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Hoar-frost deposition  
Angular momentum of the atmosphere



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# The Meteorological Magazine

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## Hoar-frost deposition on roads

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### *Summary*

*By combining physical reasoning with several case-studies it is shown that the most important factors in determining hoar-frost deposition on UK roads are moisture gradients in the atmosphere's lowest layers, wind speed, weather of recent days and time of year. The Meteorological Office road surface temperature model is shown to give useful guidance if fed with accurate input parameters, although on occasions its predictions of hoar frost accumulation are deficient because of an inability to handle the obstruction of direct sunshine. Two additional forecasting tools are proposed; one a checklist, the other based on a manual time-integral of the depression of road surface temperature below dew-point.*

### 1. Introduction

In recent years much research has been devoted to road surface temperatures (RST,  $T_r$ ), their measurement and their prediction. This has culminated in the development of one-dimensional numerical models of the 'road environment' (RST models) which are now used widely in forecasting. The main objective has been to improve the efficiency of road-salting operations during winter. Improved efficiency entails many economic, environmental and human benefits; notably safer roads, fewer wasted saltings\*, less rust damage to cars and bridges and reduced waterway pollution (Soveri 1990). An overview of recent research and its applications can be found in Boselly *et al.* (1990).

There can be little doubt that substantial improvements have been made in our knowledge of the behaviour of RSTs (Bogren and Gustavsson (1989) give a wide-ranging summary). What is less clear, however, is whether the efficiency of road-salting has improved

much as a result. A cost-benefit analysis by Thornes (1989) indicates that savings probably are being made. However, Mansell (1989) rightly points out that in the United Kingdom there is still a marked tendency to forecast ice too often and hence salt roads too often, most wasted saltings being on frosty nights when roads are dry. Such errors should show up in the verification of operational forecasts, as performed by Thornes (1989) and Thornes and Shao (1991a). Sadly they do not because the verification system is formulated such that a forecast of icy roads will be 'correct' irrespective of whether unsalted roads stay dry or turn icy, provided the RST falls to zero or below.

One reason a large number of wasted saltings occur is because recent theoretical and observational studies have tended to overemphasize RSTs, and pay scant attention to road surface conditions (RSCs; i.e. dry, wet or icy). One aim of this paper is to redress the balance.

It is convenient to subdivide occasions when ice forms on road surfaces into two categories, with nomenclature as shown:

\* The cost of winter maintenance in the United Kingdom is about £100M for an average winter (Thornes 1989).

- (a) 'Water freezing': when surface water freezes over (most commonly rainwater, but also snowmelt and seepage).
- (b) 'Hoar frost deposition': when the source of the ice is direct sublimation and/or direct condensation from the atmosphere onto the road surface. This includes occasions when dew was deposited and then froze over.

When warned of water freezing, local authorities tend not to salt roads until they are wet. Thus the wasted saltings noted by Mansell to occur on 'frosty nights with dry roads' must have been initiated, in general, by incorrect forecasts of hoar-frost deposition. This suggests that of (a) and (b) it is hoar-frost deposition which is more difficult to forecast correctly, and less well understood. It is for these reasons that this study investigates hoar frost deposition. It will also be possible, however, to apply some of the results to cases of water freezing.

Hoar-frost deposition is influenced by factors as wide-ranging as air temperature and traffic speed. The main emphasis in this paper is on *meteorological* factors. The intention is to elucidate those which favour hoar-frost deposition by bringing together physical reasoning, case-studies and site-specific numerical predictions from the UK Meteorological Office RST model. Some verification of perfect prognosis predictions from this model will also be attempted.

In section 2 results of previous work directly relevant to hoar-frost deposition are summarized. The physics which govern the process are described in section 3. Section 4 provides a brief overview of the RST model, together with a discussion of ice thickness.

Section 5 covers in detail four occasions on which hoar-frost deposition occurred during a single night. The physical processes at work are discussed, and similarities between the cases noted.

In section 6 two aids for forecasting rapid hoar-frost deposition are proposed, and tested out on data from the 1990/91 UK winter. A simple calculation reveals the financial savings which might result from using these techniques.

Section 7 looks at a case where hoar-frost deposits probably accrued over several days. It is used to investigate the differences that can arise between road conditions in built-up areas and open countryside.

Conclusions are presented in section 8.

Excluded from this study are occasions when snow was lying on road surfaces, and also occasions of widespread fog.

## 2. Previous studies

There seem to be two main reasons for the lack of past research specifically into RSCs. The first is the shortage of verifying data. Icy roads are not at all easy to measure, and it has never been standard practice to report such phenomena from manned observing stations.

The second reason is that ice formation is influenced by such a wide range of factors.

Take (1990) tried to overcome both these problems, by using the experience of authorities responsible for salting roads. His investigation began by distributing questionnaires to 125 highway maintenance garages in the American state of Iowa (latitudes 40–44° N).

One question related to factors which determine why a particular stretch of road is more prone to hoar-frost. A majority (70%) of respondents felt that 'shelter/shading' of the road was important. This is supported by the observational study of Bogren (1991), which identified large systematic differences between RSTs on shaded and open roads in southern Sweden. Similarly Milloy and Humphreys (1969) noted differences in the 'duration of ice-forming conditions' between shaded and open roads in southern Scotland. Such results give a feasible explanation for localized hoar-frost deposition, and are discussed further in section 7.

Other factors covered in the above question, namely 'road material', 'road age', 'presence of rivers/lakes nearby', 'low lying' and 'hilly' were considered unimportant by most respondents. Despite not being of general importance, such factors could still be significant in certain meteorological situations. Examples in sections 5 and 6 show this to be true for factors 'hilly' and 'low lying'.

Another of Take's questions was "does the volume of traffic affect the formation of frost?" — 70% thought it did not. This conflicts with the work of Farmer and Tonkinson (1989), who noted and discussed how rush-hour traffic affects the diurnal cycle of RSTs on different motorway lanes. A lower traffic density in Iowa may partly explain the discrepancy. However the fact that Farmer and Tonkinson used measurements suggests that their results are more reliable. Here the view is taken that higher traffic volumes generally increase RSTs. Occasional reference will be made, in a qualitative sense, to this effect.

Of past studies we are aware of that of Gustavsson and Bogren (1990) bears the greatest similarity to our work. They concentrated on spatial variations in the time of onset of hoar-frost deposition in southern Sweden. It seems that the wild swings in temperature experienced in this region can sometimes make substantial hoar-frost deposition a certainty, and thus the main forecasting problem is the time of onset. In the United Kingdom, temperature fluctuations are generally less severe; and the main difficulties in defining whether or not there will be any hoar-frost deposition, and whether any that does occur will be sufficient to cause dangerously icy roads.

Monteith (1957) showed that on calm nights the moisture which forms dew on grass comes from the underlying soil and not the atmosphere. This needs to be borne in mind when making comparisons between grass and road surface.

The local consequences of large amounts of deposition of atmospheric moisture are well illustrated in Davey (1982). In the case he studied, previously dry roads became covered in pools of water in just 7 hours, despite the absence of any rain. It is also noteworthy that during that period the surrounding grass remained completely dry. Evidently moisture deposition is not a trivial problem.

### 3. The physics of hoar-frost deposition

Hoar-frost deposition on road surfaces is essentially controlled by three factors; the RST, the moisture content of the air and the wind speed.

Equations presented in Rayer (1987) can be simplified to give an expression for the net flux of moisture onto the road surface,  $F$ ;

$$F = K_1 U(e_s(T_d) - e_s(T_r)) \quad (1)$$

where  $K_1$  (positive) is a constant given that the stability of the air is fixed,  $U$  is the 10-metre wind speed,  $e_s()$  is the saturated vapour pressure at a specific temperature, and  $T_d$  is the screen dew-point temperature. This equation is essentially Dalton's Law of evaporation.

Both deposition ( $F > 0$ ) and evaporation ( $F < 0$ ) from roads are controlled by equation (1). Whether  $F$  is positive or negative depends on whether  $T_r$  is, respectively, less than or greater than  $T_d$ . As an example of the use of equation (1) consider the single case where moisture is *known* to be condensing on a road surface. The *stronger* the wind the *greater* will be the rate of moisture accumulation. This fact is noted in order to dispell the notion that strong winds always dry off roads. In this respect it is noteworthy that the rapid condensation described by Davey (1982) occurred when mean wind speeds were a sizeable 15 knots.

Over small ranges of  $T_d$  and  $T_r$  a valid and useful approximation is that  $e_s(T_d) - e_s(T_r)$  is proportional to  $T_d - T_r$ . For values likely to give rise to hoar-frost deposition on UK roads this approximation holds to about 75% accuracy. Thus from equation (1):

$$F \approx K_2 U(T_d - T_r) \quad (2)$$

where  $K_2$  is a positive constant.

So for moisture to be deposited on the road surface  $T_r$  must be less than  $T_d$ , which necessarily means that  $T_r$  must also be less than  $T$ , the air temperature at screen level. Consideration of which physical mechanisms are likely to adjust the relative positions of  $T_r$ ,  $T$  and  $T_d$  on a temperature scale can be very informative (a thorough discussion is given in section 5.3).

As implied above,  $K_2$  remains constant if the stability remains constant. Were the stability of the air close to the road surface to increase,  $F$  would decrease slightly; whereas the opposite would happen if the air became more unstable. An indication of whether the lowest few metres of the atmosphere are stable or unstable is given

by the the sign of  $(T - T_r)$ . Using this criterion means that any occurrence of moisture transfer to or from a road surface can be assigned to one of three regimes :

- $T_r > T > T_d$ , giving 'efficient' evaporation;
- $T > T_r > T_d$ , giving 'inefficient' evaporation;
- $T > T_d > T_r$ , giving 'inefficient' hoar-frost/moisture deposition.

So evaporation generally proceeds, *per se*, more rapidly than hoar-frost deposition. This partly explains why roads do, on occasions, dry out very rapidly.

As dew-points are critical to hoar-frost deposition it is important to consider the accuracy of standard dew-point measurements. Fig. 1(a) of Painter (1973) implies that given a real (psychrometer) dew-point depression of 2 °C, dew-points derived from standard screen measurements are on average 0.2 °C too high with winds up to 5 kn, and 0.1 °C too high with winds over 10 kn. These values are probably small enough to be discounted, although it is noteworthy that there was a large amount of variability in the errors. Measurement accuracy is dependent on a lot of factors — chapter 3 of the *Handbook of Meteorological Instruments* (Meteorological Office, 1981) gives a comprehensive discussion.

Does water on a road surface freeze at 0 °C? Ritchie (1976) analysed 27 cases and found that freezing of distilled water occurred with an average temperature of -0.4 °C just above the surface, and +0.7 °C just below. So the true RST is probably about 0 °C, given that the water is free from impurities (such as salt!).

The concept of cooling due to evaporation is widely understood. What is not so widely appreciated perhaps is that the converse is also true, whereby the deposition of moisture/hoar-frost onto a surface actually warms that surface. Evidence for this effect can be seen in Fig. 6 of Thornes (1972). This shows subzero road temperatures predicted by regression equations from which the effects of latent heat had been omitted to be quite accurate on nights with heavy rain, but systematically too cold on nights with hoar-frost on the road surface (for water/ice at 0 °C the latent heat of sublimation is about 8½ times greater than the latent heat of fusion).

These latent heat differences mean that ice formed by hoar-frost deposition will in general not be as cold as ice formed by water freezing. In turn this makes ice formed by hoar-frost deposition potentially more dangerous to the motorist, because the friction of ice increases as its temperature decreases (Moore (1975), chapter 6).

## 4. The RST model

### 4.1 Description

The UK Meteorological Office RST model, described in Rayer (1987), integrates physical equations in order to calculate RST and RSC at one site over a 24-hour period beginning at midday. The effects on the RST of latent heating and 'latent cooling' are included. (The

thermodynamic constant used is the latent heat of condensation. No account is taken of the latent heat of fusion, but as this is almost an order of magnitude less, the resulting errors in RST should be negligible.) Boundary conditions for the equations are provided by the user, i.e. values of specific meteorological variables for specific times during the 24-hour period. The table in the top half of Fig. 1(d) shows what these input variables are and the times for which values are required.

## 4.2 Output

The bottom half of Fig. 1(d) contains an example of an output profile. The main part of this profile indicates how RST (vertical axis) varies through the forecast period (horizontal axis), the letter 'R' indicating the profile. Below this the line of dots and letters between 'REL' and 'ICE' indicate the predicted RSC. There is a key for these at the foot of the graph.

## 4.3 Ice thickness

Letters at the foot of an RST model output profile can be converted into the total depth of ice/water calculated to have accumulated on road surfaces at given times through the night; 'f' and 'd' represent 0.001 mm to 0.01 mm whilst 'l' and 'w' represent 0.01 mm or greater.

The lack of resolution can sometimes be misleading. For example the last in a long line of 'f's may still only represent 0.001 mm. When performing 'perfect prognosis' predictions for the case-studies this difficulty was overcome by extracting from the model the exact depths of condensed moisture/ice calculated for hourly intervals through the night.

Tiny fractions of a millimetre may *seem* trivially small. The results of Monteith (1957) indicate that they are not, however. He weighed dewfall\* on short grass on a number of occasions and found a maximum deposition rate of  $0.035 \text{ mm h}^{-1}$ , and a maximum accumulation during one night of 0.15 mm. Before equating these values to hoar-frost deposition on roads the following points should be noted: (i) when the values were measured, on 1 September 1953, the moisture content of the air was greater than it is on typical winter nights in the United Kingdom (about  $8 \text{ g kg}^{-1}$ , compared to  $4 \text{ g kg}^{-1}$ ), and (ii) on clear nights the depression of the grass temperature below air temperature is generally larger than the depression of the RST below the air temperature (typically  $2\text{--}6 \text{ }^\circ\text{C}$ , compared to  $1\text{--}3 \text{ }^\circ\text{C}$ ). As deposition on a surface is proportional to both moisture content of the air, and temperature difference between the air and that surface, it therefore follows that Monteith's values should be multiplied by  $(4/8) + (2/4)$  to give equivalent, albeit approximate, values for hoar-frost deposition on roads. This gives a potential maximum deposition rate of  $0.01 \text{ mm h}^{-1}$  and

a potential maximum one-night accumulation of 0.04 mm.

## 4.4 Verification

A satisfactory verification of model output clearly requires some idea of the minimum depth of hoar-frost likely to be dangerous to a motorist. This presents problems because such a value has never been accurately measured (to the authors' knowledge) and also depends, very probably, on the precise structure of the road surface (J.E. Thornes, personal communication). Field experiments utilizing a sensitive rain-gauge indicated that 0.01 mm of drizzle was quite sufficient to dampen roads. In addition, a simple laboratory experiment demonstrated that by spreading out a water droplet on a smooth surface it was quite easy to produce a visible layer of water only 0.002 mm thick. Thus tiny amounts do have the potential to make roads dangerously icy. We tentatively suggest that the average 'danger level' lies somewhere between 0.002 and 0.01 mm.

## 5. Hoar-frost case-studies

### 5.1 Selection

Evidence of hoar-frost deposition on the occasions to be described came from two sources: a weather diary, kept by N.J. Gait between 1972 and 1980 in Wallington, south London, and chance observations made by forecasters at weather centres in south-east England. For the most recent cases use was also made of measurements from roadside sensors in Kent and Berkshire\*.

At the outset a random search for examples of hoar-frost deposition in winters prior to 1990/91 yielded six good cases. 'Good' means there was strong evidence to suggest the observed ice was *not* due to water freezing. Other cases could undoubtedly have been found had the temporal and spatial data coverage been better.

Five of the six cases were of short time-scale, meaning most if not all the hoar-frost deposition occurred during one night. These are described in section 5.2. Regional variations can arise during these short time-scale events. Sensor data which was available for case 4 is used to highlight these.

The sixth case was characterized by a long, clear, cold spell with light winds, in which the deposits appeared to have accumulated over several days — this is dealt with later, in section 7.

### 5.2 Description of cases

Two consecutive midday North Atlantic pressure patterns are shown for each of the four cases, the dates being those which straddled the night/morning when hoar-frost was observed (Figs 1(a), 2(a), 3(a) and 4(a)).

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\* We have adopted Monteith's definition of dewfall, namely 'the turbulent transfer of water vapour from the atmosphere'. Dewfall does not, therefore, include the transfer of water vapour from soil to grass.

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\* Kent use Vaisala sensors whilst Berkshire use Scan sensors. Sensor measurements of the hoar-frost itself were discounted — the authors regard such measurements to be far too unreliable at present.

Thickness lines 1000–500 mb for 564, 546, 528 and 510 dam have been superimposed. Also shown are observations over south-east England at a relevant time (Figs 1(b), 2(b), 3(b) and 4(b)), all current weather included, and the lower part of a representative tephigram (Figs 1(c), 2(c), 3(c) and 4(c)) with its corresponding 900 m wind. The RST model was run for each case (as described below); Figs 1(d), 2(d), 3(d), 4(d) and 4(e) indicate the input values used, and the resulting output profiles.

On Figs 1(b), 2(b), 3(b) and 4(b) T denotes the location of the radiosonde ascents, P marks the sites which correspond to the RST model profiles, and F shows where hoar-frost was *observed* on road surfaces (it probably also *occurred* in many other locations).

For each case the figures should provide a comprehensive guide to synoptic micrometeorological developments during the night in question. Supplementary information is given under the heading 'synoptic background' in the case descriptions.

The RST model was in fact run for two consecutive 24-hour periods for each case (referred to as runs 1 and 2). Run 2 (shown) ended at the midday immediately after ice was observed. The purpose of run 1 (not shown) was to initialize the sub-surface temperature profile for run 2; this initialization procedure having been strongly recommended by Farmer and Tonkinson (1989), to allow for differences such as those illustrated in Fig. 5. The midday input values of RST and RDT (road depth temperature) used for run 2 were those predicted at the end of run 1. The corresponding inputs for run 1 were estimated using forecaster experience and analysis of the weather of the previous two or three days. Input values of the other variables were estimated using routine observations from the local area and, where available, observations from the weather diary and roadside sensors. In this way the model's performance under 'perfect prognosis' conditions could be assessed.

### 5.2.1 Case 1: morning of 3 December 1976

See Figs 1(a) to 1(d).

*Evidence:* Thick hoar-frost observed on suburban roads at Wallington, South London (from personal weather diary).

*Synoptic background:* A cold cyclonic north-westerly pattern covered the British Isles. The night of the 1st/2nd had been cloudy with temperatures around 5 °C. Cloud started to clear around midday on the 2nd.

*RST model:* Maximum depth of hoar-frost = 0.004 mm, 7 a.m. to 10 a.m. A prolonged period of hoar-frost is indicated, but the depth may well be insufficient.

*Discussion:* The Crawley ascent shows a plentiful supply of moisture at low levels, but dry air above 960 mb. The limited depth of moisture, together with light winds, prevented low cloud forming in Wallington. In East Anglia though (north-east corner of Fig. 1(b)),

where winds were a little stronger, road temperatures probably rose above zero when a cover of stratus formed around midnight. Clearly there was a fine balance on this night between skies remaining clear and turning cloudy — wind speed was apparently the deciding factor. The source for the observed hoar-frost was undoubtedly the moisture shown on the ascent, its deposition onto the road surface being aided by the gentle westerly wind.

The variation in dew-point depression on the ascent probably resulted from the long passage of essentially cold, dry arctic air across warm seas.

### 5.2.2 Case 2: night of 4–5 December 1977

See Figs 2(a) to 2(d).

*Evidence:* Extensive hoar-frost/ice was observed on most roads around Wallington at 2200 on the 4th. Road conditions were extremely dangerous, the frost mixed with water in places.

*Synoptic background:* A cold south-easterly flow had persisted for several days. Rain was last reported on the evening of the 1st. Skies had been clear since dawn on 2nd.

*RST Model:* Shows substantial accumulation of hoar-frost. Maximum depth = 0.022 mm at 0700. At 2200 depth = 0.006 mm. Profile considered reasonable, though hoar-frost underpredicted at 2200. Road conditions may well have deteriorated further through the night.

*Discussion:* 60 hours of clear skies and low temperatures must have left roads very cold through depth — note the low RDT. A rise in dew-point occurred right across south-east England on the afternoon of the 4th. This may have resulted from a change in the origin of the low-level air from north of the Alps to west of them, brought about by fronts pushing in from the west. The ascent again shows low-level moisture, the difference between the dew-point in the lowest 20 mb and the profile RST is unusually large. Strong winds certainly aided hoar-frost deposition.

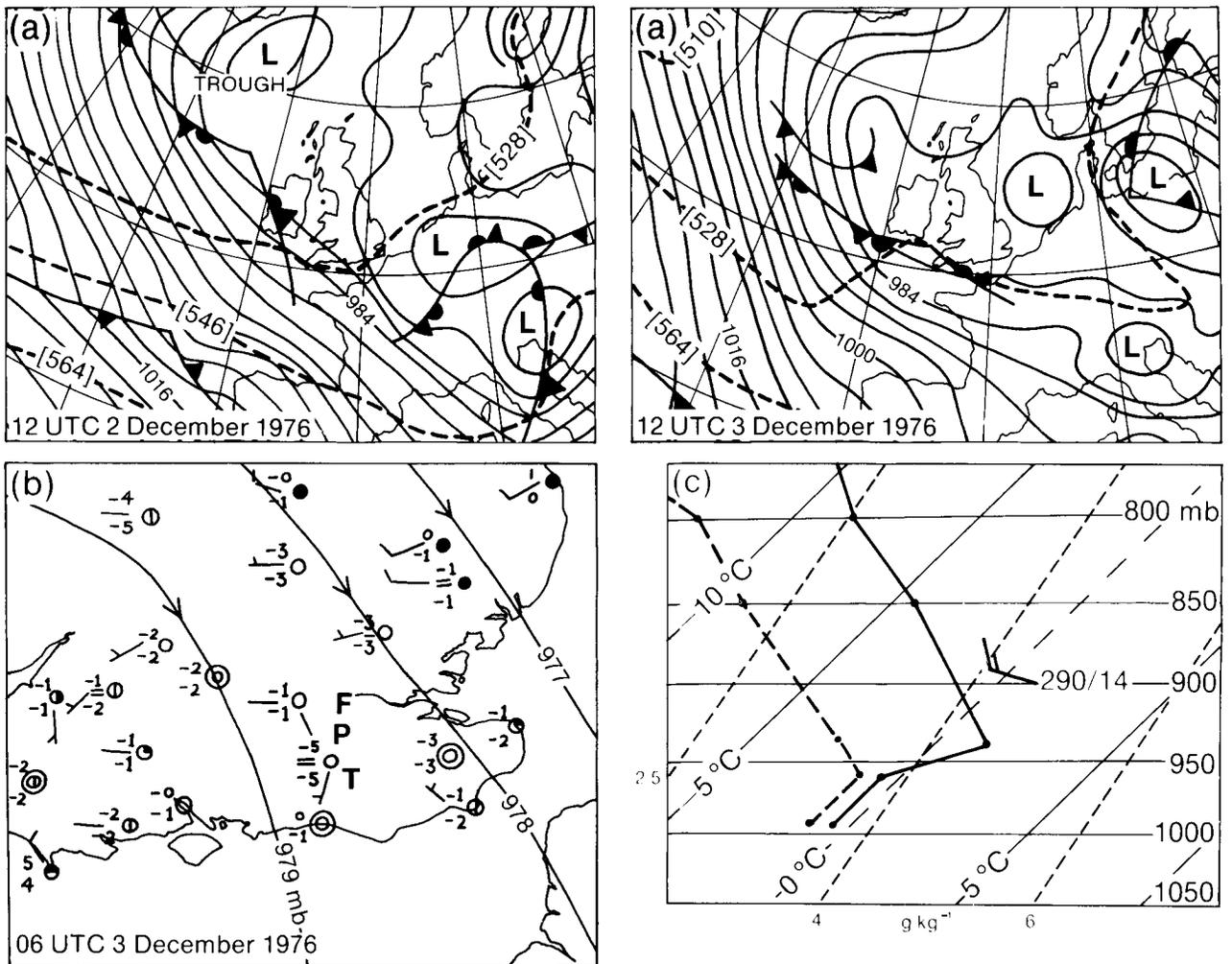
### 5.2.3 Case 3: morning of 7 December 1988

See Figs 3(a) to 3(d).

*Evidence:* Some roads in south Oxfordshire, west Berkshire, north Hampshire and Bedfordshire were affected by extensive frost/ice. The observation from south Oxfordshire indicated that the ice there was confined to roads above 300 ft.

*Synoptic background:* A rather cold north to north-westerly flow covered the British Isles. On the night of the 5th/6th a cold pool had produced localized wintry showers, but there were also long clear periods. The 6th was dry and mostly sunny.

*RST model:* Shows some accumulation of hoar-frost after 2300. Maximum depth = 0.006 mm at 0900. Seems reasonable guidance, perhaps slightly deficient.



**Figure 1.** Data for case 1, 2/3 December 1976. (a) Synoptic charts for 12 UTC on the days in question, (b) plotted chart for south-east England at 06 UTC on 3 December 1976, (c) tephigram for Crawley at 00 UTC on 3 December 1976, and (d) input values and resulting output profiles for Wallington (Greater London). For further details see section 5.2.

*Discussion:* Cold, dry air moving on a long sea track produced the type of ascent favouring hoar-frost deposition, as in case 1. The Cheshire gap (near the north-west corner of Fig. 3(b)) may have allowed low-level moisture to penetrate well inland. Note on the ascent the strong wind and the negative hydrolapse in the lowest 15 mb. The very shallow depth of moisture precluded stratus — cloud near the east coast is convective stratocumulus, base about 2800 ft. Why low-level roads were wet rather than icy is not entirely clear. However, it is probable that air temperatures and RDTs at low levels were higher than at altitude. This combined with the heat generated by the morning's traffic may have been sufficient to just keep the water there from freezing.

#### 5.2.4 Case 4: early morning of 14 January 1990

See Figs 4(a) to 4(e).

*Evidence:* White hoar-frost observed on the sides of roads near Mitcham, south London between 0800 and 0900. Roads nearby were wet. Minimum RSTs at the six

roadside sites in Kent were all subzero. The wetness of the south London roads implies that at least some of these Kent roads were icy. Observations from three sites still showed subzero RSTs at 0800. Widespread hoar-frost also observed on Norfolk roads around dawn.

*Synoptic background:* Cloud and rain linked to a cold front cleared the south-east between midnight and 0600 on the 13th; with air temperatures dipping to 1 or 2 °C at dawn. A sunny day followed.

*RST model:* Two sets of model runs were performed, using roadside sensor measurements of air temperature, dew-point and wind from Coxett Wood, an exposed site in north Kent, and Stile Bridge, a very sheltered site in the Weald. The Coxett Wood profile shows substantial hoar-frost accumulation, reaching 0.011 mm at 0600. At Stile Bridge there was barely 0.001 mm at 0900. The RSTs predicted at both sites were quite accurate, measured minima being -1.2 °C and -3.3 °C, respectively.

*Discussion:* The ascent characteristics are very similar to case 3. The moisture came north from the English Channel in the developing southerly breeze. The

(d)

SITE: WALLINGTON (GREATER LONDON) Date 2/3 Dec 76

Road Surface Temperature: 5.0} at midday, for start of profile  
Road Depth Temperature: 4.0} at midday, for start of profile

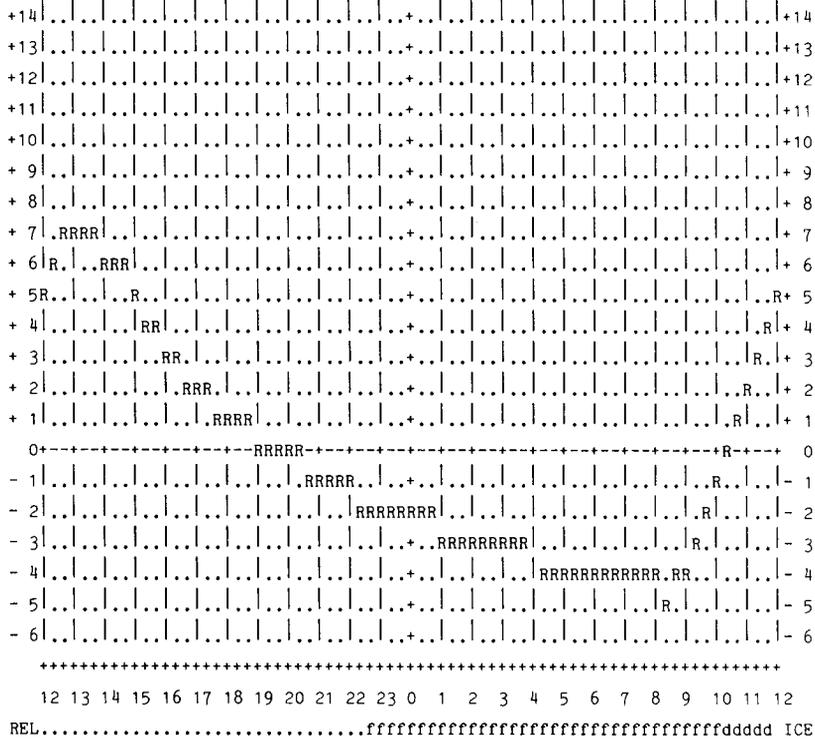
Time (UTC)	1200	1500	1800	2100	2400	0300	0600	0900	1200
Air Temp	5.5	4.5	1.0	-0.5	-1.0	-1.5	-2.0	-1.5	3.5
Dew Point	1.0	0.5	-0.5	-1.0	-1.5	-2.0	-2.0	-2.0	0.5
Avg Wind Speed	12	4	3	4	3	3	2	2	*
Avg L/Cld & C/Amt	44	22	11	00	00	00	00	00	+
Avg Cloud Type	1	1	1	0	0	0	0	0	\$
Avg Rainfall	0	0	0	0	0	0	0	0	::

'Air Temp' and 'Dew Point' are spot values for the stated times. The values for 'Avg Wind Speed', 'Avg L/Cld & C/Amt', 'Avg Cloud Type' and 'Avg Rainfall' are 'averages' over 3-hour periods.

- \* = at 10 m
- + = Average low cloud (oktas) and total cloud amount (oktas)
- \$ = '0' if no cloud, '1' if cloud mainly low cloud, '2' if cloud mainly medium cloud
- :: = '1' if precipitation during period and roads expected to be wet/icy at end of that period, '0' otherwise

FORECAST GRAPH FOR SITE: WALLINGTON

ROAD TEMPERATURE (DEGREES CELSIUS) AND ICE PREDICTION FROM 1200 2/12/76



PERIOD OF FREEZING ROAD TEMPERATURES: 1940-1020

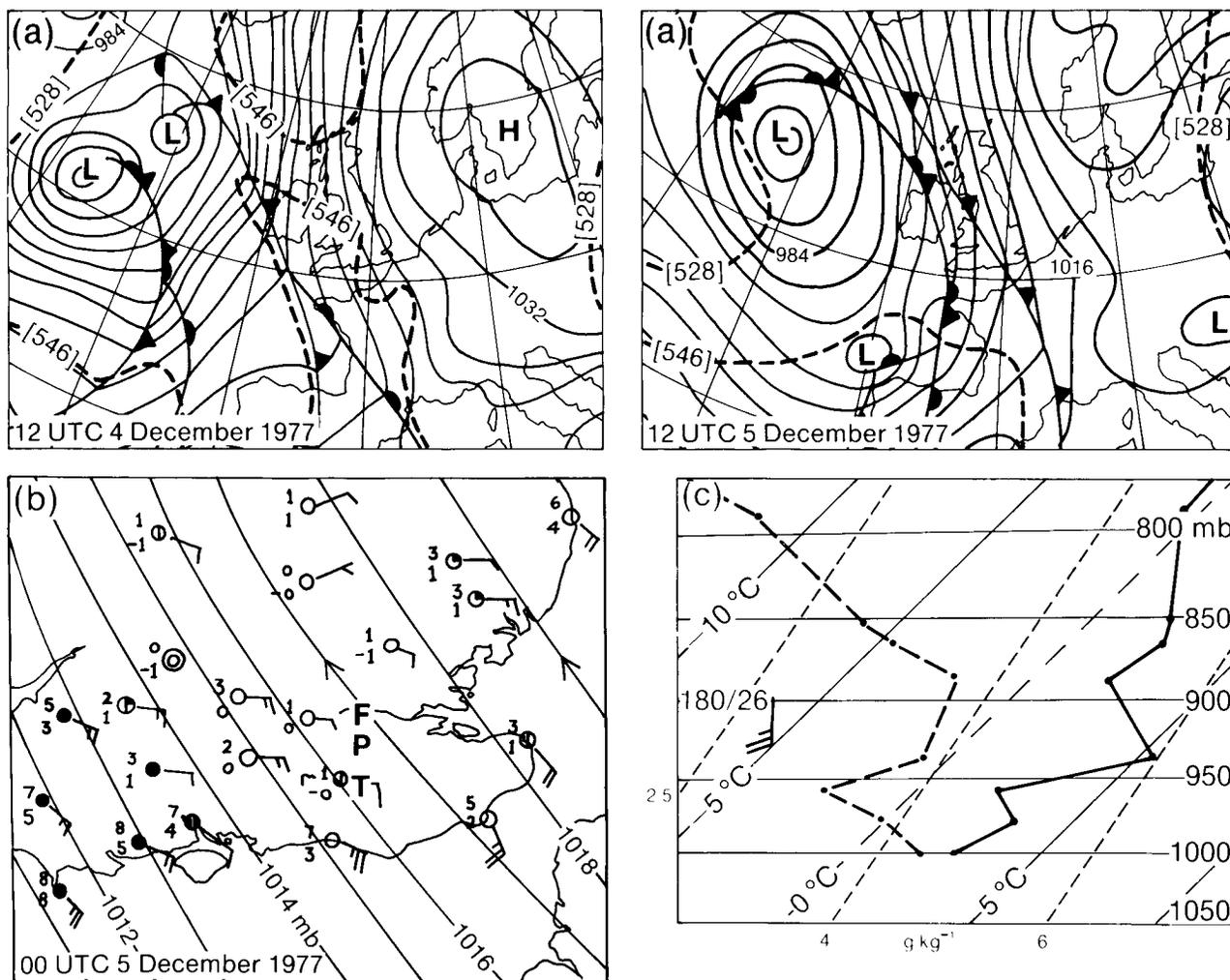
MINIMUM ROAD TEMPERATURE : -4.5

KEY: ..dry (d)ew hoar (f)rost (P)recipitation (W)et (I)ce

Figure 1. Continued

differences between hoar-frost amounts on the two profiles are very probably not erroneous, but in fact a function of site exposure. The difference in wind speed appears to be the crucial factor — the effect of this (see

equation 2) would be augmented by stability differences between the two sites. It is noteworthy that the iciest road is the warmer of the two.



**Figure 2.** Data for case 2, 4/5 December 1977. (a) Synoptic charts for 12 UTC on the days in question, (b) plotted chart for south-east England at 00 UTC on 5 December 1977, (c) tephigram for Crawley at 00 UTC on 5 December 1977, and (d) input values and resulting output profiles for Wallington (Greater London). For further details see section 5.2.

### 5.2.5 Case 5: morning of 26 December 1979

*Evidence:* Thick hoar-frost observed on roads in Wallington.

*RST model:* produced a maximum of 0.027 mm of hoar-frost, the most seen in the five cases investigated. Deposition began at 2030.

*Synoptic background:* diagrams and detailed discussion have been omitted to avoid repetition. The synoptic set up was very similar to case 4 (except that the previous night had been mostly clear with a minimum of  $-3^{\circ}\text{C}$ ). This ‘developing southerly’ synoptic situation can perhaps be considered the ‘classic’ one for hoar-frost deposition on roads in southern England, because the closest source of moisture is to the south.

### 5.3 Common features

In all the cases described, skies were clear yet there was a plentiful supply of moisture in the atmosphere’s lowest layers. These two observations are almost contradictory — in that low-level moisture usually means low cloud or fog. What seems to have precluded

cloud in most, if not all the cases, is that the layer of moisture was very shallow ( $\approx 20$  mb) and was capped by a deep layer of much drier air. The four tephigrams are strikingly similar in this respect.

Clear skies must be an important prerequisite for hoar-frost deposition. This is because far more long-wave radiation emanates from clouds than from clear skies. This radiation warms road surfaces, and hence reduces the chances both of  $T_r$  being below freezing point, and of  $T_r$  being below  $T_d$  (see equation 2). The sensitivity tests of Thornes and Shao (1991b) support this argument. They concluded ‘cloud cover is the second most important factor governing the variation in RSTs’. There is, however, a subtle difference between the two investigations — they looked at the influence on  $T_r$ ; we are effectively looking at the influence on  $T_d - T_r$ .

The low-level moisture evident on the tephigrams is similarly important, as its absence would also reduce the chances of  $T_d$  being above  $T_r$ . Thornes and Shao’s (1991b) conclusion that ‘dew-point seems to only have a minor influence on model output’ is slightly misleading. What they mean is that dew-point has only a minor

(d) SITE: WALLINGTON (GREATER LONDON) Date 4/5 Dec 77

Road Surface Temperature:	6.0									
Road Depth Temperature:	3.0									
-----										
Time (UTC)	1200	1500	1800	2100	2400	0300	0600	0900	1200	
Air Temp	4.0	3.5	2.0	1.5	1.5	1.5	1.5	4.0	7.0	
Dew Point	-1.0	-0.5	0.0	0.5	0.5	0.5	0.5	2.5	5.0	
Avg Wind Speed		14	10	8	9	7	7	9	11	
Avg L/Cld & C/Amt		00	00	00	00	00	22	66	77	
Avg Cloud Type		0	0	0	0	0	1	1	1	
Avg Rainfall		0	0	0	0	0	0	0	1	
-----										

FORECAST GRAPH FOR SITE: WALLINGTON

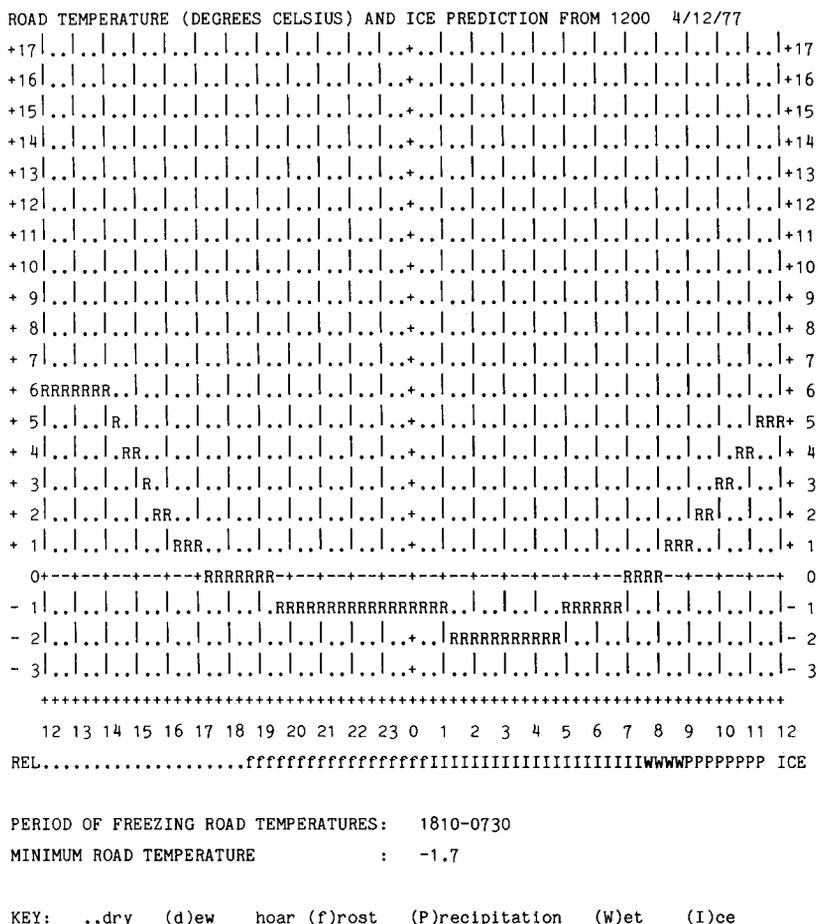


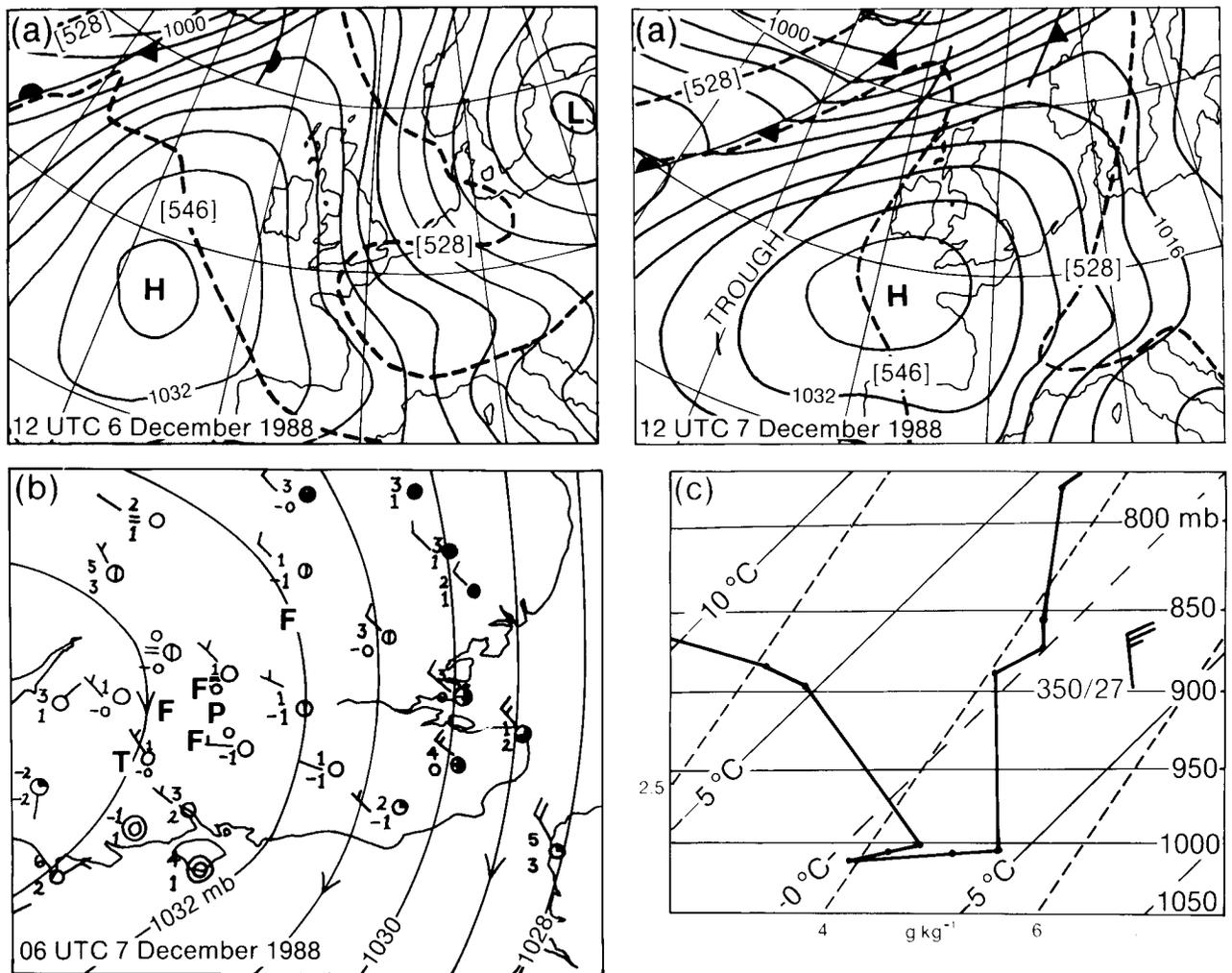
Figure 2. Continued

influence on RST, and that may only be in the absence of moisture fluxes to/from a road surface. Quite clearly dew-point has a very substantial impact on hoar-frost deposition!

It seems that on occasions the observed moisture distribution can be explained by the way in which the synoptic pattern is interacting with the physical geography of southern England and its surroundings. By physical geography is meant, primarily, the moisture sources (seas) and sinks (land, especially at altitude).

Inspection of the RST model data tables and also the thickness lines on the North Atlantic charts shows a notable absence of very cold air from any of the cases.

The fact that occasions when snow was lying on road surfaces were specifically excluded during case selection partly explains this. However, it is also physically reasonable because the capacity of air to hold water vapour (to be deposited) decreases as its temperature decreases. The depth of hoar-frost that can be deposited with a 1 °C difference between  $T_r$  and  $T_d$  at +1 °C is about 60% more than at -6 °C (1000 mb humidity mixing ratios at +1 °C and -6 °C are, respectively, 4 g kg<sup>-1</sup> and 2.5 g kg<sup>-1</sup> — calculating  $((4-2.5)/2.5) \times 100\%$  gives 60%). This effect is not accounted for by equation (2). It should also be noted that  $T_d$  does not have to be below zero.



**Figure 3.** Data for case 3, 6/7 December 1988. (a) Synoptic charts for 12 UTC on the days in question, (b) plotted chart for south-east England at 06 UTC on 7 December 1988, (c) tephigram for Larkhill at 06 UTC on 7 December 1988, and (d) input values and resulting output profiles for the Berkshire Downs. For further details see section 5.2.

Another feature common to all cases is the steady breeze. Aside from aiding hoar-frost deposition through mechanical mixing, and hence vertical transport of moisture down onto the road surface (note  $U$  in equation (2)), this breeze was probably also mixing some dry air down onto the top of the shallow moist layer, helping preclude stratus development. The strength of the 900 m wind should in itself have been sufficient to make fog formation unlikely in case 4, and extremely unlikely in cases 2, 3 and 5 (Saunders (1973) concludes that radiation fog does not form with geostrophic wind speeds of above about 21 kn ( $\approx 900$  m wind speed)).

In cases 2, 3, 4 and 5 the night preceding the hoar-frost event had been cold and at least partly clear. It is physically sound to expect this to be a contributory factor. This is because at night the roadbed and underlying soil tend to act as a reservoir of heat, generating an upward heat flux, which effectively puts a brake on the fall of RST. One cold, clear night will reduce the amount of heat in the reservoir, thus making the 'brake' less effective the following night. This implies

that on this second night  $T_r$  will be allowed to drop further below  $T$  than it would have had the first night not been cold and clear. Clearly this increases the chances of  $T_d$  being above  $T_r$ , and hence of hoar-frost deposition. The RDT gives one measure of the amount of heat stored below the road surface. Fig. 5 illustrates why the weather of the previous night is important in addition to this.

Any factor which increases the *general* risk of hoar-frost deposition will necessarily also increase the chances of hoar-frost deposition commencing *early* in the night-time period. However, this is *particularly* true for 'previous night's weather'. This is because the influence that a specific weather event has on subsequent RST must decrease with time. Thus any differences in RST profiles which can be attributed solely to the previous night's weather will be larger around dusk than around dawn. Inspection of the cases studies suggests that this effect is physically significant. Cases 2 and 5 were the only ones for which the RST model or observations indicated that the time of onset of hoar-frost deposition was before 2100. They were also the

(d) SITE: BERKSHIRE DOWNS Date 6/7 Dec 88

Road Surface Temperature: 6.0  
 Road Depth Temperature: 5.0

Time (UTC)	1200	1500	1800	2100	2400	0300	0600	0900	1200
Air Temp	6.0	5.5	4.0	2.0	1.0	0.3	0.3	0.5	4.5
Dew Point	2.0	1.5	1.0	0.0	0.0	-0.5	-0.5	-0.3	2.5
Avg Wind Speed	10	8	7	6	5	4	4	5	
Avg L/Cld & C/Amt	33	22	00	00	00	00	22	33	
Avg Cloud Type	1	1	0	0	0	0	1	1	
Avg Rainfall	0	0	0	0	0	0	0	0	

FORECAST GRAPH FOR SITE: BERKSHIRE DOWNS

ROAD TEMPERATURE (DEGREES CELSIUS) AND ICE PREDICTION FROM 1200 6/12/88

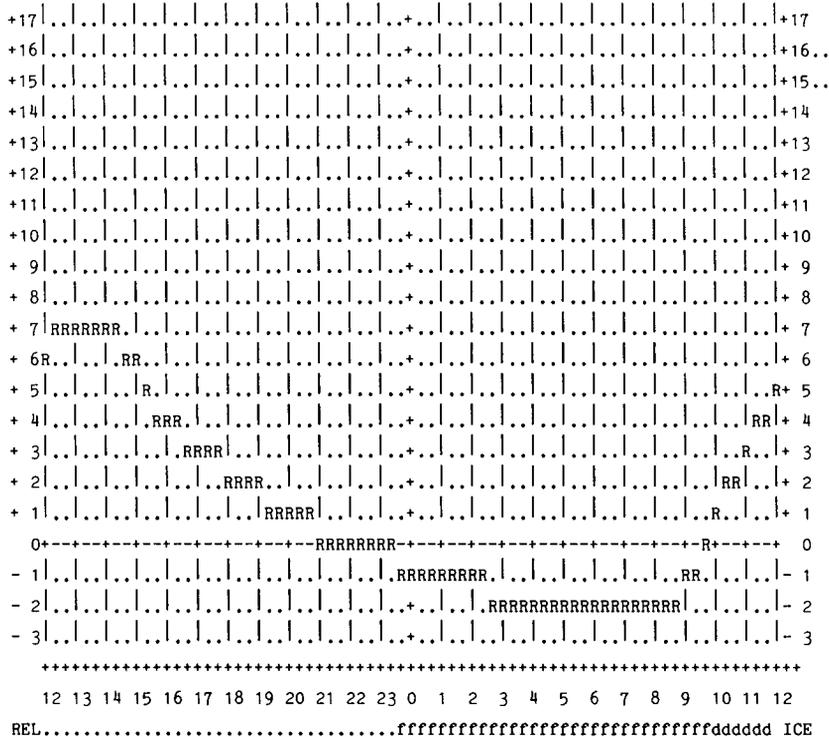


Figure 3. Continued

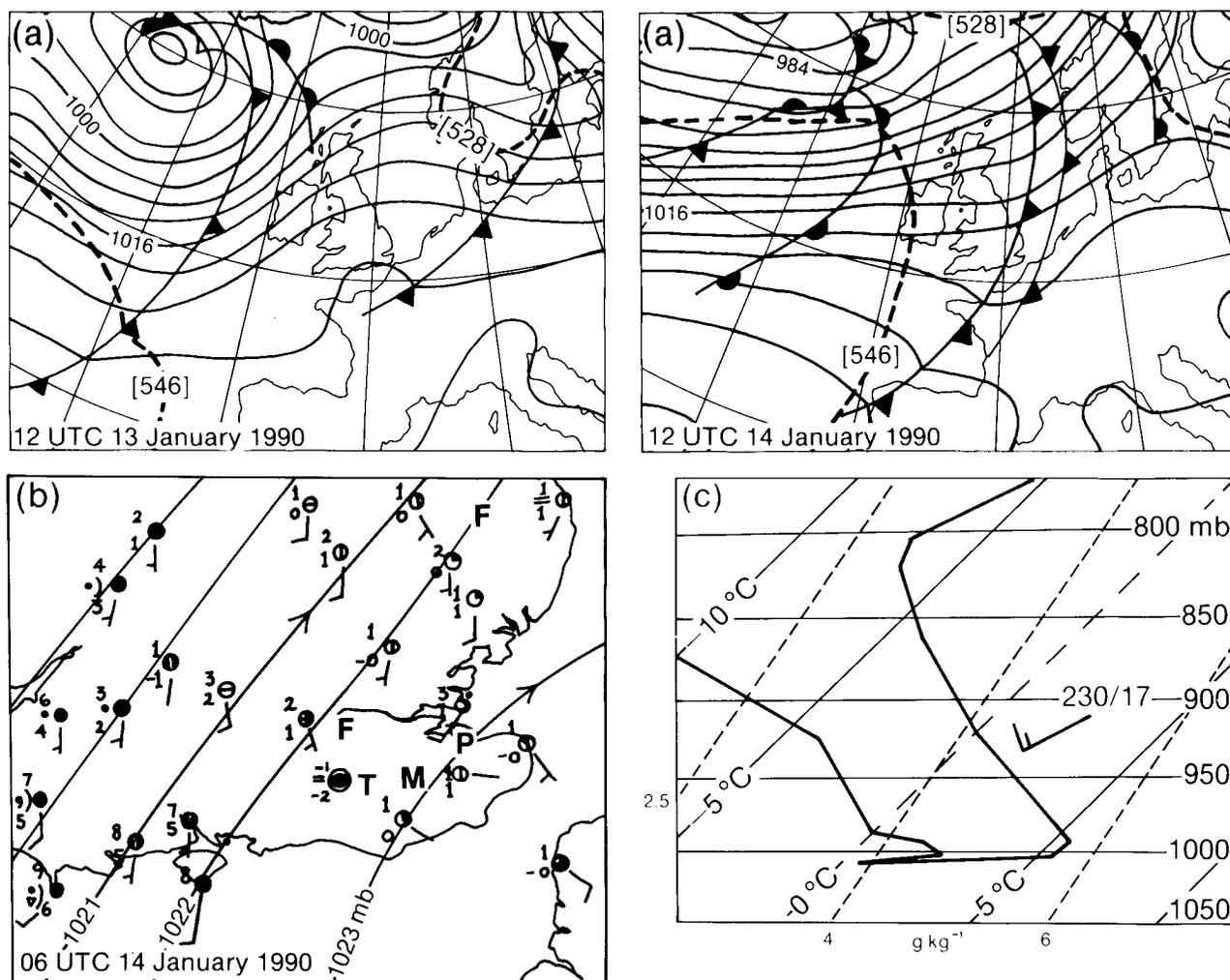
only cases in which the previous night had had a minimum of 0 °C or below as well as largely clear skies.

The distribution by month for the five cases was December — 4, January — 1. There are two reasons for expecting the prevalence of cases in December to be no coincidence:

(a) it is in December that nights are longest, and hence road cooling greatest. Daytime warming is also least in this month, not only because of shorter days, but also because of the reduction in direct insolation caused by low solar elevation. Thus, on average, the

depression of  $T_r$  below  $T$  is largest in December (as demonstrated by Parrey (1969)), and

(b) this reason is related directly to  $T_d$ . For a given wind direction over the British Isles  $T_d$  tends to be proportional to sea surface temperature upwind ( $T_{sea}$ ). Therefore one would expect  $T_{min}$  (minimum air temperature) minus  $T_{sea}$  to be roughly proportional to the night-time dew-point depression,  $T$  minus  $T_d$ . Hence  $(T_{min} - T_{sea})$  should give an indication of the risk of hoar-frost/dew deposition, whereby lower values imply greater risk. In Table I  $T_{min}$  at Heathrow



**Figure 4.** Data for case 4, 13/14 January 1990. (a) Synoptic charts for 12 UTC on the days in question, (b) plotted chart for south-east England at 06 UTC on 14 January 1990, (c) tephigram for Crawley at 00 UTC on 14 January 1990, and input values and resulting output profiles for (d) Stile Bridge (Kent) and (e) Coxett Wood (Kent). For further details see section 5.2.

airport is compared with  $T_{sea}$  in the English Channel, for November through to February. The difference column suggests hoar-frost/dew deposition is more likely early in the winter than later, and is consistent with the large number of December cases.

These arguments relating to ‘time of year’ are supported by the results of Takle (1990), who catalogued 1615 observations of hoar-frost deposition in Iowa. He found a frequency maximum split between December and January, but indicated that the way in which temperature and humidity during the analysis period had differed from climatology meant this probably gave an overestimate of January’s true hoar-frost climatology.

The link between  $T_a$  and  $T_{sea}$ , and the dependence on temperature of the air’s capacity to hold water vapour lead to another potentially useful result. This is that on a night when subzero RSTs are expected the risk of hoar-frost deposition will be greater if sea temperatures are anomalously high.

## 6. Forecasting hoar-frost deposition

### 6.1 Two new techniques

The main tool for a road condition forecaster in the UK Meteorological Office is the RST model. Comments in section 5.2 suggested that this model performs well if fed with accurate input parameters (albeit with perhaps a slight tendency to underestimate deposition). The forecaster’s main difficulty then would seem to be getting these parameters right; particularly low cloud, dew-points and wind speeds\*. In this sense it is a standard forecasting problem. Case 4 showed, however, that across a small region large differences in road conditions can sometimes arise. Given that a forecaster may have to cater for a large region by running the RST model for just one site, it is therefore important that they also appreciate the mechanisms which may lead to such differences. Only then can appropriate guidance be

\* At London Weather Centre it has been found that on occasions forecast tephigrams taken from the UK limited-area model can be useful for obtaining accurate input parameters.

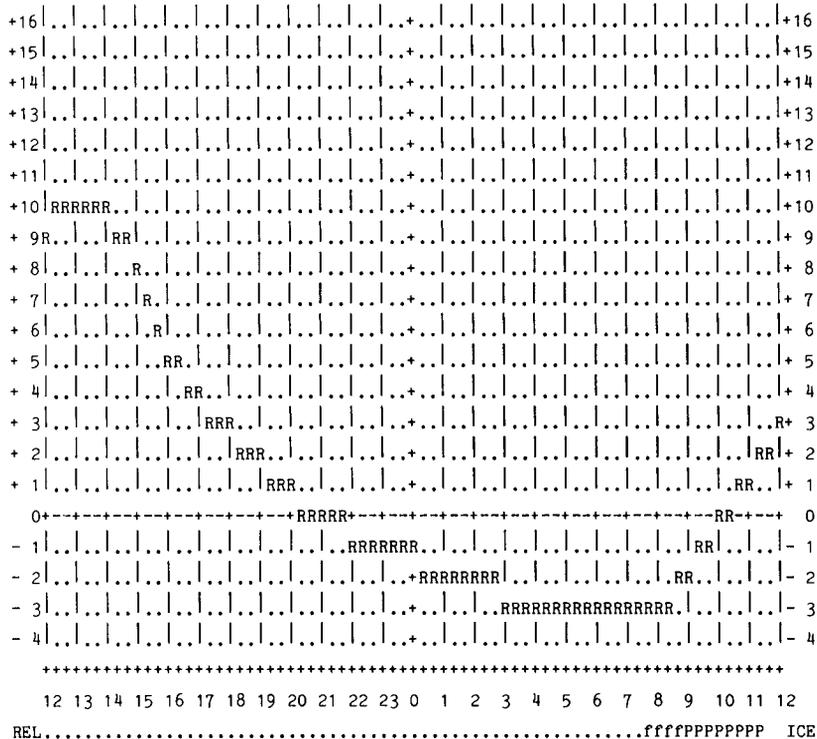
(d) SITE: STILE BRIDGE, KENT Date 13/14 Jan 90

Road Surface Temperature: 9.0  
 Road Depth Temperature: 6.0

Time (UTC)	1200	1500	1800	2100	2400	0300	0600	0900	1200
Air Temp	5.8	7.2	1.1	-0.9	-1.5	-2.5	-3.0	0.1	3.5
Dew Point	4.4	3.8	0.5	-1.3	-1.8	-2.9	-3.3	0.0	3.3
Avg Wind Speed		3	1	0	0	0	0	0	0
Avg L/Cld & C/Amt		11	02	00	01	00	01	34	88
Avg Cloud Type		1	2	0	2	0	2	1	1
Avg Rainfall		0	0	0	0	0	0	0	1

FORECAST GRAPH FOR SITE: STILE BRIDGE, KENT

ROAD TEMPERATURE (DEGREES CELSIUS) AND ICE PREDICTION FROM 1200 13/1/90



PERIOD OF FREEZING ROAD TEMPERATURES: 2110-1010  
 MINIMUM ROAD TEMPERATURE : -3.3

KEY: ..dry (d)ew hoar (f)rost (P)recipitation (W)et (I)ce

Figure 4. Continued

given to the customer. A thorough understanding also enables the forecaster to attach a suitable confidence level to a prediction, or, equivalently, an 'ice probability'. The potential practical and economic advantages of probabilistic type forecasts have been emphasized by Ayton (1988) and Takle (1990), to name but two.

It is with such benefits in mind that the following two aids to forecasting hoar-frost deposition are proposed.

#### 6.1.1 Method 1

This method requires neither an RST model, nor sensor data. It comprises a check-list of factors which

increase the risk of hoar-frost deposition (Table II). All have been discussed in section 5.3. It should be fairly quick and easy to see the extent to which they will be satisfied on a given night. To help with this values have been added alongside to suggest the level at which one might consider a particular criterion to have been met. All except (5) and (6) relate to the night in question. It is assumed that factor (6), the RDT, would be measured at midday just before the night in question.

In compiling this list factor (6) was seen to represent the weather of the previous few days and nights, whereas factor (5) represents, by definition, the weather of the

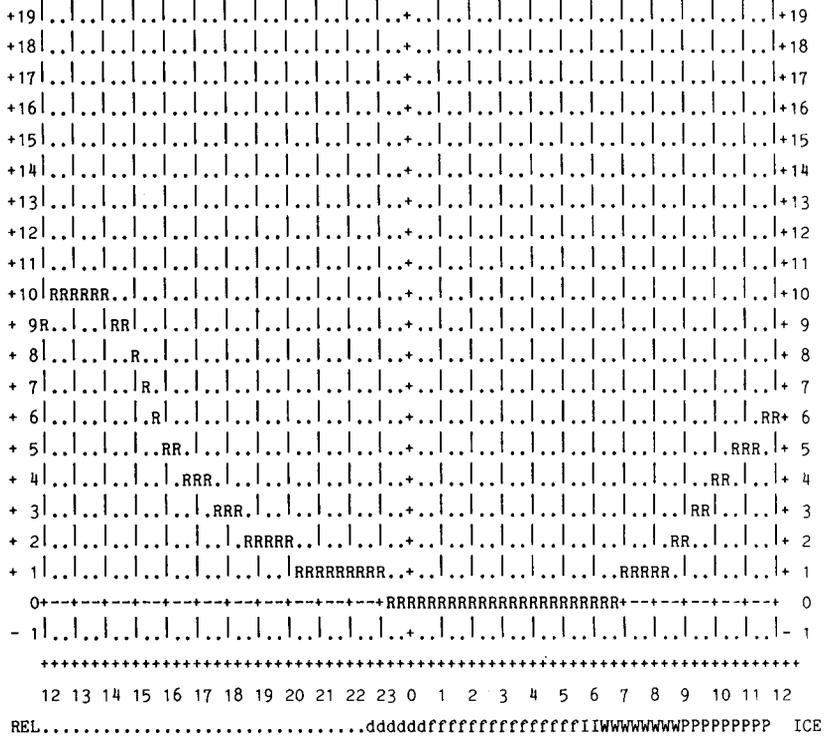
(e) SITE: COXETT WOOD, KENT Date 13/14 JAN 90

Road Surface Temperature: 9.0  
Road Depth Temperature: 6.0

Time (UTC)	1200	1500	1800	2100	2400	0300	0600	0900	1200
Air Temp	6.6	7.0	3.1	2.2	2.2	2.2	2.0	4.2	6.5
Dew Point	4.4	3.8	2.0	1.2	1.2	1.2	1.3	3.5	5.5
Avg Wind Speed	5	5	4	5	5	8	12	13	
Avg L/Cld & C/Amt	11	02	00	01	00	01	34	88	
Avg Cloud Type	1	2	0	2	0	2	1	1	
Avg Rainfall	0	0	0	0	0	0	0	1	

FORECAST GRAPH FOR SITE: COXETT WOOD, KENT

ROAD TEMPERATURE (DEGREES CELSIUS) AND ICE PREDICTION FROM 1200 13/1/90



PERIOD OF FREEZING ROAD TEMPERATURES: 0100-0600  
MINIMUM ROAD TEMPERATURE : -0.3

KEY: ..dry (d)ew hoar (f)rost (P)recipitation (W)et (I)ce

Figure 4. Continued

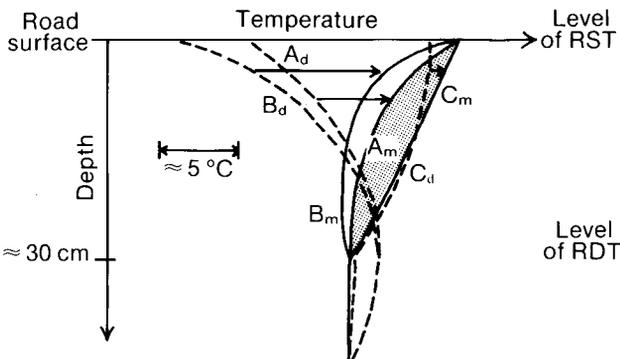


Figure 5. Schematic diagram of three midday subsurface temperature profiles (solid lines  $A_m$ ,  $B_m$  and  $C_m$ ) showing differences which can occur for a given RST/RDT combination. Corresponding dawn profiles are shown as dashed lines ( $A_d$ ,  $B_d$  and  $C_d$ ).  $A_m$  and  $B_m$  typically occur in clear weather. The curvature of the lines is due to the depth versus temperature profiles at dawn,  $A_d$  and  $B_d$ , having minima at the surface which effectively propagated downwards during the morning as sunshine increased the RST. The lower temperature on  $B_m$  reflects a lower RST on  $B_d$ , which in turn reflects a lower dawn air temperature.  $C_m$  typically occurs in cloudy conditions. The straighter line is symptomatic of a smaller diurnal range of RST. The area of shading is proportional to the difference in energy stored below the road surface between  $A_m$  and  $C_m$ .

**Table I.** Comparison of average minimum air temperature ( $^{\circ}\text{C}$ ) at London (Heathrow) Airport ( $T_{\min}$ ) with average sea temperatures in the English Channel ( $T_{\text{sea}}$ )

	$T_{\min}$	$T_{\text{sea}}$	Difference
November	4.5	12.9	-8.4
December	2.5	10.9	-8.4
January	1.4	9.4	-8.0
February	1.5	8.6	-7.1

previous night only. This is why both were included (see also Fig. 5). Factor (7) is included to represent only solar elevation and duration, and not links with  $T_d$  discussed in section 5.3.  $T_d$  is catered for by other factors.

For each case-study in section 5 the number of criteria met was as follows:

(1):4 (2):7 (3):6 (4<sub>ex</sub>):5 (5):7 (4<sub>sh</sub>):3

(‘ex’ and ‘sh’ represent, respectively, the exposed and sheltered sites.)

First impressions from these figures are that higher numbers do indicate an increased risk of hoar-frost deposition.

### 6.1.2 Method 2

This technique is an extension, in graphical form, of equation (2). An allowance is made for some accumulation of hoar-frost over and above that implied by the equation, particularly on ‘calm’ nights, by putting  $U = U + 1$  (kn). This seems justified because traffic causes extra stirring of the air which is unlikely to be reflected by the instruments on which the forecaster bases their estimates of wind speed (a measurement problem also noted in Boselly *et al.* (1990)). The ‘1’ is, admittedly, a somewhat arbitrary figure. It is being assumed that the effect of extra stirring of the air is not being offset by traffic-induced increases in RST; caused by warm exhaust fumes, warm tyres and increased downward long-wave radiation. The assumption that traffic has minimal effect on RST seems to be inherent in all but the most recent RST models (Thornes and Shao 1991a).

The method assumes the forecaster has an RST model output profile to work with. Alternatively it could be used in conjunction with RSTs measured by sensors, to monitor hoar-frost accumulation through the night:

**First plot dew-points onto the RST profile. Then estimate the area between the two lines where RST is less than dew-point (in  $^{\circ}\text{C}$  hours, say). Finally, multiply this value by a number equal to 1 plus the average wind speed in knots. The resulting value is roughly proportional to the accumulated depth of hoar-frost.**

Having performed such a calculation the forecaster can immediately get a feel for the likely error if winds were stronger than forecast, or dew-points higher, thus indicating forecast confidence (although RST is admittedly dependent on these factors).

The cases studied yielded the following values, when calculated up to the time RSTs rose to zero:

(1):50 (2):128 (3):55 (4<sub>ex</sub>):66 (5):165 (4<sub>sh</sub>):3  
units:  $^{\circ}\text{C}$  hour knots

First impressions again suggest that higher values indicate a greater risk of hoar-frost deposition.

There seems to be a very approximate relationship between these values and the depths of hoar-frost calculated by the RST model; the value *is* the depth, in ten-thousandths of a millimetre.

Equation (2) also applies when roads are drying out after rain, indicating that a similar technique could be used to assess ‘drying time’, provided the initial depth of water is known.

This method shows some similarity with the work of Gustavsson and Bogren (1990). They plotted RST and dew-point curves on the same graph and suggested that the area between the two indicated ‘risk of slipperiness’. No mention was made of the importance of wind speed however.

### 6.1.3 Application in different climate regimes

Applying method 2 to one of the examples in Gustavsson and Bogren (1990) (station 20 on 18 January 1986) yields a massive total of 314  $^{\circ}\text{C}$  hour knots, and

**Table II.** Check list of factors which increase the risk of hoar-frost deposition

No.	Description	Definition
1	Clear sky	$\leq 2/8$ cloud cover
2	Small dew-point depression	$\leq 1.5^{\circ}\text{C}$
3	High dew-point	$\geq -1^{\circ}\text{C}$
4	Wind	$\geq 4$ kn at 10 m
5	Cold and clear the preceeding night	Air minimum $\leq 0^{\circ}\text{C}$ and/or $\leq 2/8$ cloud
6	Low RDT	$\leq 4.5^{\circ}\text{C}$
7	Long night	From 21 November to 20 January

A minimum  $T_r \leq 0^{\circ}\text{C}$  is obviously also a necessary condition.

that was during the daytime! This is consistent with our earlier suggestion (section 2) that hoar-frost is more of a problem in Sweden. Method 2 should be equally valid for any climate as it was based purely on physics. However, method 1, which was based partly on south-east England case-studies, and only gives a score of about 5 for the same Swedish case, is not so valid for climates which differ from that of south-east England.

## 6.2 Validation

In both the above methods it seemed that higher scores indicated a higher risk of hoar-frost deposition. This hypothesis is tested out below by applying the methods to new data for the winter of 1990/91. An attempt is also made to define scores which separate cases of icy roads from cases of dry roads. A separate investigation of the factors which make up method 1 is also performed.

### 6.2.1 Verifying data

The winter of 1990/91 differed from most of the case-study winters in that there was a large amount of RST sensor data available. This enabled the whole period from 1 November through to 30 April to be analysed. The area of interest comprised a broad band extending along the Thames valley, from the western edge of Berkshire to central London. In this area during the winter of 1990/91 there were 10 roadside sites at which RSTs and meteorological variables were measured.

The RST data was first scrutinized to find nights when RST fell to 0 °C at at least one site. From such cases were excluded occasions on which it was considered that one or more of the following criteria had been met: (i) any ice that occurred would have been due to water freezing, (ii) snow was lying on road surfaces, (iii) widespread fog occurred. This left 19 cases. Next, these cases were divided into two categories; 'icy' or 'non-icy'. 'Icy' nights were those on which ice had been observed by Meteorological Office employees and/or Berkshire County Council highway maintenance crews. 'Non-icy' were those for which there was no evidence of ice. These definitions yielded 6 'icy' and 13 'non-icy'.

Given that ice may have been missed by our circumstantial observations some other confirmation was required. The only routine observations which are of use here are 'concrete-slab minimum temperature' and 'state of concrete slab' (dry/moist/wet/icy), both measured once a day, at 0900 UTC, at climatological stations in the United Kingdom. Seven stations were close enough to the analysis area to be of use. It has to be assumed that the state of slab observation is representative of the 'worst' conditions which occurred during the night just ended. This is not unreasonable provided no major changes in the weather occurred, which for the vast majority of nights is true.

Regulations state that concrete slabs should be about 5 cm thick and mounted on a layer of sand over bare earth. As such they do behave differently from roads.

For the 19 dates the average difference air minimum minus slab minimum at the climatological sites was +1.8 °C, whereas the average difference air minimum minus road minimum for the roadside sites was only +0.5 °C. Because a necessary condition for hoar-frost deposition is that air temperature is greater than RST (or slab temperature) it therefore follows that slabs are very probably wet or icy more often than are roads. So on occasions when the slabs were dry, roads were probably dry also.

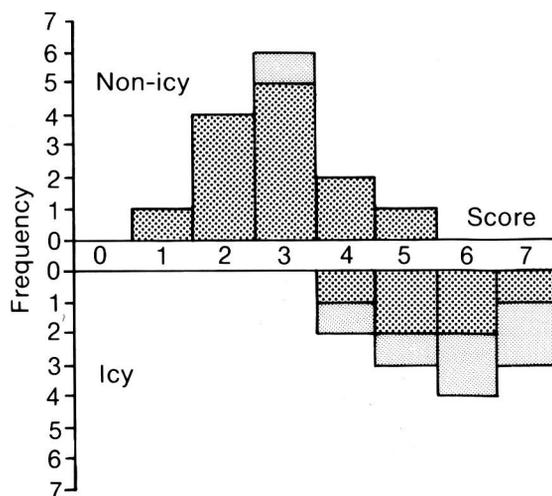
For the 13 'non-icy' cases considered together 85% of all available slab reports indicated 'dry'; and when each case was considered separately there was only one for which less than two thirds of reports indicated dry. This suggests that roads were probably dry (free of ice) on the occasions classified as 'non-icy'. This conclusion is reinforced by the fact that reports for the 6 'icy' cases were markedly different; only 38% indicated 'dry'. Further investigation allayed a suspicion that the one apparently anomalous 'non-icy' case had been incorrectly categorized.

### 6.2.2 Results for method 1

Fig. 6 depicts the scores obtained with method 1. This provides clear evidence that higher scores do indicate a higher risk of hoar-frost deposition. It also suggests that **with a score of 3 or less, hoar-frost deposition will generally not be a problem; but with a score of 5 or more there is a high probability of icy roads.**

Table II shows various statistics relating to the seven factors which make up method 1. These were calculated on a data-set comprising both the 1990/91 cases and those from section 5. The following deductions can be made:

- (a) For the proposed criteria the 'mean score per factor' is consistently greater for the icy cases.
- (b) Mean values generally accord with (a), as would be expected.



**Figure 6.** Histogram showing scores obtained using method 1 for cases in the winter of 1990/91 (dark shading) and cases described in section 5.2 (light shading).

(c) The mean wind-speed is virtually the same in both data sets. This is probably because stronger winds work in one of two ways — to increase the rate of deposition if RST is less than dew-point; or to increase the rate of evaporation if RST is greater than dew-point. Thus strong winds favour hoar-frost deposition *only* when other factors are also conducive to it.

(d) The differences between means are mostly not statistically significant. This is in part due to the relatively small data-set size. Recognizing that each factor is supported by physical argument, and noting (a) to (c) above, it is considered that all seven should be retained.

(e) Clear skies are probably *the* most important factor. This partly accords with a conclusion of Thornes and Shao (1991b) referred to earlier (in section 5.3). Every icy case considered here had a mean of  $\leq 2/8$  low + medium cloud between 1800 and 0600.

(f) There is significantly more variability in values in the non-icy cases. For factors 1, 2 and 7 this is partly because the data is not continuous.

(g) Differences in variability noted in (f) are particularly apparent for wind speed. In the icy cases wind speeds fall predominantly into the range from 4 to 7 kn.

The upper limit in (g) may well exist because stronger surface winds indicate increased mixing in the atmos-

phere's lowest layers, reducing the vertical moisture gradients seen to be so important on the tephigrams in section 5. Such mixing would lead, ultimately, to either the formation of cloud (note the discussion of case-study 1 in section 5.2.1) or a reduction in surface dew-point; both of which mollify hoar-frost deposition. A result in Bogren and Gustavsson (1991) seems to support this argument. This states that to completely destroy cold air pooling in valleys an ambient wind speed greater than 6 kn is required. In turn this suggests that mixing of the atmosphere's lowest layers is 'complete' for winds greater than 6 kn.

Monteith (1957) concluded that the optimal conditions for dewfall from the atmosphere onto short grass were clear skies, high relative humidity and a 2-metre wind of  $1-3 \text{ m s}^{-1}$  ( $\approx 3-9 \text{ kn}$  at 10 m). Although a grass surface is fundamentally different to a road surface, these conditions accord well with the results in Table III, and comments (e) and (g) above.

Quite clearly the factors comprising method 1 are not independent. On many nights the presence of one or two particular ones will preclude others. The skilful forecaster should be able to identify those few occasions when the synoptic set-up *is* conducive to the co-existence of many factors.

### 6.2.3 Results for method 2

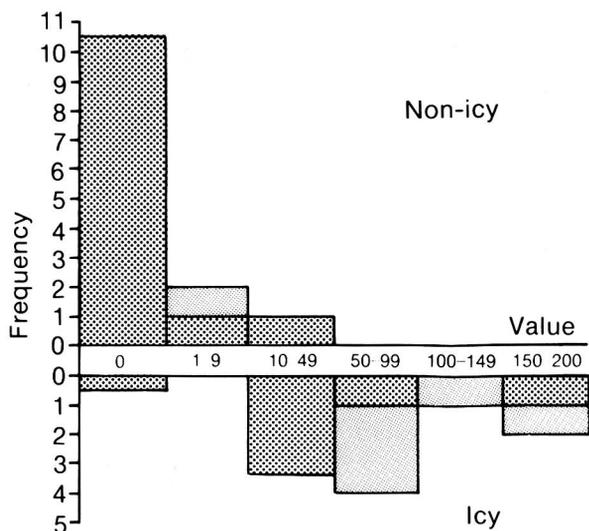
Fig. 7 depicts the scores obtained with method 2. Calculations for this were generally based on *measured* RSTs. For only one case did lack of RST measurements

**Table III.** Statistical data for the factors which make up method 1 based on all cases from the winter of 1990/91 together with those discussed in section 5.2. The symbols \*, \*\* and \*\*\* indicate differences between 'icy' and 'non-icy' cases to be significant at, respectively, the 90%, 95% and 99.5% levels (shown only for value mean and standard deviation).

	1	2	3	Factor 4	5	6	7
Mean score per factor							
Icy	1.00	0.82	0.73	0.91	0.55	0.82	0.82
Non-icy	0.36	0.43	0.21	0.50	0.29	0.50	0.43
Value mean							
Icy	0.6	1.2	-0.5	5.5	0.8	3.6	22
Non-icy	3.3 ***	2.1 *	-2.1 *	5.6	0.5	4.5	37
Value standard-deviation							
Icy	0.6	0.6	1.5	1.4	0.9	1.7	19
Non-icy	2.5 ***	1.7 ***	3.0 **	4.3 ***	0.9	2.9 *	35 *

For each factor, defined in section 6.1.1, the meaning of 'value' is as follows:

1. Mean number of oktas of low + medium cloud, 18-06 h
2. Mean dew-point depression ( $^{\circ}\text{C}$ ), 18-06 h
3. Mean dew-point ( $^{\circ}\text{C}$ ), 18-06 h
4. Mean 10 m wind speed (kn), 18-06 h
5. Number of criteria satisfied on previous night, the criteria being (i) air minimum  $\leq 0^{\circ}\text{C}$  and (ii)  $\leq$  oktas low + medium cloud
6. RDT at the midday just before the night in question.
7. Number of days from winter solstice.



**Figure 7.** Histogram showing scores obtained using method 2. Shading as in Fig. 6.

necessitate a model run. For some cases two scores were evaluated, using data from two sites. In constructing Fig. 7 each such score had a frequency of one half.

Considering non-icy cases, the three scores which fell into the 1 to 9 category were almost negligible, being just 1, 1 and 3. The single score in the next category was 28. Although four out of six 'state of slab' reports for that occasion did indicate 'dry' it is possible that ice was present. Of all sensor sites in the Berkshire area only one reported subzero RSTs, and that was only for 2 hours. The probability of anyone having observed ice there and then must be small.

So it seems there is a fairly sharp division between icy and non-icy cases, around a score of about 10 ( $\approx 0.001$  mm). The fact that this division is close to zero means that the most difficult nights to forecast will generally be those where RST and dew-point are expected to be similar. On such nights the impact of a small dew-point underestimate has to be considered. This impact depends on wind speed. The stronger the wind the greater the impact, and the greater the potential for a forecast of dry roads to go badly wrong.

In compiling data for Fig. 7 another useful result emerged. When separate calculations were performed for two close sites, whose altitude differed by 300 ft, the scores for the higher site were, in general, significantly greater. This was because the site at greater altitude had similar RSTs, but somewhat higher dew-point and air temperatures. In turn this was probably due to it being more exposed. Exposed locations tend to experience higher night-time air temperatures in clear-sky/light-wind situations, due to cold air drainage away from them (for examples see Harrison (1971), Thornes (1989) and Gustavsson (1990)). They also experience lower daytime air temperatures, reducing the daytime heat input to the road, which helps to keep RST similar, at night, to a lower, less exposed site. It seems reasonable to infer that because of the higher scores obtained the

higher site is generally more prone to rapid hoar-frost deposition. This result is similar to that highlighted in case study 4.

### 6.3 Economic implications

Thirteen non-icy cases from the 1990/91 winter were discussed in section 6.2. Berkshire County Council salted roads on eight of these. Each of the eight occasions were carefully analysed to see whether application of the two forecasting methods discussed above, backed up by an appreciation of the physics in section 3, could have changed the forecaster's advice in such a way that salting would not have proceeded. Whilst it is difficult to simulate both the conditions under which the forecaster had to prepare their forecasts, and the data available to them at the time, it does seem that two or three of the eight saltings could very reasonably have been avoided; on 17 December, 4 February and perhaps 22 January. These occasions scored, respectively, 3, 3 and 2 with method 1, and three zeros with method 2. Avoiding such saltings represents a saving for one county of about £25 000 on maintenance alone\*. Were similar figures realized in all parts of the United Kingdom the savings, per winter, would be of the order of £3M†.

## 7. The urban effect

It is well known that air temperatures in cities average higher than in rural areas at the same altitude. The difference is particularly marked overnight. Oke and Hannel (1970) state that in Reading, Berkshire, the 10 m wind speed required to overcome this heat island effect is about 10 kn. Evidence is presented below to show that similar arguments do not always apply to road temperatures.

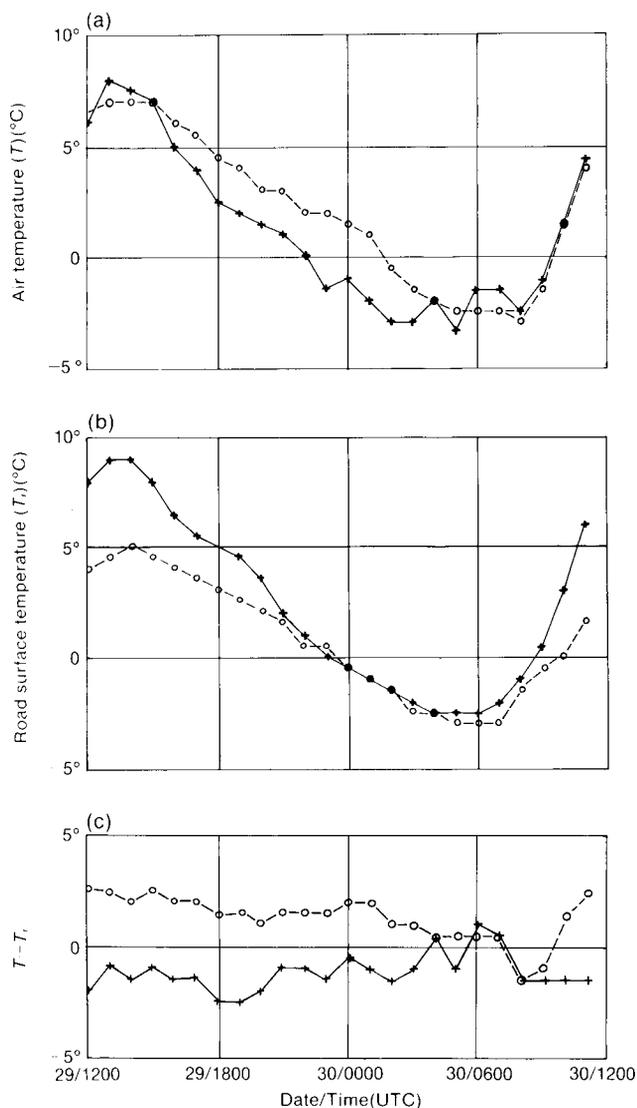
Figs 8(a) and 8(b) show sensor measurements from two road sites in Berkshire for 29–30 November 1989. The Reading sensor is on the very busy A329 about 1 mile west of the city centre, whilst the Shurlock Row sensor is on the fast westbound lane of the M4, 9 miles to the east.

Four of the five mornings prior to the 29th had produced sharp frosts. The 28th had been mostly cloudy, but the cloud cleared overnight, giving a slight frost on the morning of the 29th. Skies remained clear through the period shown. RDTs were about 5 °C at both sites on the 29th.

Fig. 8(a) shows the heat-island effect to be present for most of the period, consistent with observed wind speeds averaging about 3 kn. In spite of this RSTs at Reading are lower than at Shurlock Row for most of the time, the difference being particularly marked during daylight (Fig. 8(b)). The explanation lies in the exposure

\* Source: Berkshire County Council. Total winter maintenance costs for Berkshire are about £900,000 for an average winter.

† Derived using data given in the footnotes on page 1 and above.



**Figure 8.** Temperature profiles for two roadside sites in Berkshire; Shurlock Row (non-urban) (continuous line) and Reading (urban) (dashed line). (a) Air temperature, (b) road temperature, and (c) (air-road) temperature difference.

of the two road sensors. Shurlock Row is in open countryside, with little vegetation to block solar radiation. At Reading the sensor is shaded by a row of two-storey buildings to the south, and so receives little or no direct sunshine during winter. It is ironic that buildings which are generally responsible for higher air temperatures in towns can at the same time cause, locally, lower RSTs. The implications of this are well illustrated in Fig. 8(c). Reference to equation (2) indicates that given suitable dew-points hoar-frost/dew could continue accumulating at Reading for almost all the period, but at Shurlock Row for a maximum of only 3 hours.

At 3 p.m. on the 30th side roads in a village about 20 miles south-east of Reading were observed still to be white with hoar-frost. So RSTs there had been subzero all day. Therefore the difference in RST maxima between this site and Shurlock Row must have been at

least 9°C (assuming the RST minimum at Shurlock Row was similar to the previous day). This may have been due, in part, to lower air temperatures. However, it is reasonable to expect the RSTs of such suburban roads to at least be comparable with those of the Reading road, because of similar shading by buildings, and in fact ultimately lower because of a much smaller traffic volume.

Bogren (1991) deduced that in clear weather the difference (°C) between daytime maximum RSTs at an open site ( $T_{rmax(open)}$ ) and a site shaded from direct sunlight from sunrise ( $T_{rmax(shaded)}$ ), is given by the equation

$$T_{rmax(open)} - T_{rmax(shaded)} = 0.47 B_{max} - 1.5 \quad (3)$$

where  $B_{max}$  is the maximum solar elevation in degrees (the correlation coefficient of the regression was 0.94). For Reading on 29 November  $B_{max}$  is about 16°, giving a difference of +6°C. This can be compared with +9°C, referred to above. The slight discrepancy may have arisen as a result of the weather of previous days. Bogren shows, in addition, how RST differences also depend on 'recent' weather; during prolonged periods of clear skies there is a gradual increase, whereas the arrival of cloud causes a marked decrease.

Thus in prolonged spells of clear weather with very light winds it is probable that suburban roads are most susceptible to hoar-frost, urban roads are slightly less susceptible, and roads in flat, open countryside are least susceptible of all. A logical extension of the above arguments suggests that road stretches shaded by other objects, such as dense woodland or north facing hillsides, are probably as susceptible to hoar-frost as the suburban roads.

The magnitude of incident solar radiation (per unit area) depends strongly on solar elevation. Therefore to realize large RST differences, and hence local variations in hoar-frost deposition, it is most important that the road be shaded around the solar noon. Shading just after sunrise or just before sunset is relatively unimportant.

It is only when a period of clear weather with light winds is *prolonged* that tangible differences in road conditions between sites are likely to arise. Because of the light winds more than one night is probably needed for hoar-frost and dew to build up to dangerous levels. And similarly the RST differences increase in magnitude gradually, over a period of days.

At present the Meteorological Office RST model is unable to cope with the shading effect of obstacles — it assumes roads to be on a flat horizontal plane. This is appropriate for the Shurlock Row site, but not the Reading one. Thus under certain atmospheric conditions and at certain shaded sites the model will overestimate RSTs and underestimate hoar-frost deposition. Fig. 8 and equation (3) indicate that the discrepancies can be highly significant, a fact that the

forecaster must take account of\*. One quick (albeit imperfect) way to tackle this problem would be by generating a second RST profile appropriate to the shaded sites, by rerunning the model using a lower midday RST, this RST having been calculated using equation (3). As the model still includes solar insolation in the afternoon the profile may well not be cold enough. Nevertheless it could still provide useful guidance.

It is encouraging that a more recent RST model, the 'Icebreak' model, includes a 'sky view factor' (Thornes and Shao 1991a). This should reduce errors due to shading.

Not all shaded sites will have characteristics like those outlined above, because obstacles do also provide a negative feedback — both by reflecting back some of the road's outgoing long-wave radiation, and emitting towards the road surface some of their own. The example discussed was specifically selected to be one where this feedback was not apparent. The '-1.5' in equation (3) very probably reflects this negative feedback; in polar night conditions the shaded sites would probably be warmer.

In case 2 in section 5 the RST model appeared to underestimate the depth of hoar-frost. Bearing in mind that the model was being used for suburban roads, and that there had just been 60 hours of clear, cold weather, it is probable that many of the factors discussed in this section contributed to that underestimate. They may have also caused errors in the other cases.

## 8. Conclusions

A number of occasions when roads in south-east England became icy in the absence of precipitation have been carefully examined. By combining these case studies with physical reasoning, and testing out ideas on data from the 1990/91 winter, it was shown that the meteorological phenomena most conducive to rapid hoar-frost deposition are these: clear skies, a shallow layer of moist air in contact with the surface, high water vapour content in that layer, a gentle breeze (approximately 4 to 7 kn) and recent cold, clear weather. Short day-length is an important astronomical factor. RSTs must of course fall to 0 °C or below. Wind direction is also significant, because of a non-uniform distribution of moisture sources (seas) and sinks (land, especially at altitude) around south-east England.

Seas provide most moisture when sea surface temperatures are highest, i.e. early in the winter rather than later. This, together with the required low solar elevation, make December the most likely month for hoar-frost deposition to occur.

Evidence and physical argument suggest that the time of onset of any hoar-frost deposition will be earlier if the previous night was cold and clear.

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\* At the time of writing another problem the forecaster must take account of is that when the RST model is run it always begins with a dry road surface. Quite clearly the correct depth of ice/water will not be represented on the model output if it took more than one day for that depth to build up.

The rate of hoar-frost deposition was shown to be roughly proportional to both wind speed and depression of RST below dew-point.

Large local variations in hoar-frost deposition have been noted. The nature of these variations appears to depend on the current weather type. This is probably because the current weather type dictates which physical and meteorological factors are most important (as Gustavsson and Bogren (1990) found).

In spells of cold, clear, settled weather with very light winds the shading of a road surface appeared especially important. Hoar-frost deposition is favoured where the position and extent of this shading are such that there is both an obstruction of incoming short-wave (solar) radiation and a maintenance of relatively large net outgoing long-wave radiation. In theory these criteria are best satisfied by roads in open countryside on north facing hills. However, an example showed how roads bordered by buildings were susceptible too — particularly in suburban areas but notably also in a city centre.

In more mobile weather types, where there is only one night in which dangerous levels of hoar-frost can arise, the emphasis shifts towards other factors — notably wind speed. This puts exposed locations at greatest risk. In one example where the measured RST minima of two roads were -1 °C and -3 °C, it was shown that the warmer of the two probably became most icy, due to it being the most exposed. The 'best' situation for rapid hoar-frost deposition in south-east England appears to be in a developing southerly after the passage of a cold ridge.

During clear weather the UK Meteorological Office RST model tends to give poor guidance for areas where obstacles block out the sun, i.e. RSTs are too high and the road surface can be misleadingly dry. This is because sites are assumed to be on a flat plane. The model should perform much better in open countryside.

In the more mobile weather types the model seems to give reasonable predictions of hoar-frost accumulation, provided it is fed with accurate meteorological data. However, the forecaster must remember that it is site specific and that, on occasions, large differences can arise between exposed and sheltered sites.

There is some evidence to suggest that the minimum depth of hoar-frost likely to cause problems to the motorist is of the order of thousandths of a millimetre. Moore (1975) highlights many difficulties associated with ice-friction experiments, suggesting that a more accurate value may prove elusive.

Two hoar-frost forecasting tools have been proposed. One is valid worldwide; the other will work best in areas whose climate is similar to that of south-east England. They relate specifically to one-night events, but may also be used in settled weather provided an allowance is made for day-to-day accumulation of moisture. As well as supplementing guidance from the RST model these techniques can give insight into the physical processes at work, and also some idea of the appropriate confidence

level to attach to a forecast. Hindcasts for the 1990/91 winter suggested that application of the techniques by forecasters might yield an annual saving on UK winter maintenance bills of the order of £3M.

Many questions raised in this paper warrant further research. One of the most important is the following. In what way does traffic modify wind speed close to a road surface, what are the simultaneous changes in RST, and how do moisture fluxes alter as a result?

## Acknowledgements

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# Analyses and forecasts of fluctuations in the angular momentum of the atmosphere and changes in the Earth's rotation

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## Summary

*Fluctuations in all three components of the total atmospheric angular momentum (AAM) are evident from global meteorological data sets. The fluctuations are generated by dynamical interactions between the atmosphere and the underlying continental and oceanic regions of the surface of the planet, and they are intimately linked with baroclinic and barotropic energy conversion processes throughout the whole atmosphere. The correct representation of AAM fluctuations would constitute a most stringent test of the performance of a global numerical prediction model and the data sets used in its initialization. Research in this area exploits the facts that (a) the AAM fluctuations are accompanied by tiny but measurable irregular fluctuations in both the magnitude and direction of the Earth's rotation vector (so as to conserve angular momentum of the whole system), and (b), thanks to the introduction of a variety of new techniques, geodesists have achieved impressive refinements in their monitoring of Earth rotation fluctuations.*

## 1. Atmospheric angular momentum fluctuations

The atmosphere super-rotates relative to the underlying planet at about  $10 \text{ m s}^{-1}$  on average. If transferred to the underlying planet, the angular momentum associated with this super-rotation would reduce the length of the day (LOD) by about 4 milliseconds (ms). Geodetic observations going back several decades reveal more or less irregular LOD fluctuations of up to about 1 ms on sub-seasonal, seasonal and interannual time-scales (Fig. 1), and detailed studies using modern meteorological and geodetic data have established that these fluctuations are largely of meteorological origin (Figs 2 and 3). Fluctuations in the equatorial components of atmospheric angular momentum (AAM) make a substantial contribution to the observed wobble of the rotation axis of the solid Earth with respect to geographical coordinates (Fig. 4).

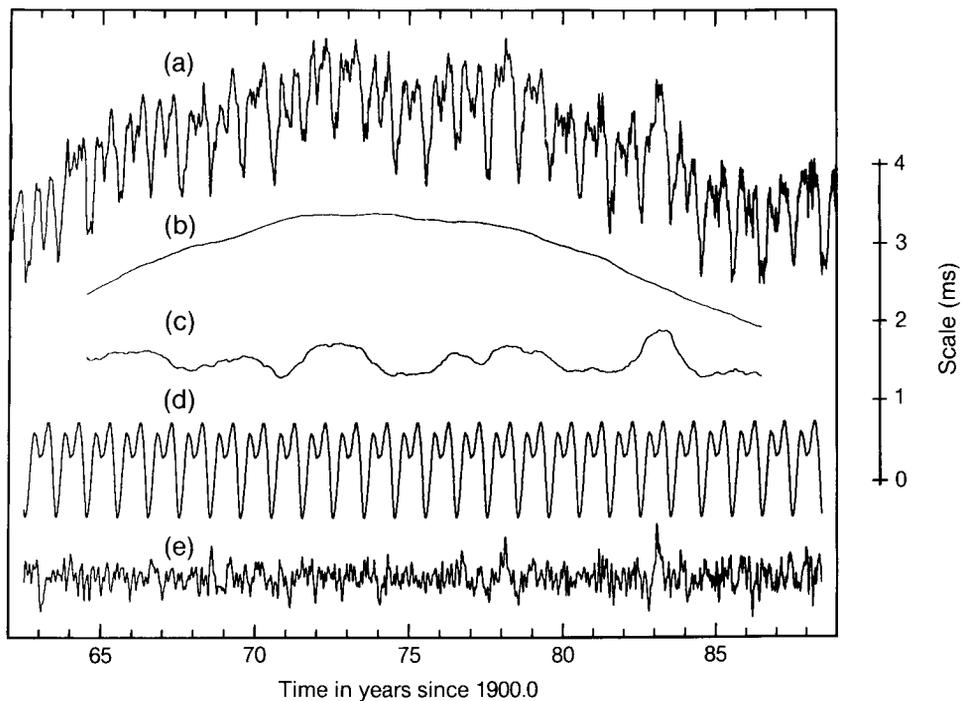
## 2. Surface torques

The torques at the surface of the Earth (Fig. 5) that are implied by meteorologically induced fluctuations in the Earth's rotation are produced by (a) tangential stresses in turbulent boundary layers, and (b) normal (pressure) stresses acting on irregular topography and other departures from the spherical shape of the Earth (including the equatorial bulge). These stresses are transmitted directly to the solid Earth over continental regions and indirectly over the oceans. The investigation

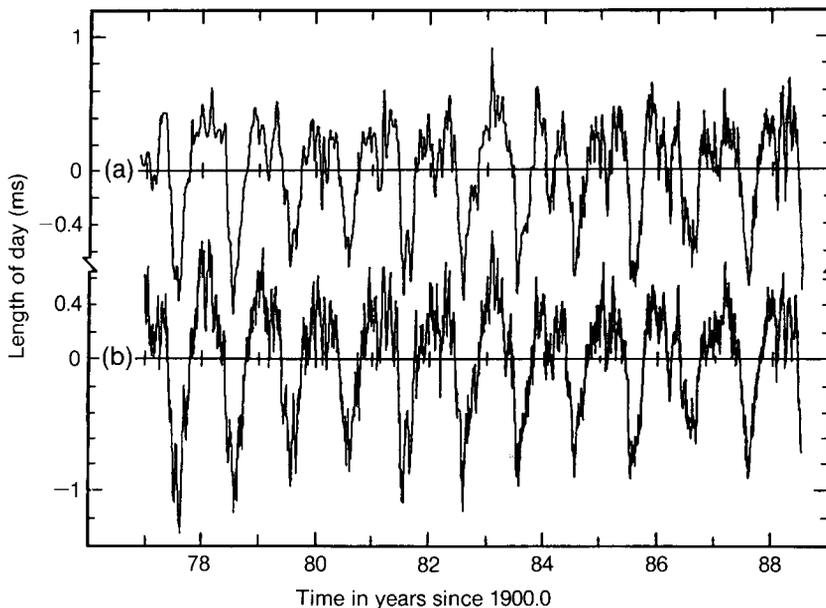
of the extent to which the stresses are represented satisfactorily in general circulation models of the atmosphere (and oceans) should be given high priority in any diagnostic schemes for assessing how well the models perform. Quite elementary reasoning shows that large errors in the treatment of energetic processes can be expected from models that fail to represent atmospheric angular momentum fluctuations satisfactorily.

## 3. Routine AAM determinations

Thanks to the First GARP Global Experiment (FGGE) of the Global Atmospheric Research Programme (GARP), in 1979 it was possible for the first time to obtain useful daily determinations of the total angular momentum of the atmosphere for comparison with geodetic data on the Earth's rotation. Manifold subsequent developments following this work done at the United Kingdom Meteorological Office (UKMO) include arrangements for producing and disseminating routine daily or twice-daily determinations of all three components of AAM. These are now made from analysis (and in some cases also from forecast) fields by several meteorological centres, namely the European Centre for Medium-range Weather Forecasts (ECMWF), the Japanese Meteorological Agency (JMA), UKMO and the United States National Meteorological Center



**Figure 1.** Irregular length of day fluctuations; (a) total, and on (b) decadal, (c) interannual, (d) seasonal and (e) intraseasonal time-scales (see Fig. 2 of Hide and Dickey (1991)).



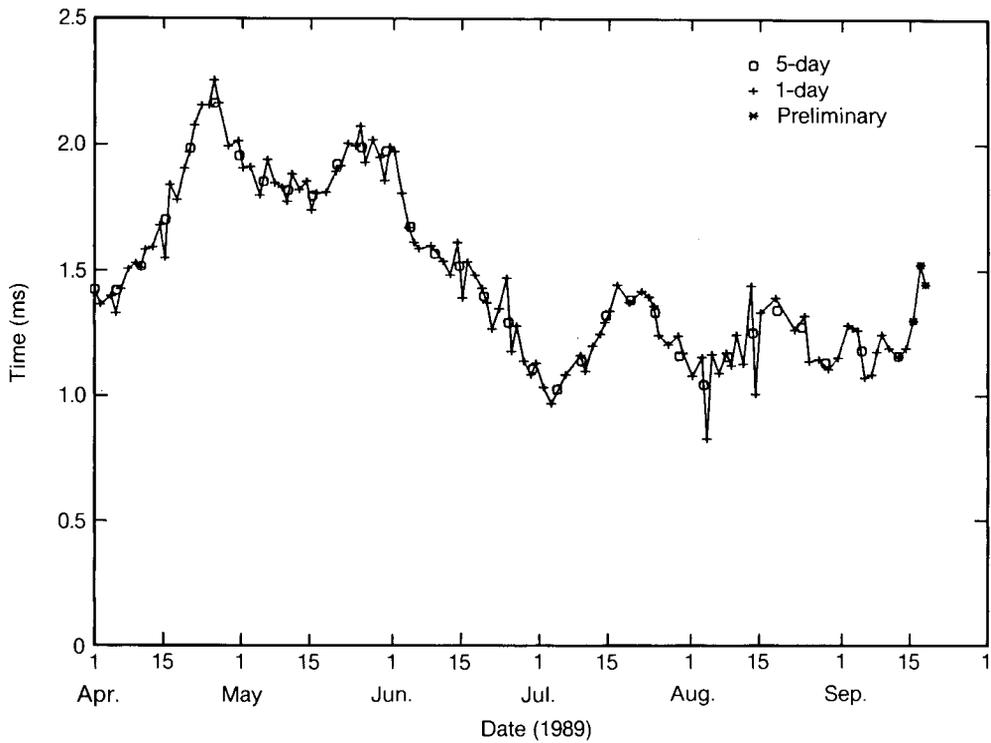
**Figure 2.** Irregular length of day fluctuations (a) measured by space geodetic techniques and (b) inferred from atmospheric angular momentum (see Fig. 7 of Hide and Dickey (1991)).

(USNMC). Plans have recently been initiated for producing routine determinations of torques from surface stresses, to supplement the AAM data and facilitate diagnostic studies bearing on their interpretation.

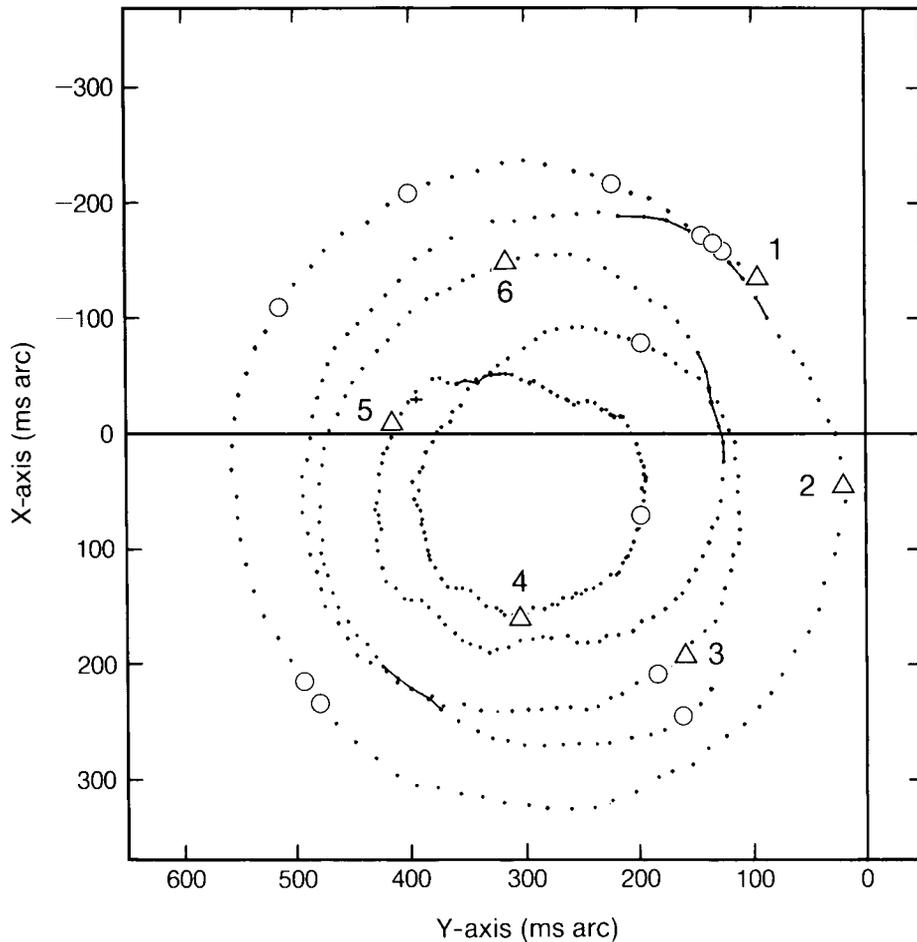
#### 4. Earth rotation fluctuations; predictions of 'Universal Time'

Earth rotation determinations have greatly improved with the intensification of routine observations using Very Long Baseline Interferometry (VLBI) (see Fig. 4),

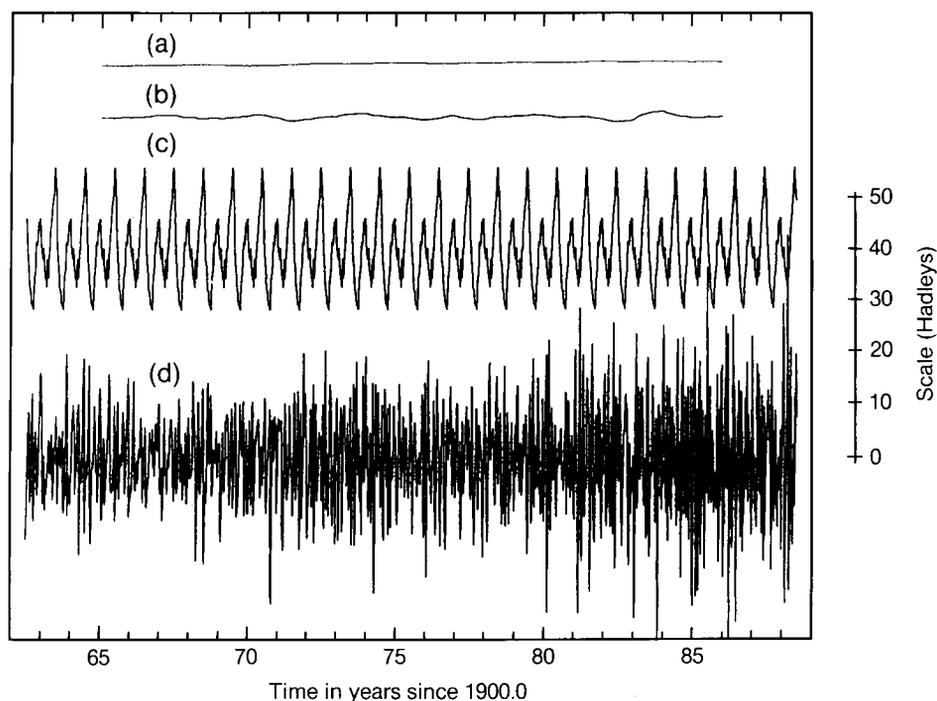
Satellite Laser Ranging (SLR), and Lunar Laser Ranging (LLR). The International Earth Rotation Service (IERS) (based in Paris) of the International Astronomical Union (IAU) and International Union of Geodesy and Geophysics (IUGG) coordinates VLBI, SLR and LLR observations. The subcommission International Radio Interferometric Surveying (IRIS) of the International Association of Geodesy (IAG) of the IUGG and the joint commission on International Coordination of Space Techniques for Geodesy and Geophysics (CSTG) of the Committee on Space



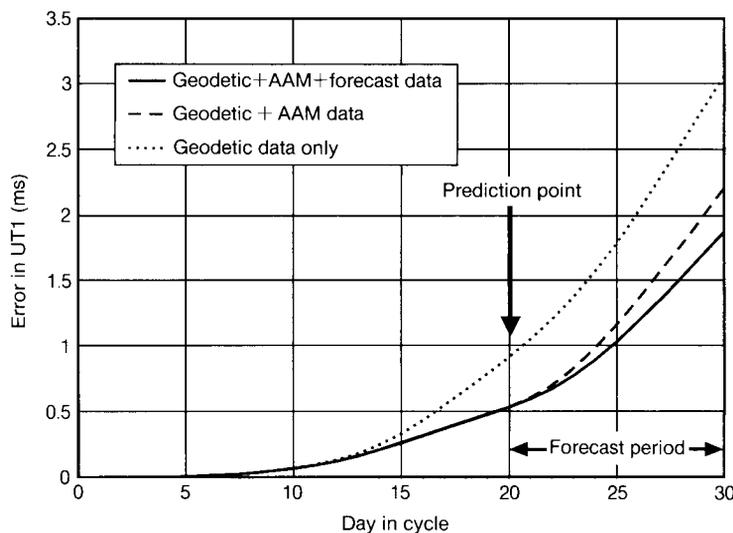
**Figure 3.** Excess length of day over a 6-month period as determined by very long baseline interferometry (from an IRIS Earth Orientation Bulletin (see section 4)).



**Figure 4.** Variations in pole position at 5-day intervals from January 1984 to September 1989 with markers at (1) 3 January 1984, (2) 4 January 1985, (3) 4 January 1986, (4) 4 January 1987, (5) 4 January 1988 and (6) 3 January 1989 as determined by very long baseline interferometry (from an IRIS Earth Orientation Bulletin (see section 4)).



**Figure 5.** Fluctuations about zero of components of equivalent axial torque on (a) decadal, (b) interannual, (c) seasonal and (d) intraseasonal time-scales (see Fig. 4 of Hide and Dickey (1991)).



**Figure 6.** Root-mean-square errors in Universal Time (UT1) for three forecast series using 45 cycles of 30 days each from 1987.0 to 1990.7. These results indicate how forecasts of Universal Time can be improved by including atmospheric angular momentum analyses and forecasts from global numerical prediction models.

Research (COSPAR) publishes a monthly Earth Orientation Bulletin giving recent determinations of the length of the day and pole positions based largely on VLBI observations (see Figs 3 and 4). Liaison between the IERS and the various meteorological centres (ECMWF, JMA, UKMO, USNMC) producing routine AAM determinations is effected by the IERS Sub-Bureau for AAM based at the USNMC in Washington DC. It is noteworthy that AAM analyses and forecasts produced by meteorologists are now being used routinely to improve predictions of the Earth's rotation angle, that is 'Universal Time' (Fig. 6), which have various applications in astronomy and geodesy including

the improvement of navigation schemes for current spacecraft missions, such as *Magellan* to the planet Venus and *Galileo* to the planet Jupiter.

### 5. Concluding remarks

In addition to its direct influence on research in meteorology and oceanography, recent work on AAM fluctuations is enabling geophysicists to refine their determinations of Earth rotation fluctuations produced by non-meteorological agencies, such as motions in the Earth's liquid core where the main geomagnetic field originates. Core motions evidently contribute little on sub-seasonal, seasonal and decadal time scales, but their

effects are dominant on decadal time-scales, where irregular LOD changes of up to 5 ms are found. 'Spin-orbit' coupling in the Earth-Moon system increases the LOD steadily at about 1.4 ms per century and (to conserve total angular momentum) expands the mean radius of the Moon's orbit at about 4 cm per year. This coupling arises largely through tidal friction in the oceans, which produces a lag in the orientation of the tidal bulge relative to the line joining the centres of mass of the Earth and Moon, thereby enabling gravitational forces to exert a net torque. In the detailed interpretation of trends in the LOD observational record over the past century or so, allowance has to be made for contributions produced by a variety of processes, such as the moment of inertia changes associated with the melting of ice and any long-term variations that might have occurred in the distribution and strength of zonal winds, including any that might have been produced by increasing CO<sub>2</sub> content of the atmosphere.

The discussion of key dynamical processes in virtually all branches of the geophysical science is central to the task of interpreting fluctuations in the Earth's rotation, and herein lies the fascination of the subject. Meteorology is both contributing to and gaining from the findings of research in this area.

### Bibliography

Extensive lists of references to the literature can be found in two recent articles 'Atmospheric angular momentum forecasts and analyses as novel tests of global numerical weather prediction models (M.J. Bell, R. Hide and G. Sakellarides, *Philos Trans R Soc London*, **A334**, 55-92, 1991) and 'Earth's variable rotation' (R. Hide and J.O. Dickey, *Science*, **253**, 629-637, 1991).

### Contributions for 'Picture of the Month'

Topical satellite and/or radar pictures have been a regular back-page feature in the *Meteorological Magazine* for over 5 years. During this time, most articles have been prepared by Mike Bader's image-interpretation group. Now, however, an imminent reorganization of work within S-Division means that 'Picture of the Month' will no longer be coordinated by this group.

To remain a regular feature, articles are required from other contributors. It needn't take long to write — one page would suffice (including large picture!) and authors do receive a free copy of the magazine!

If anyone using images operationally or in research has any good examples and would like to contribute, please contact:

Meteorological Office,  
Publications, Room 709,  
London Road,  
Bracknell,  
Berkshire RG12 2SZ  
Tel. 0344 856094

for further details.

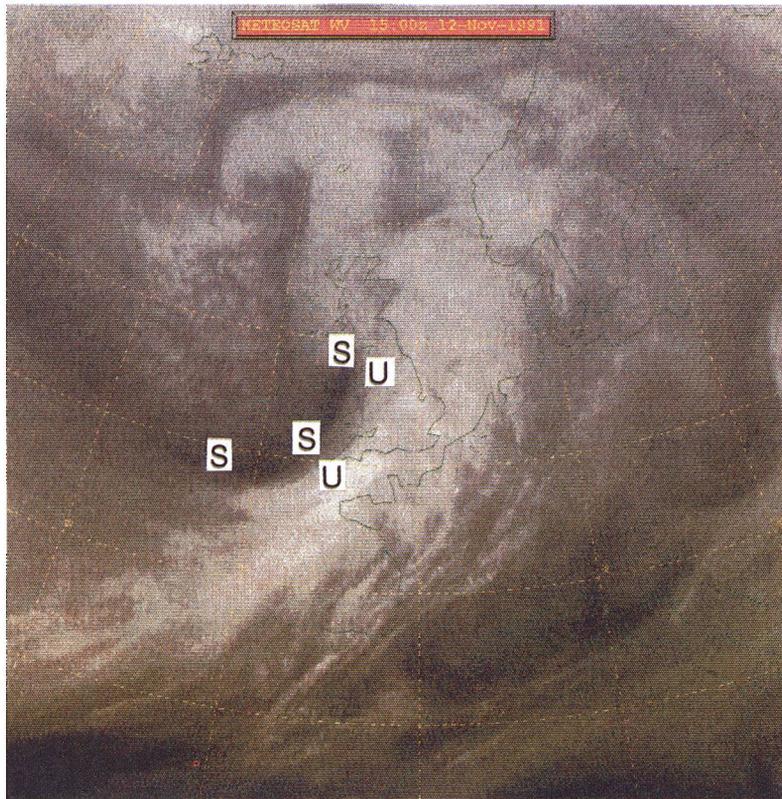
## Satellite and radar images — 12 November 1991

During the morning of 12 November 1991, a depression formed on a cold front stretching south from a primary low located to the north-west of Scotland; the secondary depression deepened during the day and moved north-east into central Scotland. The Meteosat water vapour image in Fig. 1 shows the system at 1500 UTC, during its rapidly deepening phase; a dry slot S-S-S separated the edge of the high cloud on the cold front from the cold and showery air mass behind. Comparing the image with the corresponding surface analysis (Fig. 2) reveals that the northern tip of the dry slot almost coincided with the centre of the depression; the most rapid falls in

pressure were just ahead of this point. The surface front was just forward of the driest air, but the image also shows a band of much moister air ahead marking an upper frontal zone (labelled U-U).

As the frontal system moved across Wales into England during the afternoon it became very vigorous. The network composite radar image for 1500 UTC (Fig. 3) shows a wide band of rain associated with the upper front, and a squall line, with heavy thundery rain, on the surface front (labelled F-F).

The system moved eastwards at about 40 kn, and shortly before 1900 UTC a section of the squall line,



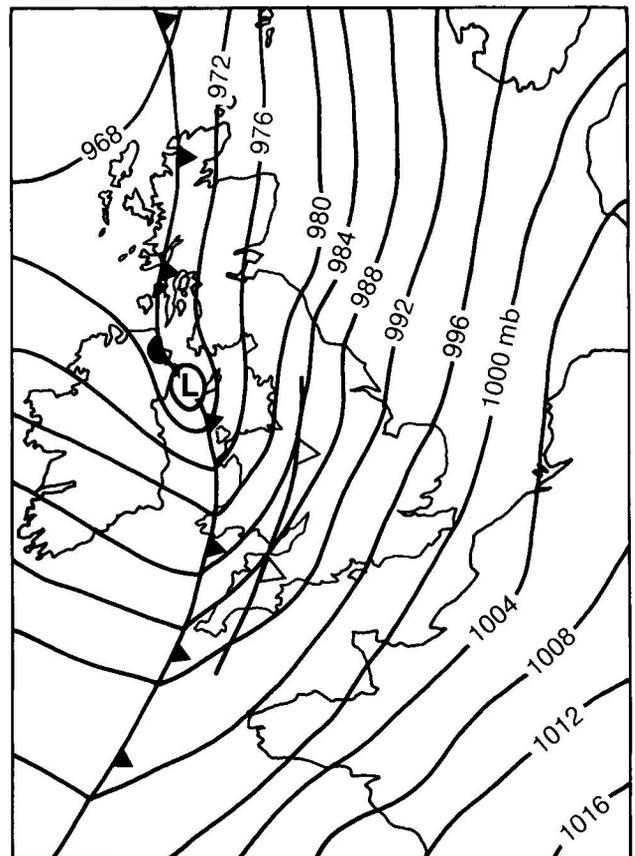
**Figure 1.** Meteosat water vapour image for 1500 UTC on 12 November 1991. S-S is the dry slot, U-U is the upper front. Black indicates dry air, and lighter shades of grey indicate increasing mid-level moisture.

approximately between The Wash and the Isle of Wight, intensified to give cells of very heavy rain and high winds. By 1930 UTC it was lying across East Anglia, and the radar image (Fig. 4) showed rainfall rates of over  $32 \text{ mm h}^{-1}$  in many places.

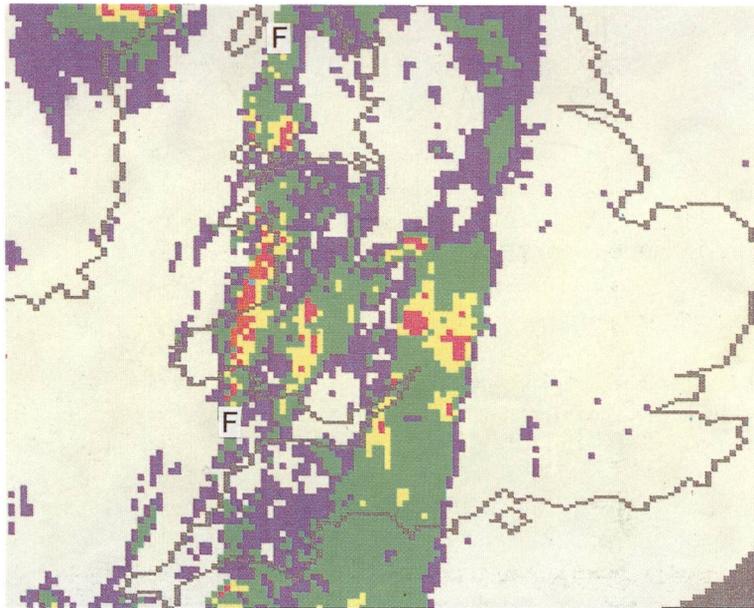
Just after 1930 UTC a tornado, which had formed on the squall line, approached the village of Dullingham in Cambridgeshire (D on Fig. 4). It moved north-east through the village, leaving a narrow trail of damage nearly a kilometre long; one house had its roof lifted off, two others lost substantial parts of their roofs, and a 200-year-old malt barn was demolished. Numerous trees were brought down, while others lost bark and branches, large branches being carried up to 200 m by the wind. The extent of the damage indicates that the tornado would be classed as T4 or T5 (strong or intense) on the international tornado intensity scale. According to this scale, the wind speed in the tornado must have been in the range 100–140 kn; the highest gusts measured on the squall line at official observing stations in East Anglia were 52 kn. Fig. 5 is a photograph taken the following day showing some of the tornado damage.

The squall line continued to move east through the evening, bringing torrential rain and high winds to most of East Anglia, but no further tornadoes were reported. By 2100 UTC it had reached the North Sea, where it eventually dissipated as the system drifted north-east overnight.

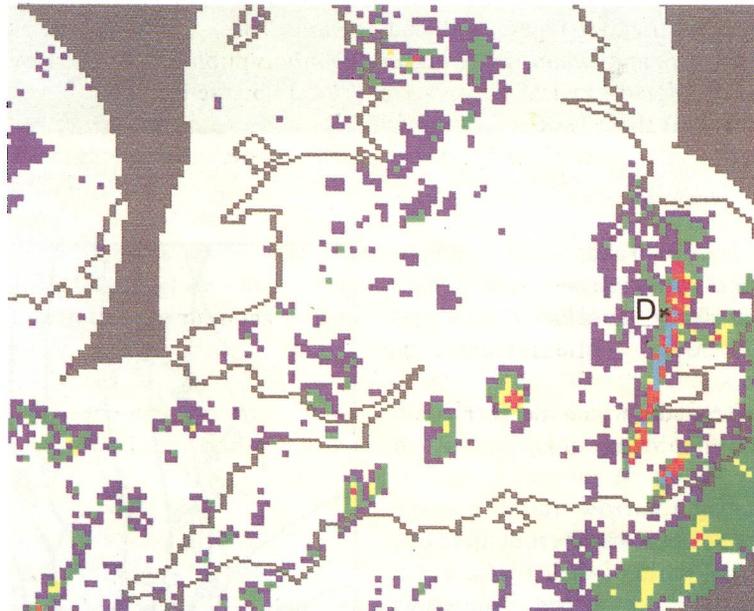
R.B.E. Lilley



**Figure 2.** Surface analysis for 1500 UTC on 12 November 1991. Closed symbols indicate surface fronts, open triangles the upper frontal zone.



**Figure 3.** Network composite radar image for 1500 UTC on 12 November 1991. Rainfall rates ( $\text{mm h}^{-1}$ ) shown are: purple 0.1-1, green 1-4, yellow 4-8, pink 8-16, red 16-32, and blue 32-64. F-F is the squall line on the surface cold front.



**Figure 4.** Network composite radar image for 1930 UTC on 12 November 1991. Rainfall rates as Fig. 3. D is the location of Dullingham.



**Figure 5.** Photograph showing some of the tornado damage, taken on 13 November 1991. (Courtesy of W.S. Pike)

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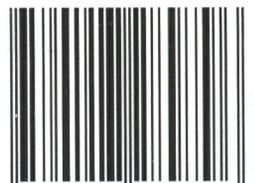
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