leading to large increments in the values reportable, especially in the region critical for minimum operating conditions for modern aircraft. Also, undulations in the profile of the main runway make the RVR assessments available using RELs for runway 09 very limited, with a large gap around the critical take-off minima. Also, the advection fog which affects Ronaldsway is sometimes accompanied by strong cross-winds which, as well as making life difficult for pilots, makes the RVR observer's position more hazardous!

Glossary of terms

Visibility or meteorological visibility (MV): By day, the greatest distance at which a black object situated near the ground can be seen and recognized, when observed against a background of fog or sky. By night, the greatest distance at which lights of moderate intensity can be seen and identified.

Fog: Conditions of meteorological visibility less than 1000 m.

Transmittance: The relative intensity which remains in a beam of light after traversing a path of given length through the atmosphere.

Extinction coefficient (EC): The relative attenuation of a light beam due to scattering and absorption in passing through a certain distance of the atmosphere.

Meteorological optical range (MOR): The length of path through the atmosphere required to attenuate a beam of light to 5% of its initial intensity. MOR approximates visibility (MV), but it can be measured instrumentally whereas visibility cannot.

Visual range (VR): The maximum distance at which an object or light is just visible under particular conditions of transmittance and background lighting.

Runway visual range (RVR): The range over which the pilot of an aircraft on the centreline of a runway can see the runway surface markings or the lights delineating the runway or identifying its centreline.

Koschmieder's Law: An equation which relates the illumination of an object against its background when nearby, compared to the same object viewed at a distance. Used to determine visual range by day, it enables MOR to be calculated from a measured value of extinction coefficient.

Allard's Law: An equation which relates the illumination produced at some point by a distant light to the intensity of the light source and the transmittance of the intervening atmosphere. Employing the visual threshold of illumination of the eye (for a light source to be just visible), it applies to the visual range of lights.

Gold visibility meter: A simple visual photometer which measures the apparent brightness of a distant light of known intensity, and hence the transparency of the intervening atmosphere. It consists of an eyepiece sliding over a variable density filter. In use, the eyepiece is moved along the filter (from the more transparent end towards the less) until the light observed is almost extinguished, and the position of the eyepiece noted on the scale of filter density, which is calibrated in units relating to transmittance (nebules).

Equivalent extinction visibility (EEV): Used in the manual RVR calibration. The observer uses the Gold visibility meter in conditions of good atmospheric visibility to obtain the value of filter transmittance required to almost extinguish a distant light. The value is used to calculate what the equivalent daylight visibility would be if the atmospheric transmittance was reduced to that value (for example, by mist or fog).

The winter of 1991/92 in the United Kingdom

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Summary

The winter of 1991/92 was generally mild and dry with about average sunshine, although quite sunny in many eastern areas and dull in the far north and west.

1. The winter as a whole

Mean temperatures were above normal nearly everywhere and ranged from 2.2 °C above normal at Kinlochewe, Highland Region to just below normal at Chivenor, Devon. Winter rainfall amounts were above normal in central and western parts of Scotland and Northern Ireland, but below normal elsewhere, ranging from more than 150% of normal along the Great Glen to less than 30% in the London area. Snowfall was less than normal generally, but particularly so in the south. Winter sunshine amounts were generally about average over England and Wales, but below average over Scotland and Northern Ireland. However, that statement fails to show the contrast between the quite sunny winter on the east coast and the very dull winter in the Western Isles.

Information about temperature, rainfall and sunshine during the period from December 1991 to February 1992 is given in Fig. 1 and Table I.

2. The individual months

December. Mean monthly temperatures were generally below normal in southern and eastern areas but above normal elsewhere, ranging from about 1.5 °C above normal in north-west Scotland to 1 °C below normal in East Sussex. Monthly rainfall amounts were below normal over the United Kingdom as a whole, and much of southern England and South Wales had less than half the normal rainfall amount, with as little as 14% of average falling at Odiham, Hampshire. In contrast, 144% of average rainfall fell at Holme Moss, West Yorkshire. The provisional rainfall value for England and Wales for the month makes it the driest December since 1988. Northern Ireland had the wettest December since 1986, ending a sequence of five dry Decembers. Monthly sunshine amounts were above average in many eastern areas, but generally dull in northern and western areas, exceeding 140% of average in the London area and around Tyneside, but with less than 40% of the average sunshine in much of the Scottish Highlands. Northern Ireland reported the dullest December, together with December 1981, since 1977.

Most parts of the United Kingdom had dry weather during the first two weeks. Over England and parts of southern and central Scotland a combination of very light winds and clear skies overnight produced some severe frosts between the 11th and 16th. The cold weather gave way gradually on the 16th and 17th to mild moist

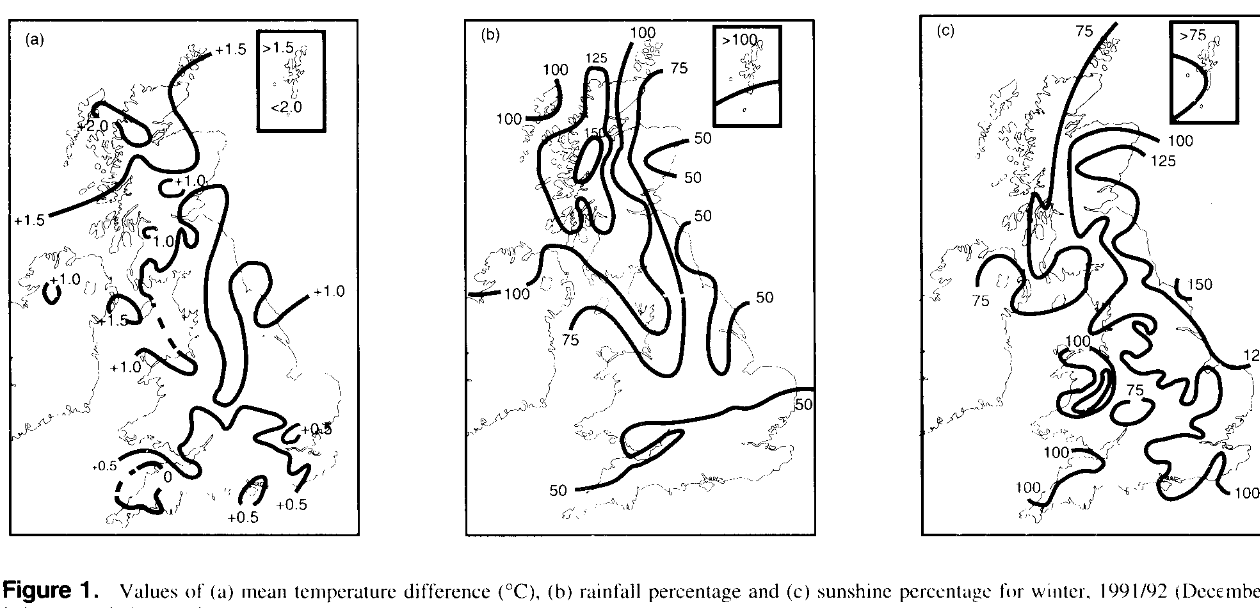


Figure 1. Values of (a) mean temperature difference (°C), (b) rainfall percentage and (c) sunshine percentage for winter, 1991/92 (December–February) relative to 1951–80 averages.

Table I. District values for the period December 1991–February 1992, relative to 1951–80 averages

District	Mean temperature (°C)	Rain-days	Rainfall	Sunshine
	Difference from average		Percentage of average	
Northern Scotland	+1.6	−2	128	68
Eastern Scotland	+1.2	−6	80	107
Eastern and north-east England	+1.0	−6	66	115
East Anglia	+0.7	−7	53	105
Midland counties	0.0	−7	63	85
South-east and central southern England	+0.5	−7	37	107
Western Scotland	+1.3	−1	131	77
North-west England and North Wales	+1.0	−2	84	99
South-west England and South Wales	+0.3	−8	52	95
Northern Ireland	+1.3	−4	103	71
Scotland	+1.3	−3	119	84
England and Wales	+0.7	−6	61	101

Highest maximum: 15.1 °C in east and north-east England in December.
Lowest minimum: −11.2 °C in western Scotland in January.

Atlantic air, bringing rain to many places; a thunderstorm was reported at Prestwick, Strathclyde Region and hail showers were reported in south-west England and South Wales on the 20th. Heavy rain on the 21st accompanied by gale-force winds washed away bridges, flooded roads and blocked railways, particularly in the areas of Sheffield, Manchester, the Severn Valley and the Welsh Marches; during the following 36 hours occasional rain continued to affect many areas, often accompanied by strong winds. It continued unsettled for the next few days as very disturbed and windy weather with bands of rain advancing from the west alternated with sunshine and showers until the 24th, when settled weather returned to much of the United Kingdom. Many parts became unsettled once more on the 31st. On the 31st winds were very strong over northern parts of the United Kingdom and several places in northern Scotland recorded gusts over 60 kn: at Butt of Lewis, Western Isles a gust of 96 kn was recorded during the late evening, equalling the record for December set at Stornoway and Benbecula, Western Isles in 1956 and at St Mary's, Isles of Scilly in 1935.

January. Mean monthly temperatures were generally above normal in northern Scotland and about normal over much of England and Wales, but below normal over south-west England, ranging from 2.3 °C above normal at Baltasound, Shetland and Kinlochewe, Highland Region to 1.2 °C below normal at Chivenor, Devon. Monthly rainfall totals were below normal everywhere, except central Scotland and an area of the Midlands from Hereford and Worcester to Cambridgeshire, where rainfall was above normal, and ranged from more than 222% at Fort Augustus, Highland Region to 16% at Bexhill, East Sussex. Monthly sunshine amounts were above average over much of eastern Scotland and north-east England, the east Midlands, East Anglia and south-east England, western Wales and southern coastal counties of England and below average elsewhere, ranging from 228% at Cwmystwyth, Dyfed to 43% at Stornoway, Western Isles.

The month started unsettled, with strong winds, heavy rain and hail, mainly in northern and western areas of Scotland, the rain turning to sleet in many places and to snow over high ground. Gales, locally severe, came to northern and western areas between the 1st and 3rd. A number of stations measured gusts in excess of 70 kn on the 1st, including a gust of 93 kn at Kirkwall, Orkney, and two of 78 kn at Lynemouth, Northumberland. Outbreaks of very heavy rain in places on the 1st resulted in extensive flooding and disruption to traffic, especially in western Scotland. Over Northern Ireland it was wet until the 8th and then mostly dry. England and Wales remained generally cloudy, but dry, with some lengthy bright periods; however, rain came to many places in southern England overnight on the 7th/8th. On the 19th and 25th small amounts of rain fell in all areas overnight. On the 26th, the pressure rose, reaching 1049 hPa in North Wales, to give the highest January pressure for 30 years over England and Wales. On the 28th northern Scotland had very small amounts of rain.

February. Mean monthly temperatures were above normal everywhere, ranging from 3 °C above normal at Inverness, Highland Region and Haydon Bridge, Northumberland to 0.6 °C at Plymouth, Devon. Monthly rainfall amounts were above normal over much of Scotland apart from the eastern coastal areas and over parts of North Wales, Merseyside and Northern Ireland, but below normal elsewhere, ranging from 283% of normal at Isle of Rum, Highland Region to less than 25% of normal in parts of Cambridgeshire. Monthly sunshine amounts were above average in eastern areas and below average in western areas, ranging from 171% of average at Whitby, North Yorkshire to less than 40% of average at Poolewe, Highland Region.

The month was generally unsettled and mild, with periods of rain or showers, heavy at times, mainly in the north and west, the rain largely dying out over East Anglia and the south-east. While conditions became somewhat more settled in southern areas around the 15th, northern areas remained unsettled with snow and sleet or wintry showers. On the 17th, after a cold sunny start in most places, a band of rain, sleet and snow spread slowly eastwards, affecting most areas by evening; the precipitation was heavy in places. Heavy snow in the Midlands led to some severe road conditions for a time on the 18th. The unsettled weather continued over the next ten days, with a change to more settled weather in southern ares on the 28th. Thunder was reported at Cape Wrath, Highland Region on the 2nd, Aberporth, Dyfed on the 12th and Manchester on the 13th, while hail was reported in West Yorkshire on the 10th and over Shetland on the 24th.

Awards

Due to an administrative oversight the 1990 awards below were omitted last year. Our apologies are extended to all concerned.

L.G. Groves Memorial Prizes and Awards for 1990

Meteorology Prize — Dr M.J.P. Cullen

The citation for this award was:

'The unexpected cancellation of the contract for the ETA-10 supercomputer, and its replacement at the end of 1989 by a Cray YMP computer led to a fundamental reappraisal of the Office's plans for its new operational forecasting model. Dr Cullen took the lead in planning and managing the project. The new model, known as the Unified Model because it meets the needs of both operational forecasting and climate research, has been constructed in a versatile and flexible way that allows it to be reconfigured to suit particular requirements; it can be run as an atmosphere model, as an ocean model or as a coupled atmosphere–ocean model; it can be run as a global model or as a limited area regional model; it can be run as a forecast model or as a data assimilation model. Internationally agreed coding standards have been followed throughout; this means that, for the first time, it will be possible to exchange software between other major national weather services and to set up fruitful cooperative research and development projects. Dr Cullen's personal scientific input to the project has provided very efficient energy conserving techniques for solving the model equations; he has also developed still more accurate methods that will be tested in the near future. His tight management of a large team drawn from three Divisions in the Office and his decision to use the PRINCE methodology for project control and quality assurance (the first time it has been used for an Office project) has allowed the model to be developed and introduced more smoothly and within a shorter time-scale than has been possible for similar exercises in previous years. The model is already producing more accurate forecasts than before for many weather features, and its clearly designed and well documented structure is ideal for permitting further development and improvement in the future.'

Meteorological Observation Award — J. Gloster

The citation for this award was:

'The impact which John Gloster has had on MRF is most easily seen in the number of hours flown by the C-130. In 1988/89 this was 75; in both 1989/90 and 1990/91 it has been over 500. Much of the credit for this must go to John, who has developed closer liaison (particularly with RAE and RAF Lyneham) to give MRF a C-130 for scientific flying.

John has been extremely effective at organizing the many international detachments, so that the airborne scientists can concentrate on the research without worrying about the details of logistics which can often make or mar a detachment. In the recent Gulf detachment, he (together with OC MRF) visited a number of the Gulf states to obtain diplomatic clearance for the MRF to operate in record time.

Part of his success undoubtedly lays in his affable personality and positive attitude, but mainly it comes from hard work and application.'

L.G. Groves Memorial Prizes and Awards for 1991

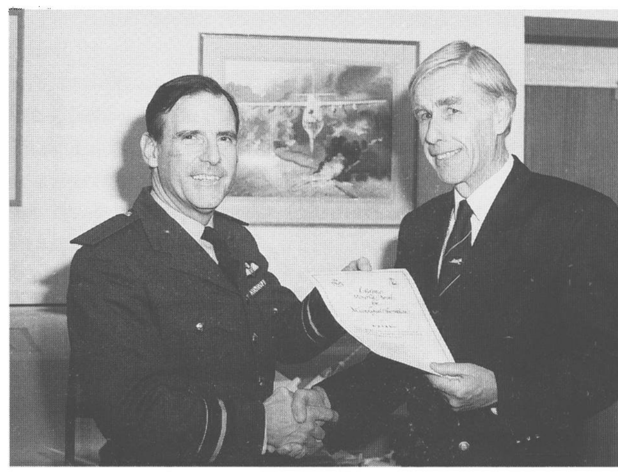
Meteorology Prize — C.K. Folland and D.E. Parker

The citation for this award was:

'Over a number of years Mr Folland and Mr Parker have led the painstaking work of assembling and analysing sea surface and air temperature data measured from ships over the period from the middle of the last century to the present day. Of particular note is their recent, unique work, on the theoretical and experimental estimation of corrections that need to be applied to sea surface temperature data collected from uninsulated (mainly canvas) buckets in widespread use prior to the 1940s, and also new corrections to air temperature data. The resulting sea surface and air temperature data sets provide the most comprehensive and consistent record currently available of changes of temperature at the global ocean surface over the last 130 years. This is particularly important for the assessment of the observational evidence for climate change (e.g. due to the greenhouse effect) and for devising methods of seasonal forecasting, especially for the semi-arid tropics.

On the basis of this work, Mr Folland and Mr Parker have made major personal contributions to the scientific assessment of observed climate variability and change, published in the 1990 Report of the Intergovernmental Panel on Climate Change, and in the Supplementary Report produced for the 'Earth Summit', held in Rio de Janeiro in June 1992. The cited work also led to the publication of a much needed and highly regarded Global Ocean Surface Temperature Atlas, in conjunction. with other scientists in the Meteorological Office and at MIT, Boston.'

Meteorological Observation Award — P.G.W. Healey



The citation for this award was:

'Mr Healey has been concerned with the measurement of the atmosphere by sondes dropped from the Meteorological Research Flight C-130 for the last 14 years, and his work has contributed directly to the success of the 1987 and 1992 campaigns for measuring the detailed structure of frontal systems. During this time he has mastered the technical difficulties of ejecting and tracking multiple sondes from an airborne platform while ensuring the quality of the measurements, by maintaining careful control of the manufacture, calibration, deployment, reception and post flight validation of the dropsondes. He routinely flies with the aircraft when sondes are being deployed and it is his skill in organizing the deployment of the sondes and in monitoring their measurements that has led to the current very high success rate in the use of this system during recent campaigns.

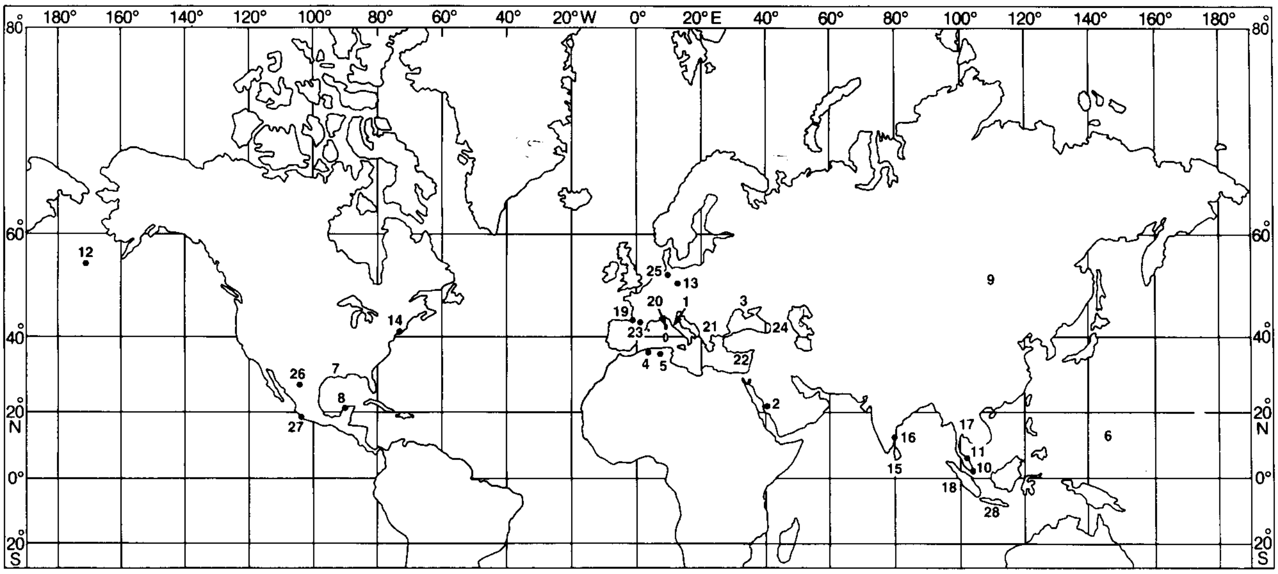
He has developed a system on the aircraft for receiving and decoding the sonde measurements in real-time and for displaying plotted profiles on request to the mission scientist. This facility has greatly increased the effectiveness of scientific research by allowing the mission scientist to optimize the flight pattern in the light of actual conditions.

He is currently working on the deployment of a highly automated, low cost, lightweight sonde, which will enable soundings to be taken routinely during scientific flights of the MRF C-130. This development will further enhance the contribution of the MRF C-130 scientific programme to improving the accuracy of weather forecasting models.'

World weather news — November 1992

This is a monthly round-up of some of the more outstanding weather events of the month, three months preceding the cover month. If any of you, our readers, has first hand experience of any of the events mentioned below or its like (and survived!), I am sure all the other readers would be interested in the background to the event, how it was forecast and the local population warned.

These notes are based on information provided by the International Forecast Unit in the Central Forecasting Office of the Meteorological Office, Bracknell and in the 'Casualty Reports' pages of Lloyd's List. *Naturally these are heavily biased towards areas with a good cover of reliable surface observations. Places followed by bracketed numbers in the text are identified on the accompanying map. Spellings are those used in* The Times atlas of the world.



Location of places mentioned in text

1	Tuscany, Florence	11	Kota Baharu	20	Corsica
2	Jiddah, Makkah	12	St. Paul	21	Albania
3	Ukraine	13	Leipzig	22	Cyprus, Adana
4	Alger	14	New York	23	Tarbes
5	Constantine	15	Sri Lanka	24	Dagestan
6	Guam	16	Madras	25	Hamburg
7	Louisiana, Houston	17	Thailand	26	Chihuahua
8	Merida	18	Sumatra	27	Manzanillo
9	Lake Baikal	19	Biarritz	28	Jawa
10	Singapore				

The month began with a report that Florence (1) had its wettest October on record. Although the city centre escaped the floods, the river Arno did flood its northern suburbs; flooding was widespread throughout Tuscany (1) and the worst since 1966 costing an estimated $745m. The disturbed weather continued into this November with Rome having strong winds and more than 60 mm of rain on the 2nd. A less likely candidate for heavy rain is Saudi Arabia, but on the 2nd and 3rd high winds and thunderstorms gave Jiddah (Jedda) (2) 42 mm and Makkah (Mecca) 83 mm in a few hours; their November average is about 10 mm.

Another unusually wet place at the start of November was the west of Ukraine (3) where heavy rains and snowfall created the worst floods for decades which killed eleven. A small low moving along the North African coast gave Alger (Algiers) (4) 93 mm (November average 85 mm) and to Constantine (5) 84 mm.

An unwelcome leftover from October was typhoon 'Elsie'. She passed about 30 miles south of Guam

(6) (causing the local elections to be postponed but only minor damage). By the 5th she was rated a super-typhoon with central pressure down to about 900 hPa and with winds of 150 kn gusting 180 kn. The storm was diminishing as it passed safely offshore of Japan but managed to dislodge some 4000 tree trunks from the deck of a bulk carrier 180 n mile east of Tokyo.

The USA got off to a bad start (a sign of what was to come) when a cold front entered Louisiana (7) on the 3rd bringing high winds, golf-ball size hail and at least one tornado which did about \$25m damage in the Shreveport–Bossier City area. Totals of 70 to 100 mm of rain were not rare in other states and the temperature fall was about 16 °C as the front passed. Part of the trouble seems to have been persistent high temperatures (often above 30 °C) around the Gulf of Mexico which gave the air great moisture-bearing capacity: Merida (8) in the Yucatan got 106 mm in 6 hours followed by 22 mm in the next six (their November average is 34 mm).

Another long-term trouble maker was the Siberian High: its central pressure got up to nearly 1063 hPa around Lake Baikal (9) on the 6th with temperatures about −10 °C by day and −30 °C by night. This cold air spread south over the next few days, reinforcing the NE Monsoon and generating some big rainstorms. Many places in Indonesia and Malaysia were to have 100 mm or more of rain from the system which caused temperatures over China to fall from about 30 °C to near zero. Singapore's (10) heavy rain and thunderstorms produced 210 mm in the 36 hours up to 1200 UTC on the 11th; Kota Baharu (11) on the east coast of Malaya got 152 mm in 6 hours and 311 mm in 24 hours. The floods drowned five in Tregganau and Kelantan states.

A fascinating item was reported on the 9th, the island of St Paul (12) in the Bering Sea had its first thunderstorm since 21 November 1951! On the 11th and nearer home, an intense depression crossed southern England into northern Europe with gales near and to the south of the centre. Mean speeds of 40-45 kn were recorded and noteworthy gusts were 62 kn at Brüggen (NW Germany) and 89 kn on the Brocken (100 miles west of Leipzig (13)). The storm brought down trees and power lines, disrupting road and rail transport. The East Scheldt storm barrier was closed for only the twelfth time since its completion in 1986.

Disasters now struck 160° longitude apart on the 12th at 80° E and W. The first does not seem to have cost any lives but did great damage to property. This was a slow-moving cold front over central and southern states of the USA. Heavy rain and severe thunderstorms were accompanied by gusts of up to 60 kn in Kentucky, Ohio, Pennsylvania and New York (14) states. Mobile, Alabama got 76 mm in a few hours and New Orleans 46 mm (here the total for the month so far was 223 mm, twice the monthly average). The worst event of November began when cyclone '10B' appeared just east of Sri Lanka (15) on the 12th. It was soon crossing the island killing 13 with falling trees and damaging thousands of homes with floods and landslides. Emerging almost unscathed by this experience the cyclone wound up to about hurricane intensity and dawdled around the southern tip of India and up the west coast. Over the next few days many places in Tamil Nadu and Kerala had over 200 mm of rain (Madras (16) 271 mm): the massive rainfall filled dams to overflowing and caused flooding and landslides which claimed at least 250 lives and rendered some 25 000 homeless. Kochi Airport was closed on the 14th by knee-deep floodwater on the runway. Huge seas damaged the breakwaters of the port of Tuticorin and closed it pending a hydrographic survey.

Tropical storm 'Forrest' developed on the 12th, it failed to reach typhoon strength but frightened workers of the offshore natural gas fields before it went ashore on the 15th and caused a lot of flooding in southern Thailand (17). The main reported casualty was the crash of a Vietnam Airlines YA4-40 in Khanh Hoa province on the fringe of the storm, 30 died and one survived. A lighter note was struck when, heeding the warnings of 6 m waves, fishermen closed the main road by hauling their boats onto it, the safest place! 'Forrest' drifted round the Bay of Bengal as a tropical depression before making his second landfall at 0900 UTC on the 21st on the Burma/Bangladesh border. Following these storms the NE Monsoon eased off in Malaysia (Kuantan (between 10 and 11) had 464 mm between 15th and 19th with 301 mm on the 16th) and temperatures rose to record highs: Rangoon's 37.5 °C on the 20th was 2.5 °C above the November record and Padang (Sumatra (18)) 1.5 °C above. 'Gay' appeared on the Dateline near the equator on the 15th and cruised steadily west-north-west. A typhoon by the 18th and super-typhoon by the 19th with winds gusting up to 190 kn, this exceptional storm headed for the North Marshall and North Marianas Islands. One third of the former was made a disaster area (no details available). In the latter group Guam had its second strike of the month; although winds were over 100 kn there were no reports of severe damage, perhaps because there was little rain with it. (Earlier Guam had had a near miss from 'Hunt' as it strengthened to a typhoon on the 18th.)

A push of cold air into the eastern Mediterranean on the 13th and 14th gave 40 mm of precipitation over much of 'Yugoslavia' with the rain turning to snow as the temperature fell to freezing and compounding the misery of its unfortunate inhabitants. A northerly gale in the Aegean reminded locals there that winter had arrived.

Back home on the 17th, a trough from Iceland to the Strait of Dover drove cold air south-east across most of south-west Europe. The cold front was preceded by 25 mm of rain in many places which turned to snow over hills. The NW wind was very strong with gusts of 60 kn in NW France and 54 kn at Biarritz (19). The strongest winds seem to have been around the north and west coasts of Corsica (20), Cap Corse having a mean speed of 52 kn with a gust to 82 kn. As is often the case in these situations a low formed in the lee of the Alps and helped maintain the activity of the front. The eastern side of the Adriatic was doused with about 50 mm of rain and eventually the river Mali broke its banks in the north of Albania killing 11 and making 35 000 homeless. As the low had drifted round the southern end of Greece its front transferred its attentions to the eastern Mediter-ranean. On the 21st Cyprus (22) had high winds (gusts to 42 kn in Paphos) with floods in Limassol and landslides in the Troodos mountains. Adana (22) in Turkey received 108 mm in 36 hours while Antalya's 125 mm in 24 hours should be compared with their November average of 119 mm.

The return of warm, moist westerly flow to southern Europe brought avalanche threats to the Alps where on the 22nd La Dole, at about 1500 m, had 56 mm of rain. The air was further warmed by descent in the lee of mountains and Tarbes (23), on the French side of the Pyrenees, had one of its highest ever November temperatures at 27.6 °C. The boundary between the warm and cold air masses generated a low which rushed south-east and deepened rapidly as it crossed Turkey; the result was gales and widespread heavy rain in the eastern Mediterranean with 25–50 mm of rain over much of Israel, Lebanon and Syria on the 23rd. The last fling of this low was to give heavy snow and then a rapid thaw in the Caucasus, the Russian region of Dagestan (24) being badly affected by the resulting avalanches and floods.

The weekend of 21st/22nd brought the third catastrophe of the month to central USA, one of the severest tornado outbreaks for many years with some ground tracks as long as 30 miles. The tornadoes were accompanied by torrential rain (50 to 100 mm) and marble-size hail. Twenty-seven were killed and more than 400 injured. Insurance claims of $425m include damage at West Houston Airport (7) where a tornado scored a direct hit on a hangar destroying 15 private planes and severely damaging another eight.

After a series of intense Atlantic depressions had curved north to Iceland, the last, on the 26th, raced almost due east along the English Channel to the southern Baltic. Winds reached 50 kn widely over north France, the Low Countries and Germany with 66 kn at Brussels and 72 kn at Vlissingen causing considerable damage to property. There was a fair amount of excitement in the port of Hamburg (25) as tugs struggled to control larger vessels.

A renewed surge of cold air across the USA brought blizzards to the Great Plains and Lakes with ten killed as level snow depths reached 50 cm in places. The effect in Mexico was dramatic: on the 27th Chihuahua (26) had a frost followed by a daytime maximum of 9 °C, in the warm air Monzanillo (27) had a new November record of 38.8 °C.

At the end of the month, Jawa (28) and the surrounding area was starting its wettest season and daily rainfall totals included 199 mm at Semarang and 133 mm at Madium were reported on the 25th. On the other side of the world, New Orleans, Louisiana (November average 96 mm) had accumulated 387 mm by the 29th. By contrast, Riverside in California had its first completely dry November since 1956.

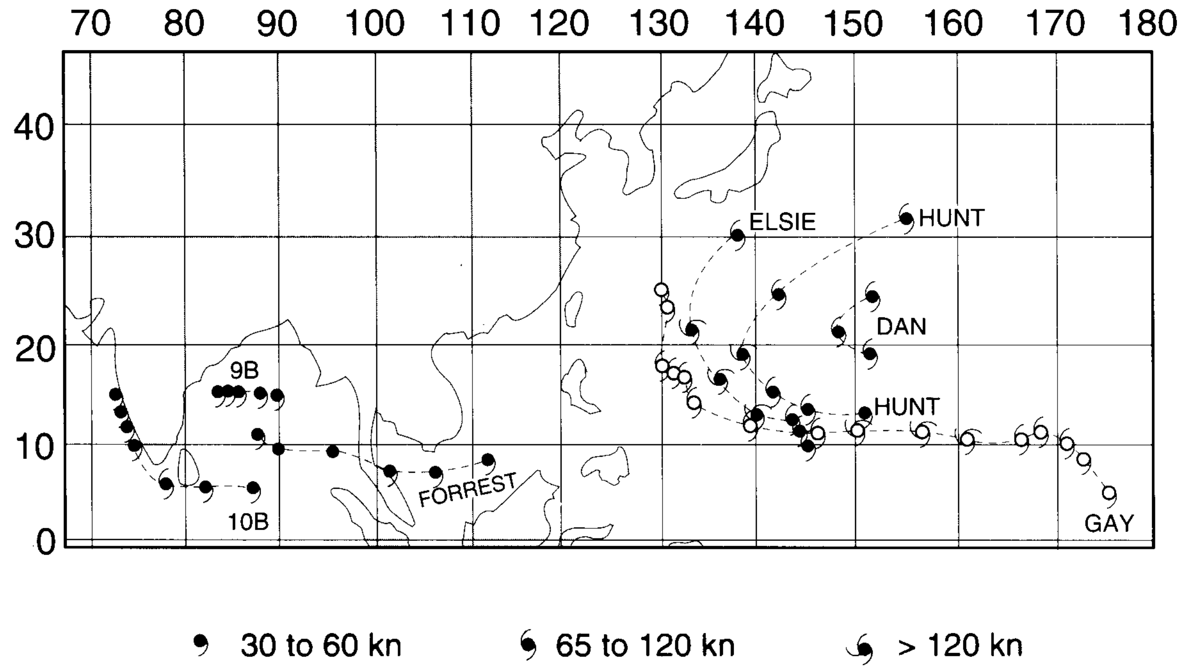
Over the United Kingdom November was mild and wet. The Central England Average Temperature was one and a half degrees higher than normal (the mildest since 1978): further north temperatures were nearer normal. Rainfall totals were above average everywhere and nearly double the average in south-east England. It was particularly wet in South Wales towards the end of the month with around 100 mm in last two days.

October tropical storms

List of tropical storms, cyclones, typhoons and hurricanes active during November 1992. The dates are those of first detection and date of falling out of the category through dissipation or becoming extratropical. The last column gives the maximum sustained wind in the storm during its lifetime. The map shows 0000 UTC positions during November, the symbols for 'Gay' have been left unfilled to distinguish its track from 'Elsie's' and 'Hunt's' which it crossed.

No.	Name	Basin	Start	End	Max.
1	Dan	NWP	24 Oct.	3 Nov.	115
2	Elsie	NWP	29 Oct.	7 Nov.	150
3	Forrest	NWP	12 Nov.	18 Nov.	70
4	Gay	NWP	15 Nov.	30 Nov.	160
5	Hunt	NWP	16 Nov.	21 Nov.	125
6	9B	NI	3 Nov.	7 Nov.	55
7	10B	NI	11 Nov.	17 Nov.	70

Basin code: N — northern hemisphere; S — southern hemisphere; A — Atlantic; EP — east Pacific; WP — west Pacific: I — Indian Ocean; WI — west Indian Ocean.



Reviews

Perspectives of nonlinear dynamics (Volumes I and II), by E.A. Jackson. 188 mm × 247 mm, pp. xix + 496 (Vol. I), *illus.*, pp. xvii + 633 (Vol. II), *illus.* Cambridge University Press, 1992. Price £19.95 (per Volume). ISBN 0 521 42632 4 (Vol. I), 0 521 42633 2 (Vol. II).

According to the author, these two books are intended to access non-mathematicians to the methods and viewpoints of the ever-growing field of non-linear dynamics. Collectively the two books certainly achieve their goal, introducing various concepts with a readable text that places emphasis on the idea and application rather than the mathematical detail. The material is presented, despite its technical nature, like a mathematical history book, providing the reader with a fascinating chronological account of many important mathematical discoveries.

Broadly speaking, the 500 or so pages of Volume I are concerned with 1st- and 2nd-order differential systems and 1st-order difference systems. Jackson begins by defining non-linear phenomena and non-linear dynamical systems and then moves on to such elementary concepts as phase and control space, phase portraits, Poincaré maps, stability, dimension and measure, bifurcations and catastrophes. He then demonstrates these ideas with specific non-linear systems, introducing further concepts such as ergodicity, period doubling and chaos, and emphasising the differences in behaviour between continuous and discrete time-systems. His exposition is elementary, and uses many well-known equations from all areas of science, including those of van der Pol and Lotka, as examples of continuous time systems, and the logistic and tent maps of discrete time systems.

Volume II continues the story moving from 2nd-order difference equations to 3rd- and higher-order differential systems, on to partial differential equations and solitons, and finally treating coupled maps and cellular automata. In a little over 600 pages, Jackson covers a vast amount of advanced material, including AM theory, lattice maps, dynamic entropies, Lorenz dynamics, integrability, FPU phenonema, solitons, chemical oscillations, cellular automata and the dynamics of living systems. This he does with constant reference to physical models and related experiments, each carefully explained with the general scientist in mind.

The two volumes have identical presentation and the references and indexing in each covers both volumes. Each chapter begins with an introduction and recap of ideas and concludes with hints and answers to the elementary exercises contained within. Many mathematical terms and concepts are left to a glossary and appendices at the back of each volume. There are plenty of clarifying illustrations, although some are perhaps unnecessary, and, since they are in text, definitions and theorems are often difficult to isolate. A large number of references are made to relevant literature and these are listed both by subject and by author at the back of each volume.

Perhaps the most refreshing aspect of Jackson's approach is the way he uses history to explain the development and refinement of each mathematical method.

This he is well-placed to do, having observed the advent of the computer and the boom of research into non-linear dynamics. He uses this experience to show us how contemporary ideas, some correct, some incorrect, led scientists towards many important mathematical discoveries. For example, in Volume I, he describes the original experiment of van der Pol and van der Mark that led to the discovery of chaos in forced oscillators, and in Volume II he relates how an uncharacteristic mistake by Fermi led to the discovery of FPU recurrence phenonema. This relaxed approach not only makes the learning process more enjoyable, but also shows how research works and therefore serves to inspire and encourage the intended audience.

Together these two books introduce an extensive range of ideas in a lucid and entertaining way and with an unusual number of references to physical models. The treatment of each topic is elementary, but many references are given for further reading. Volume II is more advanced than Volume I, but the lucid style is maintained and most of the mathematical concepts outlined in Volume I are briefly revised, making it mostly self-contained and suitable for a graduate with a basic knowledge of non-linear dynamics. Having said this, the volumes are best read in sequence as the material is arranged so that the dynamical systems are presented in increasing order of complexity.

For the researcher applying mathematics to the field of meteorology, these two volumes will provide a comprehensive introduction to this fast-growing and important field.

S. Baigent

The solar–terrestrial environment, by

J.K. Hargreaves. 177 mm × 253 mm, pp. xiv + 420, *illus*, Cambridge University Press, 1992. Price (hardback) £50.00, $79.95. ISBN 0 521 32748 2.

'Almost everyone has heard about astronomy although they might not understand it, and almost everyone knows about meteorology even if they cannot spell it. This book is all about the bit in between.'

This is the latest in the Cambridge atmospheric and space science series and is, in my opinion, far and away the best. In the days when the University of Aberdeen still had an Honours Physics undergraduate class, I taught a 12-hour course on 'Aeronomy'. There is an obvious plan to such a series of lectures and I began with gas laws applied to the upper atmosphere, continuity, radiowave probing of an ionized medium with an embedded magnetic field, Chapman layer, and went on to discussion of the solar wind and magnetosphere, geomagnetic storms and aurorae, ozone layer, water vapour in the upper atmosphere, the exosphere. In assessing the value of any textbook, therefore, I match its content against this syllabus and Hargreaves' book matches up very well. It may be a case of great minds think alike although the sceptic will quote Emerson about 'the hobgoblin of little minds, adored by little statesmen and philosophers and divines.'

Hargreaves' and my paths met in the sixties when we were both employed by the US Government in the large upper atmosphere, ionosphere, magnetosphere laboratories in Boulder (Colorado). He moved to Lancaster, myself to Aberdeen; he retained his research interests in solar–terrestrial disturbances, I moved my interests from airglow to noctilucent clouds (and, yes, these are mentioned in this book). The selection of topics for this book reflects Hargreaves' interests, very much leaning towards the ionosphere and magnetosphere.

The meteorologist will find that the boundary between 'astronomy ... and ... meteorology' is not dealt with in great detail. The transition from meteorology to aeronomy, which in general terms might be placed somewhere between 30 km and 100 km in altitude, is not dealt with in the detail one might expect. The discussion could profitably have been extended to deal with the diffusion of water vapour up through the atmosphere to the exosphere, and the accompanying chemical and ionic changes in balance of hydrogen-containing compounds. This is currently relevant to discussion of the consequences at all levels of the atmosphere of an increase in methane concentration at ground level. As it is, the section on water vapour consists of three sentences and a reference to a couple of sentences later on in the section on the D-region ('... hydrates occur when the water vapour concentration exceeds about 10^{15} m^{-3}').

The book uses SI units (unlike some of the earlier books in this series) and is therefore understandable by the modern student. The print layout is clear and the illustrations are well-chosen. I would not have included 'physical aeronomy' and 'chemical aeronomy' as subsets of 'principles of the ionosphere' and I would have chosen more apposite quotations from the great, the good, and the dead, for chapter headings. These are minor carpings: the book is a good textbook for use by students at finals level, and in the first year of postgraduate work. Principles are well covered, applications described in sufficient detail, and the range of topics approaches comprehensiveness. The book is worth the price. Those who do not want a textbook but an introduction to the science will not be disappointed.

M. Gadsden

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 (IBM-compatible or Apple Macintosh) 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 BS1991: 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 Editor, Meteorological Magazine, Meteorological Office Room 709, London Road, Bracknell, Berkshire RG12 2SZ.

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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