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WEATHER FORECASTING

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PREFACE

The Handbook of Weather Forecasting was written mainly for distribution within the Meteorological Office to provide forecasters with a comprehensive and up-to-date reference book on techniques of forecasting and closely related aspects of meteorology. The work, which appeared originally as twenty separate chapters, is now re-issued in three volumes in loose-leaf form to facilitate revision.

Certain amendments of an essential nature have been incorporated in this edition but, in some chapters, temperature values still appear in degrees Fahrenheit. These will be changed to degrees Celsius when the chapters concerned are completely revised.

CHAPTER 17

VISIBILITY

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CHAPTER 17

VISIBILITY

17.1 INTRODUCTION

Visibility is of considerable importance to the community in general. When visibility is greatly restricted, transportation is hindered and slowed down and sometimes is severely disrupted. The extent to which transportation is disorganized or even halted by a reduction in visibility depends not only on the visibility but also to a great extent on the type of transportation and the extent to which automatic controls have supplanted control by humans who need to see and recognize some distant object in order to control the vehicle. For jet aircraft with high landing speeds and limited endurance, accurate and up-to-date information on actual and forecast visibilities is vital for their safe and efficient operation. A limited visibility which might be very hazardous for the landing of jet aircraft would probably be of little consequence to the slower forms of surface transport. For some military operations excellent visibility to enable a direct visual identification of the target may be almost a pre-requisite for success. On the other hand, a reduced visibility which enables a minor redeployment of forces and material to be carried out unobserved by an enemy may contribute markedly to the success of a tactical operation. Visibility also affects the individual. For example, the scenic beauty of landscapes, panoramas and vistas can be much enhanced by a brilliantly clear atmosphere. At the other extreme, there can be few who have not suffered danger and discomfort when walking at night in a particularly thick fog.

Thus visibility is important to all, and people want to know at what range they will be able to see specified objects at given places and times. This range depends on a number of factors which include the nature of the object and its background, the size of the object, the illumination, the characteristics of the observer's eye and the state of the atmosphere. It turns out that, in general, the state of the atmosphere is much the most important of these factors and, as a rough approximation, differences between observers and objects do not lead to great differences in range. Because of this there has developed the concept of an atmospheric property called "visibility" regarded as the range at which normal people see normal objects. However, when matters are examined more closely, it is found that the distance at which an object can be seen does depend to some extent – sometimes to a considerable extent – on the object, the background, the lighting, the observer, etc. Faced with this difficulty but wishing to retain "visibility" because it is often a very useful practical approximation we fall back on a customary scientific device of specifying "ideal" or "standard" observers, objects, lighting conditions, etc. and so arrive at a definition of meteorological visibility. In the United Kingdom the meteorological visibility is defined as the greatest horizontal distance at which an object of specified characteristics can be seen and identified by an observer with normal sight under normal conditions of daylight illumination. The visibility at night is expressed in terms of the equivalent day-time visibility. In this chapter the word visibility is used generally to denote meteorological visibility but, where any uncertainty seems likely to arise, the full term meteorological visibility is used.

The term visual range will be used to denote the greatest distance at which a particular object is visible to a particular observer in particular lighting conditions. At some civil aerodromes observations of the greatest horizontal distance at which runway markers by day and runway lights by night can be seen are made

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by Control Officers. This distance is known as the runway visual range and it should be noted that this usually exceeds the (meteorological) visibility, particularly at night. Reports of runway visual range are available on a restricted distribution to some meteorological offices.

Mention is made here of the term "meteorological optical range" adopted by the World Meteorological Organization^{1*} as a new objective visibility parameter defined as follows:

"The meteorological optical range is the length of path in the atmosphere required to reduce the luminous flux in a collimated beam from an incandescent lamp at a colour temperature of 2,700°K to 0.05 of its original value, the luminous flux being evaluated by means of the C.I.E. [International Commission of Illumination] photopic luminosity function."

The adjective "photopic" refers to the state of the eye when adapted to light at a level of luminance typical of ordinary background during day-time. (For detailed and precise interpretation of some of the terms used in the definition the reader should refer to the World Meteorological Organization publication.¹)

The meteorological optical range (M.O.R.) is roughly equivalent to the day-light visibility with which meteorologists are familiar. It should be noted that in May 1960 the use of M.O.R. had not been introduced in the United Kingdom.

It is important that forecasters should be quite clear that the numerical values assigned to visibility in forecasts refer to meteorological visibilities.

17.2 THEORETICAL OUTLINE

Parts of the following brief outline are similar to that included in the *Handbook of meteorological instruments*, Part I, Chapter 9.²

17.2.1 Effect of the atmosphere on the transmission of light

When a beam of light passes through the atmosphere it is diminished in intensity by:

- (i) Scattering by molecules of the air, nuclei, solid particles and droplets in suspension.
- (ii) Absorption, which is only appreciable in the case of solid particles.

The total diminution, ΔE , in the flux density,³ E , of a parallel beam of light in passing through a distance Δx of the atmosphere is proportional both to E and Δx , that is

$$\Delta E = -\sigma E \Delta x, \quad \dots \quad (1)$$

where σ is the extinction coefficient which varies in a complicated way with the wavelength of the light and the composition of the atmosphere and is the factor which largely determines the visibility. If σ is constant over the whole path of the light, equation (1) can be integrated to give

$$E = E_0 \exp.(-\sigma x). \quad \dots \quad (2)$$

* The superscript figures refer to the bibliography at the end of this chapter.

³ The strict definitions of the terms flux density, luminous intensity and brightness are given by Middleton.³

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σ can be considered as being made up of two parts, σ_s and σ_a , σ_s being that part of σ which is due to scattering and σ_a being that part which is due to absorption. When σ_a is very small (as in air free from smoke particles) $\sigma \approx \sigma_s$.

If, instead of a parallel beam, a point source of luminous intensity[/] I_0 candle-power is considered, it is necessary to take into account the diminution due to the inverse square law and equation (2) becomes

$$E = \frac{I_0}{x^2} \exp(-\sigma x). \quad \dots (3)$$

17.2.2 Visual range of natural objects during daylight

Consider a uniform object of apparent brightness[/] at the eye, B , surrounded by a background of the same colour and apparent brightness B' . The brightness contrast, K , between the object and the background is then defined as

$$K = \frac{B - B'}{B'} \quad \text{or} \quad K = \frac{B' - B}{B'} \quad \text{when } B' > B.$$

If B approaches B' it is found that at a certain small value of K ($= \Sigma_t$) the eye can no longer distinguish the object from the background, that is, the object becomes invisible. Σ_t is called the threshold of contrast and, for normal observers in ordinary daylight illumination, is about 0.02 to 0.04. Σ_t is, however, found to be a function of the colour and angular dimensions of the object viewed (it increases for small objects) and may be greatly increased by bright lights in the field of view (glare). It also increases for very small or very large values of B . The question of colour does not normally arise when viewing distant objects in the atmosphere as all objects tend to appear grey when nearing the visual range. It may vary for any one observer with the general state of his health or over a longer term with more gradual physical changes in the eye.

The atmosphere affects the total amount of light received by the eye from any object (that is, from the direction of the object, for the eye cannot distinguish the origin of the light) in two distinct ways: it diminishes the direct rays from the object and it adds to the beam light which has been scattered and diffusely reflected from other sources, for example, the sun, the sky or the earth. This scattered and reflected light is known as the "air light".

The first factor does not alter the contrast between the object and the background, but the second factor, because it adds the same amount to both the background and the object brightness, reduces the contrast between them. If the object and background were to recede from the eye then the apparent contrast would decrease and when it had fallen to the limiting value of σ (appropriate for the conditions of illumination and object) at which the object could only just be distinguished, the object would then be at the visual range.

The maximum distance at which a given object can be seen in any given circumstances depends mainly on the state of the atmosphere (that is, on the extinction coefficient), but it also depends, usually to a much smaller extent, on the elevation of the sun, the reflecting power of the object, the reflecting power of the background, the cloudiness and general illumination, the angular separation of the sun and the object, the angular size of the object and the eyesight of the observer. It is not, therefore, possible to interpret visual observations exactly in terms of the extinction coefficient. It is, however, possible to eliminate the

[/] The strict definitions of the terms flux density, luminous intensity and brightness are given by Middleton.

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effect of some of these variables, provided certain conditions are observed, and to standardize others so that observations at different places and by different meteorological observers may be comparable. If a perfectly black object elevated above the horizon is used, the visual range is practically independent of the elevation of the sun and its angular separation from the object, and if, in addition, the angular dimensions of the object as seen by the observer are also specified and the observer has normal eyesight, then the visual observations should be comparable.

Koschmieder⁴ has shown that, if the extinction coefficient is uniform throughout the part of the atmosphere between the observer and the object, the apparent brightness, B_s , of a black object at distance D , due entirely to the scattered light, is related to the brightness of the horizon at the same azimuth, B_b , by the equation

$$B_s = [1 - \exp(-\sigma D)] B_b. \quad \dots (4)$$

Koschmieder's equation can be derived as follows. The apparent brightness, B_s , of a black object (that is, having zero intrinsic brightness) is derived from the apparent brightness of each element of the airpath between the object and observer and it is equal to the sum of the apparent brightnesses of all the elements in that airpath. If the distribution of molecules, droplets and particles is uniform throughout the airpath and the sky is uniformly illuminated, the intrinsic brightness of each element dx of the airpath is the same and may be denoted by Bdx where B is constant. The apparent brightness of that element which is at a distance x from the observer, that is, after transmission through an airpath of length x , is, from equation (2), given by the function

$$B dx \exp(-\sigma x). \quad \dots (5)$$

If the object is at a distance D from the observer the sum of the apparent brightnesses of all the elements, that is, the total brightness, B_s , reaching the observer's eye from the air light, is obtained by integrating function (5) for values of x between the limits 0 and D .

$$\text{Thus } B_s = \int_0^D B \cdot \exp(-\sigma x) dx = \frac{B}{\sigma} [1 - \exp(-\sigma D)]. \quad \dots (6)$$

The brightness of the horizon sky, B_b , is obtained by integrating function (5) between 0 and infinity.

$$\begin{aligned} \text{Thus } B_b &= \int_0^\infty B \cdot \exp(-\sigma x) dx \\ &= \frac{B}{\sigma}. \quad \dots (7) \end{aligned}$$

Substituting $B_b = \frac{B}{\sigma}$ from equation (7) in equation (6) gives

$$B_s = B_b [1 - \exp(-\sigma D)]. \quad \dots (8)$$

Equation (8) is identical with equation (4) and shows that the contrast between a black object and the horizon is given by

$$\frac{B_b - B_s}{B_b} = \exp(-\sigma D).$$

As D increases, the contrast between the black object and the horizon will fall eventually to Σ — the threshold of contrast. If Σ is set equal to 0.02, then

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D is equal to the meteorological visibility V .

$$\begin{aligned}\text{Thus } 0.02 &= \exp(-\sigma V) \\ \text{or } V &= \frac{1}{\sigma} \log_e 0.02 \\ &= \frac{3.91}{\sigma} \quad \dots (9)\end{aligned}$$

This theory holds strictly only if the sky is uniformly illuminated but errors due to non-uniformity of sky illumination are not usually large. It follows that the value of either V or σ can be calculated from a measurement of the other. Thus in an atmosphere in which the (meteorological) visibility is, say, one kilometre, σ has a value of 3.91 per kilometre. If the visibility is 10 kilometres then σ has a value of 0.391 per kilometre.

If other than dark coloured objects are used or the objects are viewed against a terrestrial background, the visual range will, in general, be less than that given by equation (9) and in some cases very much less, for example, when the reflecting power of the object is close to that of the background or when light-coloured objects are viewed with a low sun. If, however, the terrestrial background is at least 50 per cent farther away from the observer than the object is, the error due to not having a sky background is generally negligible.

Forecasters who wish to study these theoretical aspects more deeply should consult one or more of references 3, 5, 6 and 7.

17.2.3 Visual range of natural objects at night

This is of importance in a restricted number of specialized requirements. Forecasters who are required to provide such specialized services should consult the more advanced texts and original papers, some of which are listed in Section 17.2.2.

17.2.4 Visual range of lights at night

At night the distance at which a light can be seen depends on

- (i) the brightness and colour of the light,
- (ii) the sensitivity of the observer's eye,
- (iii) the presence or absence of other bright lights in the field of view,
- (iv) the general level of illumination and
- (v) the transparency of the atmosphere.

For meteorological purposes it is desirable that the visibility reports at night should indicate the same degree of atmospheric transparency as they do by day. Accordingly, in deriving the meteorological visibility from observations of fixed lights, it is necessary to eliminate, as far as possible, all effects due to the factors listed above except that of atmospheric transparency which is closely related to matter suspended in the atmosphere.

It is important to understand the difference between the physical effects of suspended matter on the visual range of lights by night and of objects by day. By night suspended matter reduces the brightness of a distant light and as the observer recedes from the light the reduction in brightness reaches a value at which the brightness becomes imperceptible to the human eye. By day, on the

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other hand, suspended matter increases the brightness of a distant object and, as the observer recedes from it, its brightness increases, the contrast with the background decreases and the contrast eventually becomes imperceptible beyond the limit of visual range.

By night the illumination from a point source (as distinct from a parallel beam) of candle-power I_0 , is propagated over the surface of a sphere centred at the source. The illumination at a point distant x from the source is reduced to I_0/x^2 in a non-attenuating medium. Equation (3) shows that, in an attenuating medium, the illumination is reduced to a value $\frac{I_0}{x^2} \exp(-\sigma x)$. When this value is equal to the minimum perceptible intensity, Σ_t , the light is at the limit of visual range, D . Thus

$$\frac{I_0}{D^2} \exp(-\sigma D) = \Sigma_t. \quad \dots (10)$$

The value of Σ_t accepted by the Meteorological Office is 0.15 kilometre-candle or 0.15 lumen per square kilometre or 1.25×10^{-7} yard-candle.

If observations are made of the distance (D) at which a light of known candle-power just disappears then, for a given Σ_t , the value of σ can be calculated from equation (10). By using this value of σ in equation (9) a calculation can be made of the equivalent day-time meteorological visibility (V) which would be observed in an atmosphere having the same condition of attenuation (that is, the same distribution of matter suspended in the atmosphere). In the United Kingdom official observations of visibility at night conform with these requirements and can be compared with the day-time (meteorological) visibility.

The relationship between the distances at which lights of various candle-power will just be visible on nights of known equivalent daylight visibility (and conversely) are shown graphically on page 357 of the *Handbook of meteorological instruments*.² (It should be noted that the graphs are valid strictly only in certain specified conditions and cannot therefore be applied indiscriminately to general problems concerning the distances at which lights can be seen at night.)

17.2.5 *Some reasons why visual range differs from the meteorological visibility*

The limitations and restrictions imposed in order to make meteorological visibilities reasonably comparable amongst themselves inevitably produce differences between those meteorological visibilities and the estimates of visual range by various users of actual and forecast meteorological visibilities. These differences arise from differing physical conditions under which the visual range is estimated and they are particularly prevalent at night. When differences do arise the opinion as to what is the "visibility" is often strongly held and strongly expressed both by the user and purveyor of meteorological information. This section has been included in an attempt to indicate to meteorologists the reasons for these differences and thereby to provide them with an understanding of some physical aspects of the problems and in the hope that it will contribute to impartial and dispassionate discussion between user and supplier on those occasions when differences have occurred.

17.2.5.1 *The nature of the object.* Objects selected for estimating meteorological visibility should normally subtend an angle of about $\frac{1}{2}^\circ$ in both elevation and width. Any substantial increase in the angle subtended, notably in the vertical, materially affects the distance at which such an object is visible,

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particularly in a poor light. The theoretical treatment of this problem is very complicated. One of the effects of a large object subtending a vertical angle of a few degrees is that a portion of the light path from the object to the observer will be shaded from illumination by the sky. Foitzik⁸ has calculated that, in a fog, a semicircular black object 10° in diameter when viewed against the horizon under a uniform sky would be visible to a distance twice that at which a similar target of 2° in diameter would be visible. No rule is known which indicates the relation between the visual range of large objects and the meteorological visibility.

In addition to being of prescribed size, objects selected as meteorological visibility marks should be black or very dark coloured. This precaution is taken in order to restrict the reflected light to acceptably small proportions. Natural objects are not perfectly black and reflect light to varying extents. Some objects reflect light in a specular or mirror-like fashion. This type of reflection is visible to an observer only over a particularly narrow range of angles depending on the bearings of the illuminating source, the object and the observer and is not to be further considered in this handbook. All natural bodies reflect light diffusely, in greater or lesser degree, and this property of diffuse reflection affects the distance at which objects are visible. Koschmieder⁴ has considered theoretically the visual range of white objects (with a reflecting power of unity) against the horizon as background and has deduced that the contrast between the white object and horizon will pass through zero at an angle of 100° azimuth relative to the sun, that is, at this azimuth the object is as bright as the horizon and therefore invisible. This variation of contrast with sun's azimuth is not just merely of theoretical interest. It is of great practical importance in the complex problem of visual range since the power of a body to reflect diffusely even a small fraction of incident light can exert a marked effect on the distance at which natural objects cease to be visible. Foitzik⁷ has considered theoretically the problem of grey objects under completely overcast skies. Wright⁹ has also studied the effect of sun's azimuth on the distances to which objects of varying reflectivity would be visible. Table 17.1, taken from his paper, indicates, as a

TABLE 17.1 Distances (as percentages of meteorological visibility) at which objects will be visible against differing backgrounds under various sun and sky conditions

Albedo of object	Background	Overcast sky	Clear sky (solar elevation 20°)						
			Bearing from line of sight						
			0°	30°	60°	90°	120°	150°	180°
		per cent	per cent						
0 (black object)	sky	100	100	100	100	100	100	100	100
0.05	sky	99	100	100	100	100	97	93	95
0.15	sky	98	99	99	99	99	89	78	81
0.25	sky	97	99	99	99	98	79	20	44
0 (black object)	object with albedo 0.25	50	24	30	32	37	86	99	97
0.05	object with albedo 0.25	45	21	26	28	33	80	93	91
0.15	object with albedo 0.25	31	12	16	17	21	63	75	74
0 (black object)	object with albedo 0.15	39	17	22	24	28	73	86	84
0.05	object with albedo 0.15	31	12	16	17	21	63	75	74
0 (black object)	object with albedo 0.05	21	7	10	11	13	48	66	58

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percentage of the "meteorological visibility", the distances to which a black object and objects with an albedo up to 0.25 would be visible under an overcast sky and for various bearings of the sun under a cloudless sky. The table also illustrates the effect on visual range of substituting backgrounds of various albedos in place of a sky background.

Table 17.1 is of no direct use in forecasting but it has been included in the handbook because quantitative information is to be preferred generally to purely descriptive text. The effect of the albedo of objects when viewed against a sky background is shown in the first four rows of Table 17.1. In the main, the distances to which objects with albedos up to 0.05 are visible lie within a few per cent of the meteorological visibility. There is, however, a very marked decrease in the distance to which objects of albedo 0.15 and 0.25 are visible against a sky background when the sun's bearing from the line of sight lies between 120° and 180° . When the sun's bearing from the line of sight is 150° an object of albedo 0.25 is visible to only one-fifth of the meteorological visibility. Under overcast conditions with a uniformly illuminated sky the effect of object albedos (between 0 and 0.25) is small.

17.2.5.2 *The nature of the background.* Table 17.1 also indicates the importance of the background. It will be noted that, when viewing a black object against a nearly black background (albedo 0.05) and when facing into sun, the object is visible to about 10 per cent of the meteorological visibility but if the object is viewed with the sun bearing about 150° to 180° from the line of sight the object is visible to about 60 per cent of the meteorological visibility. Other entries in Table 17.1 show wide variations which all emphasize the complexity of visual range. It will be seen, however, from the first two rows of Table 17.1 that if a black (or nearly black) object is viewed against the horizon the distance to which it is visible will lie within 10 per cent of the meteorological visibility. Many of the more distant objects selected as meteorological visibility points fulfil this condition. Many of the nearer objects for use in misty or foggy conditions perforce have a terrestrial background but fortunately the problem is not quite so complicated as Table 17.1 might imply. Wright⁹ has shown that, in foggy conditions, the difference between the observed visual range and the meteorological visibility is not more than 10 per cent provided the background is not closer to the object than a distance equal to one-third of the distance of the object. This is due to the fact that when an object is near the limit of visual range the apparent background is not the terrestrial background but the air light extending from the observer to some limited distance beyond the object.

Thus, provided objects used to estimate the meteorological visibility are selected according to the prescribed conditions, observed visual ranges of these objects will generally be within 10 per cent of the standard meteorological visibility, except in the rather special circumstances when an object which is not nearly black is viewed in direct sunshine and the solar bearing lies within a critical range of azimuths.

The conditions under which observed or forecast values of meteorological visibility are put to practical use for various purposes will not, in the very nature of things, always be within these rather stringent restrictions. This is particularly so in aviation. During a low-level approach to, circuit round and landing at an aerodrome the conditions under which a pilot is seeking to identify objects on the ground is often varying continually and quickly as the heading of the aircraft changes during the circuit. Further, the horizontal and vertical fields of view from a cockpit are usually quite restricted. Consequently objects

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are in the pilot's field of view for a very short time and, in poor visibility and fitful sunshine, the illumination of the terrestrial background against which objects may have to be identified will be varying markedly and abruptly. In hazy sunny conditions, glare will hamper a pilot's visibility when looking towards the sun.

Forecasters should bear these factors in mind when discussing with pilots their estimates and experiences of the "visibility" encountered during flight.

17.2.5.3 *The non-uniformity of the air light.* A further factor which causes differences between meteorological visibility and the distances at which some objects are just visible is the non-uniformity of the light illuminating the air. Theory assumes uniform lighting under a completely cloudless or overcast sky. Even when there is a uniformly thick overcast the brightness over the entire sky is not uniform, the zenith sky being usually the brighter. Under partly cloudy conditions variations in the extent, disposition and thicknesses of clouds cause patchy and sporadic sunlight and introduce great complexities, and theory gives no practical guidance.

17.2.5.4 *The nature of lights.* At night, meteorological visibilities in the United Kingdom are largely determined by using lights specially installed for this purpose. The type of light and the candle-power conform with regulations so that the visibilities reported can be directly compared with day-time meteorological visibilities. Lights for general area lighting or for rather more specific purposes are, however, often specially designed and beamed with the prime object of assisting navigation by land, sea or air. This is particularly true of approach and runway lights which, at many aerodromes, are directed and beamed towards the various positions through which an aircraft should pass during an ideal approach to and landing on a runway. If, in making the approach or landing, the aircraft moves to one side or the other or above or below the optimum path, the intensity of the lights as seen by the pilot may vary appreciably and so affect the distances to which he can identify the lights. Further, at some aerodromes the intensity of the lights may be varied by controllers so as to provide the maximum possible assistance to aviators during approach and landing in the particular weather conditions and level of atmospheric illumination pertaining at the time. The distances at which these lights at aerodromes are visible to pilots when making landings at night bears no simple relationship to the meteorological visibility. Forecasters should bear in mind that forecasts of visibilities refer to equivalent day-time visibilities, that there may well be differences between those forecasts and a pilot's assessment of the visual range of airfield lights and that part of these differences may be caused by the characteristics of the airfield lighting.

17.2.5.5 *During twilight.* During both the dusk and dawn period the level of natural illumination varies quite rapidly in time and from eastern to western horizons. Little has been published on the distances at which natural objects or lights will be visible during twilight. It is clear from first principles that contrasts in time and in azimuth will vary appreciably. Also the human eye is likely to be in transition between the light and dark adapted states. The problem is undoubtedly complicated and, although of limited duration, may be of considerable practical importance to aviation. It is further complicated at aerodromes when approach and runway lights are burned during the twilight periods. Some work on this problem has been published by Garbell.¹⁰

17.2.5.6 *The nature of the human eye.* The relationship between day-time and night-time visual ranges is further complicated by the characteristics of the human eye. Vision does vary somewhat from person to person but for people with

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"normal" eyesight the variations are probably small. In the short term a person's vision may be temporarily affected by physical ill-health (for example, a heavy cold) but usually recovers to its former level with a return to good health. The effect of weariness on a person's visual response is not known. In the longer term there may be some more general and permanent changes in visual response associated with the ageing of the eye. These variations are not further considered.

The main purpose of this section is to describe the broad differences of the human eye when seeing under day-time and night-time conditions. In the day-time the human eye sees primarily through receptive organs located in the central part of the retina. These receptive organs are sometimes called "cones" and are sensitive to colour. This type of seeing is referred to as photopic vision. When the human eye has been fully adapted to night-time conditions (about 30 minutes exposure at the general level of night-time illumination) the eye sees through receptive organs which are located mainly round the periphery of the retina. These receptive organs are called "rods" and they are insensitive to colour. This type of seeing is called scotopic vision. For our purpose the main difference between the rods and the cones is that the rods can detect lights at a level of brightness much lower than that at which the cones could detect them. Thus an eye which is in the fully dark-adapted state can distinguish lights of a given intensity at greater distances than a light-adapted eye. This is a common experience.

It is useful to describe briefly the changes taking place during transition from the light-adapted to the dark-adapted state. Transition to the fully dark-adapted state takes about 30 minutes. On leaving a lighted room the eye is in the light-adapted state and sees through the central cones by looking directly at the light. The threshold contrast which the cones can detect decreases very rapidly in the first two minutes in the dark surroundings. This decrease in threshold (or increase in sensitivity of the eye) continues, but at a much slower rate from the third to about the fifth minute after leaving the lighted room. After about five minutes the further increase in sensitivity due to the central cones shows only a very small rise with continued exposure to the dark surroundings. About ten minutes after leaving the lighted room the rods round the periphery of the retina begin to be effective and contribute to the ability to see. Their sensitivity subsequently increases at a fairly steady rate until, after about 30 minutes in the dark, the eye is in the fully dark-adapted state and there is little further change with continued exposure to dark surroundings. When viewing with the rods (scotopic vision) one tends to see objects or lights to somewhat greater distances when they are slightly off the direct line of sight. Thus at night the distance to which a given light is visible varies greatly with the state of adaption of the eye. The uniform time delay between leaving a lighted room and making a night visibility observation is introduced expressly for the purpose of ensuring that, within reasonable limits, the eye is in the same state of adaption for each observation. This restriction imposes a measure of uniformity and comparability for meteorological visibilities at night. Recipients of meteorological visibilities will seldom use the information in comparable conditions.

17.2.5.7. *Oblique visual range.* Observed and forecast meteorological visibilities refer to visibilities in the horizontal at a height of about five to six feet. As far as the aircraft pilot is concerned his vision of objects on the ground is more or less horizontal only during the actual take-off and landing. In some of the larger aircraft the pilot's cockpit may be some 20 or 30 feet above the ground so that even during landing and take-off the pilot's vision of objects on the ground is not strictly horizontal. During the climb after take-off, in level

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flight and during descent and the approach to the runway his sight of the ground is by oblique vision.

One factor which makes the problem of oblique visual range very complicated is the variation in the vertical distribution of matter in suspension in the atmosphere. Matter in suspension scatters light and it is clear that variations in the concentration of suspensoids will cause variations in the scattering coefficient of the atmosphere. Marked variations in the vertical are most likely to occur with marked thermal stability when atmospheric pollution and/or fog droplets tend to be concentrated at some level(s) within the stable layer. Numerical values for the scattering coefficient of the atmosphere at various levels up to about 30,000 feet have been determined experimentally on a few days by Waldram.¹¹ Routine observations of the vertical variation of turbidity are not available even for the lowest levels of the atmosphere and there is no satisfactory technique for advising aircraft operators of a probable value of oblique visual range on those days when visibility is restricted and any reasonably reliable estimate would be useful.

The complexity of the problem of oblique visual range is illustrated by the following not uncommon situation. Assume an aircraft is approaching an aerodrome on a cloudless day with a haze layer or ground fog with a well marked top at about 500 feet, illustrated schematically in Figure 17.1. When the pilot is in clear air at A, looking down-sun and at the ground at a sharp angle, the

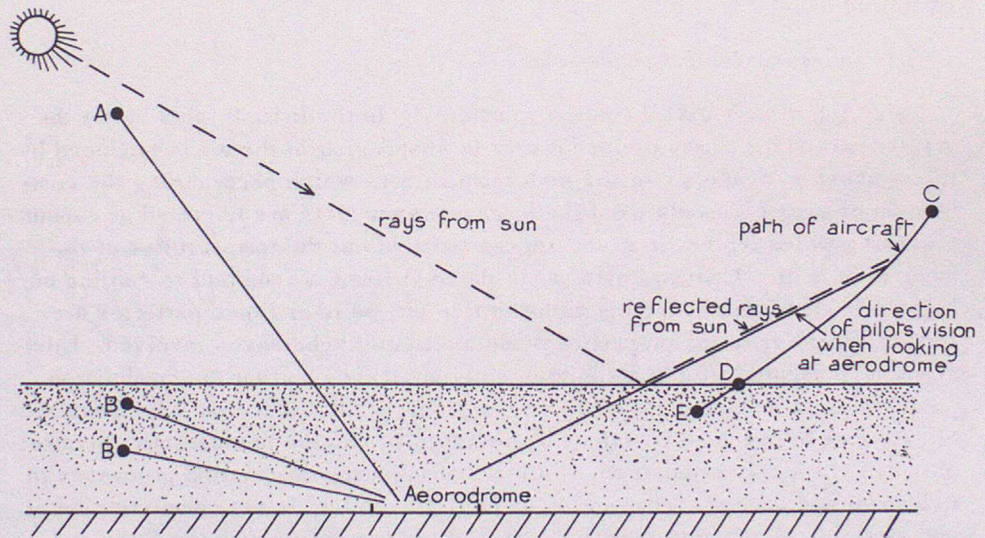


FIGURE 17.1 Schematic diagram illustrating variation of oblique visual range with azimuth and elevation

length of the path of light through the haze (fog) layer is relatively short and he may be able to distinguish ground detail at and around the aerodrome. When the pilot is at B, in the haze layer, looking down-sun towards the aerodrome, the increased length of light path through the haze layer may render the aerodrome invisible from B. If there is a marked increase in concentration of pollution near the haze-top, the aerodrome might well be visible from B', a point somewhat below B.

Consider now an approach from the down-sun side. The interface between the dust (fog) layer and the clean air above causes a certain amount of mirror-like

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reflection and, with a low sun, the pilot may, at some point(s) on his approach path between C and D, suffer a marked diminution of oblique visibility due to reflected sunlight. Within the haze (fog) layer at E the oblique visibility will be different from that at a comparable point (B) on the up-sun side because of the variation with azimuth in the amount of light scattered by particles. From this example it is clear that when descending to and orbiting an aerodrome on a clear sunny day with a haze or fog layer a pilot will experience marked variations in oblique visual range.

17.2.6 *Summary*

It will be realized from all the foregoing that "visibility" is not a simple property of the atmosphere. Apparatuses are available for measuring extinction and scattering coefficients but are not in general use in meteorological services. It is debatable whether wide use of these instruments would lead to improvements in the observation of visibilities. It is most important for forecasters to remember that the values they include in forecasts refer to meteorological (horizontal) visibilities.

17.3 VISIBILITY AND SUSPENDED MATTER IN THE ATMOSPHERE

When considering visibility and the atmospheric suspensoids it is convenient first to describe the suspensoids under two main headings (finely divided matter and condensation nuclei) and then to indicate their effect on visibilities in the British Isles.

17.3.1 *Suspensoids of the atmosphere*

17.3.1.1 *Finely divided matter (particles)*. In the British Isles by far the greater part of the finely divided matter in suspension in the air is produced by the combustion of fuels. At the high temperatures which occur during the combustion of most commonly used fuels, gaseous products are liberated at vapour pressures which represent strong supersaturations at the temperatures of the ambient free air. Consequently, when these vapours are subject to cooling on being released into and mixing with the free air, solid or liquid particles are formed according to the properties of the particular substances involved. Most common combustible fuels are mixtures of substances so that the combustion products are also mixed. In addition the products of combustion may coagulate or take part in chemical reactions or interactions and the products are therefore of mixed chemical composition. Further, during many combustion processes in industrial and domestic combustion of fuel, all the fuel is not completely burnt and particles of unburnt or partly burnt fuel are carried through the flues and, if not removed, are discharged into the atmosphere.

Regarding smoke in this context as the waste products emitted during the combustion of common fuels it is clear that its constitution is always complex. The main constituents of smoke are soot particles (carbon), various oils, tars, hygroscopic substances and particles of unburnt or partly burnt fuel. Typical sizes of many smoke particles would probably lie within the range 10^{-6} to 10^{-4} centimetres (0.01 to 1.0μ). Particles of unburnt or partly burnt fuels are probably larger than about 10^{-5} centimetres (0.1μ) but particles larger than about 20μ possess appreciable fall speeds. Thus when the flue up-draught is no longer effective in carrying the larger particles up into the atmosphere they commence to settle and usually fall to the ground fairly close to their point of emission.

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In the larger cities and industrial areas combustion of fuels produces these particles in great numbers. The greatest concentrations are normally around and immediately downwind of the centre of the pollution-producing area. At downwind sites the concentration of pollution varies with the wind field, the vertical extent and degree of turbulence in the atmosphere and the local topography. Average concentrations on winter days are much greater than on summer days because, other things being equal, day-time heating and the vertical extent and the degree of turbulence are so much less in winter than in summer. In addition the winter concentration is enhanced by the increased consumption of fuels for domestic, office and industrial space heating. Wright¹² showed that at Kew at 1500 G.M.T. the average monthly concentration of smoke particles was within the range 500 to 4,000 per cubic centimetre from late autumn to early spring, but in summer the concentration was generally less than 100 per cubic centimetre. No general rule can be given which will enable forecasters theoretically to determine satisfactorily the amount of pollution at any one site.

A very detailed survey¹³ of the distribution of smoke and other types of atmospheric pollution in Leicester is available. This classic survey is based on intensive observations over three years and should be consulted by forecasters intending to study the problem in great detail. Dobson¹⁴ has included some of the Leicester results in a paper on the meteorological aspects of smoke pollution. This latter paper should give forecasters an understanding of the general problem. It should not be forgotten however that, in other localities, there will be important differences in detail from the Leicester results. In many towns and cities the local authorities organize measurements of smoke pollution. The results are published by the Department of Scientific and Industrial Research in the monthly *Atmospheric Pollution Bulletin*.¹⁵

In addition to the particles formed from the combustion or part combustion of fuels, other particles are formed by the mechanical disintegration of larger bodies. The most frequent radius of mineral particles, which are formed by this process and are raised by the wind, is, according to Mason,¹⁶ about 2.5×10^{-5} centimetres (0.25μ). Only a very small proportion have radii less than 10^{-5} centimetres (0.1μ) and particles of radii greater than about 20μ possess fall speeds of order 5 centimetres per second and will remain suspended in the air for only a short time. In those localities where the top surface of the ground contains an adequate supply of sufficiently small particles in a suitable dry state, strong winds will be likely to lift these particles into suspension and cause a diminution in visibility. Except in quite limited areas blowing sand and dust is quite infrequent in the British Isles. Occasionally, however, in the Fens very dry and finely divided topsoil may be raised and carried along by the wind. Apart from the considerable loss to agriculture and the fertility of the land, blowing topsoil occasionally causes a marked reduction in visibility over extensive areas in East Anglia. Spence^{17,18} has described two occurrences.

17.3.1.2 Condensation nuclei. The small ions which are always present in the atmosphere have radii of order 10^{-7} centimetres (0.001μ or $1\text{ m}\mu$) and require supersaturations of about 400 per cent before they can act as centres for condensation. These supersaturations do not occur naturally in the free atmosphere. In view of this and their smallness these small ions are unlikely to have any practical effect on visibility and will not be further considered.

Condensation nuclei are produced in very great numbers by combustion. In industrial areas the numbers of such nuclei will probably be of the order of tens of thousands per cubic centimetre and may at times be much greater.

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Another source of condensation nuclei is the sea. Sea-salt nuclei may be produced by the breaking of waves in high winds and by the bursting of air bubbles in sea water. Over the United Kingdom sea-salt nuclei are nearly always present but in smaller concentrations than combustion nuclei, typical concentrations probably being of the order of hundreds per cubic centimetre. Rather more detail about sizes and concentrations of condensation nuclei was given in Chapter 16, Section 16.2.1.2.

In an investigation Wright¹² found the average concentration of both combustion and sea-salt nuclei at Kew at 1500 G.M.T. for the years 1928–30 to be 29,000 per cubic centimetre. The mean for the months October to March was 38,000 and that for April to September was 20,000 per cubic centimetre. The highest reliably observed concentration was 106,000 per cubic centimetre in December on a day of dense fog with a light south-south-easterly wind and the least number observed was 4,000 per cubic centimetre in August on a day with very good visibility and a light south-south-westerly breeze. Most of Wright's observations were made at 1500 G.M.T. so that these values may represent approximately the minimum for the day.

A proportion of these condensation nuclei carry electric charges which are probably acquired by the capture of one or more ions. As far as is known the presence (or absence) of an electric charge naturally acquired by a condensation nuclei has no significant effect on the visibility and no distinction will be made between charged and uncharged condensation nuclei.

At coastal stations with an onshore wind and in very isolated country districts sea-salt nuclei may predominate. In most inland districts of the United Kingdom and in many coastal areas also the number of combustion nuclei will greatly exceed the sea-salt nuclei. It will be seen in the following section, however, that sea-salt nuclei exert a great effect in the reduction of visibility.

17.3.2 *The effect of particles and nuclei on visibility*

Wright⁹ has made a study of the effect of particles and nuclei on visibilities at a number of stations in the British Isles. He used observations made mainly at 0700, 1300 and 1800 G.M.T. and, although the values published are mean values and cannot be applied directly to day-to-day forecasting, a knowledge of the results should contribute to an understanding of the effect of particles and nuclei on the reduction of visibility.

The observations were divided into two main classes depending on whether the visibility was above or below fog limits (that is, fog when visibility <1100 yards) and these two classes were called "clear" and "foggy" conditions respectively. For each of these classes Wright computed the contribution of various types of atmospheric pollution to the reduction of visibility. He was able to assess the effect of sea-salt nuclei separately. Wright recognized that the concentrations of particles and condensation nuclei were higher in winter than in summer and he found it convenient to consider their effect in two parts. In the first part he included the particles and nuclei which might be expected to be produced all the year round from the combustion of fuels at power stations, factories and industrial plants. He termed these "perennial". In winter he recognized that there was an additional source of particles and nuclei to be attributed mainly to the increase in combustion of fuels for space heating of homes, factories and offices. This additional winter supply was termed "hibernal".

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Wright assessed the contribution of each of these three types of atmospheric pollution (that is, sea-salt nuclei, perennial and hibernal particles) in units of nebules per kilometre. The nebule is a measure of obscuring power and was first introduced by Gold.¹⁹ It is sufficient for our purpose to know that if the atmosphere is regarded as homogeneous in obscuring power in the horizontal and contributes a screen of n nebules per kilometre and the threshold of contrast (Σ) is 0.02, then $nV = 57$ is the relation between nebules and meteorological visibility, V , determined by the distance at which a black object would be just visible when viewed against a sky background. Thus if the opacity of the atmosphere is one nebule per kilometre the visibility is 57 kilometres and if the opacity is 100 nebules per kilometre the visibility is 570 metres. Table 17.2 summarizes the contribution of the three types of atmospheric pollution to atmospheric opacity in both clear and foggy conditions.

TABLE 17.2 *Contribution of various types of pollution to atmospheric opacity*

<i>Atmospheric pollutant</i>	<i>Opacity in clear conditions (visibility > 1100 yd.)</i>	<i>Opacity in foggy conditions (visibility < 1100 yd.)</i>
<i>nebules per kilometre</i>		
Sea-salt nuclei	3.1	about 120 at clear coastal and inland stations
Perennial particles and nuclei	1.2 to 4.4	9 to 16 depending on the intensity of pollution to which the station is liable
Hibernal particles and nuclei	0.2 to 2.7	ranging from 33 at a clear coastal station where pollution is slight to 149 at an inland station where pollution is high

Wright⁹ deduced that "sea-salt nuclei exercise an influence out of all proportion to their numbers. Even on occasions of good visibility . . . they produce a high proportion of the opacity except at urban stations [with heavy pollution] where their effect is out-weighed by combustion nuclei and particles; and in foggy conditions they produce almost all the opacity, except again at urban stations.

"Remembering that sea-salt nuclei are considerably fewer than combustion nuclei their dominating influence can only be explained on the assumption that they are considerably larger than combustion nuclei.

"Consideration of the ratio of the respective opacities in "clear" and "foggy" conditions indicates that the opacity due to sea-salt nuclei in clear conditions is increased forty-fold in foggy conditions, that due to perennial "particles" is increased about five-fold, and that due to hibernal "particles" is increased more than fifty-fold. In the case of the nuclei the increase in opacity may be attributed to growth of the nuclei as humidity conditions approached saturation; in the case of the particles the increase in opacity may be attributed to enhanced concentration of particles in the lowermost layers of the atmosphere due to (a) very light winds, whereby particles from smoke sources are accumulated in the air, and (b) an inversion of temperature or a small lapse rate, whereby particles are prevented from escaping to higher levels".

Wright considered theoretically the variation in the rate of growth of both sea-salt and combustion nuclei with relative humidity. By using a formula which he had developed in 1936²⁰ he calculated that there would be copious condensation on sea-salt and condensation nuclei with relative humidities of 100.03 per cent and 100.38 per cent respectively. Since the supersaturation for condensation

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on the sea-salt nuclei was very small, it was thought that the surplus water vapour in conditions of supersaturation would condense exclusively on sea-salt nuclei which would grow to relatively large droplets whilst the combustion nuclei would remain almost the same size. Thus the importance of active sea-salt condensation nuclei in forming radiation fog in relatively clear air was explained at least qualitatively. More recent work tends to lessen the importance of sea-salt nuclei compared with other nuclei and the clear distinctions drawn by Wright are now somewhat blurred.

As an example of the complexity of fogs it is convenient to refer to observations on the composition of some fogs at Kew. These observations have been discussed by Stewart.²¹ The results indicated that, in fogs with visibilities between about 100 and 300 metres, practically all the droplets were very small (less than 2μ in diameter) and these small droplets contributed a large part of the liquid water content of the fog and almost all the opacity. In the thicker fogs (visibility below about 100 metres) the contribution to opacity from small drops was increased several times but, in addition, there was a considerable increase in the number of larger drops (diameter greater than about 7μ) which provided almost all the liquid water and up to half the opacity of the fog. It should perhaps be mentioned that these results may be influenced by the situation of Kew and pollution from London.

It is difficult to assess the contribution of particles to reduced visibility in conditions of relative humidity too low (perhaps below 90 per cent) for much condensation on suitable nuclei to occur. The visibility characteristics of a locality due to particulate matter in suspension are probably best determined from analysis of a long series of observations. It is often possible to relate the characteristics for different seasons of the year to a number of surface wind directions, to particular synoptic situations or to the thermal stability of the air. Except near the larger sources of smoke pollution, visibility is seldom reduced to fog limits over extensive areas by smoke alone. Stewart has found that at Kew the meteorological visibility V (in metres) is given very approximately by the expression $V = 660/W$ metres where W is the weight of smoke pollution in milligrams per cubic metre. This formula does not apply in conditions of high relative humidity nor necessarily at other localities. It does, however, give a rough indication of what the values of smoke pollution published by the Department of Scientific and Industrial Research¹⁵ mean in terms of visibility in conditions of low relative humidity.

17.4 CLASSIFICATION OF FOGS

In 1928 Willett²² devised a classification of fogs. There were two main classes, one consisting of fogs which formed in a particular air mass and the other consisting of fogs formed in association with fronts. Within each of these two main classes were several sub-divisions which related primarily to the process which caused the fog to form. To some extent the following classification resembles that of Willett but the order of treatment is different and the number of sub-types is less. The first three main types, namely radiation, advection and up-slope fogs occur as air-mass fogs; the fourth type occur as frontal fogs.

17.4.1 Radiation fog

Radiation fog occurs in an air mass when sufficient cooling *in situ* occurs due to radiative loss of sensible heat. Although radiational loss of heat may be a minor factor in the formation of sea fogs, radiation fogs are primarily land

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phenomena. The essential requirements for a radiation fog to form are clear (or only partly clouded) skies, an adequately high initial relative humidity in the lowest few hundred feet (or a wet ground) and an absence of moderate or strong surface winds. The broad pattern of the sequence of events is well known and is only briefly summarized here. The absence of cloud permits strong cooling to occur by night at the ground and in the lower levels of the atmosphere. This cooling soon establishes an inversion of temperature in the lower levels of the air. Since the winds are light there is little mechanical turbulence which can transport heat downwards from the upper levels of any inversion towards the ground and so destroy the inversion. As the air cools, the relative humidity at low levels rises. If the relative humidity rises sufficiently, copious condensation takes place on active condensation nuclei and a fog is formed. This very simple account presents only a broad outline. Extensive studies have been made of the finer detail of events occurring on a night of radiation fog and a more complete description is given in Section 17.5. Radiation fogs may be subdivided into the following sub-types.

17.4.1.1 *Ground fogs.* These fogs form when the base of the temperature inversion is at or very near ground level – and often occur as the result of a single night's cooling. Except in winter, day-time heating on the following morning is often sufficient to destroy the inversion and evaporate the fog which may, however, in suitable conditions, reform on subsequent nights.

17.4.1.2 *High fogs.* These are mainly winter phenomena over continental land masses in fairly high latitudes. They are characterized by an inversion whose base is above the ground – perhaps several hundred feet – and they are the result not of a single night's cooling but of continued cooling over land in high latitudes where there is an overall loss of outgoing over incoming radiation. There is usually a continuous and fairly thick sheet of stratus or stratocumulus in the inversion together with fog or mist from ground level to the cloud base. There may be some variation in the density of the fog with the normal diurnal changes in temperatures but these are usually severely damped by the cloud layer. The accumulation of atmospheric pollution in the inversion cuts down sunlight and contributes to the general gloom. High inversion fogs are mainly confined to extensive land areas but persistent fogs in the United Kingdom which commence as ground fogs may gradually transform into a type approximating to high inversion fogs.

17.4.1.3 *Advection – radiation fogs.* As the name implies these fogs are the result of a combination of advection and subsequent radiation. They are almost entirely confined to the advection inland of a maritime air mass which is then subject to cooling by outgoing radiation – particularly at night. These fogs require an adequate wind to transport the air but subsequently the wind must not be so strong that mechanical turbulence will prevent their formation. There must also be adequate time for sufficient radiative cooling to occur. The sequence and timing of events is rather stringent and, with the limited land areas of the British Isles, fogs coming strictly within this category are infrequent. There is, however, always an element of advection at some stage preceding the formation of radiation fog.

17.4.2 *Advection fog*

As the name implies the primary cause of advection fogs is the advection of air from a locality with one temperature régime to another locality where the temperature régime is different. Thus with advection fog the existence of wind

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is essential and this is in marked contrast to the radiation fog where the absence of any but light winds is essential.

It is convenient to subdivide advection fogs into two types: those which occur when warm air is advected across a cooler surface and those which occur when cold air moves across a warmer surface.

17.4.2.1 *Fogs due to the transport of warm air over a cold surface.* Cooling of air by contact with the underlying cold surface causes this type of advection fog. Although radiation is a complicating factor which may contribute to or detract from the cooling, it is always a subsidiary factor in an advection fog. Cooling by contact tends to establish an inversion of temperature from the surface upwards and the turbulence associated with the advecting wind works to distribute the cooling through the lowest few hundred feet of the atmosphere. Fog forms when sufficient cooling has occurred.

Fogs formed in this manner are conveniently further subdivided into sea fogs and land fogs.

17.4.2.1.1 *Sea fogs.* Sea fogs often occur as moist tropical air moves steadily and over prolonged periods from warmer to cooler sea surfaces – a situation which often obtains when broad currents of tropical air move gradually to higher latitudes. The gradient of sea temperature need not be sharp and the formation of this type of sea fog tends to be a gradual process. Once formed they tend to be persistent and extensive and, when the associated low-level inversion is strong, they can continue to exist with surface winds of moderate speed. Near the British Isles this type of sea fog occurs most frequently in the south-west approaches in the seasons late winter, spring and early summer and such sea fogs may drift inland.

Some sea fogs are caused by quite rapid cooling of warm moist air. In localities where the sea surface isotherms show a tight gradient of temperature, warm air which is carried across the isotherms to lower temperatures will be rapidly cooled and sea fog is quickly formed. Sea surface isotherms just off the New England coast of the United States of America, the maritime provinces of Canada and Newfoundland show a tight gradient, particularly in early summer, and sea fog is prevalent along those coasts at that time.

Rapid cooling may also occur when warmer continental air is advected across a much colder sea. Haars or sea fogs on the east coast of England and Scotland are often formed in this way as a general easterly flow brings warm continental air across the relatively cold North Sea. On some occasions, however, haars on the east coast may occur (or existing haars be intensified) when warm maritime air from southerly latitudes enters the North Sea in the circulation of an anticyclone centred near the north-west of the British Isles. A paper by Lamb and Frost²³ contains a detailed account of "haars".

On a few occasions a sea-breeze may bring sea fog across coastal areas but the fog does not usually penetrate more than a few miles inland.

17.4.2.1.2 *Fogs over snow and frozen (or cold) ground.* Strong cooling by contact occurs when warm air is advected over much colder ground and this leads frequently to the formation of extensive stratus and occasionally to fog formation but the fog does not usually last long because the ground is warmed up by the air in a few hours. This type of fog sometimes occurs in the British Isles when warm maritime air is advected across the country which is still

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covered by snow from a previous cold spell. It then tends to be persistent until the snow has melted and any resultant melt-water has drained from the ground surface.

17.4.2.2 *Fogs due to the transport of cold air over a warm water surface.* These fogs are formed when cold air with stable stratification passes over a water surface much warmer than the air (say 5° or 10°C. at least). Evaporation from the water goes on rapidly because the vapour pressure above it is much less than the saturation vapour pressure at the water temperature. The air is also warmed but as the pockets of warm moist air rising from the surface mix with the cold dry air above, a mixture is formed in which the vapour pressure exceeds the saturation vapour pressure (see *Physical and dynamical meteorology*²⁴) and condensation takes place as fog droplets. As long as the stable stratification or inversion of the cold air persists a shallow fog is formed. When, however, heating of the cold air by contact with the warm water and by the release of latent heat of condensation is sufficient to destroy the stability of the air the fog is dispersed, although steaming from the water surface may continue.

17.4.2.2.1 *Arctic sea smoke.* This is most prevalent in polar regions. It occasionally occurs in much lower latitudes when very cold continental air associated with a very cold spell is advected across a continental coast. Such fogs may occur almost as far south as 40°N. off the eastern coast of the United States of America.

17.4.2.2.2 *Autumn steam mists and fogs.* These are formed mainly by katabatic drainage of air cooled by night radiation from the land to an adjacent warmer water surface. They are mainly confined to lakes and rivers well inland in an extensive continental land mass. This type of fog seems likely to be very rare or exceedingly local in the British Isles. Lough Neagh is one place where it has been reported.

17.4.2.3 *Up-slope fogs.* These fogs are formed when air becomes saturated by cooling due to adiabatic expansion as it moves up a land slope to higher levels and lower pressures provided the saturated air is stable. Extensive and general up-slope fogs form only where the land slopes gradually upwards over extensive areas as on the Great Plains of the United States of America and Canada. Over the British Isles the topography is not suitable for the formation of extensive up-slope fogs but, on ranges of hills and the more extensive masses of high ground, hill fog may form under suitable conditions of high humidity. This is more conveniently considered as the formation of cloud and is discussed in Chapter 16.

17.4.3 Frontal fogs

Frontal fogs form near the ground in or near the boundary regions separating the two air masses.

17.4.3.1 *Pre-frontal fogs.* When precipitation falls through unsaturated air there is evaporation from the precipitation to the air. Thus the dew-point of the air is increased. Further the latent heat of vaporization is extracted mainly from the air through which the precipitation falls so that the air temperature is decreased. Both processes tend to make the air saturated. When warm rain falls through colder stable air beneath, supersaturation can be caused with the consequent formation of stratus clouds or fogs. These conditions may obtain when a fairly active warm front is overrunning a cold air mass which itself exhibits a stable lapse rate or even an inversion beneath the upper frontal stable layer.

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They may also occur, but are usually less marked, with warm-type occlusions. Pre-frontal fogs do not normally occur with cold fronts.

When fronts are active they are usually associated with a cyclone and moderate or strong winds. The presence of wind tends to prevent the formation of fog at the ground and then low stratus is more usually formed by the evaporation of rain. Nevertheless there are synoptic situations in which warm fronts can persist with extensive rain areas and with only light surface winds in the cold air ahead of the front. In some such cases pre-frontal fog can be extensive and last for several hours and move only slowly with the front. Flying conditions are poor due to precipitation, to clouds which are often extensive both vertically and horizontally and to pre-frontal fog which near industrial areas is often aggravated by a concentration of atmospheric pollution in the stable cold air ahead of the front.

17.4.3.2 Frontal passage fogs. Fogs which occur during the passage of a front and are not preceded by pre-frontal fog are rare at low levels in the British Isles. From the synoptic viewpoint they are best regarded as a cloud system which reaches down to ground level. The fogs usually clear with the passage of the front although in some hilly areas local topography may delay the clearance of fogs when there is stable air and the winds are light.

17.4.3.3 Post-frontal fogs. Post-frontal fogs can occur in warm sectors when the ground beneath is still cold from a preceding cold spell when cooling by contact can form extensive low stratus and fog. This type of fog can also be classified as an advection fog and has been included in Section 17.4.2.1.2.

Behind a cold front where there is steady advection of cold unstable air, post-frontal fogs do not form as instability would quickly lift any fog which might momentarily form from evaporation from a warm wet ground. Where a cold front is almost stationary and there is an extensive rain area extending to the cold side of the front, post-frontal fog may form. The conditions are closely parallel to pre-warm-frontal fog since the quasi-stationary cold front resembles a warm front in its characteristics. This type of fog is quite infrequent but a favourable place for it to occur is a col area between two depressions where the frontal surface separates a very warm moist air mass to the south from an old modified polar air mass with a stable lapse to the north of the front.

17.5 FORMATION OF RADIATION FOG

The preceding section has given an account of fogs in quite broad terms. Much of the finer detail of the physics of fogs cannot yet be given – partly owing to lack of detailed observations. At sea and in fogs which are transported at an appreciable speed by the wind there are obvious difficulties in setting up suitable apparatus to enable very detailed observations to be made. In radiation fogs over land there is normally little air movement and observational programmes of considerable complexity and duration have been made. Despite such investigation a full and complete understanding of the microphysics of fog has not yet been achieved. The following account indicates the extent of existing published material and should assist forecasters to keep in mind the physics of radiation fogs both when they are forecasting and when they are considering in retrospect a forecast of visibility which may have proved unsuccessful due to the occurrence or non-occurrence of radiation fog.

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Most textbooks on meteorology contain a section which explains the general physics of the formation of radiation fog. Most forecasters with some experience soon realize that the processes of formation of radiation fog seem far more complex. There are variations from one night to another which the observational material available at most stations does not explain, let alone enable those variations to be forecast. As an example, radiation fogs do not always form when the air temperature falls to or below the pre-existing dew-point; on some occasions they do. On other occasions air temperatures and dew-points may have been equal for some time – perhaps a few hours – and yet no fog forms. Then suddenly – in a few minutes – a dense fog may form. The precise and detailed physical conditions which are necessary and sufficient for fog formation are not yet known. An attempt to obtain a more complete and detailed understanding was made by Stewart²⁵ in a prolonged investigation of radiation fogs at Cardington. Stewart distinguished two types of radiation night on which fog formed and the following account is based on his work.

17.5.1 Cooling and fog formation on a typical radiation night

In Chapter 14 on Temperature an explanation was given of the modification to the thermal structure of the air near the ground on a radiation night. Air is cooled by contact with the cooling surface of the ground and by radiation from the air in the lower levels of the atmosphere which is warmer than the ground beneath. There is a rapid decrease in the temperature of the air near the ground just before and for a few hours after sunset. Under conditions of clear sky and calm (or light winds), air at the surface of the ground is often cooled below its dew-point. Ground fog seldom forms at this time and usually dew is deposited on foliage, vegetation and other objects on the ground. This deposition of dew causes the dew-point of the air very near to the ground to fall. Saunders²⁶ has drawn attention to a sudden decrease in the rate of fall of temperature of air at the surface of the ground which seems to be almost coincident with the deposition of dew on clear calm evenings. It seems probable that the release of latent heat during the formation of dew may be the main reason for the discontinuity in the fall of temperature. Similar but somewhat less well defined discontinuities in the fall of temperatures of the air can be identified up to about screen level but not much higher. The net result is that on clear calm evenings, from an hour or so before sunset, temperatures in the lowest few feet of the atmosphere fall rapidly for a few hours until dew is deposited, when there is often a sudden decrease in the rate of cooling. Thus the differences between screen temperatures and dew-points are reduced rapidly from just before until about two or three hours after sunset when dew is deposited. Thereafter the differences are reduced less rapidly owing to the slower cooling of the air and the continued fall of the dew-point as the deposition of dew continues. If cooling continues it is found that the air temperature gradually approaches dew-point. On some occasions fog forms when they are equal. On other occasions air temperatures and dew-points may be equal for some time (perhaps for a few hours) and although both continue to fall fog may not form. On some occasions, just before fog forms, screen temperatures and dew-points become rather erratic with sudden variations superimposed on the general fall. These variations may be due to horizontal movements of air with variations of temperature and dew-points due to local characteristics. After a period with coincident temperatures and dew-points it is often found that, if fog forms, it does so quite suddenly and visibilities can be reduced from a value in excess of 1,100 yards to one as low as 220 yards in a period of about 15 minutes. This rapid decrease in visibility cannot be explained by gradual condensation on sea-salt nuclei

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whose radii might be expected to increase steadily when relative humidities were sufficiently high to cause condensation to occur on them. A gradual increase in radii would be accompanied by a corresponding gradual decrease in visibility but a sharper more sudden reduction in visibility seems to occur — particularly in country districts with relatively small concentrations of smoke particles. In some localities where the atmosphere is very heavily polluted with smoke particles and other products of combustion, some fogs do show a rather more gradual thickening which seems to be associated with the gradual condensation on suitable nuclei and accumulation of pollution in the lower level of the atmosphere. Nevertheless any adequate explanation of the formation of fogs must account for the sudden formation often observed in relatively clean atmospheres.

Best²⁷ has considered theoretically the rate of growth of a drop of salt solution in an atmosphere with which the drop is not in equilibrium. His treatment is too theoretical for any direct application to forecasting but he was able to show that a droplet of radius 2μ with a sodium chloride nucleus of mass 10^{-14} grams, when exposed to an atmosphere at a temperature of 10°C . (50°F .) and relative humidity maintained constant at 100.1 per cent, would grow to a droplet of radius 5μ in a time rather less than three minutes (157 seconds). Visibilities in fogs are roughly inversely proportional to the square of the radius of the droplets so that, if these presupposed conditions pertained in a fog and if the droplets were of uniform size, visibility could be reduced in about three minutes to $4/25$ of its initial value. This yields a possible explanation of the sudden growth of fogs provided the relative humidity can be regarded as constant. In his investigation of radiation fogs at Cardington, 1951–54, Stewart²⁵ has discussed the rapid formation of fog and considers that conditions of constant relative humidity are unlikely to pertain during the period when droplets are growing rapidly. He replaced the condition of constant relative humidity by one of constant temperature and derived some equations for the rate of growth of droplets by taking into account the radiative cooling of the droplets when exposed to the clear skies before a fog forms. He found that there seemed to be a critical size of droplet beyond which the radiational cooling became important. Thus droplets above the critical radius could be cooled rapidly by radiation so that the surrounding air would then be supersaturated with respect to the cooler droplet which would then grow rapidly in size. This critical radius of the droplet was about 1.5μ and Stewart calculated that the rate of growth would be about 1μ in four minutes. This rate of growth was very much less than that deduced by Best²⁷ but it is still a rapid rate of growth. A droplet of radius 1.5μ would be increased to 5μ in about 14 minutes, that is, the visibility could be reduced in a ratio of $2.25/25$ or to about $1/10$ of its initial value in about 14 minutes.

There must be a limit to this period of rapid growth since fog droplets do not indefinitely increase in size. In the mechanism suggested by Best²⁷ a decrease in the supersaturation would check the growth so that the droplets could remain in equilibrium. Stewart²⁵ suggested a different possible explanation. Rapid growth depended on radiational cooling of the droplets so that the surrounding air was supersaturated with respect to the temperature of the droplets. As the fog thickened the fog droplets near the fog top would effectively shield other droplets in lower layers from radiational cooling and their growth would be checked. The fog, however, might continue to grow deeper.

In atmospheres which are heavily laden with smoke pollution the formation of water fog is often less rapid. Visibilities are however poor to start with and may reach fog limits due to the accumulation of pollution well before any fog droplets are formed. A possible explanation of slower fog formation is that the heavy concentration of smoke pollution in the lower layers reduces the radiational cooling

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of the ground but permits a slow cooling of the deeper air layer which contains the haze. This causes the growth of fog droplets to take place over a longer period. This slower formation of fog may not always occur and forecasters should not place undue reliance on its occurrence on any one occasion. Furthermore it is emphasized that this slower rate of formation does not mean that visibilities in smoke-laden air will not drop to very low limits. Some of the densest fogs occur when dense water fogs form in association with heavy atmospheric pollution in and to windward of large industrial areas.

17.5.2 Cooling and fog formation on some other radiation nights

The essential characteristic of the cooling described in Section 17.5.1 was that it originated at ground level and spread upwards quite slowly during the night except during the time when the fog was forming and deepening. Stewart²⁵ observed another characteristic type of cooling. On some occasions the air temperature fell at roughly the same rate at all heights up to several hundred feet or even 1,000 feet. When fog formed on these occasions, it did so in a fairly deep layer; sometimes it appeared as low cloud which quickly extended downward to the surface. These cases were most marked when the wind was fairly strong, particularly when it blew from the North Sea, and in these circumstances the fog might perhaps be better classified as advection fog. But similar characteristics were noticeable in light wind conditions whenever there was an appreciable subsidence inversion. It is clear that the existence of a subsidence inversion does not constitute a forecasting criterion for this type of behaviour but the information has been included so that forecasters may recognize such cases when they occur and so accumulate an experience of such situations. Further research and experience may lead to the formulation of reliable rules for forecasting this type of fog (or the onset of low stratus).

17.5.3 The extent and rate of growth of fogs in the vertical

Where fog at ground level has formed to a sufficient density, the fog droplets act as a cloud and shield the ground from further outgoing long-wave radiation. The main radiating surface is then transferred from the ground to a level within the fog layer. Thus the air near the fog top is cooled by radiation and this cooling can be quite rapid – as much as 4°F. in about 30 minutes (see Chapter 14, Section 14.7.5). As the fog deepens the effective radiating surface is transferred to higher levels.

There are very few statistics relating to the depths of radiation fogs or their rate of growth in the vertical. Leaving aside the very shallow ground fogs, many radiation fogs occurring as a result of cooling during a single night probably have a depth of about 100 to 500 feet but a few may be as thick as 1,000 feet or so. Stewart²⁵ obtained some measurements of the heights of fog tops at Cardington but his observations were made mostly at two- to three-hour intervals so that the detailed growth of these fogs was not known very precisely. From some curves showing the height of fog top against time Stewart concluded that "there is apparently little tendency for fogs to grow deeper steadily throughout the night; the more typical behaviour is a fairly rapid growth at first, followed by a more or less static period and a final brief period of upward growth as a preliminary to the dispersal of the fog by rising wind and temperature." Examination of the curves shows that although this sequence occurred in some cases, there were others when fogs did deepen at a fairly steady rate after formation. In the present state of knowledge it is clear that any estimate of the probable depth of a fog must be approximate. Only if the moisture content of the lowest few hundred feet of the atmosphere shows a very marked diminution with height can the top be estimated within close limits with any confidence.

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17.6 FORECASTING VISIBILITIES

17.6.1 *The basic assessment*

Visibilities are so dependent on other meteorological conditions that one of the first principles is that most of the elements of a forecast must be determined before final estimates of future visibilities can be made. Forecasters with only a little experience soon realize that a forecast of a visibility, say, 200 yards or four miles at any particular time or place may well depend on the absence or presence of a layer of cloud, a surface wind direction, a change in the humidity as air is advected over wet or dry ground or a sudden cooling of warm air over a cold sea. The following procedure should normally be followed before forecasting visibilities:

- (i) Analyse the latest synoptic charts and consider (or prepare) suitable forecast charts.
- (ii) From (i) determine the fronts (if any) and air mass(es) which will affect the forecast area and examine available reports of visibilities on the fronts and in the air mass(es). If no recent observations are available (for example, a narrow warm sector over the sea) an estimate must be made from general climatological knowledge of such air masses and physical principles.
- (iii) Forecast wind directions and speeds in the lowest 2,000 feet.
- (iv) Forecast temperatures and dew-points in the lower levels and assess the stability of the air.
- (v) Forecast cloud amounts and heights and precipitation.

Having made the above forecasts it is then necessary to assess the effect on visibility. The effect of various meteorological conditions on visibility is discussed generally in the following sub-sections which should assist forecasters to make that assessment.

17.6.2 *Visibilities and air masses*

17.6.2.1 Warm air masses. Warm air masses reaching the United Kingdom direct from their source regions seldom have very good visibility. They are usually stable in their lower levels (see Chapter 14, Section 14.8.1) and fairly humid. A typical visibility would be about five to ten miles. If the dew-point of the warm air is above the temperature of the sea, visibilities may be reduced below fog limits, a typical visibility at sea being about 500 to 1,000 yards. Near exposed coasts, where topography may cause a limited forced ascent of very moist air and so enhance the concentration of condensed water on the fog droplets in a sea fog, visibilities in fogs can fall to very low limits – sometimes to a few yards. Except over frozen or snow-covered ground advection fogs are rare on low ground inland. Occasionally in winter with snow lying, the advection of warm moist air over the snow surface can lead to fairly prolonged thick fog (and extensive stratus cloud). Warm air may also reach the United Kingdom from a general south-easterly direction, having originated over North Africa or the Mediterranean. This type of air is usually fairly dry in its lower layers which show marked stability and there is extensive slight haze, typical visibilities being around five to ten miles. Atmospheric pollution collected during the passage across Europe may also contribute to somewhat lower visibilities in this air in southern and eastern England.

17.6.2.2 Cold air masses. Cold air masses arriving over the United Kingdom direct from their source regions with a depth of several thousand feet have good visibilities (apart from local reductions due to showers etc., – see Section 17.6.9

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below). Visibilities usually remain good as the air crosses the country since instability and convection are normally sufficient to distribute through an appreciable vertical extent any atmospheric pollution which may be collected over industrial areas. Typical visibilities would exceed 15 or even 20 miles. Some cold air masses reach this country from a westerly or south-westerly point after a prolonged track from their source region over the North Atlantic Ocean. The air mass is transformed by its long sea passage and visibilities are usually not so good but they do not normally decrease to typical values for warm air since the cold air retains some instability. Ten to fifteen miles would be typical values in "clean" localities but these might be reduced to about four to six miles in the lee of extensive industrial areas.

In winter, cold air masses sometimes reach the United Kingdom from an easterly direction – particularly during cold spells in a prolonged easterly situation. The source region is the Eurasian land mass and the air is of continental type. Such air reaching south-eastern and southern England has usually had a relatively short sea track and atmospheric pollution acquired over Europe may restrict visibilities to a few miles. Elsewhere the longer track over a relatively warm sea is usually sufficient to disperse the pollution through a greater vertical extent and visibilities are normally about five miles or above. In this type of air, visibilities can be reduced below fog limits during moderate or heavy snow (see Section 17.6.9 below).

17.6.2.3 *Older and intermediate air masses.* In practice forecasters have to deal with air masses which may have reached this country after long and devious routes from their source regions. Cold air may have burst south across western Europe in the rear of an eastward-moving depression and after remaining perhaps several days over southern Europe may reach the United Kingdom from a southerly or south-easterly direction. Another example would be warm air which had been carried well towards the Arctic Circle turning south and arriving over the United Kingdom from a northerly point. It is clear that the characteristics of the air masses will have been changed by exposure to those processes which, over a prolonged period, change one air-mass type into another. The infinite variety of tracks by which air masses reach this country and the time which has elapsed since leaving their source regions make any general comment on visibilities in such situations almost impossible. Visibilities likely to be experienced must be assessed from any recently reported visibilities in that air mass amended according to the physical processes which are likely to occur and also in the light of synoptic climatological experience.

17.6.3 Visibilities and fronts

As fronts move through reasonably open country under the influence of a fairly vigorous wind régime, the post-frontal air mass completely replaces the pre-frontal air mass quite quickly often within a few minutes of the frontal passage at the surface, and the problem of forecasting the visibility is in the main solved by timing the arrival of the fronts. In hilly country, however, the terrain sometimes delays the complete change of air mass in valleys and this may affect the visibility. The effect is so variable that each locality must be considered specially by the forecaster. In certain synoptic types in winter, a range of hills to windward may effectively prevent warm air for several hours from penetrating to ground level in the low-lying land to the lee of the hills, as described in Chapter 14 Section 14.11.3. In such types bad visibilities are often associated with the pre-frontal cold and very stable air due to radiation fog and/or heavy atmospheric pollution. The passage of a warm-type front at the level of the

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hill tops does not imply an immediate change of air mass at ground level over the lee ground, and the timing of the change of air mass and therefore of the visibility is a matter of some difficulty. The Vale of York is prone to this type of occurrence with high pressure to the east, a light southerly gradient and a warm-type front crossing the Pennines with a light south-westerly wind.

This sequence of events does not usually occur with cold-type fronts since the post-frontal cold air is usually denser than the pre-frontal air and is also accompanied by mechanical turbulence and convection. It may, however, occasionally occur when the pre-frontal air has been cooled by radiation from the ground so that it is slightly colder than the post-frontal cold air in the lowest layers. The front acts primarily as a cold front but, in those layers nearest the ground which affect the visibility, the advent of the post-frontal air can be delayed.

Although genuine frontal fogs are rare in the British Isles the existence or likelihood of pre-frontal, frontal or post-frontal fogs should be considered. Where these fogs form it is nearly always due to the effect of precipitation in modifying temperatures and dew-points of the air in the layers near the ground, as described in Section 17.4.3. If the precipitation is sufficiently prolonged the air becomes saturated, cloud forms and under suitable conditions this cloud extends downward to the surface. The most suitable conditions are usually found near slow-moving warm fronts when warm rain falls from the warmer air aloft through the underlying wedge of cold air. Cloud builds downward to ground level and reduces visibility to a few hundred yards. Once formed, these conditions tend to persist for several hours and move slowly with the front. The area of this frontal fog is not however always constant or static and an extension of the rain area or an increase in the intensity of precipitation may extend the frontal fog quickly forward at a speed well in excess of the frontal movement.

17.6.4 The effect of surface wind direction

Surface wind directions must be carefully considered and forecast so that assessments can be made both of the track the air will take as it moves to the forecast area and the changes in concentration of atmospheric pollution which will occur during that movement. The former is inherent in many forecasting problems and is not further discussed here. The changes in atmospheric pollution can be assessed in only a qualitative manner on the forecast bench. Each area or spot locality must be considered separately and it is very useful to display in the forecast room a map which shows the major smoke-producing areas, their distances and bearings. The precise format and scale of such maps is a matter for local discretion. For the more distant sources it will usually be sufficient to indicate the more extensive areas producing smoke pollution, namely, the greater London area and areas with many heavy industrial plants in neighbouring towns and cities concentrated in certain localities, for example, various centres in the Midlands, around Sheffield, Lancashire, south-west Yorkshire, Durham, Scottish lowlands etc. For more detailed forecasting for particular localities it will often be necessary to indicate individual towns of medium size within a radius of perhaps 10 to 20 miles. For very small areas (for example, airfields) individual factory sites, from which heavy pollution is emitted, may cause marked deteriorations in visibility with wind directions between close limits.

An examination of past records of visibilities and wind directions (and speeds) should be made to see if a limited range of visibilities is associated with some wind directions and speeds. This is often the case and it is then

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usually possible to inscribe on a chart legends which describe, in as condensed a version as possible, the relation between visibility and wind for that location. A consideration of this chart and of the degree of pollution (or the reported visibilities) in the air before it passes over the polluting areas to the forecast area, the extent of turbulence, convection etc., usually leads to a close estimate of the forecast visibility. This type of diagram is discussed more fully in Section 17.11.

17.6.5 The effect of wind speed

The time required for smoke to be carried from its source of production to the forecast area depends closely on the speed of the wind. The speed of the wind also determines the time during which the air remains over the smoke-producing area so that the concentration of pollution in air near the ground is less with a stronger wind. Visibilities are seriously reduced by smoke only when the air is thermally stable at some level(s) in about the lowest 2,000 or 3,000 feet. In such circumstances the wind speed exerts a secondary effect on visibilities due to the association between an increase of wind speed and the increase of turbulence of the air flow in the lower levels. In general, the stronger the wind the greater is the turbulence and the greater also is the vertical depth through which the flow is turbulent. Thus with strong winds atmospheric pollution is dispersed through a greater vertical depth so that, other conditions being the same, ground visibilities are better with strong than with light winds. However, in the haze layer horizontal visibility at levels between about 500 and 3,000 feet above the ground may be poorer when the wind is moderate than when it is light. The upper limit of the haze layer is generally known from the height of the inversion or very stable layer and the haze just below the inversion is often more dense than at levels a few hundred feet lower. This is probably due to the higher humidity there but may arise from differences in trajectory at the various levels.

17.6.6 The effect of temperature and the stability of the air

If convection is taking place from the ground to some upper level, vertical motions distribute smoke pollution throughout that layer. When that layer is several thousand feet deep visibilities are usually good. In some situations a shallow unstable layer may be overlain by a markedly stable layer and on such occasions thick haze in the unstable layer may persist. A thermally stable stratification near the ground provides the most favourable conditions for dense smoke haze and for fog.

It is important that the variation of temperatures and thermal stabilities in the lowest few thousand feet of the atmosphere should be carefully estimated before forecasts of visibilities are prepared. Using techniques described in Chapter 14 the times and levels at which a lapse changes to an inversion or vice versa can usually be estimated so that an assessment can then be made of the time and nature of changes in the visibility.

The most striking effect of changing temperatures on visibilities is shown by the formation and dissipation of radiation fog. Techniques for forecasting radiation fog are discussed at length in Sections 17.7 and 17.8.

17.6.7 The effect of dew-points

The dew-point is one of the most important factors in determining the temperature (and hence the time) at which fog will form. Changes in the dew-point arising from vegetation, the ground or water surfaces may need to be taken into account. Dry air a few hundred feet above the surface appears to discourage

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fog formation and practical forecasting rules which take into account the surface dew-point and the hydrolapse are given in Section 17.7.

17.6.8 The effect of cloud

Clouds affect visibility indirectly through their effect on the radiation balance and the temperatures in the lowest layers of the atmosphere. It was shown in Chapter 14 that a layer of thick low cloud greatly restricted diurnal ranges of temperature due to its effect on both long- and short-wave radiation. Clear skies by day and night are usually associated with large diurnal ranges in temperature since incoming solar and outgoing terrestrial radiation are not impeded by clouds. The effect of thin high clouds is small. Moderately thick layers of medium cloud or broken low or medium cloud exert an intermediate effect. The effect of clouds on visibilities is considered through their control on temperatures.

17.6.9 The effect of precipitation

As precipitation falls through unsaturated air it evaporates and both increases the humidity and lowers the temperature of the air through which it is falling until saturation is reached. If rain is warmer than the air through which it falls, distillation may take place from the raindrops with recondensation on suitable nuclei producing fog or low stratus as described in Sections 17.4.3 and 17.6.3. When continuous snow falls for several hours through air with a dew-point higher than 32°F. the air is usually cooled to about 32°F. There is then supersaturation and fog usually forms. Lumb²⁸ has described the formation of such a fog which occurred at Little Rissington.

The liquid droplets or solid particles which are present in the air during precipitation have a direct obscuring effect. Sizes and distribution of sizes of droplets of precipitation are not observed as routine and there is no quantitative technique for forecasting the reduction in visibility during precipitation. Wright⁹ made some calculations of the deterioration in visibility during precipitation and concluded that a visibility of about 12 to 30 miles would be reduced by moderate rain to between about 2 and 6 miles and by exceptionally heavy rain to 2,200 to 4,400 yards. A visibility of 2 to 6 miles would be reduced by moderate rain to 2,200 to 4,400 yards and by heavy rain to 1,100 to 2,200 yards. Little information is available on the reduction in visibilities due to the presence of drizzle droplets. Thick drizzle often seems more effective than moderate rain in reducing visibilities but the extent of the direct contribution due to the presence of the droplets – rather than secondary effects, for example, modifying humidities of the air – is not known.

Reduction in visibility during showers may be estimated from a broad comparison of the expected intensity of the shower. During very heavy showers (which may or may not be accompanied by hail) visibilities may fall below one mile.

In moderate or heavy snow, visibilities are generally reduced below 2,000 yards and when the flakes are large and numerous, visibilities are sometimes as low as 100 yards. On some occasions very slight snow falls from stratocumulus sheets and this type of snow is usually comprised of thin small dry flakes. Such snowfall reduces visibility only slightly. Although periods when snow is lying on the ground are fairly infrequent in this country, it should be remembered that strong winds can raise loose surface snow and cause blowing snow which may reduce visibilities. Local variations of ground contour sometimes produce funneling effects which should be considered when deciding which localities may be affected by blowing snow.

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As precipitation droplets fall through polluted air they may capture and carry to the ground some of the impurities present. Little is known about the effectiveness of this washing out process which should normally be ignored in short-period forecasting.

17.7 FORECASTING THE FORMATION OF RADIATION FOG

17.7.1 General

As early as 1917 Taylor²⁹ examined the formation of fog and mist at Kew and produced some diagrams which had prognostic value. Work on the investigation of fog in the United Kingdom has been continued by a number of workers, some of whom have made detailed observations of temperatures and humidities in the lowest layers of the atmosphere (often as part of a larger investigation). Other workers have examined various techniques which might be of value as an aid to the forecasting of fog.

An account of a sustained investigation of the physics of formation of radiation fog in the United Kingdom has been given by Stewart.²⁵ Experiments were made at Cardington over the period 1951–54 and, by means of apparatus installed on towers or carried aloft by tethered balloons, measurements were made of some of the physical variables at frequent time intervals at various heights. It was hoped that this detailed information would shed general light on the understanding of fog formation and possibly lead to a more accurate forecasting technique. Although the experiment could already be described as being on a considerable scale and of considerable complexity, Stewart found that some of his observations were neither sufficiently frequent nor of sufficient accuracy to permit a quantitative assessment of the importance of various physical processes in the formation of radiation fog. The investigation also failed to produce an improved technique for forecasting. Although the investigation produced disappointing results from the forecasting viewpoint practising forecasters should study the report as it conveys a useful insight into the problem.

17.7.2 Some available techniques

It is fairly easy to recognize by about midday, from synoptic charts, when the ensuing night may be a typical radiation night and the problem of forecasting radiation fog resolves into a detailed assessment of the temperatures and water content in the lowest levels of the atmosphere during the night. Some techniques seek to do just this. Others use diagrams on which a critical curve is shown so that with points falling to one side fog is to be expected and to the other – no fog. A variety of parameters has been used and some techniques will now be described in detail.

17.7.2.1 The Craddock – Pritchard³⁰ technique. This technique is based on a statistical investigation. A brief description of the method of investigation was given in Chapter 14, Sections 14.7.2.1 and 14.7.2.3 relating to the forecasting of screen and grass minimum temperatures. The authors examined the fog-point (that is, the temperature at which fog was expected to form) for nights during which there was no considerable change of air mass. As the fog-point is not an observed meteorological quantity the authors studied its variation over substantial areas of England. They concluded that "there did seem to be some tendency towards uniformity of behaviour, with regard to fog formation, in geographical areas up to about the size of East Anglia, but even in such areas, the fog point at individual stations was often 2–3°F different from the mean value,

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while the time of formation [of fog] might vary among the stations by several hours. The inference is that a forecast of fog point should apply to a single station only, and take account of conditions at that station. If instead a single fog point is assumed to apply to an area, then the area should be the appropriate geographical district, such as East Anglia, the Upper Thames basin or Lincolnshire and East Yorkshire, and the forecast should be worded to suggest degrees of fog incidence, so as to allow for the local variations which will certainly occur."

The formula for the fog-point is:

$$T_F = 0.044T_{12} + 0.844D_{12} + 2.60 \quad \dots (11)$$

where T_F is a first assessment of the fog-point, T_{12} is the screen temperature at 1200 G.M.T. and D_{12} is the dew-point at 1200 G.M.T.

The value of T_F so calculated is modified by adding a correction from Table 17.3 to make allowance for different values of mean geostrophic wind speed, G , and cloud amount, C .

TABLE 17.3 Mean value of correction to add to T_F to allow for different values of mean geostrophic wind speed, G , and cloud amount, C

Cloud amount*	Geostrophic wind speed (kt.)*	
	0-12	13-25
<i>oktas</i>	°F.	°F.
0-2	0	-3
2-4	0	0
4-6	+2	+1
6-8	+3	+1

* Mean of values at 1800, 0000 and 0600 G.M.T.

The calculation of the fog-point by this method is carried out as follows:

- (i) Take the observed values of the dry bulb and dew-point in the screen at 1200 G.M.T. (if a forecast is required before 1200 G.M.T. these values must be estimated).
- (ii) Calculate T_F by means of equation (11).
- (iii) Forecast the mean geostrophic wind speed and cloud amount during the night.
- (iv) Obtain a correction from the appropriate part of Table 17.3.
- (v) Add this correction to T_F to obtain the final estimate.

Having obtained the fog-point it is necessary to determine the minimum temperature during the night. If this is expected to be equal to or below the fog-point an estimate must then be made of the time at which the air temperature will reach this value so that the time of fog formation may be forecast.

An examination of two years' data showed that there was no critical value of the difference between the screen minimum and calculated fog-point which separated foggy nights from non-foggy nights, and when the screen minimum is within $\pm 3^\circ\text{F}$. of the calculated fog-point, there is considerable doubt whether fog will or will not form. This is unfortunate since the critical occasions are often among the most difficult to forecast. The authors point out that the performance of the method can be improved on by forecasters by taking into account the variation of dew-point with height (as revealed by a representative radio-sonde ascent), the state of the soil and the nature of atmospheric pollution. None of these parameters

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appears in the formula. Some further improvement may be achieved for particular locations by making a further empirical correction.

17.7.2.2 Saunders' technique. Saunders³¹ technique differs from that of Craddock-Pritchard³⁰ in that it makes use of the variation of dew-point and dry-bulb temperatures with height on the 1500 G.M.T. tephigram.

Saunders examined some 48 occasions of fog at Northolt during the period August 1948 to November 1949 and found that a constant mixing ratio line through the fog-point (T_f) intersected the 1500 G.M.T. dew-point curve on a representative radio-sonde at a level very close to the afternoon condensation level of air at screen-level temperature and dew-point. Further examination of cases enabled some refinements to be added so that a close estimate of the fog-point could be obtained from a construction on the afternoon tephigram. The refinements consist of minor modifications to reported dry-bulb and dew-point curves. The constructions on the tephigram to obtain an estimate of the fog-point are described below.

(i) Dry-bulb curves (Figure 17.2). — The corrected surface temperature (T_c) is obtained by following the dry adiabat of the lowest potential temperature in the layer affected by diurnal heating down to the surface pressure, that is, it effectively ignores super-adiabatic layers near the surface, that is, in type I the dry-bulb temperature T is taken but in type II, T must be reduced to T_c by constructing the dry adiabat through the lowest potential temperature.

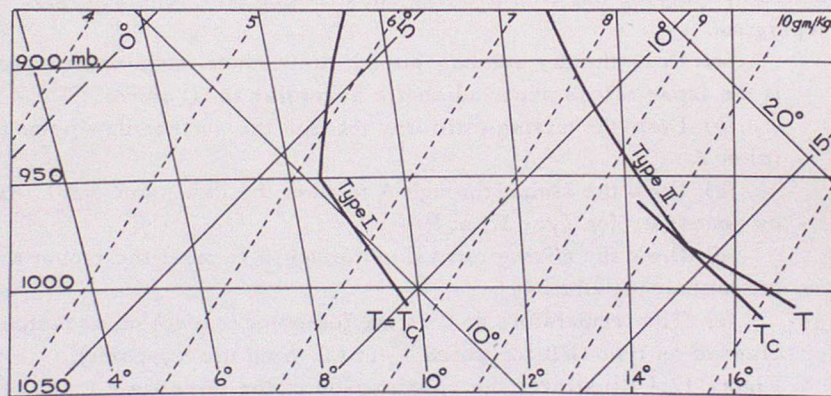


FIGURE 17.2 Dry-bulb curves, 1500 G.M.T.

(ii) Dew-point curves (Figure 17.3). — Saunders noted three main types of dew-point curves. These are reproduced in Figure 17.3.

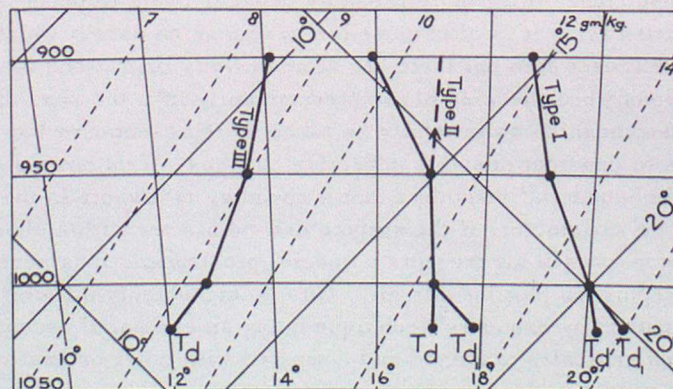


FIGURE 17.3 Dew-point curves, 1500 G.M.T.

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Type I: As a result of heating and turbulence, moisture has become distributed to give a constant hydrolapse. The surface value of the dew-point (T_d) may be in alignment with the higher values or may be displaced a little to the right (T_{d_1}) in harmony with a super-adiabatic lapse rate of the dry bulb.

Type II: The hydrolapse increases above some point in the lower layers. This may occur when subsidence extends down to this level or a dry air-stream is flowing over a moister current. To obtain consistent results in the construction described below the hydrolapse in the lower moister air must be produced upwards in its own direction.

Type III: The lapse of dew-point in the lowest layer is less than that prevailing above. There are two sub-divisions.

Type IIIA: The dry bulb fails to attain the dry-adiabatic lapse rate or by 1500 G.M.T. the dry bulb has fallen slightly below a dry-adiabatic lapse previously attained and the dew-point has fallen with it. These cases are dealt with as for type I.

Type IIIB: This dew-point distribution is occasionally found even with a dry-adiabatic lapse reached or exceeded by the dry bulb when turbulence is exceptionally slight during the afternoon. This is characterized by very small values of the wind shear from the ground to 900 or 850 millibars. In these cases it seems that the surface moisture does not become completely mixed and the afternoon dew-point is itself the fog-point.

(iii) Construction on the tephigram (Figure 17.4). — The fog-point is estimated by carrying out the following construction on a representative afternoon tephigram.

(a) Draw the dry adiabat through the surface temperature — corrected if the lapse rate is super-adiabatic according to (i) above.

(b) Draw the mixing ratio line through the surface dew-point to meet (a) at A.

(c) Draw the isobar through A to meet the dew-point curve (extended as necessary for Type II) at B.

(d) Draw the mixing ratio line through B to meet the isobar through the surface pressure at C.

(e) The temperature at C is the fog-point (except on occasions classed as type IIIB for which T_d is taken as the fog-point).

Figure 17.4 illustrates the construction in the three main types of cases. Full lines indicate the dry-bulb and dew-point curves and broken lines the construction for the fog-point.

The key to success in using this technique is in the selection of a representative tephigram. With the reasonably dense network of upper air stations over the British Isles it is often possible to choose an ascent which lies upwind of the forecast area but there are some obvious limitations for areas in coastal regions when the wind blows predominantly from the sea. If there is an upwind ascent this can generally be taken as representative but it is necessary always to consider possible advective changes. If an upwind ascent is not available Saunders³¹ considers that a sounding elsewhere in the same air-stream may be satisfactory if the surface dew-points are within about 1°F. The advection of moist sea air presents a special problem and it is necessary to estimate a tephigram plot for this air. This is undoubtedly difficult and any fog-points determined by Saunders' technique using an estimated ascent should always be most critically examined and compared with other estimates of the fog-point which can be made.

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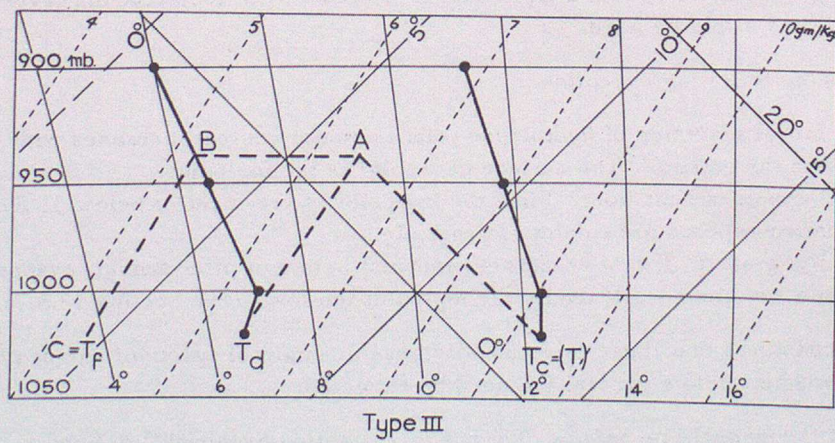
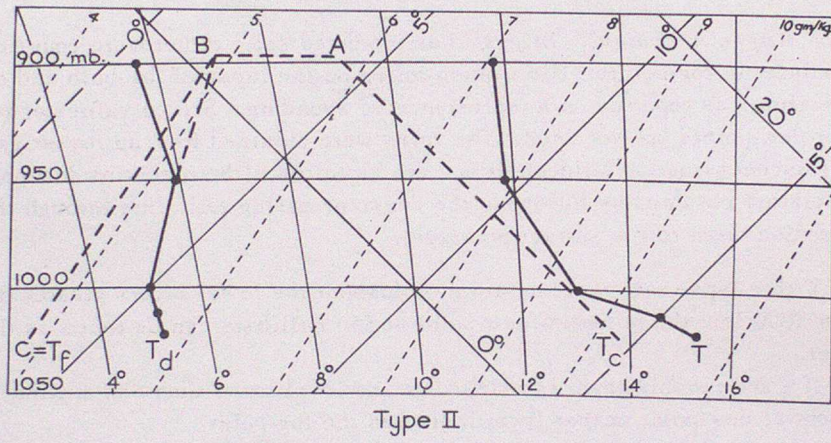
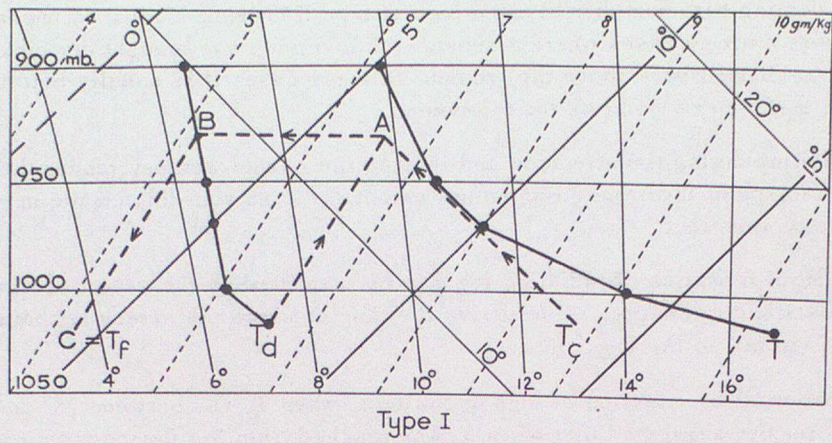


FIGURE 17.4 Constructions on a tephigram to obtain the fog-point for various types of dry-bulb and dew-point distributions at 1500 G.M.T.

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When dealing with humidity distributions of type II (Figure 17.4) it is important to note those extreme cases where a subsidence inversion has brought dry air down to only 20 or 30 millibars above the ground. In these cases it is usually better to use the surface dew-point as the fog-point.

Rain falling during the afternoon and leaving the ground wet may render the calculated fog-point incorrect. Fog-points calculated from soundings made in rain would also be incorrect.

The time of formation of radiation fog may be estimated by the use of cooling curves (described in Chapter 14) to derive the time at which the screen temperature is expected to fall to the fog-point.

In Saunders'³¹ examination of fogs at Northolt, when T_f was between 25° and 32°F., the results suggested that when T_f was reached, thin fog formed with a visibility of the order of 600 to 1,000 yards, provided there was not also thick smoke.

Informative reports on tests of the use of the fog-point in forecasting radiation fog have been compiled by Corby and Saunders³² and by Saunders.³³

17.7.2.3 Briggs' technique. Briggs³⁴ has produced some rather more empirical rules for estimating fog-points. His method relies on the lapse of dry-bulb and dew-point temperatures as reported on a representative sounding. Screen values of temperatures or dew-points are not used. The rules were obtained from an investigation of upper air ascents made at Mildenhall and are as follows (the potential dew-point is the temperature obtained by following the constant mixing ratio line through the point in question down to the surface pressure).

(i) With a lapse rate of temperature throughout the lower layers greater than 4°F. per 1000 feet the potential dew-point at 850 millibars can be taken as the fog-point.

(ii) If a more stable layer is reached at any level lower than 850 millibars the potential dew-point at that level indicates the fog-point.

(iii) If the air is definitely stable from the surface upwards then the surface dew-point is itself the fog-point.

(iv) In intermediate cases the fog-point is given by the potential dew-point at intermediate levels. With a lapse rate of 3° to 4°F. per 1000 feet the level of 900 millibars would be used.

Briggs lists the following exceptions:

(a) Initial inversion of hydrolapse (that is, water content increases with height from the ground). The surface dew-point is the fog-point.

(b) Deposit of hoar frost. When the fog-point is very near or below 32°F. fog formation appears to be delayed generally.

(c) Wet ground. If rain or showers fall just before or after sunset, evaporation from a wet ground will render the fog-point too low. (See Section 17.6.7).

Briggs considers that these rules usually have a margin of safety of one or two degrees Fahrenheit before general fog need be expected.

17.7.2.4 Swinbank's technique. For his investigation Swinbank³⁵ defined a radiation night as any night during which the cover of low cloud did not exceed one half at any of the synoptic hours of observation. High cloud was regarded as having little effect and, on radiation nights, medium cloud was uncommon. The occurrence of fog during October and November over England, south-east of a line the Wash – Birmingham – Southampton was examined in relation to observed values of the

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hydrolapse and the mean square of the wind shear between the surface and the gradient winds at selected stations for the three hours 1800, 0100 and 0700 G.M.T. On a plot of hydrolapse against mean square wind shear Swinbank was able to draw two lines which divided the plot into three distinct areas:

- A: containing occasions when fog is certain and may be widespread
- B: containing occasions when local fog only may be expected
- C: containing occasions when no fog will form

That diagram alone had considerable value for prediction but there were a few occasions when it failed due to unusually high or low initial water-vapour content of the air. Swinbank prepared a further diagram from actual occurrences of fog, obtained by plotting the occurrence of widespread fog against the mean depression of the dew-point and the hydrolapse. On this latter diagram he was able to draw a curve dividing the plot into two parts X and Y separating areas of fog from areas of no fog or only local and patchy fog.

Both diagrams were then combined in the form shown in Figure 17.5.

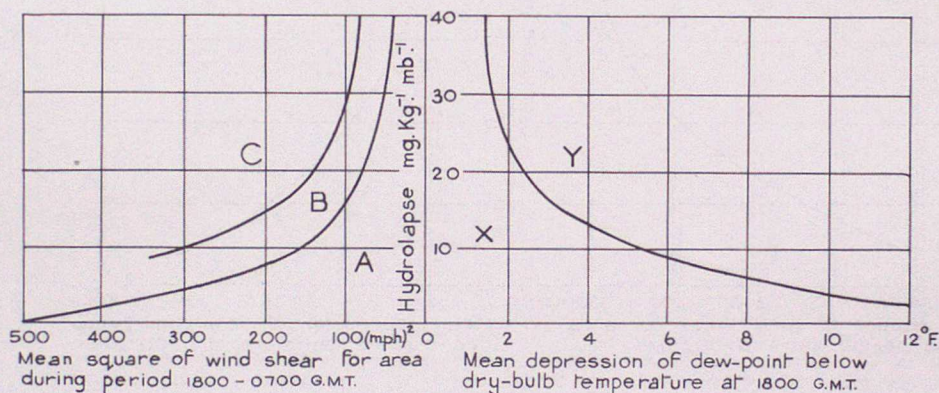


FIGURE 17.5 Fog prediction diagram for October and November over England, south-east of a line the Wash – Birmingham – Southampton

The diagram is used as follows:

- (i) Determine a representative upper air ascent for 1500 G.M.T.
- (ii) From this ascent determine the hydrolapse in units of milligrams per kilogram of air per millibar in the layer from the surface to the base of the region of markedly increased stability. If there is no region of marked stability the hydrolapse is often rather independent of height up to about 850 or 800 millibars and the hydrolapse can be readily estimated.
- (iii) Forecast the surface and gradient wind speeds for the hours 1800, 0100 and 0700 G.M.T., square their scalar differences (that is, neglect change of direction) and obtain the mean square value. (Note the shears are squared first and the mean is then taken.)
- (iv) From the observed (or forecast) values of dry-bulb temperatures and dew-points at 1800 G.M.T., compute a mean depression of the dew-point below the dry-bulb temperature for south-east England.
- (v) From (ii) and (iii) determine a point P in the left-hand diagram of Figure 17.5.
- (vi) From (ii) and (iv) determine a point Q in the right-hand diagram of Figure 17.5.

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The resultant plot should be interpreted as follows:

If P falls in area A and Q in area X then fog will develop and there is about an even chance that it will be widespread.

If P falls in C and Q in X or if P falls in A and Q in Y then fog may or may not develop. If it does develop the fog will be patchy or local.

If P falls in C and Q in Y then fog will not develop.

If P falls in B and Q in X local fog is more probable than if P fell in C.

If P falls in B and Q in Y even local fog is improbable.

Swinbank³⁵ prepared another diagram for the Lincolnshire and Yorkshire area for the months of October and November. This is reproduced as Figure 17.6.

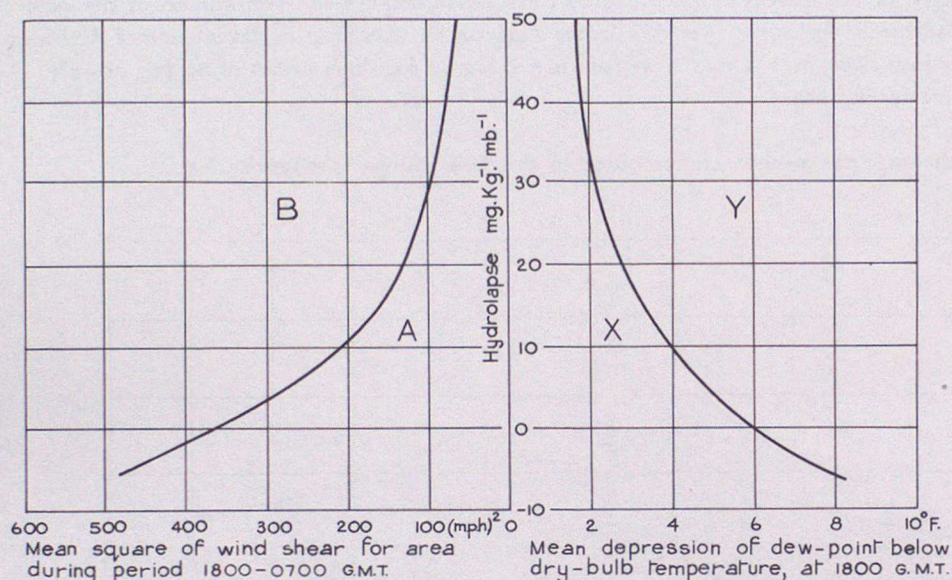


FIGURE 17.6 *Fog prediction diagram for October and November over the Lincolnshire and Yorkshire area*

On the left-hand diagram only one curve is shown, separating the region of widespread fog from that of only local or patchy fog. The curve corresponds to the curve separating areas A and B in Figure 17.5. Swinbank was unable to determine an area on Figure 17.6 corresponding to area C on Figure 17.5 but area B may be regarded as one of gradually decreasing risk of fog with increasing distance from the origin. The use of this diagram is similar to that of Figure 17.5. It should be interpreted as follows:

If P falls in area A and Q in area X widespread fog is likely.

If P falls in area B and Q in area Y fog is unlikely.

In other cases (that is, P in B and Q in X or P in A and Q in Y) fog may occur but will be local or patchy.

Swinbank produced two further diagrams for use with Figure 17.6 (that is, during October and November for Lincolnshire and Yorkshire) so that an estimate of the time of fog formation could be made. The diagrams are reproduced in Figures 17.7 and 17.8

Diagrams 17.7 and 17.8 are used in the following way:

(a) Using the mean square of the wind shear during the night and the depression of dew-point below dry-bulb temperature at 1800 G.M.T. (see (iii) and (iv) above) determine a point in Figure 17.7.

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(b) If the point falls in A or B a value corresponding to the pecked lines is determined – say R.

(c) Use R and the hydrolapse determined in (ii) above to determine from Figure 17.8 the time of fog formation in hours after sunset.

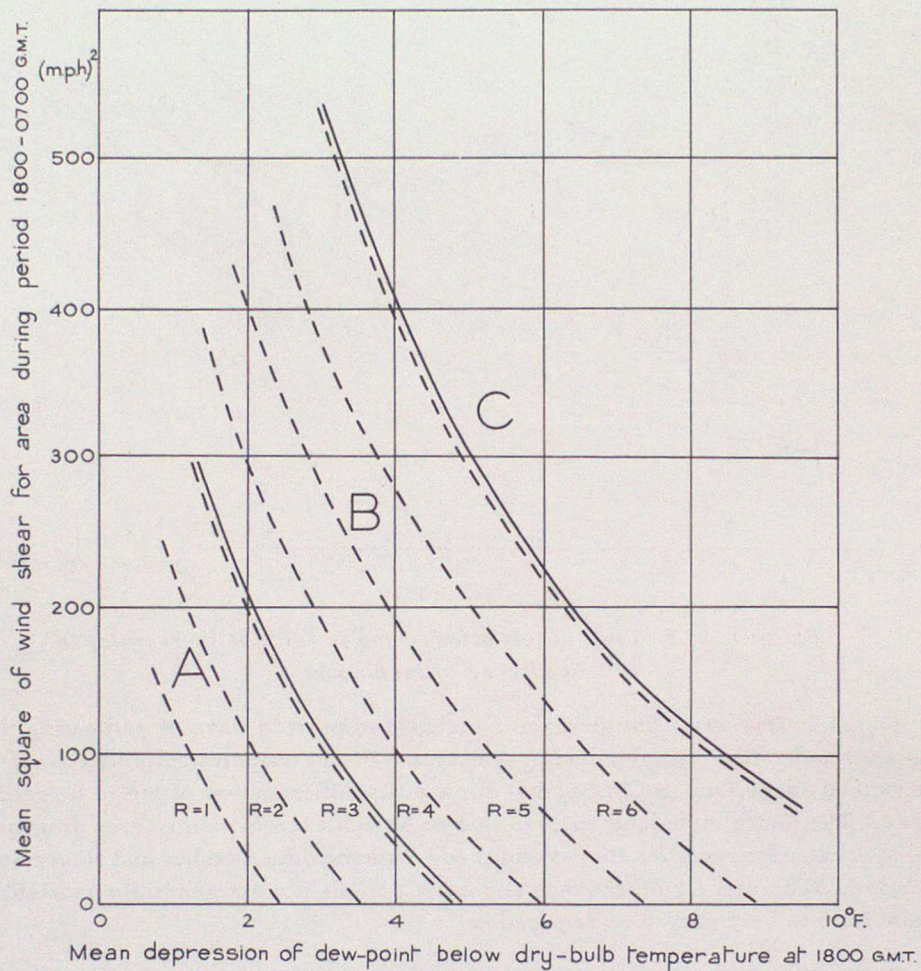


FIGURE 17.7 Incidence of fog in Lincolnshire and Yorkshire

A = widespread fog; B = patchy fog; C = no fog.

The pecked lines divide the diagram into zones in which the combined effect of wind shear and depression of dew-point on the time of formation of fog is practically constant.

The interpretation to be placed on the times so obtained is implicit in the conventions adopted to construct the diagrams. These conventions were, if point P fell in area A on Figure 17.7 (that is, widespread fog probable) the time was taken as that when fog had formed at half the stations and when P fell in area B (local fog) the time taken was the mean time of occurrence at stations reporting fog. Forecast times obtained by the use of these diagrams must be interpreted similarly.

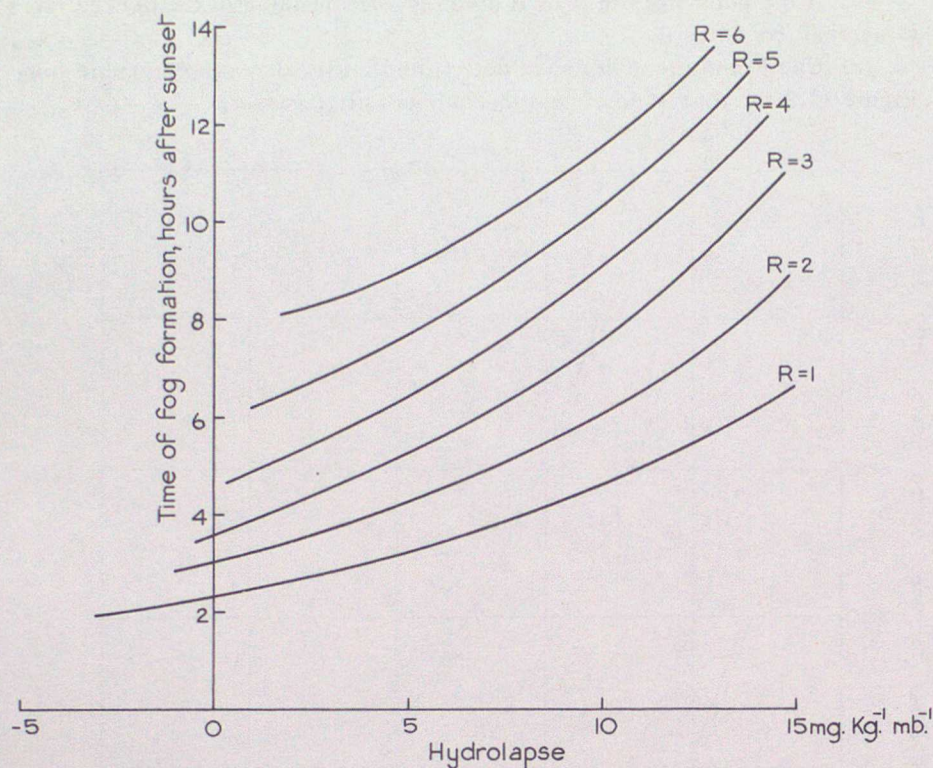
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FIGURE 17.8 *Time of formation of fog in relation to hydrolapse and zone of incidence*

17.7.2.5 *Summary.* The first three techniques provide ways of estimating the fog-point and, where combined with an estimate of the temperature profile made by the methods described in Chapter 14, allow a time of formation of fog to be determined. The fourth technique enables this to be achieved by using three diagrams, and specimen diagrams for Lincolnshire and Yorkshire for October and November are included. Diagrams for other areas and other periods are not generally available and would have to be prepared as required.

It is recommended that forecasters should regularly practise at least two techniques but not to the complete exclusion of others. Empirical methods inevitably have limitations and constant use of techniques coupled with a knowledge of the local characteristics of the location or area to which the forecast refers should enable the forecaster to make judicious adjustments on individual occasions. The less favoured technique may well prove valuable when the familiar and favoured techniques occasionally yield rather disappointing results.

17.8 FORECASTING THE DISSIPATION OF RADIATION FOG

In the day-time fog is often dispersed by incoming solar radiation; at night it may disperse when outgoing radiation is cut off by a layer of cloud; and at any time it may be cleared by an increase of wind or the advection of drier air.

Jefferson³⁶ has suggested a rule for forecasting fog clearance on cloudless mornings. It depends on the estimation of the probable rise in temperature which would be expected to occur if there was no fog and the sky was cloudless and the application of a "delay factor" which the fog is expected to exert on the rise of temperature. From an examination of a representative tephigram and any available

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reports (or estimates) of the fog top, a screen temperature, T_c , can be estimated which will show a dry-adiabatic lapse rate to the level of the fog top. This is the temperature at which the fog is expected to disperse. If this assessment of the temperature required is made on the basis of reports of the fog top which were made at or before dawn, forecasters should make some allowance for the possible upward extension of the fog layer due to increased turbulence expected after dawn.

To forecast the time of fog clearance an estimate is required of the time at which the screen temperature (T_c) will be reached, making allowance for the decrease of incoming solar radiation at ground level due to the presence of the fog. Jefferson has suggested how this can be attempted in an approximate manner. Figure 17.9 illustrates the method.

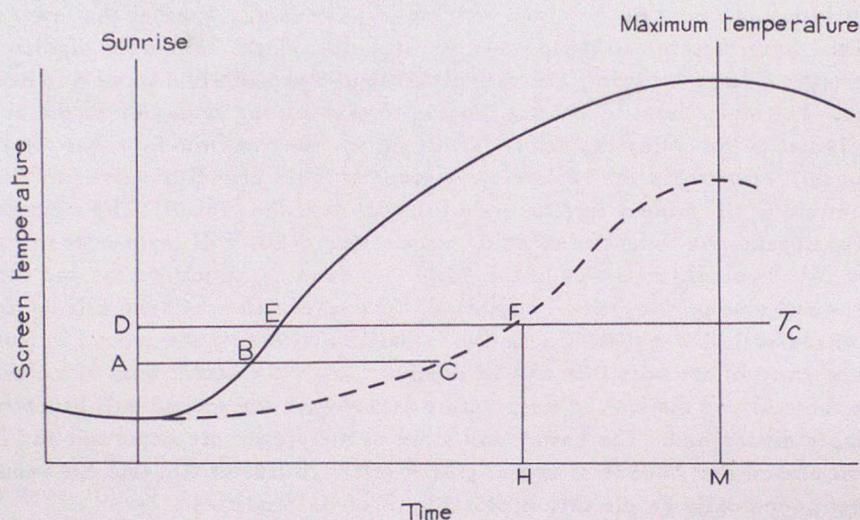


FIGURE 17.9 *Corrected forecast-temperature curve*

The full line represents the forecast-temperature curve for clear mornings and the broken line the corrected forecast-temperature curve.

T_c is the critical temperature for fog clearance and the full line represents the forecast rise of temperature assuming that there was no fog and no cloud. The dotted curve is obtained from the full curve by drawing lines AB, DE etc. parallel to the time axis and extending them to C and F so that $AB/AC = DE/DF =$ the delay factor. This process is easily carried out by means of a graduated scale or by working on squared paper. It is then possible to construct the dashed curve. If the dashed curve reaches the critical temperature the time is determined. If T_c is not reached the inference is that the fog will not be cleared by solar radiation. The precise value assigned to the delay factor on any individual occasion cannot be pre-determined from information normally available in forecasting offices. However, according to Jefferson, approximations for the delay factor for typical morning fogs in autumn and spring are:

- (i) thin and shallow fogs – delay factor 35 per cent (or $BC = 2AB$ approximately),
- (ii) thick and deep fogs – delay factor 25 per cent (or $BC = 3AB$ approximately).

On cloudless days the use of these figures should provide a reasonable basis to which minor modifications can be made in the light of experience and further local investigation.

When cloud has formed or been advected over the top of the fog the estimation of the clearance of fog is more difficult. If the fog is so thick vertically that the sky is

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obscured the presence of cloud cannot be observed from the ground and the forecaster may be unaware of its existence. It may be possible to infer its presence from tephigrams or observations from locations upwind where the sky is visible, but the forecaster who is preoccupied with the consideration of clearance of fog may overlook the indications that cloud exists over a thick fog. Positive reports of the presence or absence of clouds, their thickness and heights are invaluable and forecasters are strongly recommended to ask for aircraft reports. It is not sufficient to wait for reports to be handed in; they must be sought and requests should be made in accordance with recognized procedures for such reports.

Saunders³⁷ has shown that when a sheet of cloud spread over an existing radiation fog at Exeter, the fog cleared in a large proportion of cases (40 out of 50 cases) following the arrival of the cloud, and on nearly half the nights when fog cleared it did so within one hour of the cloud arriving or increasing. Further the lower the cloud the more certain and rapid was the clearance of fog. The most significant temperature change following the arrival of cloud was usually a rapid rise near the ground. The main physical causes leading to this are the reduction of the net outgoing radiation following the arrival of the cloud cover and the fact that the heat flux is still upwards in the soil near the ground. This heat flux serves to raise the temperature of the ground surface and of the air near the ground. The magnitude of the flux depends on the differences of temperature in the soil layer near the surface and on the physical properties of the soil — its density, specific heat and conductivity — and also on its general condition. The rate of flow of heat will be more rapid if the soil is wet than if it is dry. It will be slower if the ground is frozen because some of the heat flux will be used to supply the latent heat of melting the ice in the soil and the rise in temperature at and near the ground will be correspondingly diminished. The nature and state of the ground are important and it must be remembered that Saunders' investigation refers to Exeter and that the results will not necessarily be directly applicable to other localities.

The cloud sheet also sets up downward radiation which was not present when the sky was clear. The net outgoing radiation is reduced to an amount which depends largely on the height of the cloud and its temperature.

Saunders³⁸ made a further investigation with the object of separating those cases in which fog cleared due to the arrival or increase of cloud from those in which it failed to do so. Soil temperatures were measured at a depth of two inches beneath the ground surface. The individual cases under investigation were carefully examined so as to exclude cases where the fog clearance might possibly be ascribed to the freshening of wind or to insolation. The remaining cases in which cloud sheets appeared over the fog were subdivided into occasions of clearance and of no clearance of the fog, and these cases were plotted on a scatter diagram in which the abscissae were the difference between the soil temperature at two inches and the air temperature in the screen (°F.) before the arrival of the cloud and the ordinates were cloud heights in thousands of feet. (Cloud heights were measured by searchlight.)

The results are shown in Figure 17.10 in which it appears that a line AB can be drawn to separate most of the cases in which fog cleared from those in which it failed to do so. The main result which emerges from Figure 17.10 is that continuous sheets of stratocumulus cloud which commonly occur in association with anticyclonic inversions will cause fog clearance unless initially the ground-to-air temperature difference is small.

There are several difficulties in the application of the type of relation in Figure 17.10 to forecasting at most airfields. Soil temperatures at a depth of two inches

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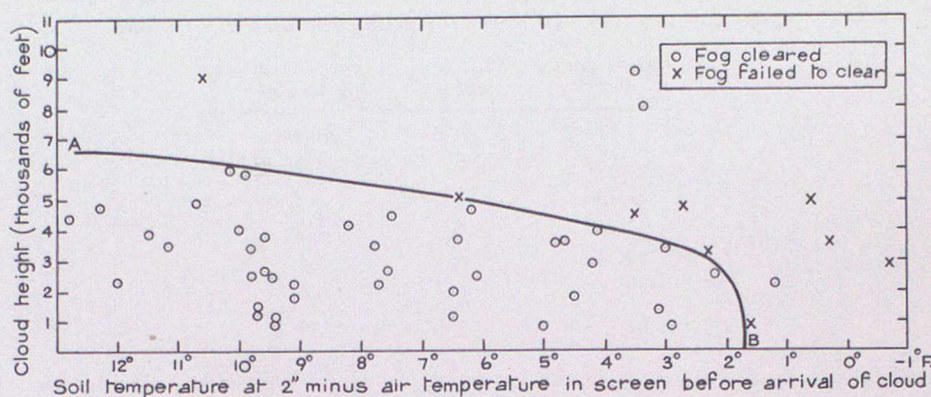


FIGURE 17.10 *The relation of fog clearance at Exeter, following the arrival of cloud, to the cloud height and the soil-to-air temperature gradient*

Three x-cases under cirrostratus cloud above 20,000 feet are not plotted.

are not measured as routine at airfields and, if observations are commenced, a period must elapse before sufficient observations have been accumulated to enable a relationship, similar to that in Figure 17.10, to be established for the particular site. In a further paper Saunders³⁹ has described a technique for forecasting the lowest two-inch soil temperature on clear nights using values of the eight-inch soil temperature (read at 0900 G.M.T. preceding the clear night) and the forecast screen minimum temperature. However, the curves derived by Saunders for Exeter are not included in the handbook primarily because observations of eight-inch soil temperatures also are not currently made as routine at airfields. Details of this method of forecasting the lowest two-inch soil temperature are contained in Saunders' paper.

If Figure 17.10 is applied for forecasting purposes at localities other than Exeter the following points should be borne in mind:

- (i) The cases included in Saunders'³⁸ investigation were those in which the fog was thin enough vertically for the arrival of the cloud to be observed. Some cases were noted where a "sky obscured fog" cleared to reveal a sheet of cloud and, while it might be inferred that the cloud had caused the fog clearance, these cases were not included owing to lack of information about the time of arrival of cloud. If these had been included, the position of AB on Figure 17.10 would have been different.
- (ii) The fogs at Exeter are water fogs. There is no reason to suppose that fog containing a higher proportion of solid particles could be cleared as rapidly or at all by the arrival of a cloud sheet.
- (iii) The line AB reflects the soil characteristics at Exeter and may be differently placed at locations on other types of soils.

Saunders³⁸ also examined the time taken for fog to clear following the arrival of the cloud. On some occasions the fog commenced to clear within a few minutes of the arrival of cloud. In general, the rate of rise of temperature near the ground will depend materially on the state of the ground and especially upon whether or not it is frozen. Saunders grouped the cases under investigation within certain ranges of grass temperatures immediately before the arrival of the cloud and computed the average time for fog to clear. His results are shown in Table 17.4.

In regard to clearance of fog due to freshening surface winds it is not possible to quote critical, precise and accurate values of wind speeds which will just cause visibility to improve above fog limits. Surface wind speeds are considerably

*Handbook of Weather Forecasting*TABLE 17.4 *Variation with grass-level temperature of time taken for fog to clear at Exeter following the arrival of cloud*

<i>Initial grass temperature</i>	<i>No. of cases</i>	<i>Average time for fog to clear</i>
^{°F.}		<i>hours</i>
<32	10	3.1
32-36	10	2.2
37-41	5	1.1
42-46	10	1.5
47-51	5	0.9
52-56	3	0.5

influenced by the stability of the lower layers of the atmosphere and by topography and, for a given geostrophic wind, there is often a large difference in surface wind speeds at different sites. The practical forecaster has to take this into account when assessing the wind which is necessary to disperse a fog. Experience suggests that the following values of the geostrophic wind speed (that is, at 2,000 feet) would be typical in the localities described.

On a flat coast: 15-20 knots
 On a "normal" site: 20-25 knots
 In a deep valley with a cross-wind: 30 or perhaps even 40 knots.

17.9 FORECASTING ADVECTION AND FRONTAL FOGS

17.9.1 *Advection fogs*

Advection fog, as its name implies, depends primarily on the transport of air from one locality to another. The forecasting of advection fog may be considered under two headings: (a) forecasting the formation of the fog in an airstream as it is cooled by the underlying surface and (b) forecasting the movement of existing fog.

Textbook descriptions of the conditions required for the formation of advection fog in an airstream may be summarized as:

- (i) Original dew-point of the air higher than the temperature of the underlying surface
- (ii) A stable lapse of temperature and only a slight hydrolapse
- (iii) A moderate wind speed
- (iv) A suitable wind direction to transport the air from the warm surface to a colder surface.

The first estimate of the region in which advection fog will form is the area where the surface temperature falls to the original dew-point of the air. If water is the underlying surface and the dew-point in the lowest few hundred feet is either fairly constant or slightly increasing with height this estimate should be a fairly good one. Dew-points often decrease with height and, although one of the necessary conditions for advection fog is that the hydrolapse should be not more than slight, the effect of turbulence in the lower levels will be to decrease the surface dew-point. The estimation of temperature (or fog-point) at which advection fog will form is then a matter for judgement. Corby and Saunders³² have suggested that the technique for obtaining the fog-point described in Section 17.7.2.2 may be used but the problem of estimating a reasonably correct upper air sounding from an extensive sea area may be a difficult one since the network

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of upper air stations is so sparse – particularly to the south and west of the British Isles. No sounding is made as routine over the North Sea but an estimate of the cooling of warm air over the North Sea may be obtained from the techniques described in Chapter 14, Section 14.10.2. Experience suggests that advection fog in oceanic air masses occurs only when the sea temperature along the air trajectory has fallen by at least 10°F.

Increasing turbulence is associated with increasing wind speeds and, where the dew-point decreases with height, drier air will be transported from higher levels to the surface thus preventing the formation of fog. Increasing wind may transform an existing fog into low stratus. Over land advection fog is unlikely if the wind exceeds about 10 knots but a sea fog with a wind of 25 knots is not uncommon.

It is convenient to consider the movement of advection fogs under two types of wind systems: (i) extensive wind systems accompanying the synoptic systems of the weather chart and (ii) local winds, for example a sea-breeze.

(i) Advection due to general gradient wind.— Advection follows closely the trajectory of the surface winds over sea areas but over land areas the movement is far more irregular and depends on topography. The existence of a range of low hills can exert a minor föhn effect, the fog on the windward side being transformed into very low stratus to the lee of the hills. Increased turbulence over the land may be sufficient also to lift the fog into a layer of low stratus. Over the land the diurnal change of temperature often exerts a considerable effect on the penetration inland of sea fog. Temperatures which will disperse the fog can normally be fairly accurately determined but their accurate forecasting demands a nicety of judgement between the restriction of solar radiation reaching the ground due to the fog and to the presence of any cloud and the rate of rise of temperature. In summer insolation is normally sufficient to "burn off" advection fog almost up to the coasts but at other seasons the relation between the temperature required to clear the fog and the available insolation is often critical. Unless there is a margin of safety of a few degrees (°F.) of temperature it will generally be unwise to make a firm and unqualified statement that the fog will clear.

The North Sea fog or "haar" which is most common along the east coast of northern England and Scotland in spring and summer often presents difficult problems to the practical forecaster. Much of the difficulty arises from the scarcity of surface and upper air reports from upwind areas (that is, over the sea) and the corresponding lack of knowledge of the position and orientation of any banks of fog (or very low stratus) at sea. The accurate forecasting of a "haar" and its spread inland requires accurate data on sea temperatures, knowledge of the existence of fog in coastal waters and extensive knowledge of local topography. A haar usually extends inland by night partly by advection but often also to some extent by formation *in situ*. By day, in late spring and summer, insolation will normally clear the fog (or low stratus) right up to the coast although, in some cases, it may be after midday before the clearance spreads back upwind to coastal areas and, if the general synoptic situation remains unchanged, there will then be but a few hours before fog (or stratus) reforms and spreads inland again.

If, from a consideration of the distribution of wind, of air and sea temperatures and of dew-points, it is decided that the haar will spread inland as a sheet of very low stratus it should be noted that visibility just below stratus sheets is usually fairly poor. As a guide it may be taken that visibility at

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levels more than 300 feet below cloud base approximates to the general visibility of the underlying air mass. Horizontal visibility deteriorates as the cloud base is approached and just below cloud base may be only a few hundred yards. Accordingly, if very low stratus (base below about 300 feet) is forecast some reduction in surface visibility should be forecast also.

It occasionally happens that a wind blows a fog formed by radiation at night over the land out to sea. When this happens in winter the sea temperature is often above the fog-point and the warmer sea will normally disperse the fog. It sometimes happens that radiation fogs drift considerable distances over slightly warmer seas before they are dispersed. Douglas⁴⁰ considers that the important factor in maintaining such fogs in existence over warmer seas is the strong radiation from the fog top which effectively disperses much of the heat supplied by the warm water to the lowest layers of the fog and which is transported through the fog by turbulence.

(ii) Advection due to local winds.— Over the United Kingdom advection of fog by a "local" wind is rather uncommon. It occasionally happens, however, that sea fog exists right up to the coastline but is not present overland (fog inland may have been dispersed by insolation). If temperatures over the land rise sufficiently a sea-breeze may be set up and this sea-breeze may cause the sea fog to cross the coastline. The sea-breeze may cause this either by the setting up of its own local circulation when there was no preceding general wind or by modifying the direction and speed of the winds maintained by the general pressure distribution.

17.9.2 Frontal fogs

Frontal fogs require a marked temperature contrast across the frontal surface so that warm rain may fall through an underlying layer of cold stable air. The precipitation must also continue sufficiently long to ensure that the cold air becomes supersaturated so that fog forms. Further, the winds must not be too strong otherwise the fog will be lifted as a layer of low stratus by mechanical turbulence. The fact that all these conditions must persist simultaneously means that frontal fogs are fairly rare. There is no known technique for application on the forecast bench and each synoptic situation must be treated on its merits.

17.10 FORECASTING VISIBILITIES IN FOGS

It is unfortunate that techniques for making a quantitative forecast of visibilities in fogs do not exist. In each case the forecaster must make a subjective assessment and the following remarks may be of some assistance, particularly to inexperienced forecasters.

17.10.1 Visibilities in advection types

For advection fogs at sea all that can be done is to forecast decreased visibilities with increased cooling of the air below its initial dew-point. When the temperature gradient of the sea surface is slight, variations from existing visibilities would be slight. Some indication of visibilities in sea fogs over the eastern North Atlantic to westward of the British Isles can be obtained from some hourly observations of visibilities in sea fogs which affected ocean weather stations Juliett and India during the summer seasons of 1957 and 1958. The distribution of observed visibilities was as shown in Table 17.5.

Table 17.5 indicates that in the majority of cases visibilities in sea fogs are likely to exceed 220 yards but lower visibilities may occur at times. There is

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TABLE 17.5 *Visibility observations in sea fogs at ocean weather stations Juliett and India during the summer seasons 1957 and 1958*

Location	Visibility (yards)				Total
	55	55-220	220-550	550-1,100	
	No. of observations				
Ocean weather station Juliett (52°30'N., 20°W.)	0	15	56	53	124
Ocean weather station India (59°N., 19°W.)	9*	48	31	31	119

* All 9 observations occurred during one spell of fog at ocean weather station India.

also some evidence that visibilities are lower in sea fogs in more northern (and cooler) waters. This would seem reasonable particularly when sea fogs were occurring in a long broad southerly or south-south-westerly current of air flowing from a region near or to south of the Azores towards Iceland and Scandinavia. When sea fogs form as a moist land-breeze crosses the coast to an adjacent cold sea and there is marked rapid cooling below the dew-point (for example, North Sea fogs in early summer) very dense fog may be quickly formed.

When sea fogs are advected across the land the topography may cause great variations in visibility. When a sea fog is subject to adiabatic cooling due to forced ascent, additional water vapour is condensed and the fog may then be much thicker – in some cases visibilities may be reduced to a few yards. Localities to the lee of hills may have better visibilities than those obtaining at sea.

Winds are associated with advection fogs and the effect of mechanical turbulence on fog is difficult to assess. Due to the greater roughness of the land, mechanical turbulence is normally greater over land than over the sea. On some occasions this increased turbulence coupled with topography may cause sea fog to be lifted to very low stratus as it is carried a few miles beyond the coastal belt.

17.10.2 Visibilities in radiation types

The techniques described in Sections 17.7 and 17.8 provide a means of forecasting the formation or dispersal of radiation fog but not of the visibilities in the fogs. The depression of the air temperature below the fog-point does not seem a particularly useful parameter and no close relationship between it and the visibility has been found. Stewart²⁵ observed during his experiments at Cardington that there was usually a rather abrupt change from a state of no fog, with visibilities of the order of 1,500 yards, to one of thick fog with visibility between 50 and 200 yards. Visibilities between 200 and 1,000 yards were rare except when fog formed at temperatures well below 0°C. Cardington may be regarded as a "country" district with the air reasonably clean, and the sudden reduction in visibility to about 200 yards is probably typical of country fogs.

In districts where there is heavy smoke pollution which is several hundred feet thick vertically, such sudden deteriorations are not always observed. The increase in smoke concentration may reduce visibility to below 1,100 yards long before the temperature has reached the fog-point. There is also some evidence that the subsequent fall of visibility as condensation takes place is also more gradual than in "clean" air.

When the fog-point is several degrees below 0°C. and a fog forms, it is sometimes quite thin – at least initially for a few hours. The smaller amount of water condensed per °C. fall of temperature at low temperatures compared with higher

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ones is one factor. The heat transfers involved in the freezing of any liquid water in the top layers of the soil and also in the direct deposition of hoar frost on the ground from the water vapour in the air are other factors. The relative importance of these factors in preventing the initial formation of thick fog is unknown.

When fog formation is definitely expected a fairly sudden reduction to values of 200 yards or below should normally be forecast except when smoke pollution is heavy and fairly thick vertically or the fog-point is well below 0°C . when a somewhat slower deterioration may take place. At this stage experience is the only factor which can indicate when this slower formation should be forecast.

When the formation of radiation fog seems marginal or when the fog-point is below 0°C ., rather thinner fogs are likely and visibilities between 200 and 1,000 yards may be forecast with some discretion and caution but, even in these circumstances, there is no certainty that thick fog will not occur.

The improvements in visibility when radiation fog is being dispersed are usually rather more gradual than during formation but the final stages in the dispersal of a water fog are of short duration. This fairly rapid increase in visibility may be due to some physical processes occurring during the evaporation of fog droplets or, where insolation causes dispersal, may be due to cumulative effect of the lowering of the albedo of fog, the penetration of more solar radiation to the ground and the consequent more rapid rise of temperature in the lower layers of the atmosphere.

On some occasions after radiation fog has commenced to thin after sunrise, there is a deterioration in visibility and the fog becomes thicker again temporarily until further insolation once again causes the fog to thin. The temporary deterioration in visibility may be due to changes in low-level turbulence or to evaporation of dew or hoar frost from the ground but the cause is not yet fully understood. The possibility of a temporary deterioration at a site should be borne in mind when giving very short-range, detailed forecasts of visibilities (that is one to two hours) in the hour or two after sunrise.

On occasions when radiation fogs are wet fogs, or the surface of the ground and objects are very wet due to deposition of heavy dew, some delay factors must also be used.

17.10.3 *Up-slope and hill fog*

Forced ascent due to the terrain may cause copious condensation of water and the formation of thick fogs on hills. In some cases visibilities are reduced to a few yards. The level at which these fogs form can normally be assessed from a representative tephigram. Forecasters should note that these fogs will not be extensive or persistent if the layer of air which is subject to forced ascent becomes convectively unstable. Whether convective instability is likely to be released from the amount of forced ascent, which will probably occur as the air surmounts the obstacle, can be determined from a tephigram according to the procedure described in Chapter 3.

17.10.4 *Frontal fogs*

Over level country visibilities in frontal fogs are often several hundred yards and, once formed, visibilities seem to vary only slightly. Local hills which cause forced ascent will experience much worse visibilities. The stability of the lower levels of the cold air in which frontal fogs form often causes

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the accumulation of smoke pollution and the reduction of visibility due to smoke must also be considered.

17.11 FORECASTING THE EFFECT OF SMOKE POLLUTION ON VISIBILITY

The extent to which smoke pollution affects visibility in any one area is essentially a local problem and it is not possible to include in this handbook detailed information for a large number of sites. The following discussion will indicate the factors which should be taken into account in assessing the effects of pollution. They are:

- (i) Thermal stability of the lower layers of the atmosphere
- (ii) Surface wind speed and associated mechanical turbulence
- (iii) Surface wind direction
- (iv) Pronounced geographical features
- (v) Variation of pollution with the season of the year
- (vi) Variation of pollution with the time of the day
- (vii) Variation of pollution with the day of the week

Factors (i) and (ii) may be discussed together. It is clear that the concentration of pollution at ground level must be closely related to the rate at which it can be dispersed vertically and the depth through which it can be mixed with the air at higher levels. On a radiation night with clear sky and little wind an inversion will develop at low levels, there will be a decrease in both the wind speed and mechanical turbulence and any smoke emitted in the air will be largely concentrated in the lowest levels. During summer any such inversion would be expected to break down by day – at least in the lowest few hundred feet of the atmosphere – and the pollution would be spread through the unstable layer. In winter the diurnal rise of temperature may be so small that the atmosphere remains thermally stable throughout the day with no variation in smoke pollution due to factors (i) and (ii) (see Chapter 14, Section 14.7.1). When such conditions are coupled with winds of only one or two knots over periods of 24 hours or more smoke fog or "smog" becomes extensive over large cities.

The effect of factors (iii) and (iv) is fairly obvious. It should be emphasized that the worst concentrations of smoke occur with almost calm or very light winds in thermally stable conditions when the smoke is confined to the lowest layers. Thus the surface wind direction is critical – not the gradient wind direction. The effect of geographical features on surface wind is often greatest under these conditions also.

The seasonal variation of smoke pollution can be considered in relation to its two prime sources: industrial processes, power plants etc. and domestic fires. Industrial smoke continues throughout the year at substantially the same level. Domestic smoke, mainly for space heating, shows marked seasonal variations. Domestic fires are normally burning from 0800 to about 2200 G.M.T. during November to March and in the evenings during the late autumn and early spring. It was seen in Section 17.3 that Wright¹² obtained some average values for the effect of domestic smoke during winter at Kew but values for other localities are not available. The relative importance of industrial and domestic smoke in reducing visibilities at any one location must be determined from a study of available observational records.

An indication of the variation of smoke pollution on week-days and on Sundays can be obtained from an investigation made by Ratcliffe⁴¹ who examined the differences in visibility between a week-day and Sunday at Finningley near to an

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industrial area. He used observations made between 0600 and 1800 G.M.T. on Fridays and Sundays at Finningley (near Doncaster) for the winter six months 1 October to 31 March for the years 1946–52. His results are shown in Table 17.6.

TABLE 17.6 *Variations in visibility on Fridays and Sundays at Finningley*

Range of visibility	Friday		Sunday	
	No. of observations	Percentage frequency	No. of observations	Percentage frequency
below 880 yd.	106	8.3	83	6.5
880 – 2,000 yd.	164	12.9	143	11.2
2,000 – 3,000 yd.	157	12.3	132	10.4
3,000 yd. – 3½ mi.	300	23.5	240	18.9
above 3½ mi.	547	43.0	674	53.0

It will be seen that Sunday, on average, has better visibility than Friday at Finningley. Visibility is 3,000 yards or less on 33.5 per cent of occasions on Friday compared with 28.1 per cent of occasions on Sunday. Also Sunday has 53.0 per cent of occasions with visibilities greater than 3½ miles while Friday has only 43.0 per cent. There was no significant difference between the periods October–December and January–March. Ratcliffe attributes these improved visibilities to much of the coal-burning industrial plant being shut down completely or considerably banked down on Saturday afternoons and Sundays. On Sundays any increase in domestic smoke is not sufficient in the Finningley area to offset the smaller amount of industrial pollution at the week-end.

The diurnal variation of smoke production from extensive industrial centres can probably be ignored. Where pollution at one locality is predominantly due to the proximity of one or two large industrial sites, some allowance can be made for the variation which would seem to be related to the period during which the plant is in full production or the fires are damped down and the plant is idle. The production of domestic smoke is directly related to the period when the fires are burning but the concentration of domestic smoke at ground level is affected by stability and turbulence. There is a smoke maximum at about 0800–1000 G.M.T. on week-days when the stability and lack of turbulence prevent the smoke from being dispersed vertically. When the turbulence increases and stability decreases the smoke is dispersed so that there tends to be a minimum around midday and early afternoon. Towards sunset, particularly on radiation nights, the formation or intensification of the ground inversion concentrates the smoke in the lower levels and there is another maximum. This later maximum may be markedly accentuated in October and April due to freshly lighted fires. Towards midnight the production of domestic smoke decreases markedly and smoke concentration decreases gradually throughout the rest of the night as smoke is deposited or carried away by the wind. The concentration normally shows a minimum around 0600 G.M.T.

At week-ends domestic fires are lit rather later in the morning so that the maximum concentration noted between 0800 and 1000 G.M.T. on week-days tends to occur rather later – say about 1000 to 1100 G.M.T.

17.12 SOME USEFUL VISIBILITY DIAGRAMS

In Section 17.6.4 it was suggested that maps showing the sources of smoke pollution and containing legends about visibilities commonly experienced at the locality with certain types of synoptic situation would be found useful. A

Visibility

number of other types of diagram which are very useful in portraying the visibility characteristics of a site have been prepared and some are described below.

Davis⁴² has produced a diagram showing the diurnal variation of fog at London Airport throughout the year. The diagram is reproduced in Figure 17.11 and the isopleths show the percentage frequencies of fog (visibility less than 1100 yards).

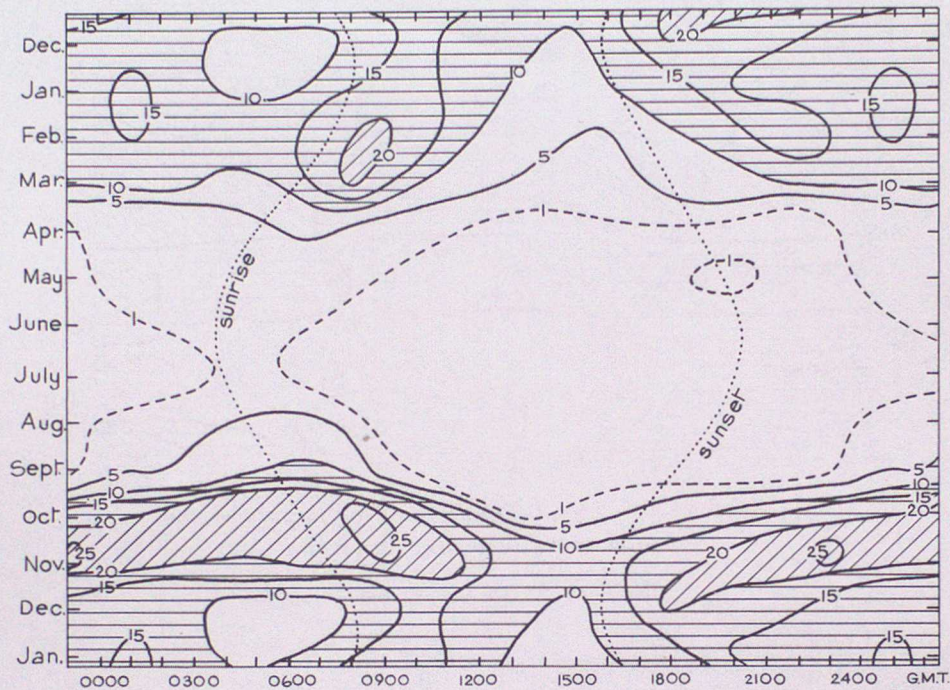


FIGURE 17.11 Diurnal variation of fog at London Airport
Isopleths show percentage frequencies of fog

Davis deduces the following salient points about the variation of fog at London Airport:

- (i) The rapid increase in fog frequency from September to October and November.
- (ii) The high frequency of fog in the mornings in October and its rapid clearance about four hours after sunrise.
- (iii) The high frequency of fog in November and its tendency to persist throughout the day.
- (iv) The relative low frequency of fog in the early hours in December and January.
- (v) The high frequency of fog in December two to three hours after sunset and to a less extent in January and February.
- (vi) The gradually increasing tendency from November to March of the fog to clear in the afternoon.
- (vii) The high frequency of fog about two hours after sunrise in February and March.
- (viii) The rapid decrease in fog from March to April.

A similar diagram for Wellesbourne Mountford (near Stratford-on-Avon) for the months September to February only has been prepared by Cleaver and Ratcliffe⁴³ and is reproduced in Figure 17.12.

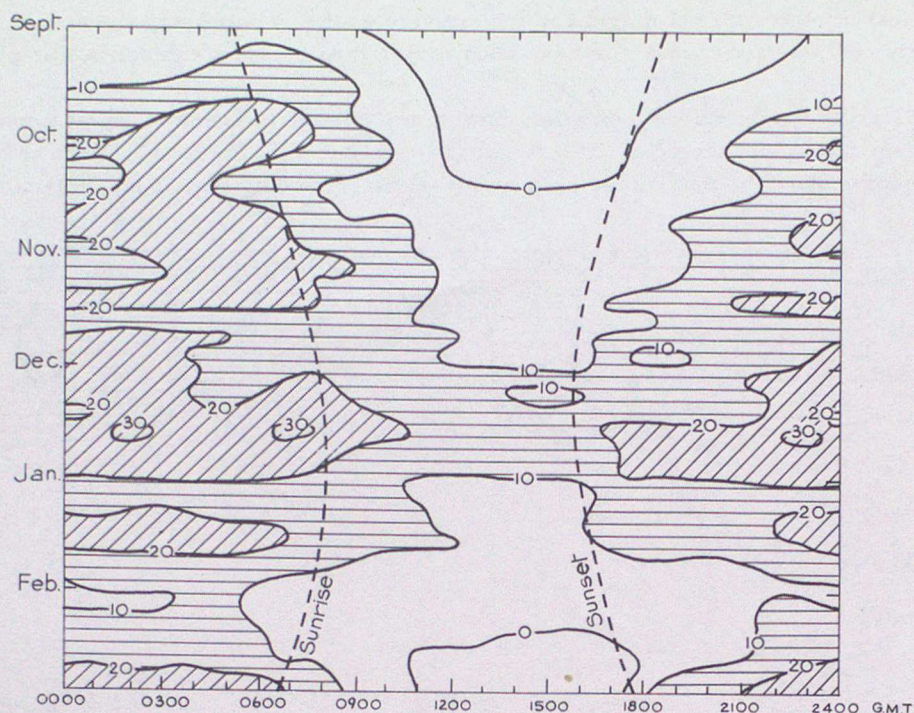
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FIGURE 17.12 *Diurnal variation of fog in autumn and winter at Wellesbourne Mountford*

Isopleths show percentage frequencies of fog

It will be seen that Wellesbourne Mountford differs from London Airport in the following respects:

- (i) Maximum frequency of fog at Wellesbourne Mountford always occurs immediately before sunrise whereas London Airport has a maximum some two to three hours after sunrise during the winter months.
- (ii) There is no minimum before sunrise in winter such as occurs at London Airport.
- (iii) There is a higher general fog frequency at Wellesbourne Mountford.

The preparation of similar diagrams need not be restricted solely to visibilities below 1,100 yards. Much useful general information can be obtained from diagrams relating to somewhat better visibilities. Using a limit of 2,200 yards diagrams for Northolt and Mildenhall were prepared by Corby⁴⁴ and Durst⁴⁵ respectively and these are reproduced in Figures 17.13 and 17.14.

Both figures emphasize some differences between these two aerodromes, namely:

- (i) The marked minimum in frequency before dawn in midwinter at Northolt and its complete absence at Mildenhall.
- (ii) The very well marked maxima in frequency in midwinter at Northolt just after sunrise and sunset. These maxima are clearly related to maxima in smoke pollution.
- (iii) The greater frequency of mist and fog at Northolt than at Mildenhall.

Visibility

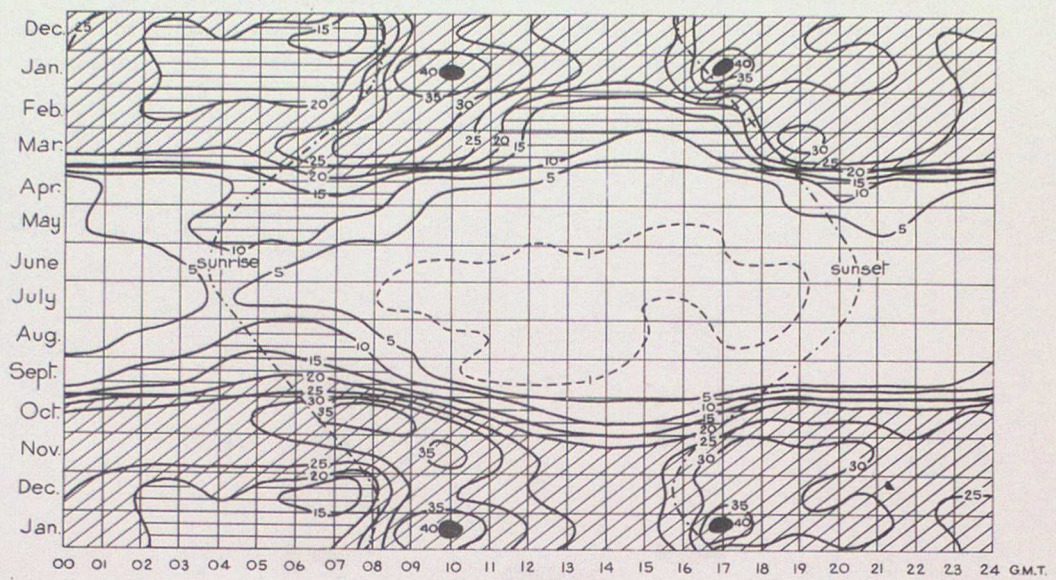


FIGURE 17.13 Diurnal and annual variation of mist and fog at Northolt based on the five years 1946-50

Isopleths show percentage frequencies of mist and fog (visibility <2,200 yd.)

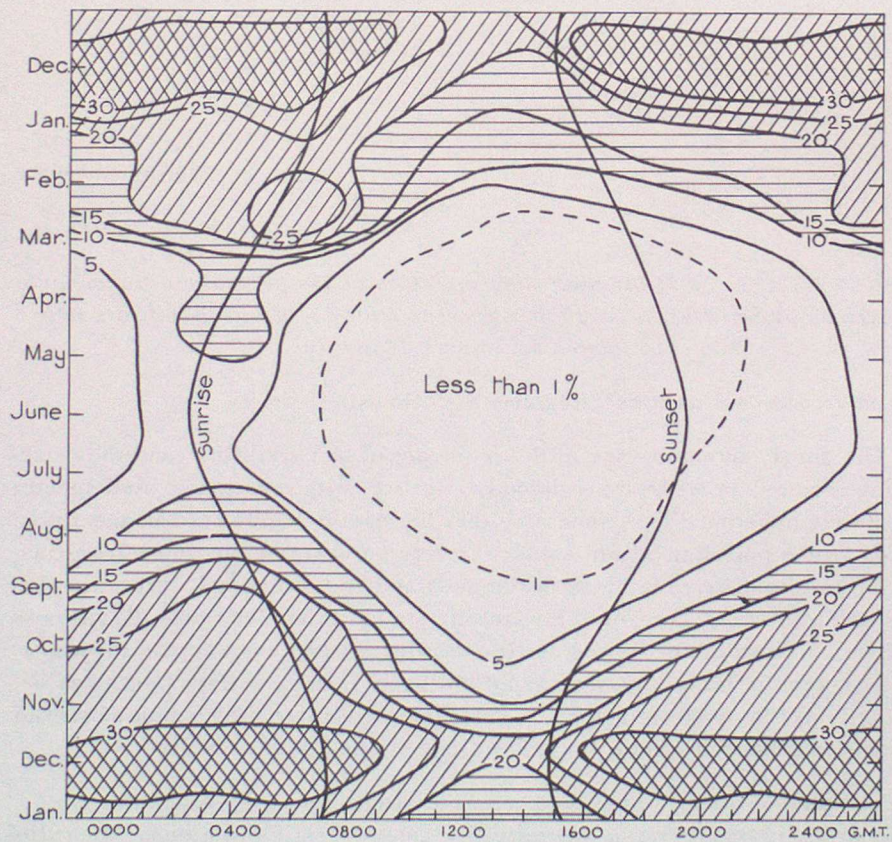


FIGURE 17.14 Diurnal seasonal isopleths of percentage frequency of mist (visibility <2,200 yd.) at Mildenhall, September 1939 - August 1945

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Corby⁴⁴ has prepared diagrams illustrating the variation of visibility at Northolt with both wind speed and direction. Two diagrams are reproduced as Figures 17.15 and 17.16 to indicate the type of representation and the information which can be obtained from them.

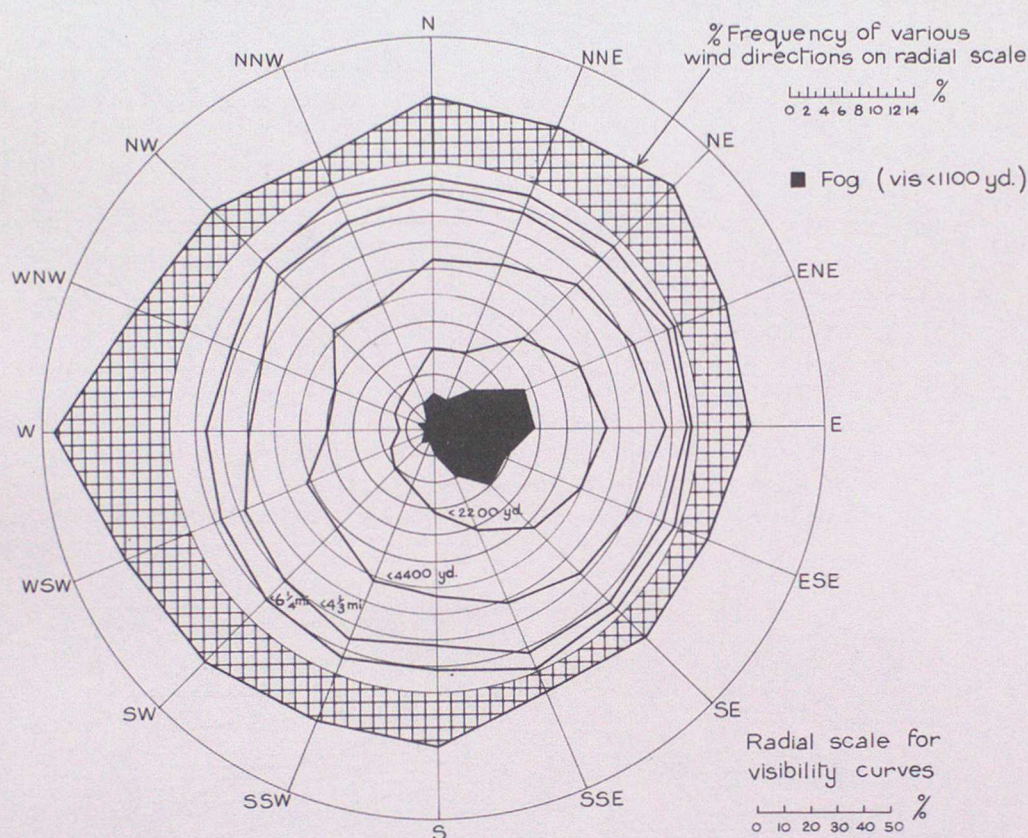


FIGURE 17.15 Variation with wind direction of the percentage frequency of various visibilities at Northolt Airport in winter – winds 1–6 knots only (based on 5 years 1946–50)

Corby comments on these diagrams as follows.

"The successive decrease in the incidence of bad visibility (and the corresponding increase in moderate and good visibility) with increasing wind speed is immediately apparent. It is seen also that increasing wind speed concentrates London smoke pollution within a successively narrower sector and intensifies still further the difference between the good and bad directions. For example, considering winds of 1–6 knots the liability to visibility less than $2\frac{1}{2}$ miles is just over twice as great with easterlies as with westerlies, whereas for winds over 11 knots the factor becomes about 43 times. Many similar effects can be observed directly from the graphs." For a more complete discussion of similar diagrams relating to Northolt the original paper should be consulted.

The value of all these types of representation lies in the concentrated diagrammatic presentation of the visibility characteristics of a site. Such illustrations are free from the personal bias which inevitably creeps in when a forecaster with wide experience of one site attempts orally to pass on to a less experienced forecaster the benefits of that wider experience. Any forecaster

Visibility

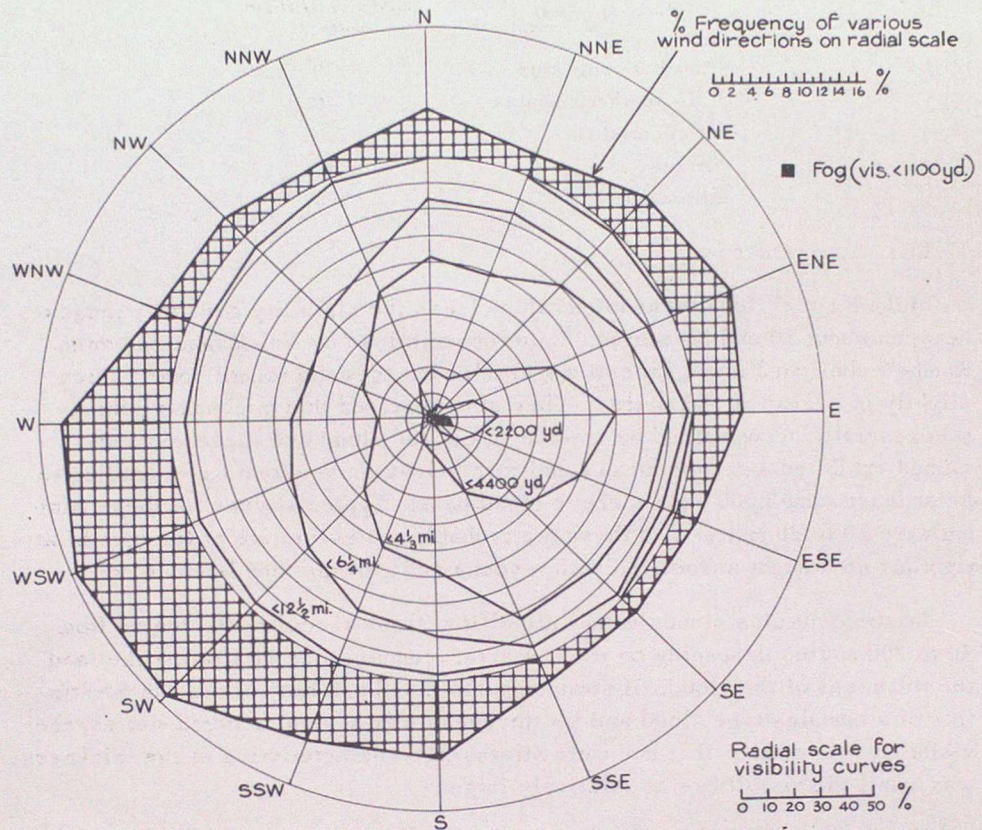


FIGURE 17.16 Variation with wind direction of the percentage frequency of various visibilities at Northolt Airport in winter – winds ≥ 11 knots only (based on 5 years 1946–50)

with no first-hand experience of the sites but who has studied carefully Figures 17.11 to 17.16 can scarcely fail to have obtained a very useful understanding of the visibility characteristics which would be extremely useful when forecasting for those sites. It is important to note that the diagrams apply only to the sites for which they were prepared and a site even a few miles away may possess important different characteristics. This is illustrated by a comparison between London Airport and Northolt which are to the west of London and less than 5 miles apart. Readers who wish to study such differences should consult a paper by Saunders and Summersby.⁴⁶ This paper refers to Northolt and can be compared with Davis⁴² work for London Airport.

17.13 VISIBILITIES IN CLOUDS

Forecasts of visibilities in clouds are not normally made but occasionally some operators ask for an indication of the visibility which may be expected in clouds. Clouds are far from homogeneous and visibilities will vary markedly both in time and place, and the figures quoted below must be interpreted with care.

Aufm Kampe⁴⁷ measured the visibility in low and medium clouds in the free atmosphere and gives the following mean values for different types of clouds.

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<i>Type of cloud</i>	<i>Mean visibility metres</i>
Cumulus congestus	20
Fair-weather cumulus	40
Stratocumulus	100
Stratus	140
Altostratus	150

17.13.1 *Low clouds*

Aufm Kampe⁴⁷ found that in cumulus clouds the visibility generally ranges between about 10 and 80 metres. Later observations by Weickmann and aufm Kampe⁴⁸ confirmed these general magnitudes but they did record some values slightly in excess of 150 metres. They also observed that minimum visibility was generally accompanied by up-draughts in the cloud and these minimum values exhibited a certain mean trend with height above cloud base, tending to be at least some 2000 metres above cloud base. Typical values for these minima were 10 to 20 metres and these are probably representative of the core of a vigorous up-draught associated with a young and growing thunderstorm cell.

In stratocumulus clouds aufm Kampe⁴⁷ found the visibility fluctuated from 30 to 200 metres depending on the character (cumulus-like or stratus-like) and the thickness of the cloud. If stratocumulus cloud had more of the characteristics of a cumulus-type cloud and its thickness was several hundred metres, the visibility was small; if it had more stratus-like characteristics or the thickness was small the visibility was relatively large.

In stratus and high fog he found that the visibility ranged between approximately 40 and 150 metres and that if the net radiative loss of heat from the top of the high fog was great, visibility could be very low. He quotes an example of a high fog in the early morning with a visibility of about 250 metres in the base of the fog and about 40 metres near the top.

17.13.2 *Medium clouds*

Only a few observations were made in altocumulus and altostratus clouds and aufm Kampe⁴⁷ found that visibilities ranged between 80 and 300 metres.

17.13.3 *High clouds*

Instrumental observations of visibility in cirriform clouds do not seem to have been published. Murgatroyd and Goldsmith⁴⁹ give the following account of visibility in cirrus cloud based on experience of flying in Meteorological Research Flight aircraft in high cloud:

"High cloud usually limits the visibility from air to ground but only when the high cloud is a continuation of medium cloud is it likely that the surface will be completely obscured. Normally the ground (or low cloud) is still clearly visible for several miles ahead when the aircraft is flying in high cloud, indeed sometimes the cloud is so thin that its presence makes little or no difference to vertical visibility. However, vertical visibility is often more limited when the aircraft is above the high cloud. This effect is similar to that of surface haze; when flying just above surface haze the ground is often more indistinct than when actually in the haze layer.

"The horizontal visibility in high cloud is a more difficult factor to estimate, but when aircraft of the M.R.F. have been forming in high cloud, although the

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horizontal visibility was more limited than in clear air, this limitation was not serious and no difficulty was experienced."

Clodman⁵⁰ has examined some 40 reports of visibilities in cirriform clouds. Many of the reports were only rough estimates so that the values given below should be regarded as approximate.

Visibility in cirriform cloud (after Clodman⁵⁰)

Visibility less than	1 mile	$\frac{1}{2}$ mile	$\frac{1}{4}$ mile
Percentage of reports	70	60	30

17.14 SELECTED SYNOPTIC EXAMPLES

Examples of visibilities in various air masses and the occurrence and clearance of straightforward radiation fogs have not been included. Even a relatively short spell of practical work will bring an abundance of such experience to any practical forecaster engaged on day-to-day forecasting. The synoptic situations which are illustrated are therefore biased towards the somewhat less usual. It is important that inexperienced forecasters should bear this in mind when a current synoptic situation bears a superficial resemblance to one of those illustrated herein.

17.14.1 *Example of extensive sea fog, 14 June 1955*

Sea fog was widespread in the western approaches and to westward of Ireland on 14 June 1955. Plate I shows the surface synoptic situation at 0600 G.M.T., 14 June. Between the belt of high pressure extending from Madeira to Western Germany and the belt of depressions extending north-eastwards from north of the Azores to Norway flowed a warm moist south-westerly airstream. The air which at 0600 G.M.T. on the 14th was located in the south-west approaches had left the region near the Azores with dew-points in the mid-sixties and fog had formed extensively at sea as can be seen from Plate I. Sea temperatures near the Azores appeared to be in the upper sixties whilst sea temperatures reported from ships in the foggy areas were in the upper fifties.

During the 14th the warm front WD and the warm air to its rear continued to move across the country. Examination of detailed hourly charts showed that during daylight on the 14th there was an occasional report of coastal fog from isolated stations in the south-west. Reports of coastal fog increased substantially after dark and by midnight fog was reported extensively on coasts of the south-west peninsula and south Wales. Inland there was very extensive low stratus cloud, bases in southern England being generally 200 to 600 feet in the west and 600 to 1,000 feet in central England, but there was no report of any substantial advection of fog inland. In the extreme east of England at midnight, cloud remained well broken and the base of the generally small amounts of cloud was 3,000 feet or above.

Figure 17.17 contains tephigrams for Valentia and at sea. These show the temperature and dew-point structure in the lowest 3,000 feet or so. No ascent from the British Isles showed an inversion from the surface upwards but it can be seen from Figure 17.17 that the air was very stable and moist from the surface to about 3,000 feet.

Visibilities in the fog at sea were reported generally as between 220 and 1,100 yards. At many of the coastal stations visibilities in fog were mainly within the range 330–770 yards but there were some reports as low as 110–220 yards.

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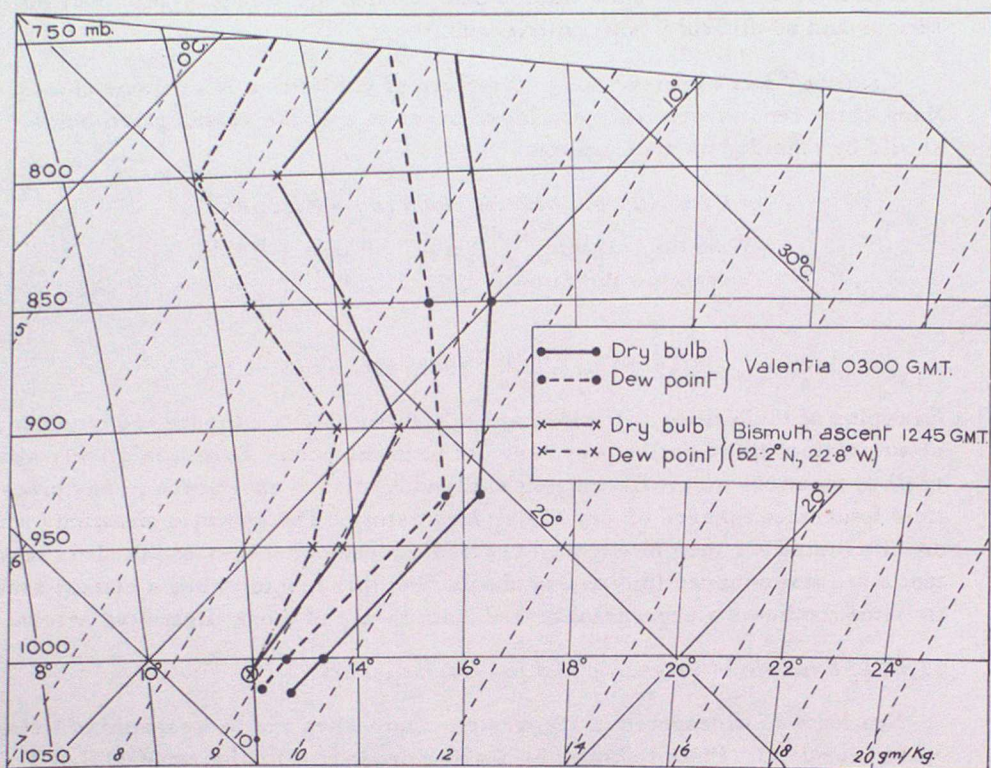


FIGURE 17.17 Tephigrams for Valentia and the Bismuth ascent, 14 June 1955

17.14.2 Example of North Sea haar, 25 August 1955

Plate II shows the detailed hourly chart for 0600 G.M.T., 25 August 1955. The ridge in the North Sea formed the western limb of an anticyclone which had been located in the North Sea – southern Scandinavia area since late on 22 August. This pressure system had maintained a general light wind with an easterly component across the North Sea since 22 August but there had been some variation in direction from time to time. The whole period was one when haars were experienced northwards of the Wash along the east coast of the United Kingdom. To the south of the Wash the short track across a sea with temperatures in the lower sixties was insufficient to form low cloud and the airstream remained virtually cloudless. The longer sea track to northward and the slightly lower sea temperatures, about sixty or just below near the British coast, caused extensive fog and/or low stratus to occur generally at sea and in coastal regions by night. Fog and low stratus also occurred well inland at night and in some places could be ascribed to advection but in others the fog and stratus probably formed *in situ*.

It will be seen from Plate II that the fog on the coasts was very dense and in general thicker than that which occurred farther inland (but it would be generally unwise to expect inland fog in such cases of haar always to be generally less dense than on coasts).

Figure 17.18 shows the early morning tephigrams for Hemsby, Leuchars and Lerwick. All three ascents showed a pronounced inversion in the very lowest layers of the atmosphere. That at Hemsby was relatively dry, whilst those at Lerwick and Leuchars were reported as saturated up to the top of the inversion

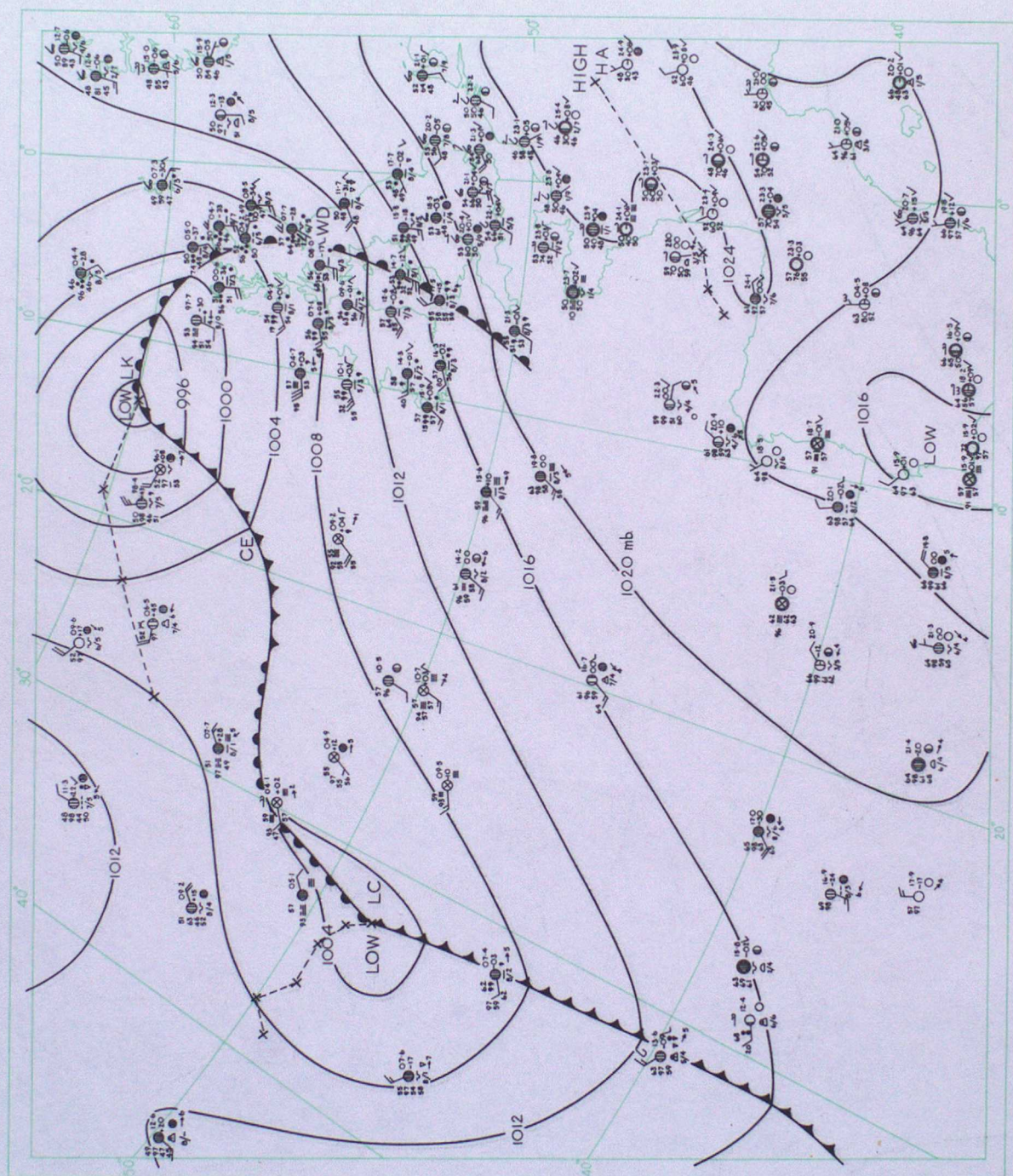


PLATE I Synoptic situation, 0600 GMT, 14 June 1955

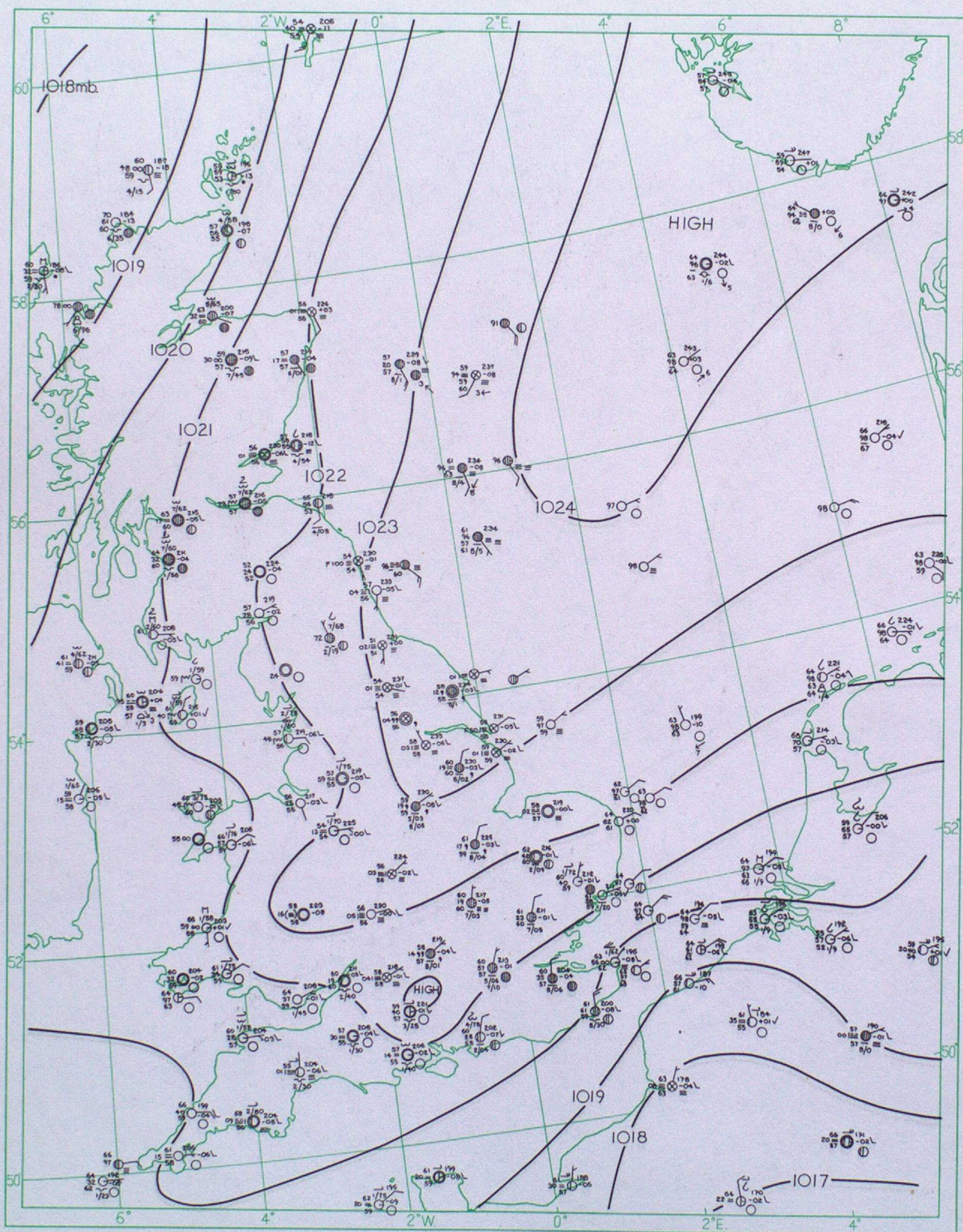


PLATE II Synoptic situation, 0600 G.M.T., 25 August 1955

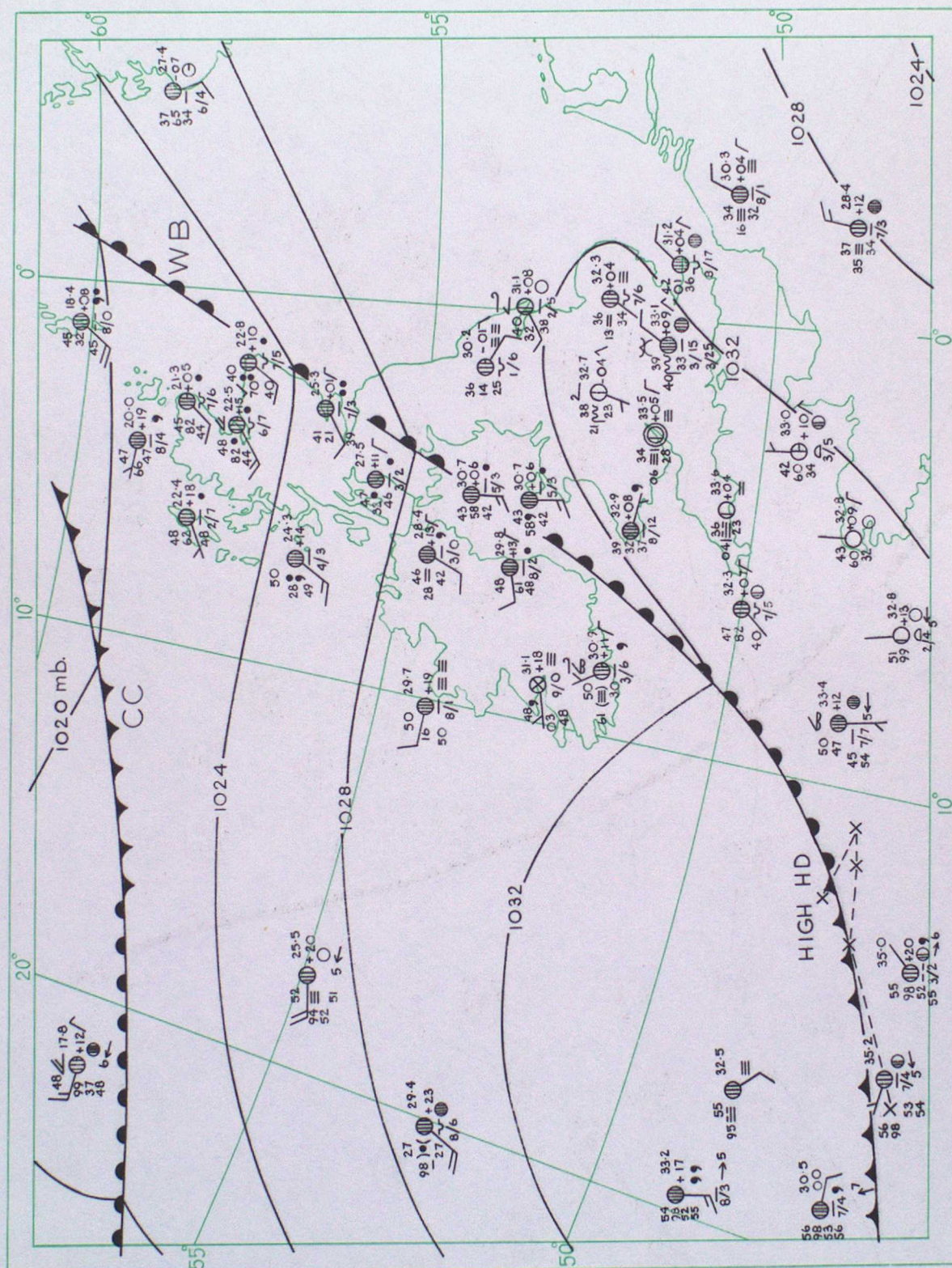


PLATE III Synoptic situation, 1200 G.M.T., 14 January 1958

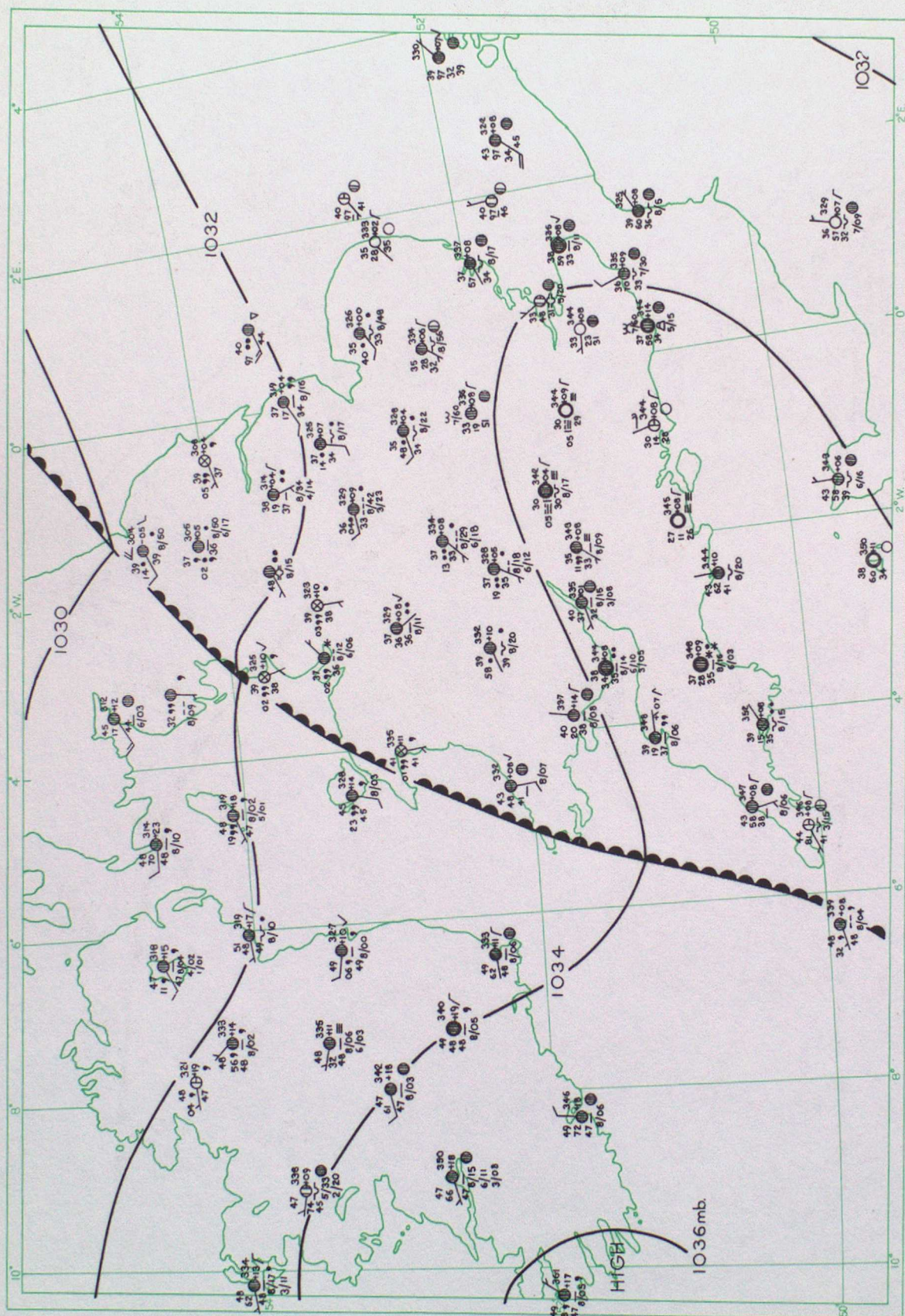


PLATE IV Synoptic situation, 2100 G.M.T, 14 January 1958

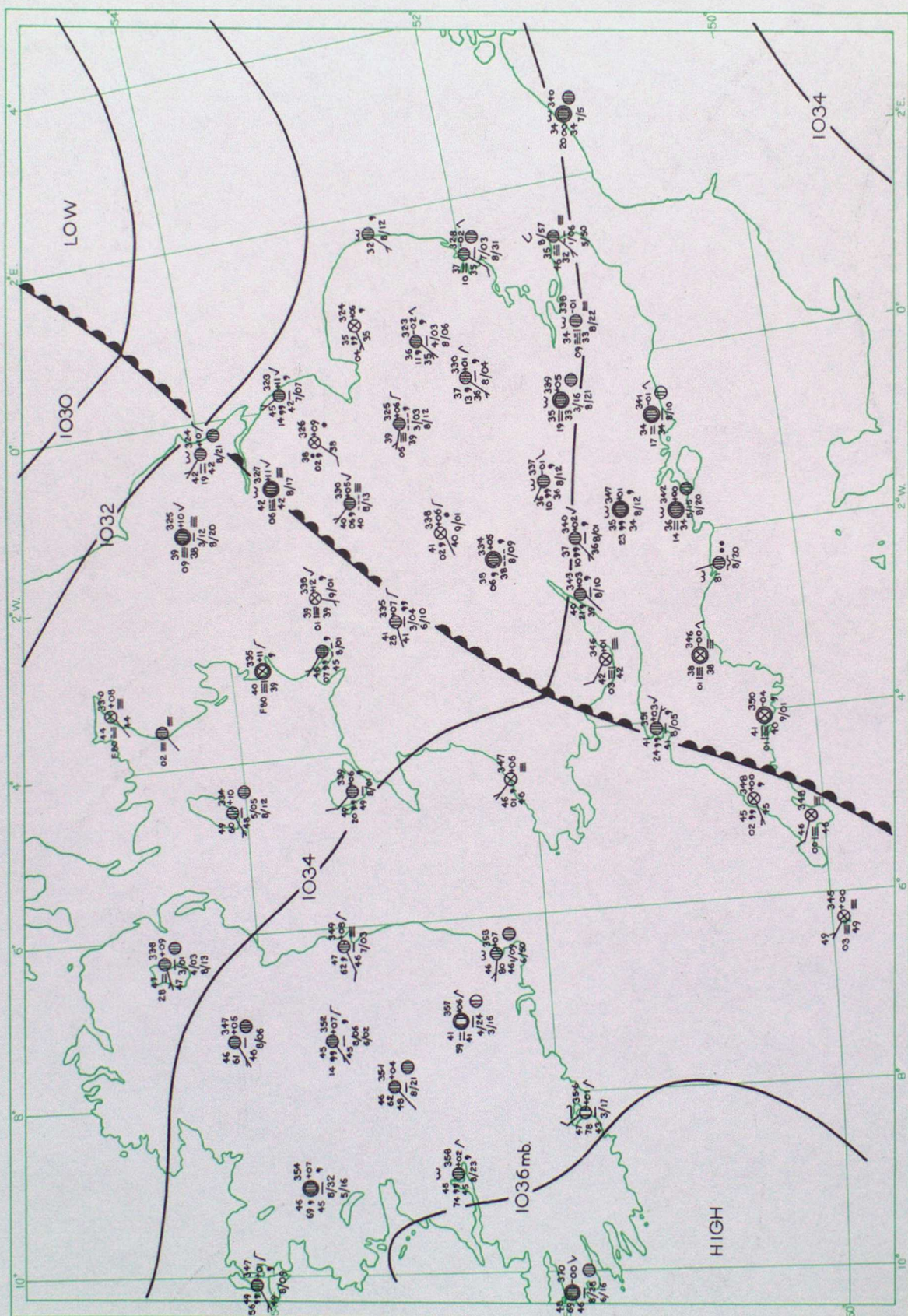


PLATE V Synoptic situation, 0400 GMT, 15 January 1958



PLATE VI Synoptic situation, 0900 GMT, 15 January 1958

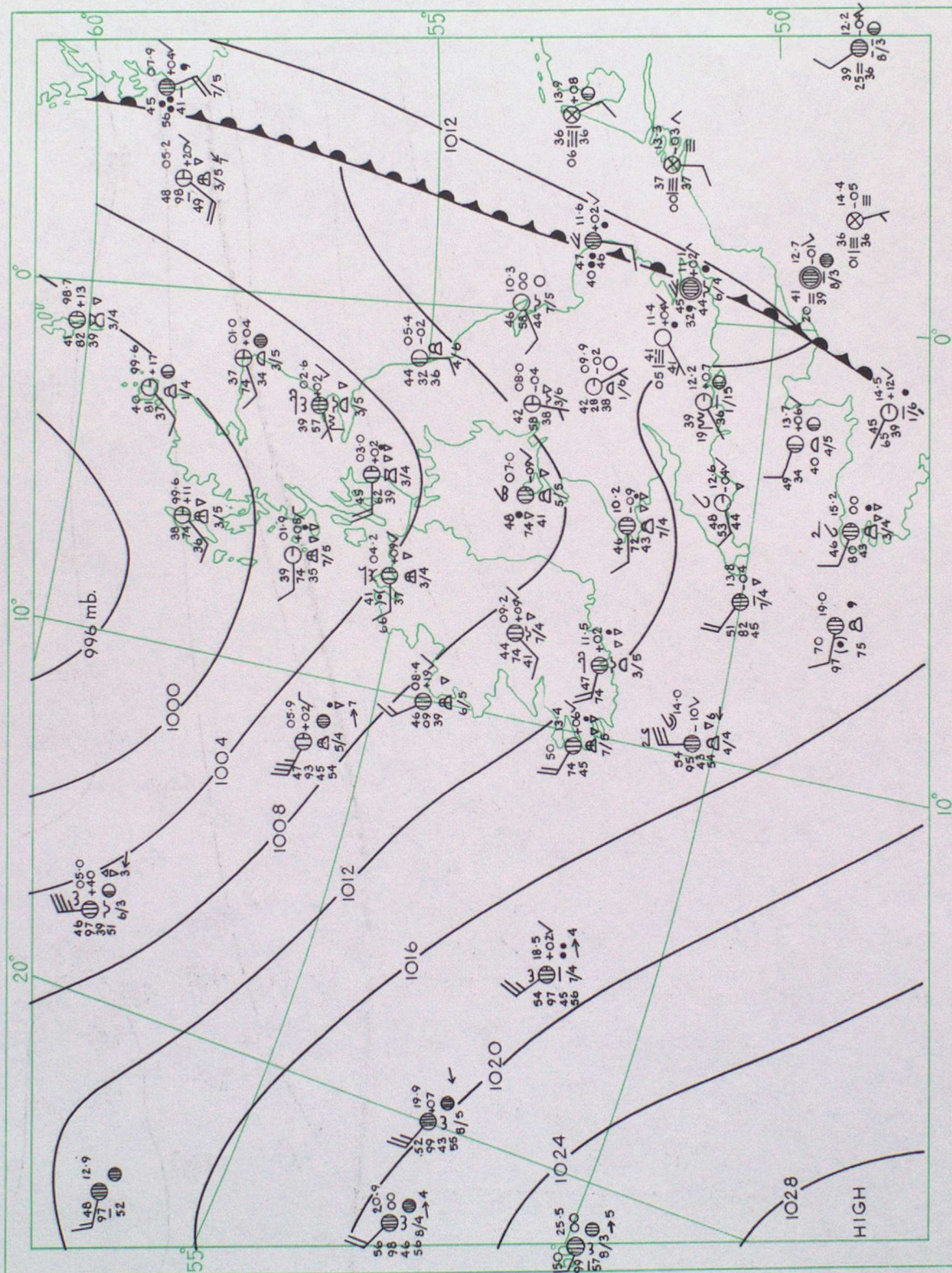


PLATE VII Synoptic situation, 1800 GMT, 12 November 1958

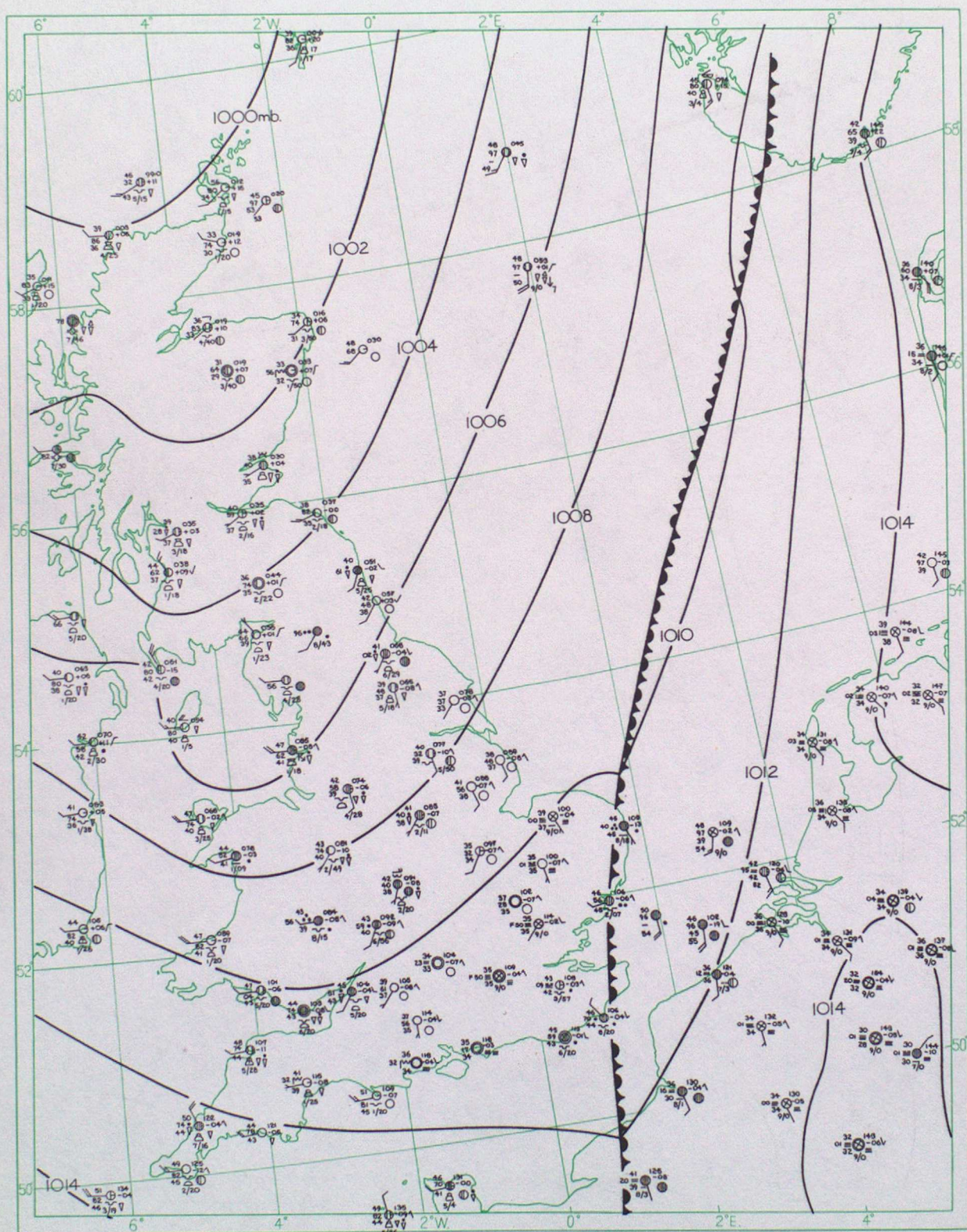


PLATE VIII Synoptic situation, 2100 GMT, 12 November 1958

Visibility

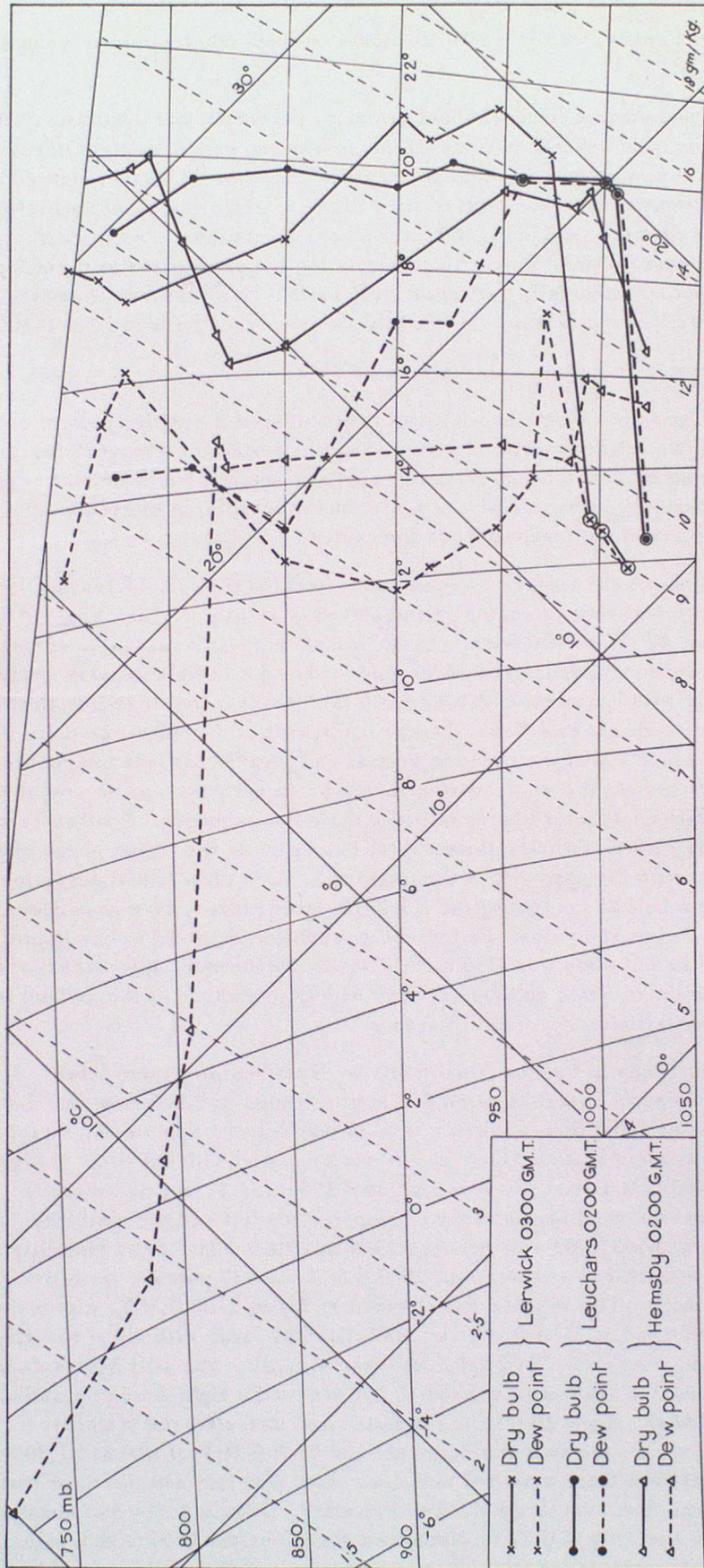


FIGURE 17.18 Tephigrams for Lerwick, Leuchars and Hemsby, 25 August 1955

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which, in both cases, was near 1000 millibars or about 600 feet above mean sea level.

The fog and stratus cleared inland generally between about 0900 and 1000 G.M.T. and by noon several stations on the east coast were also clear of fog and low stratus. Examination of the detailed hourly charts on 25 August showed that fog or low stratus continued to affect some districts along the coast until after midday. For example, at 1200 G.M.T. a few coastal stations in north-east England and east Scotland were still reporting fog but visibilities in these foggy areas had improved generally as 550 to 1,100 yards. At Tynemouth, however, the fog was still very thick and the visibility was only 60 yards at 1200 G.M.T.

17.14.3 *A complexity of fogs, 13-14 January 1958*

This situation has been chosen as an illustration of a complex pattern of variations in visibility associated with a synoptic system as it moved slowly across the country. Such complex changes are not common but some part or parts of the variations do occur at times in winter and a description of events should prove instructive to the inexperienced forecaster.

Plate III shows the surface synoptic chart for 1200 G.M.T., 14 January 1958. A ridge of high pressure extending north-eastwards across southern England and the warm front WB in its rear were both moving slowly south-eastwards across the country. In the south-east region of the ridge existed a fairly extensive stratocumulus layer with bases about 2,000–3,000 feet but near the ridge-line weather conditions were almost cloudless. To the north-west of the ridge-line there was warm-frontal cloud which increased in amount and lowered towards the position of the surface front. As the whole system moved as an entity across an area the weather conditions at many places followed a similar sequence. Conditions were mainly cloudy with visibilities about two to four miles in the region ahead of the ridge-line but with the approach of the ridge-line, skies cleared and dense fog formed along a belt aligned along the ridge. In some places, even at midday, visibilities were below 100 yards. Farther west visibility improved as the frontal cloud spread in and there was also a little wind. As the front approached, visibilities again deteriorated and fog occurred widely just ahead of the surface front and persisted well after the frontal passage.

The occurrences at London Airport will be described in greater detail. At 1200 G.M.T. London Airport reported 8/8 stratocumulus at 2,500 feet with 3/8 stratocumulus at 1,500 feet, a surface wind of 030 degrees 8 knots and a visibility of 2.5 nautical miles. These conditions persisted with but little change until after 1400 G.M.T. but, between 1400 and 1500 G.M.T., the sky cleared completely and the wind became calm. Temperatures fell and the visibility decreased to below 1,100 yards between 1900 and 2000 G.M.T., the visibility and present weather being reported at 2000 G.M.T. as 770 yards – visibility reduced by smoke. The weather was reported as fog at 2100 G.M.T. with visibility 550 yards and at 2200 G.M.T. as visibility 330 yards with fog – sky visible and cloudless, wind calm. At 2300 G.M.T. the visibility was still 330 yards but there were then 7/8 altocumulus, base 10,000 feet and a light southerly surface wind. By midnight slight drizzle was reported and thereafter the visibility increased slowly for the next few hours until at 0500 G.M.T. it reached 2,300 yards. At this time there were 8/8 low cloud, base 900 feet and the warm front lay along a line from near Spurn Head to Plymouth. Drizzle which had ceased between 0100 and 0200 G.M.T. recommenced shortly before 0600 G.M.T. and there was an associated lowering of the cloud base and the visibility and by

Visibility

0750 G.M.T. clouds were 8/8 stratus at 300 feet, 3/8 at 100 feet and visibility 770 yards. A visibility of 330 yards was reported at both 0800 and 0900 G.M.T. by which time the front had reached the Chilterns. It is almost certain that the fog from 0500 to 0900 G.M.T. must be regarded as pre-frontal fog. Figure 17.19 shows the tephigrams for 2300 G.M.T. (14th) for Liverpool (in warm air) and Crawley (in cold air). It will be seen that the temperature difference across the front was not very great at low levels but the cold air displayed a marked inversion. The temperature distribution was thus favourable for the formation of the warm-frontal fog but the temperature contrast was not particularly great. In the post-frontal warm air visibility continued poor and there was much low cloud, due primarily to cooling by contact with the cold underlying ground which on the 14th had been reported as "frozen" at many stations in the Midlands and south-east England.

Plates IV, V and VI show the detailed charts at 2100 G.M.T., 14 January and 0400 and 0900 G.M.T., 15 January 1958. The sequence of events at London Airport only has been described but at many other stations a similar sequence occurred, namely a cloudy period ahead of the ridge, clearing skies and radiation fog in the ridge, improving visibility as the warm-frontal upper cloud spread in and a little wind occurred followed by further fog and extremely low stratus before frontal passage with rather less dense fog in the warm air. Comparison of observations for many stations on Plates IV, V and VI will reveal that the changes in weather followed this sequence.

It should be emphasized that this sequence is by no means common and inexperienced forecasters should not read too much into the example, that is, whenever something similar appears on the charts in winter the above pattern should not be slavishly forecast to recur without very good supporting evidence. The example does illustrate a number of facts of importance in the forecasting of visibility, namely importance of cloud in preventing radiation fog and in improving or thinning an existing fog and that a few hours of cloudless sky can cause fogs to form. It also illustrates pre-frontal and post-frontal fog. The example also emphasizes, for very short-period forecasting of visibility, the importance of accurate forecasts of small synoptic features and their associated weather conditions.

17.14.4 Formation of fog in a narrow belt behind an occlusion, 12 November 1958

Plate VII shows the synoptic situation at 1800 G.M.T., 12 November 1958. The occlusion which was situated over the extreme east of East Anglia and Kent had moved steadily but slowly across England from the position which it occupied near the Welsh border at 0300 G.M.T. on the 12th. At that time there was a very narrow warm sector over southern England which had been occluded out as the front moved eastwards. The gradient across the cold front had opened out during the day and although there was a suspicion of an elongated secondary forming near the point of occlusion no such centre could be identified on successive charts with any certainty, even on the detailed hourly charts. It will be seen from Plate VII that by 1800 G.M.T. the pressure gradient over south-east England was very slack. Close behind the surface position of the front, clouds cleared completely and in the evening many stations only about 30 or 40 miles to westward of the front were cloudless. The ground was wet from the effects of the frontal rain and cooling due to the outgoing radiation under clear skies caused fog to form in this relatively narrow belt of clear skies. The fog was quite dense in places and a number of stations reported visibilities less than 110 yards. Farther to westward the trough which is clearly visible in Plate VII brought a renewal of cloudy and wet weather. Associated with this surface trough was a well marked upper trough which became progressively sharper during the 12th and 13th. These troughs continued to move eastwards in the

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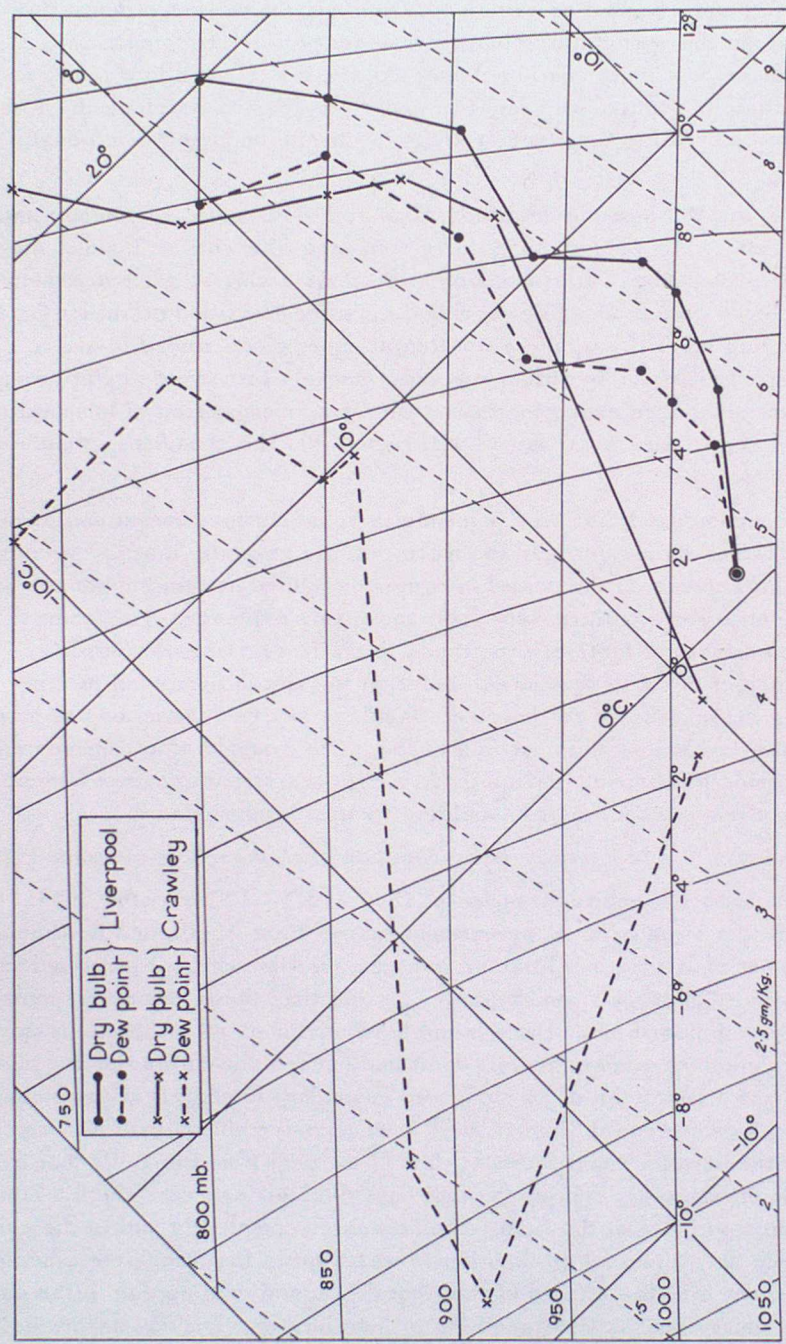


FIGURE 17.19 Tephigrams for Liverpool and Crawley, 2300 G.M.T., 14 January 1958

Visibility

rear of the occlusion and to bring the cloudy rainy weather to the areas affected by the fog which formed during the few hours of clear skies shortly after the frontal passage.

Plate VIII shows the detailed chart for England and Wales at 2100 G.M.T., 12 November 1958. The belt of fog extended from west Norfolk to Sussex and was closely aligned to the surface front. The cloudy wet weather associated with the troughs, which at 2100 G.M.T. were located near Wales, was already affecting the western parts of the Midlands. This trough moved eastwards and by 0200 G.M.T., 13 November it had brought cloud and rain as far east as the Greenwich Meridian and fog had cleared up to that line. By 0200 G.M.T. the occlusion had moved into the southern North Sea and, in its rear, skies had cleared over the extreme east of southern England and East Anglia where, as a consequence, fog had formed extensively.

Figure 17.20 shows the tephigram for Crawley for 2300 G.M.T., 12 November. The low-level inversion which contained the fog is clearly shown. It can be seen that, above the inversion, the air behind the occlusion is conditionally unstable. The air in the trough to westward was still more unstable. During the evening of the 12th in north Wales and north-western England there were reports of heavy showers and thunder occurred here and there. The combination of fog and heavy instability showers occurring at the same time over England and Wales must be a fairly rare occurrence and the combination is therefore noteworthy.

17.14.5 A persistent fog, 5–8 December 1952

Fog was fairly widespread over eastern England during the period 5–8 December 1952. The fog was thickest in the London Basin in which visibility over large areas was below 20 yards for many hours on end and was often below 10 yards. An account of this fog has been given by Douglas and Stewart⁵¹ in the *Meteorological Magazine* which is available at all outstations.

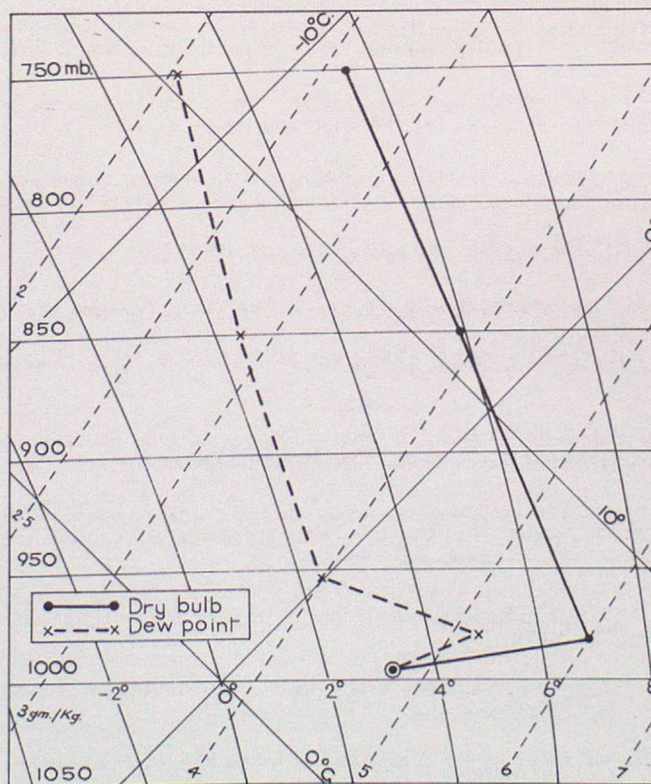


FIGURE 17.20 Tephigram for Crawley, 2300 G.M.T., 12 November 1958

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