

Swinnerton-Dyer/Pearce Report  
Noise assessment model  
Llanthony experiment  
Summer of 1987



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## Summary and conclusions from the Secretary of State's enquiry into the storm of 16 October 1987

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### Summary

The Secretary of State for Defence invited Sir Peter Swinnerton-Dyer (Chairman of the University Grants Committee) and Prof. Robert Pearce (University of Reading) to consider the findings of the internal enquiry carried out by the Meteorological Office into the storm of 15-16 October. A summary of their report and the conclusions about the internal enquiry are given.

### 1. Introduction

Following the storm of 15/16 October 1987, the Director General of the Meteorological Office instituted an internal enquiry into the weather forecasts that the Meteorological Office made in the period preceding the storm over southern England. The Secretary of State for Defence invited us to consider the findings of the internal enquiry (a shortened version of which appeared in the April issue of the *Meteorological Magazine*) and to report our conclusions to him. Our report was published in February 1988 and the following is the summary and conclusions taken from that report.

### 2. Summary

The lack of adequate public warning of the storm of 16 October arose from two direct causes, both related to the production of the forecast for that day at the Central Forecasting Office of the Meteorological Office (MO).

- (a) The computer forecasts available to the MO on 15 October were not in agreement, and all, including that from what is usually the most reliable model, underestimated the winds over south-east England.
- (b) The duty forecasters followed the guidance of their model too closely and did not recognize a situation in which the model was likely to underestimate the strength of the winds.

The presenters and the media cannot be held responsible for failing to issue warnings with which they were not supplied. But it must be said that on this occasion the television forecasts played down the winds over land even more than the forecasters' guidance did.

### 2.1 *The computer forecasts*

The main underlying factors responsible for 2(a) were as follows:

- (a) The usually more reliable high-resolution model is particularly sensitive to error under conditions of rapid storm development where sufficient observations are lacking.
- (b) There were, as usual, rather few observations over the sea, particularly to the west of Spain where the storm developed on Thursday 15 October. Because the coarse-mesh model is run later than the fine-mesh model it was able to take account of more observations; this seems to be the reason why the coarse-mesh model, which should in principle be inferior, performed better on this occasion. Subsequent analysis has shown that wind observations in this area from transatlantic aircraft would have been particularly crucial; more surface ship reports received in good time would also have helped.

These aspects of model failure are recognized in the MO report, and the recommendations made there provide sound guidance for attacking these problems. The computer forecasts available at the French Meteorological Service were somewhat more consistent than ours, mainly because they have access to a more powerful computer, but they equally underestimated the storm's intensification.

The MO fine-mesh model has a well-deserved reputation; indeed, when we visited the French Meteorological Service, they went out of their way to praise it. We believe both the mathematical formulation and the computer simulation to be as good as any in the world — though we trust that both of them will continue to be improved by incorporating the results of continuing research. But the model does suffer from one unnecessary handicap. The computer on which it runs (a Cyber 205) is significantly less powerful than the Crays available both to the ECMWF and to the French Meteorological Service, and in particular it has a smaller memory. One consequence is that the French fine-mesh model uses a mesh twice as fine as that of the MO.

In this context we would stress the importance of ensuring that the Meteorological Office always has at its disposal the most powerful computer available. Underprovision of computing power would indeed be a false economy, because it would undermine the campaign to increase the MO's commercial income — and this campaign is essential to the MO's future funding strategy. We are relieved to hear that the MO will be provided with an ETA 10 supercomputer in the Spring, even though the cost has had to be found by internal economies. We are not in a position to comment on the damage done by these economies beyond saying that it will have to be endured because the new computer is essential.

The computer models, and their enhancements, are among the major products of the Research Division of the MO. That Division provides good value for money, and without it the MO would rapidly fall behind its competitors in other countries. There is a continuing need for research, both in the MO and in universities. The division between the two is about right, research and development in the MO being closely motivated by operational needs and research in universities being more fundamental — though that too will eventually be reflected in better forecasts. In atmospheric science, the MO's links with university departments have recently been strengthened. We regret, however, that it has not been possible to interest academic numerical analysts in the (probably very difficult) problems related to weather forecasting, including the fundamental problems of atmospheric predictability. This is particularly true of the 'spin-up' problem — the problem of transforming initial observations to initial conditions on the grid on which the computer calculations are done. If the MO were to fund one or two CASE studentships in this area, that might create useful links at inconsiderable cost.

## 2.2 *The issued forecasts*

So far as 2(b) is concerned, no individual should be seriously blamed for the failure to forecast the severity of the storm. There are two main reasons for this. One is that the demands on the forecasters on this occasion were unusually heavy. Whoever happened to be on duty on 15 October was going to face what was likely to be the severest test of his career. The interpretation of computer forecasts is largely a subjective process and the model's guidance was, on this occasion, unusually confusing. Although most forecasters would have stressed the possibility of severe land gales, as indeed did the French, it seems to us possible to defend the failure of the senior forecaster actually on duty to do so.

The other reason relates to the senior forecaster's work schedule. His first task on taking up his duty is to assess the meteorological situation. He then prepares his 'synoptic review' describing his assessment and this is subsequently used, with periodic updating, as guidance for the detailed forecasts issued to the public and subscribers. The senior forecaster taking up duty at 0800 is expected to issue his review by about 1000. Under normal conditions this gives him reasonable time in which to study the charts and computer forecasts and to identify and deal with any tricky aspects of the situation. Under exceptional weather conditions, however, his assessment needs more information than is at present readily available, and more time. Consultation with senior colleagues could also help. This was an occasion when none of these conditions could be met.

## 3. Conclusions

The question then arises 'What steps need to be taken to enable our forecasters to cope more effectively with exceptional conditions?' The general public understandably expects forecasters nowadays, with computer and weather satellites at their disposal, to be able to predict the weather more accurately than in the past and, in particular, give due warning of exceptionally severe events. The experience of this storm shows that, if forecasters are to meet these expectations, they need improved computer models. But, equally important, they also need sufficient background knowledge and experience to not only interpret computer forecasts but also assess their reliability. We are therefore led to recommend a re-examination of certain aspects of training and organization within the MO. The ones that particularly concern us are as follows:

(a) The training which our forecasters receive needs to be improved and lengthened. Compared with the French forecasters, the training which ours receive is shorter (and therefore cheaper) and lays less emphasis on meteorological theory. French forecasters complete two years of a first degree course, usually in mathematics or physics, followed by a three-year course at the meteorological college at Toulouse. In effect, when they start work they already have a Master's degree in Meteorology. Our forecasters are recruited on the basis of a first degree, again usually in mathematics or physics. During their career they will take a number of short courses at the Meteorological Office College, but their training relies extensively on on-the-job training — in effect an apprenticeship system. This does not give them the background of theory which they need if they are to take the fullest advantage of the strengths and weaknesses of the computer models at their disposal. It also puts them at a disadvantage when they are faced with exercising judgement in a situation that has no precedent within the collective memory of the MO. We recommend that the training of our forecasters be reviewed, and that the review should include a more detailed comparison with what happens in other countries than we have had time to carry out.

(b) The duty senior forecasters carry on their shoulders the full responsibility for forecasts and warnings issued by the Meteorological Office. Their rank of Principal Scientific Officer is below that of senior research scientists (and senior administrators), who however have no responsibility for issuing forecasts. These disparities reflect the relatively lower status of the senior forecasters within

the hierarchy which, in view of their ultimate responsibility for the successful performance of the organization, is inappropriate. At least the best of them should have the opportunity of being promoted to Senior Principal Scientific Officer on merit, without thereby being forced to move to other jobs within the MO.

(c) It is our impression that, as a result of the economies imposed on the MO in recent years, the staff on duty in the Central Forecasting Office has been cut to the minimum needed to do the work in normal circumstances. Any increased staffing would be in a sense a diseconomy; but the effect of the cuts is that when exceptional problems occur there is no spare effort that can be devoted to thinking them through. An alternative, and probably better, way to remedy this would be to provide better display facilities and more interactive computing; this would need considerable extra programming effort.

(d) There seems to be no formal arrangement within the MO under which, when there is a situation of unusual uncertainty with a possibility of particularly severe conditions, the senior forecaster on duty can consult more widely than usual. That this was such a situation should have been obvious very early on 15 October when it became clear that different computer models were giving diverse guidance; also fewer than usual midnight observations were being received from France. Wider consultation on 15 October would have enabled decisions, possibly different ones, to have been made at a high level as to whether the threat of an exceptional storm was sufficient to warrant alerting the public and, if so, at what stage.

(e) Similarly, when there are conditions of unusual uncertainty that uncertainty should be allowed to come through to the general public. The senior forecaster's synoptic reviews issued during 15 October reflect some uncertainty — though less than he probably felt at the time — but little if any of this came through in the radio and television forecasts. Part of the senior forecaster's responsibility should be to assess the degree of uncertainty that should be presented to the general public.

(f) There are times, particularly when the weather situation is complex, when the time allocated to the presenter is inadequate if the public is to be provided with sufficient detail, particularly of weather hazards. The media should be prepared to introduce sufficient flexibility into their programme scheduling to allow, at short notice, more time to the weatherman on such occasions.

Our first three conclusions are not reflected in the MO report. The report does, however, contain a recommendation concerning instructions to Senior Forecasters in dealing with critical situations, i.e. to provide more information to the public on alternative possibilities. This recommendation, which we support, relates to our fourth and fifth conclusions but we perceive the need for a more radical initiative.

## **The Larkhill noise assessment model. Part I: Theory and formulation**

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### **Summary**

Noise forecasting is a routine task performed operationally for a number of Ministry of Defence ranges in support of artillery training exercises and explosives testing. The forecasts are produced using a numerical model which is run on a desk-top computer. This paper, Part I, describes the current operational model and discusses the theoretical background. Part II of the paper (Turton *et al.* 1988) assesses the model and describes its use, and also presents a simplified technique for providing noise assessments for remote sites using synoptic data.

### **1. Introduction**

Since the First World War, it has been well known that the sound generated by gunfire and explosions can travel long distances in the atmosphere. There are many recorded instances when the bombardments preceding the major battles in northern France were heard in south-east England. Generally such incidents were attributed to freak atmospheric conditions. During the last ten years there has been a steadily growing requirement for some assessment of when the noise from gunfire and explosions is expected to be unusually loud. This requirement has come mainly from the military ranges in southern England where a combination of newer and more powerful guns, an increasing population living close to the ranges, and a growing awareness of the environment have combined to produce numerous claims against the Ministry of Defence for causing 'noise nuisance' and sometimes actual structural damage to buildings.

The task laid upon the Meteorological Office was to predict the level of noise expected to reach various centres of population within about 20 km radius of the ranges. This work was undertaken by the Meteorological Office at Larkhill and some earlier results were published by Sills (1982).

Part I of this paper discusses the theoretical background and describes the current operational model. In Part II (Turton *et al.* 1988) the accuracy, sensitivity and limitations of the model are assessed, and some empirical results that allow noise assessments to be prepared using synoptic data are presented.

### **2. An overview of the theory**

The speed of sound depends on both the temperature and the wind speed, but the wind speed is the dominant parameter. On a calm day, assuming isothermal conditions, sound rays travel in almost straight lines (Fig. 1(a)). However, in windy conditions the sound rays are bent (Fig. 1(b)), the degree of bending depending upon the vertical wind shear. This produces the well known effect of the noise from a gun being heard more loudly downwind than it is upwind.

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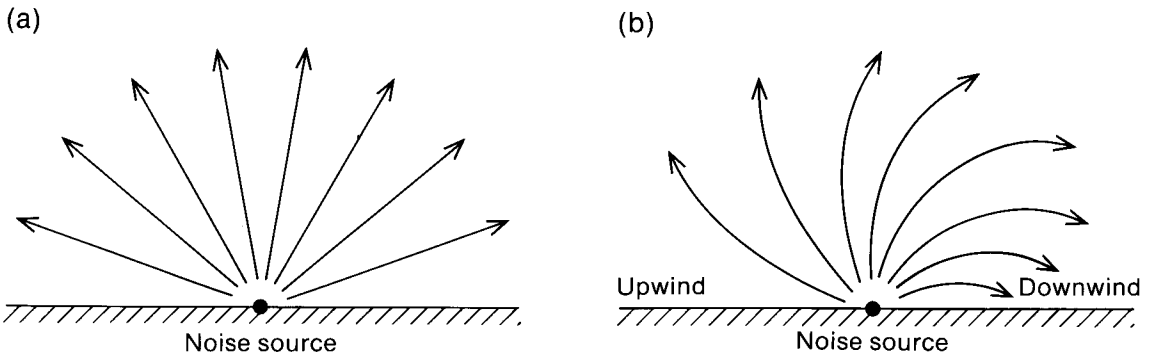


Figure 1. Illustration of the propagation of sound for (a) calm and (b) windy conditions.

### 2.1 Effects of wind

Let  $c$  be the speed of sound in an isothermal atmosphere at rest. Now consider a small section of a shock wave as it spreads out from an explosion in a region where the wind speed,  $v$ , increases with height (see Fig. 2). The top of the element has a speed relative to the ground of  $c + v_2$  and the bottom of the element a speed of  $c + v_1$ . If  $v_2 > v_1$  then the top of the element travels faster than the bottom and the inclination of the section to the horizontal changes as shown — the process is very similar to the way in which light waves are bent as they pass through a water-air interface. The result is that the sound rays are bent towards the region of lesser wind speed. The mathematical theory is outlined below.

The speed of sound relative to the ground,  $V$ , at a height  $z$  above a reference level  $z_1$  is given by

$$V = V_1 + G(z - z_1). \quad \dots \dots \dots (1)$$

where  $G = dV/dz$  is the gradient of the speed of sound, and  $V_1$  is the speed of sound relative to the ground at height  $z_1$ . Fermat's principle, which states that the path of a ray between two points is that which has the least propagation time, gives rise to Snell's law of refraction. Thompson (1972) discusses the various approximations that can be made to Snell's law for the case of a moving atmosphere, the simplest generalization being

$$\frac{V}{\cos \theta} = \frac{V_1}{\cos \theta_1}, \quad \dots \dots \dots (2)$$

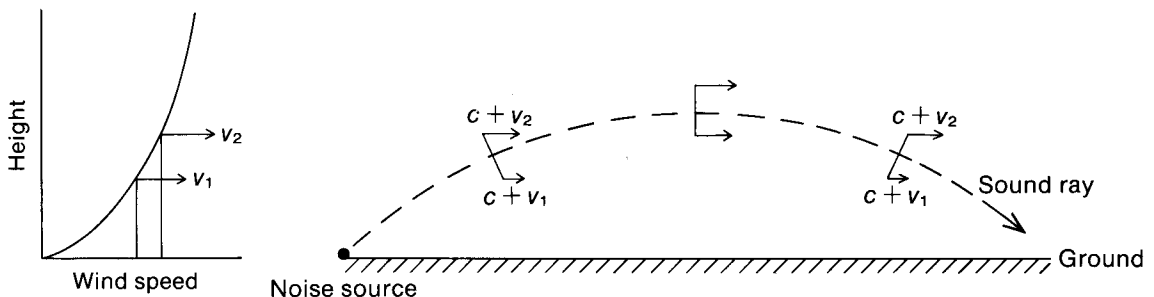


Figure 2. Illustration of the way in which a sound wave is refracted by a wind speed gradient. For explanation of symbols see text.



where  $\theta$  and  $\theta_1$  are the inclinations of the sound ray to the horizontal at  $z$  and  $z_1$  respectively, which allows equation (1) to be written as

$$z = \frac{V_1}{G} \left( \frac{\cos \theta}{\cos \theta_1} - 1 \right) + z_1. \quad \dots \dots \dots (3)$$

Differentiating with respect to  $\theta$  and using  $\tan \theta = dz/dr$ , where  $r$  is the horizontal coordinate, gives

$$\frac{dr}{d\theta} = - \left( \frac{V_1}{G} \right) \left( \frac{\cos \theta}{\cos \theta_1} \right), \quad \dots \dots \dots (4)$$

and integrating gives

$$r = - \left( \frac{V_1}{G} \right) \left( \frac{\sin \theta}{\cos \theta_1} \right) + r_1 \quad \dots \dots \dots (5)$$

where  $r_1$  is a constant of integration. Combining equations (3) and (5) gives an elliptic equation which describes the trajectory of a sound ray

$$\left( z - z_1 + \frac{V_1}{G} \right)^2 + (r - r_1)^2 = \left( \frac{V_1}{G \cos \theta_1} \right)^2. \quad \dots \dots \dots (6)$$

Two special cases are worthy of mention. Firstly, if the speed of sound is constant with height (i.e. in a homogeneous atmosphere) then  $G = 0$  and the right-hand side of equation (6) approaches infinity, and the sound rays travel in a straight line. Secondly, if  $G = \text{constant}$ , then the right-hand side of equation (6) is constant so the equation becomes of the form  $z^2 + r^2 = \text{constant}$ , and the ray path is circular.

Thus, if the atmosphere is divided into a number of uniform layers, the ray paths through each layer describe an arc of a circle. The complete trajectory can then be built up from a series of arcs, and is relatively simple to determine. The use of this approximation was discussed by Suggitt (1978).

Further examination of equation (6) reveals some general characteristics about the propagation of sound in the atmosphere. For rays which have a shallow elevation,  $\cos \theta \approx 1$ , and the radius of curvature approximates to  $V_1/G$ ; thus for a value of  $G = 0.1 \text{ s}^{-1}$  ( $15 \text{ m s}^{-1}$  over  $150 \text{ m}$  — a typical atmospheric value) the radius of curvature is of the order of  $3000 \text{ m}$ . The curvature is shallow and therefore it is only rays with an initial elevation of less than about  $20^\circ$  which are brought back down to ground downwind of the source. Higher elevation rays will bend but are unlikely to come back down to the ground, except perhaps in mountainous terrain. Upwind, the rays are bent away from the ground, as illustrated schematically in Fig. 1.

Wind shear may also result from directional changes, rather than from changes in wind speed. This can also lead to the bending of sound rays back down to the ground.

## 2.2 Effects of temperature

The speed of sound also varies with temperature

$$c = (\gamma R T_v)^{1/2} = 20.05 (T_v)^{1/2}, \quad \dots \dots \dots (7)$$

where  $\gamma$  is the ratio of the specific heats of dry air at constant pressure ( $c_p$ ) and constant volume ( $c_v$ ) ( $\gamma = c_p/c_v = 1.40$ ),  $R$  is the specific gas constant for dry air ( $R = 2.87 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}$ ) and  $T_v$  is the virtual temperature. Equation (7) gives  $c = 331.4 \text{ m s}^{-1}$  at  $0^\circ \text{C}$  and  $337.4 \text{ m s}^{-1}$  at  $10^\circ \text{C}$ . Therefore in adiabatic conditions  $G = -0.006 \text{ s}^{-1}$  and the rays are bent away from the ground. If the temperature increases with height, i.e. in an inversion,  $G$  is positive and the sound rays are bent back towards the ground.

Note that, whereas the presence of wind shear gave a preferred direction for noise enhancement, the presence of a low-level inversion bends sound rays towards the surface in all directions, giving noise enhancement uniformly around the source.

### 2.3 Combined effects of wind and temperature

Fig. 3(a) shows the trajectories of the sound rays in both the upwind and downwind directions for typical daytime conditions with light winds; the meteorological profiles are shown in Fig. 3(b). In the downwind direction, the effects of the winds are sufficient to overcome the effects of the lapse rate and the sound rays are bent back down to the ground. Upwind, the wind and temperature effects combine in bending the sound rays away from the ground. The fact that the winds have a stronger influence on the sound rays than do the temperatures can also be seen by differentiation since  $dV = dc + dv$ . Considering only the effect of temperature gives  $dV \approx 0.6 dT_v$  for  $T_v \approx 280$  K, whereas for wind only  $dV = dv$ . Typically the effect of wind shear is an order of magnitude greater than that of temperature.

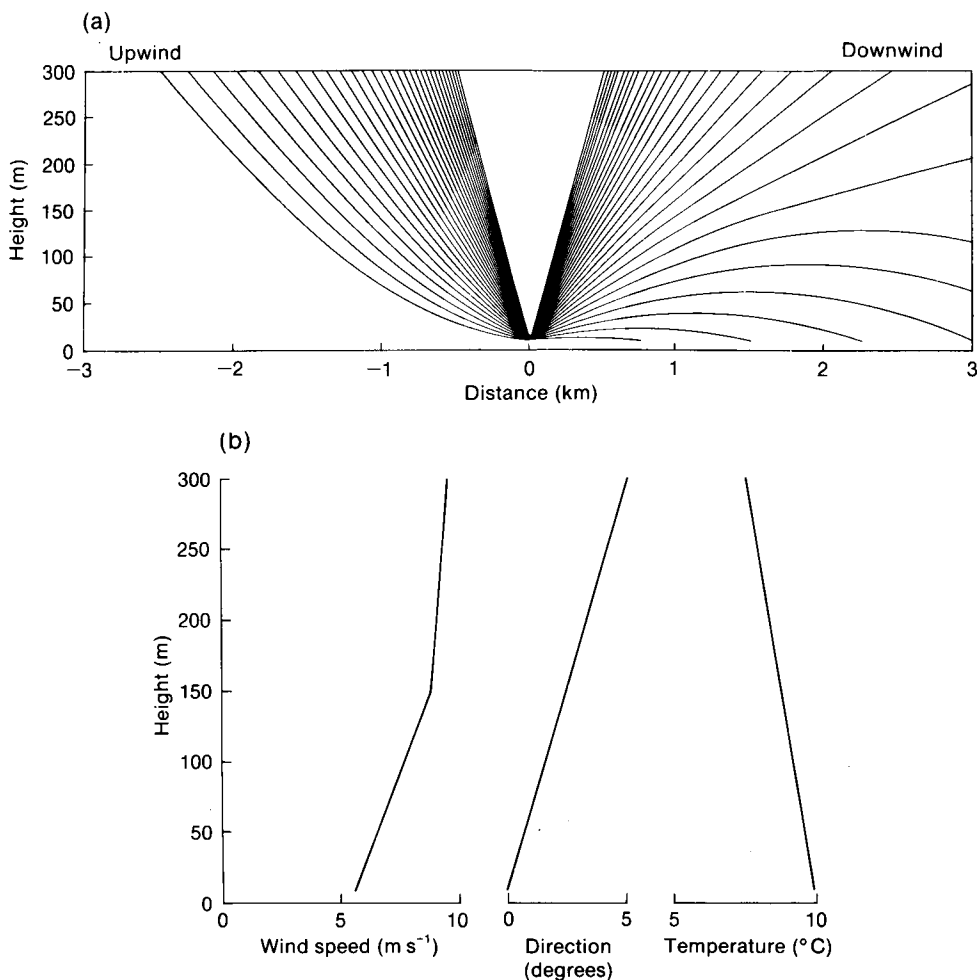


Figure 3. (a) Predicted sound-ray trajectories for typical daytime conditions with rays drawn at 1° intervals and (b) profiles of wind speed, direction and temperature specified in the model.

At night, the situation would be expected to be rather different as the presence of a nocturnal inversion (of typically a hundred metres or so depth) would tend to increase the bending of sound rays back towards the ground.

Also, elevated inversions associated with areas of subsidence or frontal systems may occur, and the presence of these may indicate regions of significant wind shear. Clearly such features will influence sound propagation. In particular, sharp inversions are often found capping cloudy layers, e.g. the inversion capping stratocumulus can be as large as 10 K over a distance of less than 10 m, and nearly horizontally inclined sound rays may be reflected by such inversions.

#### 2.4 Behaviour in the atmosphere

From a consideration of the above effects it might be expected that the noise from gunfire would be loudest in a downwind direction on days when there is a marked low-level inversion, and quietest in an upwind direction on convective days. Although this is generally true, the situation is seldom that straightforward.

Consider, for example, the conditions for 1100 GMT on 20 August 1985 at Larkhill. The wind and temperature profiles are given in Fig. 4, and show the warmer air aloft and veering of the winds associated with a warm front which was approaching from the south-west. These profiles were used to calculate the trajectories of sound rays emanating from a point source. A plan view of the density of sound rays returning to the ground is shown in Fig. 5, which illustrates the three distinct regions for sound propagation that can occur. The first of these, marked A in Fig. 5 occurs in the downwind direction ( $035^\circ$ ). In this region only shallow rays of less than  $12^\circ$  initial elevation are brought back down to the ground. This is also shown by Fig. 6(a), which shows a cross-section with the ray trajectories for  $035^\circ$  (note that the scales are different from those in Fig. 3(a) in this example). In the upwind direction (Fig. 5 region B and Fig. 6(b)) no rays return to the surface, as they are all bent away from the ground. A third region also occurs (Fig. 5 region C), where a number of rays come to ground over 10 km from the source over a range of directions, particularly between  $090$  and  $180^\circ$ . Fig. 6(c) shows the ray trajectories for  $150^\circ$ , where a number of sound rays are brought back down to the surface around 10–15 km from the source.

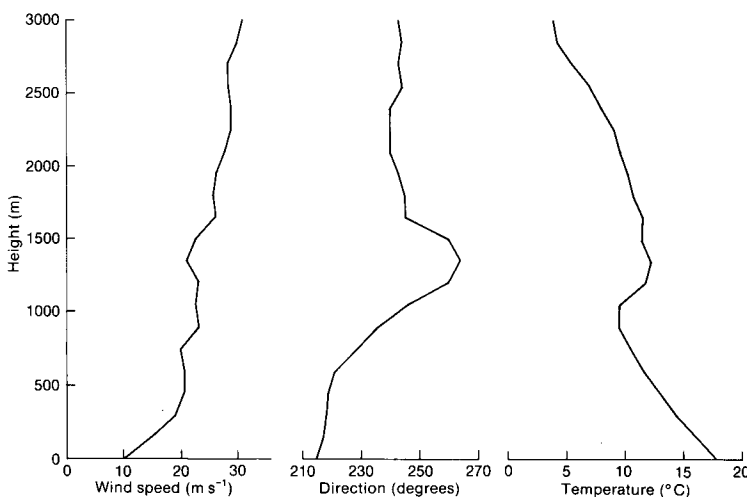


Figure 4. Profiles of wind speed, direction and temperature at Larkhill for 1100 GMT on 20 August 1985 as used in the model assessment.

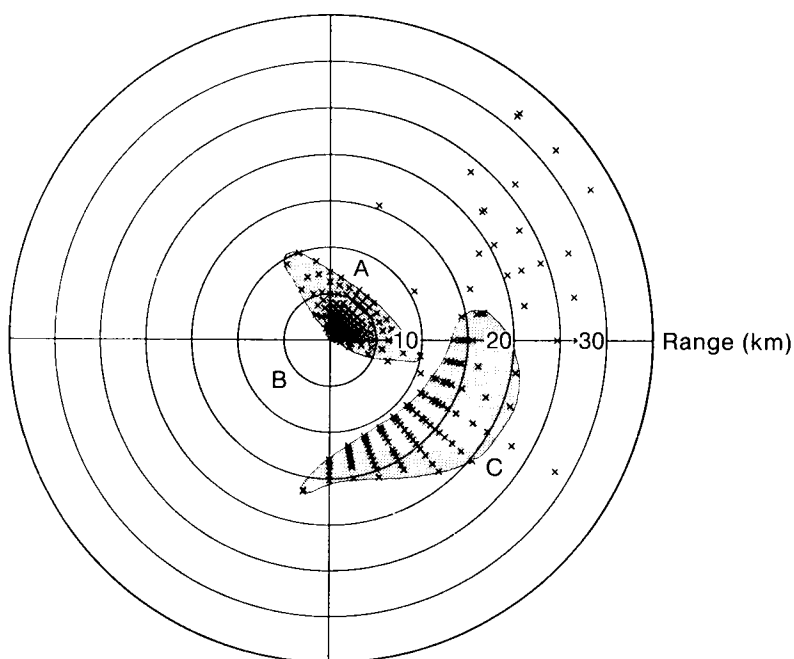


Figure 5. Polar diagram for Larkhill at 1100 GMT on 20 August 1985 showing the predicted locations at which sound rays return to the ground.

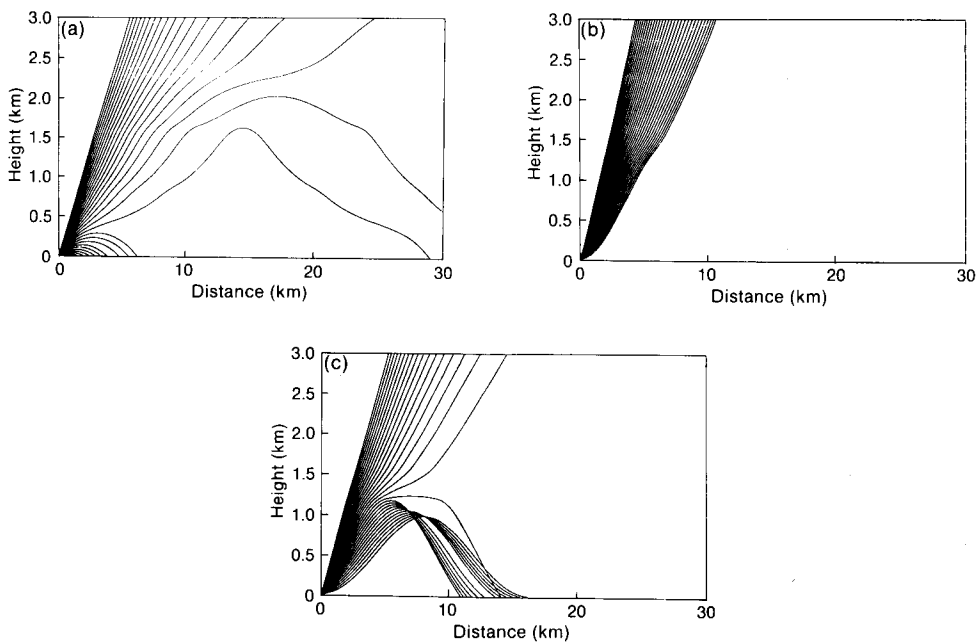


Figure 6. Predicted sound-ray trajectories for Larkhill at 1100 GMT on 20 August 1985 for (a) 035°, downwind, (b) 215°, upwind and (c) 150°. Rays are drawn at 1° intervals. Note the different scales from those in Fig. 3(a).

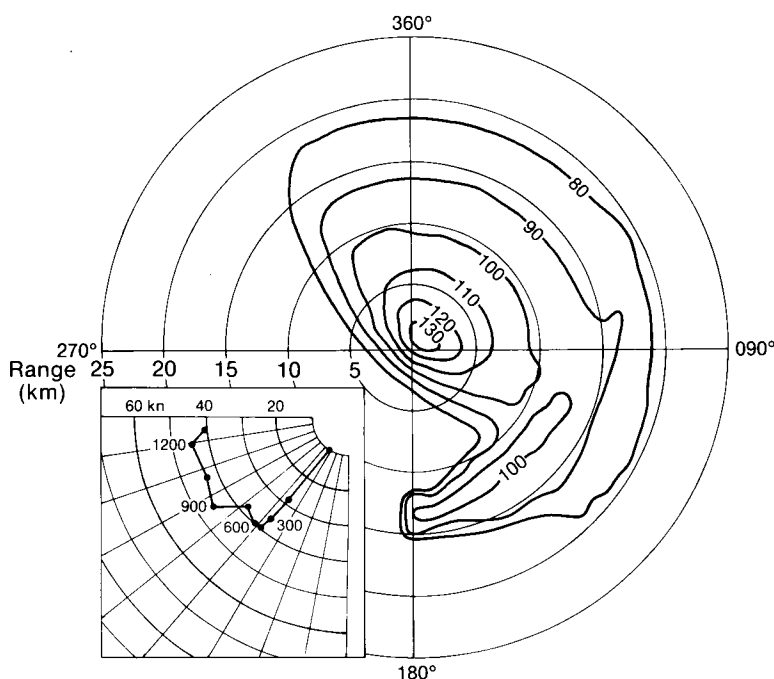


Figure 7. Polar diagram for Larkhill at 1100 GMT on 20 August 1985 showing model-predicted noise levels (for a 5 lb charge). Inset is a hodograph (with heights in metres) showing the winds on this occasion.

In the current model the predicted noise levels are related to the density of sound rays which return to the ground. The details of the method by which the noise levels are determined are described fully in the following section. However, the calculated noise levels for this example are shown in Fig. 7 to illustrate the three regions A, B and C mentioned above. To the north-east the downwind 'enhancement' of noise levels results (region A), whilst to the south-west, in the upwind direction, a sound 'shadow' with reduced noise levels occurs (region B). To the south-east, where many rays come down to ground away from the source, is a sound 'focus' where increased noise levels result (region C). Such foci tend to occur between 5 and 20 km away from the source and are often the cause of unexpectedly loud noise levels.

The relationship between these two enhanced regions of noise may be understood by considering the structure of the winds. These are shown by the hodograph inset in Fig. 7. The downwind enhancement is due to the difference in wind speed over the lowest few hundred metres, while the focus is caused by the changes in wind direction above 600 m, and lies in the direction of the wind shear vector. Basically, the downwind enhancement is mainly due to the differences in the wind speed whilst the focus primarily results from directional changes.

### 3. Determination of the noise levels

Although the above theory of the behaviour of sound within the atmosphere may appear fairly straightforward and account for many of the observed properties, it is inadequate as a predictive model when attempts are made to forecast the actual sound levels. There are a number of reasons for this, but the primary ones are the lack of any representation of the scattering of sound by turbulence, the difficulty in describing how sound rays combine when they come together, and the effects of the underlying surface. The first is a problem of defining the degree of turbulence on a particular day and

knowing how the turbulent motions interact with sound waves. The last two are more fundamental problems. These factors are discussed in more detail in Part II of the paper (Turton *et al.* 1988).

Thus, although a forecast model can be based on the above theory, there is a requirement for a number of empirical constants before forecasts of actual noise levels can be produced. The work of Kerry *et al.* (1987) provided these empirical constants, and the current 'noise assessment' model used at the range stations was developed from that work. For the purposes of defining noise levels from artillery, the loudness in decibels (dB) is related to the peak acoustic over-pressure; the units used to describe sound levels are discussed in the Appendix.

In the current model the actual noise levels are predicted using the equation

$$L = L_0 - 20 \log_{10} r - c_1 r + c_2 N (\Delta e / \Delta r) \log_{10} r + c_3 G_s r^{1/2} \quad \dots \quad (8)$$

where  $c_1$ ,  $c_2$  and  $c_3$  are empirical constants ( $c_1 = 0.0015$ ,  $c_2 = 500$  and  $c_3 = 20$ ).  $L$  is the peak sound pressure level (in decibels) at a distance  $r$  (in metres) from the source,  $L_0$  is the effective peak sound pressure level (at a distance of 1 m) from the (point) source.  $N$  is the number of sound rays returning to the surface within an incremental distance  $\Delta r$  (in metres),  $\Delta e$  is the increment of initial ray elevation which is used in the ray tracing procedure (in the current operational model  $\Delta r = 1000$  m and  $\Delta e = 1^\circ$ ). The final term is applied in regions where no sound rays return to the ground ( $N=0$ ), then  $G_s = \min(0, G_1)$ , where  $G_1$  is the gradient of the speed of sound from the surface (10 m) to 150 m (i.e. through the bottom layer in the model).

The various terms in the prediction equation describe some of the physical processes relevant to acoustic propagation.

- (a)  $20 \log_{10} r$  describes the free-field (hemispheric) expansion of the wave front.
- (b)  $c_1 r$ , which gives a linear attenuation of the sound level, is an attempt to describe the effect of the terrain in dissipating sound energy. (Note that the constant  $c_1$  was determined from measurements made over undulating terrain.)
- (c)  $c_2 N (\Delta e / \Delta r) \log_{10} r$  accounts for the effect that returning rays have in enhancing the sound levels, e.g. it is this term that gives the enhanced sound levels which occur either downwind or within a focus.
- (d)  $c_3 G_s r^{1/2}$  gives the reduction in sound levels which occurs in the sound shadow region.

The sound shadow region is predicted to be strongest in the direction in which the speed of sound gradient  $G_1$  is most negative, i.e. at an angle  $\alpha$  to the surface wind.

$$\tan \alpha = \frac{v_2 \sin \beta}{(v_2 \cos \beta - v_1)} \quad \dots \quad (9)$$

where  $\beta$  is the veer between the surface and 150 m winds. Usually the strongest sound shadow is predicted to be in a direction which veers some  $10$ – $30^\circ$  from the surface wind. Because the region of enhancement results primarily from the bending of sound rays within the lowest 150 m layer the direction of maximum enhancement, i.e. where  $G_1$  is most positive, is also given by equation (9), being in the opposite direction to that of the strongest shadow.

However, in order to predict actual noise levels resulting from particular guns or types of explosive the effective source level  $L_0$  must be specified.  $L_0$  is determined from an empirical relationship:

$$L_0 = K_1 + K_2 \log_{10} W \quad \dots \quad (10)$$

where  $W$  is the explosive charge weight (in pounds) and  $K_1$  and  $K_2$  are constants which depend upon the type of explosive being used (the model is set up for plastic explosive with  $K_1 = 185.5$  and  $K_2 = 11.0$ ).

As seen from equation (8) the noise levels are determined by considering the contributions of the various terms in the equation. The accuracy, sensitivity and limitations of the predicted noise levels are examined in Part II of the paper (Turton *et al.* 1988). The practical use of the model is also discussed, together with a simplified method of producing noise assessments using only synoptic data.

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## Appendix — Units of sound intensity

The intensity ( $I$ ) of a travelling sound wave is defined as the energy propagating through a unit area per unit time. The range of intensities that can be heard by the human ear is about  $10^{-12} \text{ W m}^{-2}$  (the threshold of audibility) to  $1 \text{ W m}^{-2}$  (the threshold of feeling), a dynamic range with a factor of  $10^{12}$  in intensity. To cope with such a large range it is convenient to define a logarithmic scale.

$$L = 10 \log_{10}(I/I_0), \quad \dots \dots \dots (A1)$$

where  $L$  is the sound pressure level in decibels and  $I_0 = 10^{-12} \text{ W m}^{-2}$ . Thus the dynamic range of the human ear is about 120 dB; beyond this level the sound produces a tickling sensation which gives way to one of pain at about 140 dB (the threshold of pain). An increase in intensity by a factor of 10 is then given by an increase of 10 dB. A person with normal hearing can barely detect an increase in loudness of 1 dB. The over-pressures associated with even very loud noises are small compared to atmospheric pressure, e.g. for  $L = 130 \text{ dB}$  the over-pressure is only  $\approx 0.65 \text{ mb}$ .

The following table shows the intensity levels of some familiar sounds.

Intensity dB	Source/effect
140	threshold of pain
120	roar of a jet engine, threshold of feeling
90	pneumatic drill
60	busy street with traffic
30	suburban street at night
20	faint whisper
0	threshold of audibility

Noise from gunfire or explosions is of short duration; it is called impulsive noise and is usually given by its peak level (which is usually in the range 80–140 dB), and is determined from the peak over-pressure  $P$ . The peak level  $L_p$  is then given by

$$L_p = 20 \log_{10}(P/P_0), \quad \dots \dots \dots (A2)$$

where  $P_0$  is a reference pressure of  $2 \times 10^{-7}$  mb which corresponds to  $I_0$ . Because of its short duration, impulsive noise does not usually sound as loud as continuous noise of the same level. Impulsive sound levels in excess of 130 dB tend to lead to complaints and may cause structural damage to buildings.

The subjective loudness of a sound is related to its intensity, although it also depends on its frequency. Sounds of a higher frequency tend to be more annoying than those with low frequencies. However, the absorption of sound by the atmosphere is frequency dependent with the higher frequencies being most strongly attenuated. Noise from artillery contains mostly low frequencies, whilst that from rifles and small arms contains mainly high frequencies.

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## **Turbulence measurements above rugged terrain: the Llanthony experiment**

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### **Summary**

The drag force transmitted to the atmosphere by boundary-layer turbulence is one of the physical processes that must be parametrized in large-scale numerical models. While a large amount of data has been collected over flat surfaces, experimental data on turbulent boundary-layer flow over rugged terrain are scarce and generally limited to wind, temperature and humidity profiles obtained with pilot balloons and/or radiosondes. Although such data has been used to suggest parametrizations for the surface drag in areas of rugged terrain, there is an urgent requirement for direct estimates of the surface drag based on turbulence data. In the spring of 1986 the Meteorological Research Unit, based at RAF Cardington, carried out a number of tethered-balloon flights in South Wales. Probes attached to the balloon's tether-cable were used to collect turbulence data up to heights of 1000 m above the tops of a series of ridges. Turbulence data from two of these flights are briefly presented and a value of the roughness length for the area derived.

### **1. Introduction**

An important area of boundary-layer research is the parametrization of surface fluxes in terms of large-scale flow variables, for use in numerical weather prediction models. Over the past twenty years data have been collected over a variety of surfaces (the sea, homogeneous areas of land covered by crops, forests, etc.). However, one area which has received relatively little experimental attention is the parametrization of surface fluxes in areas of rugged terrain (i.e. areas where the topographic features are a few hundred metres high and have horizontal scales of a kilometre or two). This gap in our knowledge is a result of the difficulty in obtaining such data, in particular obtaining direct estimates of the turbulent fluxes. This paper will describe some measurements of surface drag obtained in an area of rugged terrain during a recent experiment.



A widely used parametrization for the surface stress is the drag coefficient, defined by:

$$\frac{\tau_0}{\rho} = C_d U^2(z) \quad \dots \dots \dots (1)$$

where  $\tau_0$  is the surface stress,  $U(z)$  the wind speed at a height  $z$ ,  $C_d$  the surface drag coefficient and  $\rho$  the density of air.

The drag coefficient depends on the nature of the surface, the height above the surface, atmospheric stability, etc. For most natural surfaces the physical mechanism for the transfer of momentum from the atmosphere, which is to be represented by equation (1), is drag due to pressure differences generated across the roughness elements (e.g. grass, trees, mountains, etc.). This type of drag is known as form drag and is generally much larger than the drag due to viscous stresses generated at the surfaces of the roughness elements.

For a simple surface, such as the sea or a flat homogeneous land surface, the structure of the cloud-free boundary layer is shown schematically in Fig. 1. Near the surface there is a region which is shallow compared to the total depth of the boundary layer but is far enough above the surface not to be directly affected by the flow around the roughness elements. Within this region, which is known as the surface layer, the turbulence length scales depend largely on height above the surface. When the effects of surface heating or cooling are negligible, the drag coefficient in the surface layer is

$$C_d = \frac{k^2}{(\ln(z/z_0))^2} \quad \dots \dots \dots (2)$$

where  $k$  is Von Kármán's constant (later taken to be equal to 0.4) and  $z_0$  is the roughness length.

The roughness length characterizes the underlying surface and values have been estimated for a wide variety of surfaces. Equations (1) and (2) can be combined to give the well known logarithmic wind profile,

$$U(z) = \frac{(\tau_0/\rho)^{1/2}}{k} \ln(z/z_0) \quad \dots \dots \dots (3)$$

which describes the variation of the wind speed with height near the surface. It cannot be taken for granted that the above results, obtained for flat terrain, can be extended to rugged terrain since, in this case, the heights of the roughness elements (hills, ridges, etc.) may be an appreciable fraction of the boundary-layer depth so that the surface layer, as described above, will not exist. However, as a starting point it is reasonable to see whether the drag coefficient can be described by equation (2) and, if so, to estimate a value for  $z_0$ . In order to be able to define such a roughness length the boundary layer must be in approximate equilibrium with the underlying terrain. Model results suggest that such an equilibrium will only be achieved if the terrain is statistically homogeneous over areas of  $10^2$  to  $10^3$  km<sup>2</sup>.

In the spring of 1986 the Meteorological Research Unit, based at RAF Cardington, carried out series of measurements using instruments attached to the tether cable of a captive balloon above the Black Mountain region of South Wales. The balloon was flown from a site in the Llanthony valley, which is situated on the border between England and Wales and forms one of a series of approximately parallel ridges and valleys.

## 2. Instruments

The Llanthony experiment was the first major trial involving the newly developed Cardington turbulence probe system. The probes, which can measure wind, temperature, humidity and pressure, are clamped to the cable of a captive balloon and can be flown to heights of about 2000 m. Unlike the

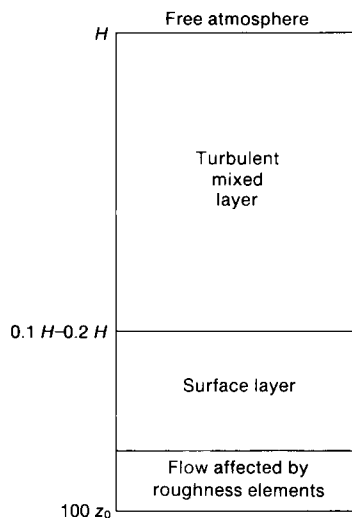


Figure 1. Schematic diagram showing the various regions in the cloud-free boundary layer, where  $H$  is the total depth of the boundary layer and  $z_0$  the roughness length.

previous turbulence probes produced at Cardington, in which damped pendulums kept the wind-measuring instruments horizontal, the new probes use a combination of inclinometers and magnetometers to determine the probe orientation. The measurement of wind from tethered balloons is complicated by the motion of the balloon caused by turbulence and aerodynamic instabilities. These motions typically have amplitudes of about  $1 \text{ m s}^{-1}$  and periods of a few minutes, which are comparable with the amplitudes and periods of the energy containing turbulent eddies. With the new probe system it is possible to use the data from the inclinometers and magnetometers to derive an approximation to the catenary of the tether cable; from this the positions of the probes with respect to the tether point can be derived and the velocities of the probes calculated. Comparisons with probe velocities obtained directly by tracking a light source attached to the cable show that this procedure produces good results (Lapworth and Mason 1987).

The probe, which is free to turn around the cable, is kept pointing into the wind by a wind vane. Three Gill propeller-anemometers, mounted so that their axes lie on a cone, measure the wind vector relative to the probe. These data are combined with the probe orientation to provide the wind vector in a coordinate system fixed with respect to the ground. The wind data can then be corrected for the motion of the probe using the probe velocity determined by the procedure outlined above.

Temperature is measured using a fast-response platinum-resistance thermometer mounted between the Gill propellers. In addition there is also a more robust slow-response thermistor mounted in an aspirated radiation shield. Two wet-bulb thermistors, one a small fast-response bead thermistor and another which is slower but more robust, are used to measure humidity.

The outputs from all the sensors are sampled at 20 Hz. The data are digitized and then transmitted by radio link to a ground station which separates the data from different probes and passes it to a PDP 11/34 minicomputer where it can be stored on cartridge tape or disk. (A Micro Vax II computer has recently been acquired to replace the PDP 11/34 for logging turbulence-probe data.)

During the trial a total of twelve flights were carried out using up to six turbulence probes attached to the cable. The main limitations on flying during the experiment were winds in excess of  $20 \text{ m s}^{-1}$  and/or the occurrence of a significant lightning risk.

In addition to the tethered balloon a Doppler acoustic sounder was also operated from the valley and provided wind speed and direction up to 800 m above the valley floor. A sonic anemometer was used to provide turbulence data at about 20 m above the valley floor.

### 3. Results

The results from two flights will be presented here. The flights took place on 18 and 22 May 1986 in strong south-westerly winds (approximately perpendicular to the axis of the valley). The wind speed and direction remained constant throughout the flights which lasted nine and five hours respectively. The wind profiles from the two flights are shown in Fig. 2. The winds have been normalized by the wind speed at 150 m above the valley floor and heights ( $z$ ) have been measured relative to the mean height of the valley system which has been taken to be 150 m above the valley floor. The profiles are very closely logarithmic up to 800 m. The line drawn through the data corresponds to a roughness length of 11 m. The surface stress has been obtained by extrapolating the stress values estimated from the turbulence data obtained at the different probe levels to the mean level of the topography. The drag coefficient estimated from the stress data, using equation (2), gives a value for  $z_0$  of about 9 m. This is very close to the value derived from the wind profile alone and indicates that although there is no surface layer, such as found over smoother surfaces, the roughness length is still a useful basis for parametrizing the surface stress over rugged terrain.

Studies of turbulent flow over arrays of obstacles show that as long as the density of obstacles is not too large

$$\frac{z_0}{h} = c \frac{A}{S} \quad \dots \quad (4)$$

where  $h$  is the height of the roughness elements,  $A$  is the total silhouette area of the obstacles in a horizontal area  $S$ , and  $c$  is a constant which will be a function of the shape of the obstacles. (Dimensional analysis would suggest that, for geometrically similar obstacles,  $z_0 = hf(A/S)$ , where  $f(A/S)$  is some function of  $A/S$ .)

Fig. 3 is a plot of  $z_0/h$  against  $A/S$  for experimental data obtained in areas of rugged terrain (see Table I for sources). With the exception of the results of Mason (1987), which were calculated from stress data obtained with a prototype of the present Cardington turbulence probe, these estimates were obtained from wind profiles. The plot suggests that  $c$  is about 0.36 for the types of terrain that have been studied. This model of the roughness length assumes that all the drag is due to form drag on the large-scale topography. Mason (1986) has proposed the following formula to account for a contribution to the drag from the small-scale roughness elements covering the topography:

$$\ln \left( \frac{h}{2z_0} \right) = \frac{k}{\left( \frac{1}{2} D \frac{A}{S} + \frac{k^2}{(\ln(h/2z_0))^2} \right)^{1/2}} \quad \dots \quad (5)$$

where  $D$  is the drag coefficient for the obstacles and depends on their shapes,  $z_0$  is the roughness length associated with the surface cover (e.g. trees, rocks, etc.) and  $k$  is von Kármán's constant.

The two terms in the denominator of the right-hand side of equation (5) represent the form drag on the large-scale topography and the drag due to small-scale roughness respectively. Comparison with numerical simulations of the flow over sinusoidal topography suggests a value of 0.3 for  $D$ . To apply equation (5) to the data in Table I a value for  $z_0$  is required. This can be estimated from a compilation of roughness lengths appropriate to various types of surface cover (e.g. Engineering Sciences Data Unit 1976). Unfortunately the descriptions of the topography and the surface cover, given in the references

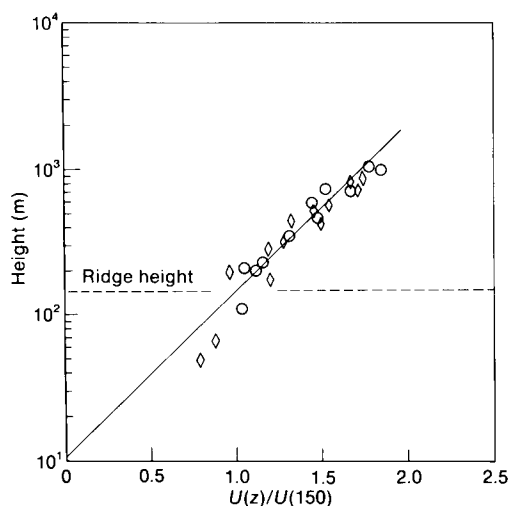


Figure 2. Wind profiles for two flights carried out at Llanthony on 18 May 1986 ( $\diamond$ ) and 22 May 1986 ( $\circ$ ). The height,  $z$ , is measured from the mean topography height of the surrounding area, taken as 150 m above the floor of the Llanthony valley. The wind speeds are normalized by the wind at  $z=150$  m.

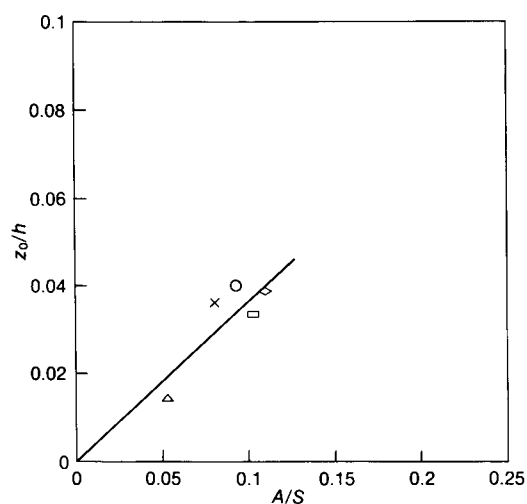


Figure 3. Plot of  $z_0/h$  against  $A/S$  for published values of the roughness length obtained for rugged terrain. Sources of the data are given in Table I.

**Table I.** Published values of roughness length obtained for rugged terrain. For explanation of symbols see text

Source	Symbol in Fig. 3	$z$ (m)	$h$ (m)	$A/S$
Thompson(1978)	$\diamond$	5.8*	150	0.110
Noilhan <i>et al.</i> (1982)	$\triangle$	2.0	140	0.053
Kustas and Brutsaert (1986)	$\circ$	3.8	95	0.093
Mason (1987)	$\times$	9.0	250	0.080
Present data	$\square$	10.0	300	0.103

\* Recalculated from the data given in the paper using height measured relative to the mean topography height, taken to be 70 m.

listed in Table I, tend to be sketchy thus making it difficult to estimate  $z_{01}$  precisely, but a value in the range 0.1–0.5 m is probably reasonable in most cases. Fig. 4 shows a comparison between measured values of  $z_0$  and values calculated from equation (5) for  $z_{01} = 0.1$  and 0.5 m. Fortunately the value of  $z_0$  is not very sensitive to the choice of  $z_{01}$  and the agreement between the measured and calculated values is very good.

Although both equations (4) and (5) give good results it is worth stressing the difference in their assumptions. Equation (4) assumes that all the drag is due to form drag on the large-scale topography, while for equation (5) the drag is partitioned between the large-scale topography and the small-scale roughness. For the data listed in Table I, equation (5) indicates that, for  $z_{01}$  between 0.1 and 0.5 m, around 20–30% of the total drag is due to small-scale roughness elements. A further feature of equation (5) is that as  $A/S$  and  $h$  become small  $z_0 \approx z_{01}$ , as would be expected.

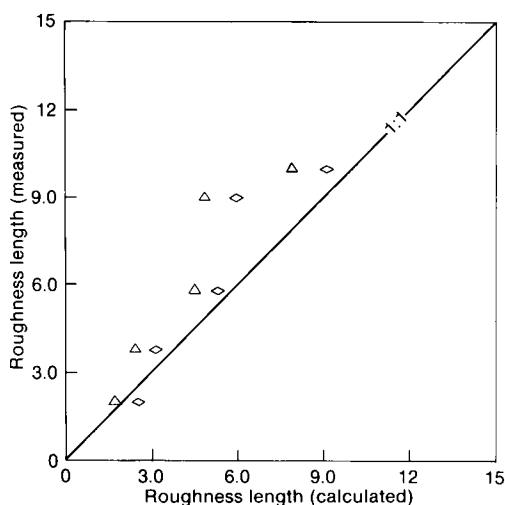


Figure 4. Comparison between the experimental values of  $z_0$  listed in Table I and values calculated from equation (5) for  $z_{01} = 0.1$  m ( $\Delta$ ) and  $z_{01} = 0.5$  m ( $\Diamond$ ).

The level of turbulence in windy conditions is related to the roughness of the underlying surface; so, for example, the wind is generally gustier over land ( $z_0 \approx 1-10$  cm) than over the sea ( $z_0 \approx 0.1$  mm). Fig. 5 shows the turbulence intensity ( $\sigma_u/U$  where  $\sigma_u$  is the standard deviation of the wind speed) and the standard deviation of the wind direction ( $\sigma_\theta$ ) measured at Llanthony as a function of height. For comparison the over-sea data of Nicholls and Readings (1979) have also been included. Consistent with the much larger roughness length the turbulence levels are considerably larger over Llanthony than over

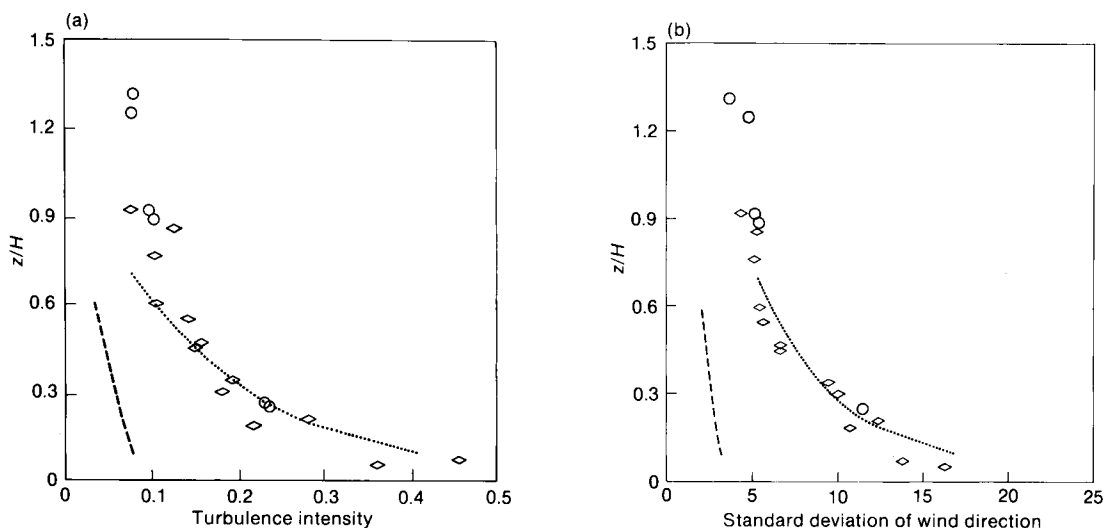


Figure 5. (a) Turbulence intensity and (b) standard deviation of the wind direction ( $\sigma_\theta$ , degrees) observed at Llanthony from two flights. The height ( $z$ ) is normalized by the height ( $H$ ) at which the momentum flux extrapolates to zero. The dashed curve shows the results of Nicholls and Readings (1979) obtained over the sea while the dotted curve shows turbulence levels calculated from the over-sea turbulence data for a roughness length of 10 m.

the sea. The dotted curve in Fig. 5 shows the turbulence intensity and  $\sigma_\theta$  profiles calculated using the turbulence results in Nicholls and Readings (1979) and equation (3) with a roughness length of 10 m. The agreement between the measured values of  $\sigma_u/U$  and  $\sigma_\theta$  and those deduced from the Nicholls and Readings data suggests that the presence of the large ridges and valleys does not lead to any dramatic change in the basic structure of the boundary-layer turbulence compared to that observed over smoother surfaces; that is, if the present data were to be non-dimensionalized using the appropriate velocity and length scales (see, for example, Holtstlag and Nieuwstadt (1986) for a discussion of boundary-layer scales) the results would be similar to those obtained over the sea.

#### 4. Concluding remarks

The results presented here show that the concept of the roughness length is useful in parametrizing the surface stress over rugged terrain. The measured roughness length can be estimated from easily determined characteristics of the terrain with fairly simple formulae (see Mason (1986) for an outline of the use of such formulae). The present data go beyond most previous estimates of  $z_0$  for rugged terrain by determining the drag coefficient using direct estimates of the surface stress obtained from turbulence measurements.

The Llanthony experiment concentrated on the drag exerted on the atmosphere via the turbulent boundary layer. However, a second mechanism which appears to be significant is the drag associated with the generation of gravity waves by topography. Brown (1983), using aircraft data, measured momentum fluxes of up to  $-0.35 \text{ N m}^{-2}$  associated with gravity waves over the British Isles. For comparison the surface stresses observed on the two balloon flights described here were of the order of  $-2 \text{ N m}^{-2}$  (note: the present measurements obtained at a point are unable to give the flux due to gravity waves which are stationary with respect to the surface, such as lee waves). Although the magnitude of the momentum flux associated with gravity waves appears to be only a relatively small fraction of the likely surface stress, these wave fluxes are significant since they can directly affect the atmosphere remote from the surface.

The Llanthony experiment was the first major field trial involving the new Cardington turbulence probe system and illustrates its potential in atmospheric boundary-layer studies.

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## The summer of 1987 in the United Kingdom

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### Summary

The summer of 1987 was rather cool, dull and wet in many areas; in particular June was very wet nearly everywhere. July and August were mainly settled months in southern coastal areas and were particularly so in the south-western peninsula.

### 1. The summer as a whole

Rainfall amounts during the summer (June–August) of 1987 were above normal over all parts of the United Kingdom except the south-western peninsula, north-west Scotland and Shetland. In parts of the south-west, and in parts of Devon in particular, there was less than 60% of normal rainfall, despite the heavy rain there in early June. In parts of East Anglia, however, there was as much as twice the normal rainfall during the summer. Sunshine amounts were near normal over south-west England and South Wales, but elsewhere it was generally dull. The mean temperatures were below normal everywhere, apart from one or two places in the far south of England. The greatest difference was around the Tyneside area, where the mean was about 1 °C below normal for the season.

Information about the temperature, rainfall and sunshine during June–August 1987 is given in Table I and Fig. 1.

**Table I.** District values for the summer months, June–August 1987, relative to 1951–80 averages

District	Mean temperature (°C)	Rain-days	Rainfall	Sunshine
	Difference from average		Percentage of average	
Northern Scotland	−0.4	+2	88	79
Eastern Scotland	−0.5	+3	113	82
Eastern and north-east England	−0.4	+4	130	74
East Anglia	−0.3	+5	162	75
Midland counties	−0.4	+4	119	81
South-east and central southern England	−0.1	+2	120	89
Western Scotland	−0.5	+1	115	89
North-west England and North Wales	−0.4	+3	163	84
South-west England and South Wales	−0.2	0	86	93
Northern Ireland	−0.2	+2	115	78
Scotland	−0.4	+2	105	83
England and Wales	−0.3	+3	117	82

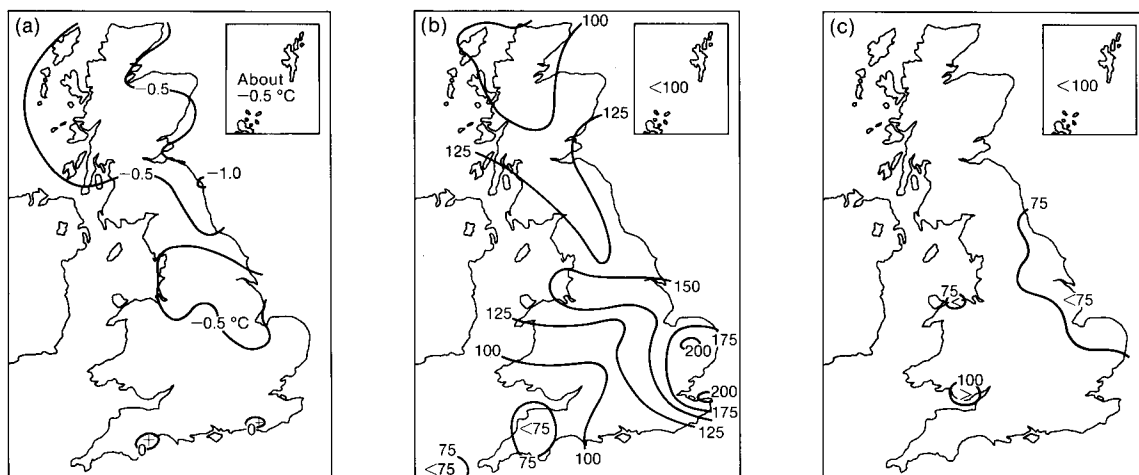


Figure 1. Values of (a) mean temperature difference, (b) rainfall percentage and (c) sunshine percentage for summer 1987 (June–Aug.), relative to 1951–80 averages.

## 2. The individual months

**2.1 June.** Mean monthly temperatures were below normal throughout the United Kingdom, ranging from 2.3 °C below normal in north-east England to less than 1 °C below normal in the London area. Monthly rainfall totals were above normal in all areas except northern Scotland and the Western Isles, ranging from 289% of average at Ringway, Greater Manchester to 52% at Benbecula, Western Isles. Sunshine amounts were below normal everywhere except for parts of northern Scotland and the Western Isles and ranged from 117% at Tiree, Strathclyde to less than 40% in Cambridgeshire.

**2.2 July.** Mean monthly temperatures were near normal generally, ranging from about 0.8 °C above normal in the south-west to 0.3 °C below normal in places in eastern England. Rainfall totals were above normal in most parts of the British Isles except south-west England, central and southern Wales and parts of the Midlands where it was rather dry; amounts ranged from less than 50% of average in parts of south-west England and Northern Ireland to 232% at Manston, Kent. Sunshine amounts were about normal nearly everywhere in the United Kingdom, apart from northern Scotland where it was a rather dull month, ranging from 42% at Cape Wrath and Poolewe, both in Highland Region, to 120% in the Isles of Scilly.

**2.3 August.** Mean monthly temperatures were near normal in most parts of the United Kingdom, ranging from 0.6 °C above normal in south-west England to 0.9 °C below normal in eastern Kent. Monthly rainfall totals were above normal in southern Scotland, Northern Ireland, northern and eastern England, parts of the Midlands and North Wales, but below normal elsewhere. Rainfall amounts ranged from as little as 13% at Plymouth, Devon to 273% in Norfolk. Sunshine amounts were above normal generally in South Wales, south-west England and eastern Scotland, and below normal elsewhere, ranging from 70% in the Western Isles to 118% in Shetland.

## 3. The weather month by month

**3.1 June.** The first half of June was cool and showery, with many places on the eastern side of the United Kingdom having twice as much rain as could normally be expected. It remained unsettled for the



rest of the month; there was only a little improvement during the third week, with the best of the weather being in the north. During the last week there was a further deterioration and, for the first time since 1969, there was no play on the first day of the tennis championships at Wimbledon. However, the weather improved in the last few days of the month.

**3.2 July.** Most of England and Wales was dry throughout the first half of July with no measurable rain reported in many areas south of a line from South Wales to The Wash up to the 13th, while it remained unsettled in Scotland and Northern Ireland. By about mid month outbreaks of rain, with isolated thunderstorms, had spread from the south-west into Wales and southern England, becoming persistent and at times heavier in eastern areas of England on the 16th. For the next week it remained generally unsettled, with the worst of the weather in south-east England. Central and eastern areas of England had heavy showers or longer spells of rain with thunder in places but Wales and western areas of England were mainly dry with sunny spells. From the 27th to 31st rain belts crossed all areas from the west followed by showery outbreaks but also some sunny spells.

**3.3 August.** The month of August was cool everywhere for the first 10 days, but became warm for a while in the middle of the month and then ended cool in the east but warm in the west. It was dry and warm over most parts on the 29th and 30th, but cooler and more cloudy on the 31st. Thunderstorms brought heavy rainfall to parts of South and West Yorkshire on the 9th, causing flooding and disrupting traffic. Over England and Wales during the weekend of the 21st and 22nd, widespread and at times violent thunderstorms gave very heavy rain in many places, especially from North Wales to East Anglia, causing floods in some parts of eastern and northern England and the Midlands. On the 22nd Suffolk and Essex suffered havoc and destruction caused by the worst storm in living memory, particularly affecting the area from Chelmsford to Ipswich. East Anglia had the wettest August for over 30 years, while south-west England had the driest August since 1981. North Wyke, Devon reported the driest August since records began there in 1959. While southern areas enjoyed a hot spell on the 16th, Scotland, Northern Ireland and some northern parts of England and Wales had heavy rain and storms; some minor roads in the Highlands were almost impassable because of flooding. Heavy falls included 87 mm at Creebridge and 86 mm at Bargrennan, both in Dumfries and Galloway, on the 16th, 73 mm at Birmingham Airport, West Midlands on the 22nd, and 56 mm at Hemsby, Norfolk on the 25th.

## Reviews

*The physics of atmospheres*, second edition, by J.T. Houghton. 176 mm × 252 mm, pp. xi + 271, *illus.* Cambridge University Press, 1986. Price £27.50, US \$54.50 (hardback), £9.95, US \$16.95 (paperback).

For a well-prepared physicist who wants a compact introduction to the physical and dynamical processes that determine the structure and motion of (neutral) planetary atmospheres this is an excellent book.

The first edition (1977), given a cautious welcome by a *Meteorological Magazine* reviewer, proved a valuable addition to the literature — the author has not found it necessary to make much change to his account of the basic processes. The major modification is to the chapter on radiative transfer; this was given a relatively detailed treatment in the first edition and is now restructured. Here, and in other chapters, there are additions to the extensive sets of problems which are designed not only to check comprehension but also to extend the succinct text (one, for example, derives and illustrates Ertel

vorticity). It may be regretted that the opportunity was not taken to revise other chapters — that on turbulence remains rather dated (though it is good to see that the spelling of Ekman's name has been corrected) and that on clouds could do with more dynamics, even though it does manage to give a serious account of condensation and coalescence mechanisms together with an indication of the radiative properties of clouds, all in five pages.

The new material is mainly in the chapters concerned with application of the basic physics to studies of the general circulation and to climate, especially by computer modelling. These chapters give a concise indication of the problems and possibilities of this important and rapidly developing field, not neglecting advances in observational technique.

The new edition is slightly bigger than the old one, an increased page size and larger fount making it more legible, though I feel the equations now stand out less clearly from the text; the opportunity has also been taken to include some satellite images and photographs. A physicist who gets seriously involved in meteorology will necessarily go to specialized texts (the bibliography has been updated) but this relatively small introductory volume will suit good students admirably.

H. Charnock

*Acidic precipitation*, edited by H.C. Martin. 2 Vols 170 mm × 246 mm, pp. Part 1 xvi + 1053, Part 2 xvi + 1118, *illus.* Dordrecht, D. Reidel Publishing Company, 1987. Price £196.00, US \$240.00, Dfl.560.00.

These two massive tomes include roughly half the 400 papers presented at the Muskoka Symposium held in central Ontario in September 1985. Apparently these papers have already been published in issues of the journal *Water, Air and Soil Pollution*, volumes 30 and 31, in 1986, which makes it even more surprising that anyone would have the energy and zeal to bring them together in book form. Of course the standard of papers inevitably varies quite a lot, but some at least seem very good, and so the editor, Hans Martin, is to be congratulated on finishing such a mammoth task with such a comparatively short time delay, and Reidels on producing two books which are aesthetically presentable.

It does raise the impish question as to whether the forests of the world are at greater risk from air pollution or from the paper requirements of books like these. However I cannot imagine that the sales will be very large — only the larger scientific libraries will, I imagine, contemplate acquisition.

Very briefly, the books cover the following topics: the transport and deposition of acidifying species, and the influences of these depositions on soils, forests and aquatic biological communities. The largest number of papers are concerned with this last aspect, the influence on freshwater life.

To review each of the papers properly, or even a fair selection of them, would be an almost impossible task for any reviewer. Alternatively it seemed fair to see how well the books could be used to answer or comment on a few relevant questions within the scope of the subject matter. The questions were chosen after a very quick survey of the books and before I knew whether or not answers would be forthcoming. Four questions were chosen:

- (1) How important are episodes of acidic occult deposition? (Occult deposition arises from the direct impaction of contaminated fog or cloud droplets blown by the wind onto vegetation.)
- (2) Have techniques been developed to measure dry deposition by direct methods?
- (3) What is the influence of emissions of ammonia on the deposition fields of acidity?
- (4) How bad is the effect of acid rain (in its popular general sense) on forests in Ontario?

I was able to find some comment or answer to all these questions using the index and the titles as a guide to where to look. The process was quite quick although I cannot be sure other answers were not missed.

In summary, one paper by Barrie and Schemenaur discussed question (1). For clouds at ground level, the rate of deposition of cloud water apparently depends almost linearly on wind speed, being typically  $1.1 \text{ mm h}^{-1}$  for a wind speed of  $10 \text{ m s}^{-1}$ . This rate is comparable to the rate of light rain. The associated acidity in wind-blown fog droplets is, however, often much higher than in rain (pH values below 3 are not uncommon) and this could lead to a high accumulated deposition.

Question (2) was the subject of an excellent paper by B.B. Hicks which reviews the various possible techniques, none of which seem suitable for general operational use outside research conditions. Two other papers, one by Dasch and the other by Edwards and Ogram, discuss specific techniques of considerable promise. The method discussed by Dasch is essentially a simple one — that of washing off particulate depositions from tree branches.

Question (3) is discussed only in a single paper (Schuurkes *et al.*) in which it is concluded that emissions of ammonia in the Netherlands lead to higher depositions of ammonium sulphate and this in turn leads to increased acidification through nitrification in the soil. It is interesting that this question, which is now very topical and the basis for many research studies, had barely surfaced just two years ago.

The final question, chosen because it was somewhat parochial to the venue for the Symposium, attracted comment from only two papers, one by Linzon and the other by Crocker and Forster. According to Linzon there is some evidence that acid rain is contributing to the extensive decline in maple trees in Ontario, which are commercially grown for maple syrup. The second paper attempts to assess the economic consequences of acid rain on timber yields in Ontario. It estimates that roughly 5% is lost from a gross annual value of just over \$1 billion. If this is true it is a very sizeable loss, although to verify it must be well-nigh impossible.

Overall then, the books provided some useful comments on these randomly chosen questions. To anyone in the field of acid rain, the implication is that access to these books could prove very useful on occasions, although the price must surely preclude individual scientists buying them for their own bookshelves.

F.B. Smith

*Monsoons*, edited by J.S. Fein and P.L. Stephens. 167 mm × 240 mm, pp. xix + 632, *illus.* New York, Chichester, Brisbane, Toronto and Singapore, John Wiley and sons, 1987. Price £71.75.

This is an interesting and wide-ranging book covering almost every conceivable aspect of monsoons: meteorological, oceanographical, historical, sociological and political.

The editors have done a good job in bringing together such diverse material and organizing it in such a way as to present a fairly coherent and balanced account of the monsoon. The material is well presented and generally very readable, and a 12-page index provides very useful cross referencing. The book is primarily aimed at the non-specialist; indeed, the editors suggest that it should be useful to administrators, policy makers and interested lay people. With the exception of a few chapters, any reasonably intelligent reader should experience little difficulty in following the text; in parts, however, a scientific background would be an advantage. Many useful and up-to-date references are provided throughout; those so inclined should have no difficulty in using these to pursue their interests further. For the specialist, the book offers an interesting and painless account of the broader aspect of monsoons.

Although other monsoons are mentioned, the emphasis is on the Asian monsoon and, in particular, the Indian summer monsoon. The material is fairly up to date and, by its nature, much of the material is unlikely to date very quickly. In some areas, notably numerical modelling, current work is still very much at an experimental stage and our understanding is increasing more rapidly.

The material is divided into six sections: an elementary account of the physics of monsoons; a review of the monsoon in literature and folklore; economic impact and political response; historical and current understanding of the physics of the monsoon; monsoon variability and interactions; prediction and government response. This material is covered by 16 authors, each an expert in his own field. With so many authors some overlap is inevitable; this, however, is kept to a generally acceptable level. The 30–60 day oscillation, for example, is covered a number of times. Many of the authors tend to exhibit their own biases which provide the reader, in some cases, with alternative explanations of certain phenomena.

I found little to fault. However, some of the mathematical definitions in the chapter on *Physics of Monsoons* are a little loose. Also the chapter on *Interannual Variability of Monsoons* is heavy going for the non-lover of statistics with 22 pages of tables! At one point there is a confusion between the text and figure legend (Fig. 15.1) as to precisely whose model is being depicted. It was surprising to find no use of satellite pictures by any of the authors. Also, whilst photographs are used to advantage on the dust cover, there are none within the book itself.

The authors and editors deserve congratulation on providing such a modern and readable account of the monsoons. The book is a natural choice for libraries, and provides good coffee-table reading, but at £71.75 an individual would require more than a casual interest to buy it. Whilst it serves to provide a very useful introduction and good references, mathematics is kept to a bare minimum, which may widen the book's appeal, but it limits its utility as a student text. As to its suitability for administrators and policy makers, at 632 pages, such people might prefer a more concise account.

W.A. Heckley

*Statistical analysis of spherical data*, by N.I. Fisher, T. Lewis and B.J.J. Embleton. 155 mm × 234 mm, pp. xiv + 329, *illus.* Cambridge University Press, 1987. Price £35.00.

I found this book a stimulating introduction to a body of statistical knowledge of which I knew nothing, but which I enjoyed encountering for the first time.

The spherical data of the title are measurements of the orientation of straight lines in space, where the lines may be directed (and called vectors) or undirected (and called axes). The theoretical starting point for the book is the question 'What is the analogue on the sphere of the normal distribution on the line or plane?' The problems for which this question is important range from archaeology to geomagnetism. Examples discussed in the text include measurements of pole position from palaeomagnetic data, arrival directions of cosmic ray showers, measurements of facing directions of conically folded bedding planes and serial correlation of wind directions.

The text develops the theory of statistical analysis of directional data of this kind in a coherent step-wise fashion that is a pleasure to read. The main emphasis is on practical applications. The mathematics is clearly presented, the examples are well chosen and lucidly expounded, and the illustrations are crisp and uncluttered.

The statistical topics appropriate for spherical data that are discussed in the book have been mainly developed since the 1950s. They roughly parallel the range of topics one expects to find in a good beginning graduate textbook on conventional statistical methods: exploratory analysis, statistical

models, analysis of unimodal and multimodal distributions, tests of uniformity and symmetry, analysis of several samples of vectorial or axial data, correlation, regression, and temporal/spatial analysis. The mathematical prerequisites are final-year calculus and matrix algebra.

For someone having to work for the first time with data of this kind, I can warmly recommend the book.

By the way, an elegant analogue of the normal distribution on the sphere is the function  $\exp(k \cos \theta)$  which has the usual Gaussian behaviour for small angular separation  $\theta$ .

A. Hollingsworth

## **Books received**

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

*Gravity currents in the environment and the laboratory*, by J.E. Simpson (Chichester, Ellis Horwood Ltd, 1987. £35.00) explains the nature of gravity currents (buoyancy-driven flow in fluids) and their manifestation in the atmosphere, the oceans and the earth sciences. Factors influencing the behaviour of gravity waves are reviewed and descriptions of numerous laboratory experiments are included.

*Satellite remote sensing*, by R. Harris (London, New York, Routledge and Kegan Paul Ltd, 1987. £10.95 (paperback), £22.50 (hardback)) is designed to give students a sound basis and introduction to this fast-changing and exciting field. The physical principles, methods of processing, applications and the way forward are examined.

*Weather patterns of East Anglia*, by A. Glenn (Lavenham, Suffolk, Terence Dalton Ltd, 1987. £14.95) sets out to show that, however apparently freakish, the weather conforms to certain recurring patterns. Simple rules for predicting weather changes and advice on setting up a weather station are given.

## **Award**

Congratulations to Brian Hoskins, Professor in Meteorology at the University of Reading, who has been elected to the Fellowship of the Royal Society in recognition of his analysis of the physical processes that control weather systems and his development of mathematical methods that have led to the understanding of weather fronts and to major improvements in weather forecasting. Brian Hoskins has many connections with the Meteorological Office and is a member of the Research Subcommittee which advises the Meteorological Committee on the general scientific lines along which meteorology and geophysical research should be developed within the Office.

## **Correction**

*Meteorological Magazine*, April 1988, pp. 121/122. The charts shown as Figs 3(a), 3(b), 3(c) should have been respectively Figs 4(a), 4(b), 4(c), and vice versa in the article 'Numerical forecast studies of the October 1987 storm over southern England'.

### Satellite photograph — 30 January 1988 at 1721 GMT

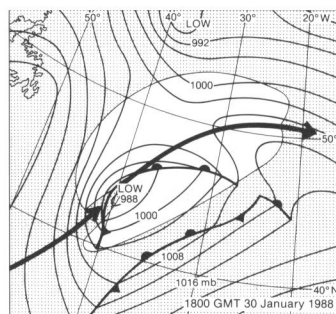
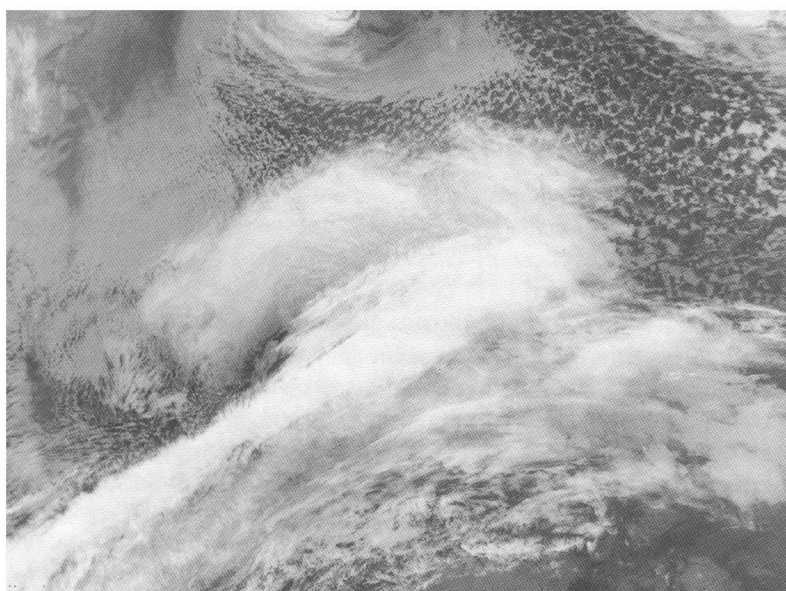
The central feature of this infra-red image is an outstanding example of a 'cloud head', a pattern that often precedes rapid cyclogenesis and very strong surface winds (Böttger *et al.* 1975, Monk and Bader 1988)\*.

Cloud heads such as shown here are regions of cold-topped cloud that are more extensive than those associated with most developing frontal waves. Their distinguishing features are

- an unusually broad extension of cloud into the cold-air mass (poleward of the upper tropospheric jet stream — see surface chart, with envelope of cloud unshaded),
- a pronounced convex poleward edge,
- a wedge of dry air aloft, shown by the presence of only lower cloud through the middle of the head,
- curved bands of convective cloud immediately poleward of the dry wedge.

When significant cyclonic development occurs, considerable convection which partially moves beneath the head is normally present within the cold air mass, and sustained cloud-top warming occurs within the frontal zone upwind of the system.

The head shown in the picture had existed for 12 hours — a characteristic lifetime for heads — and a surface low was beginning to deepen rapidly (see chart). Following its deepening to 946 mb in the next 24 hours, ship reports indicated mean winds as high as 70 kn, and a gust of 90 kn was recorded at Land's End (Cornwall).



Photograph by courtesy of University of Dundee

\* Böttger, H., Eckardt, M. and Katergiannakis, U.; Forecasting extratropical storms with hurricane intensity using satellite information. *J Appl Meteorol*, 14, 1975, 1259–1265.

Monk, G.A. and Bader, M.J.; Satellite images showing the development of the storm of 15–16 October 1987. *Weather*, 43, 1988, 130–135.

# Meteorological Magazine

## GUIDE TO AUTHORS

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

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

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

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