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A FIVE-YEAR CLIMATOLOGY OF ELEVATED INVERSIONS AT HEMSBY (UK)

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ABSTRACT

Temperature inversions up to the 500-mbar level are studied in 50-mbar depth layers over Hemsby, in eastern England. The inversions are characterized by vertical gradients of temperature, potential temperature, dew point temperature, and depth. An inversion index, which is the product of potential temperature gradient and frequency of occurrence, is used. The zone of maximum activity for elevated inversions is 950–800 mbar, resulting from subsidence within anticyclones. A theoretical explanation of the processes is given. Inversion characteristics are essentially similar for day and night, except in the 1000–950-mbar layer, where daytime frequency is greater. It is suggested that turbulence-capping inversions and/or sea-breeze effects may be the reason. The implications of elevated inversions for air pollution dispersion are discussed.

KEY WORDS Temperature inversions Elevated temperature inversions Air pollution Hemsby (UK).

INTRODUCTION

Stability conditions in the lower troposphere are important factors for air pollution dispersion (Hanna *et al.*, 1982; Henderson-Sellers, 1984) and for other phenomena, such as the propagation of electromagnetic waves (Battan, 1966). The isothermal lapse rate is usually taken as a limiting lapse rate to separate out inversions—stable layers having negative lapse rate (i.e. temperature increasing with height)—from the rest of the stable layers with positive lapse rate. However, as far as atmospheric stability is concerned, there is no strong physical reason to support the choice of the isothermal lapse rate as the limiting one. On the other hand, from the point of view of radiation balance, there is a strong physical reason to separate out inversion layers, as radiative transfer (for those wave lengths where scattering or absorption by atmospheric constituents occurs) will be in the direction of the temperature gradient. Moreover, the first stable layer encountered in a temperature profile is, in many cases, an inversion layer. Indeed, during the night, a surface radiation inversion (i.e. with its base-height at the surface of the Earth (Oke, 1978)) is very frequently formed. During the day, just above the atmospheric boundary layer (ABL), within which lapse rates are generally adiabatic or superadiabatic, an inversion layer, (usually called a capping inversion) is very frequently formed. The first stable layer encountered in a temperature profile is important, particularly from the point of view of air pollution. This is the main reason why, although there have been some studies of stable layers with positive lapse rate (e.g. Sivaramakrishnan *et al.*, 1972), it is usually only inversion layers that are considered (e.g. Hosler, 1961; Baker *et al.*, 1969; Tyson *et al.*, 1976; Preston-Whyte *et al.*, 1977).

The climatology and characteristics of ground, and near-ground elevated (base-height above ground) inversions have been examined extensively using data from radiosondes (Hosler, 1961; Tyson *et al.*, 1976; Preston-Whyte *et al.*, 1977), towers (De Marrais, 1961; Baker *et al.*, 1969), or acoustic sounders (Maughan, 1979; Spanton, 1985). Short-term experiments also have been conducted using helicopter measurements (Von Gogh and Tyson, 1977). The basic characteristics of inversions that are usually considered when radiosonde data are used are: (i) the strength (dT), which is the difference in the dry-bulb temperatures between the top

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and the base of the inversion; (ii) the depth (dH), which is the difference between the height of the top and the height of the base of the inversion.

Emphasis in pollution studies has been on the relationship between ground and low-level elevated inversions and local-scale air pollution (Biertly and Hewson, 1962; Holzworth, 1972; Chalupa, 1975; Remsberg *et al.*, 1979). Inversion data from acoustic sounders are particularly useful for such studies, as they provide a continuous record up to heights well above the limits of most towers (Maughan, 1979; Prater and Colls, 1981). Studies of long-range pollutant transport have focused on the capping inversion, which is frequently formed just above the ABL, and acts as a lid for the vertical diffusion of pollutants (Smith and Hunt, 1977; Davies *et al.*, 1988). This capping inversion actually separates the ABL, which is the area of the atmosphere where turbulent diffusion is assumed to take place, from the free atmosphere, where more laminar flow is assumed (Stull, 1988). However, emissions with high initial values of momentum and buoyancy can penetrate this capping inversion and enter into the free atmosphere (Henderson-Sellers, 1984; Apsimon and Wilson, 1986).

Another physical phenomenon that occurs in the atmosphere and in which inversions play an important role is the propagation of electromagnetic waves in the troposphere, as the refraction index for these waves is a function of, amongst other factors, the temperature of the atmosphere (Bean and Dutton, 1968). Non-standard refraction of electromagnetic waves (radio-ducting) is associated with inversions (Battan, 1966).

Despite their importance, knowledge of the variation of the physical characteristics of the inversion layers with height is relatively scanty. This is particularly the case for inversions not directly associated with the ABL, but related to other processes, such as subsidence and frontal surfaces. In one of the few studies undertaken, Maenhout and Legrand (1971), using data from Uccle in Belgium, find that inversions with greater strength occur mainly below 700 mbar, and that about 95 per cent of all inversions between the surface and the 500-mbar pressure level occur below 600 mbar. In this paper, we develop the analysis undertaken in such studies, and apply it to data from a UK upper air station.

THE DATA

Data were provided by the Meteorological Office for midday and midnight radiosonde soundings for the period 1976–1980 from Hemsby upper air station, which is in eastern England (Figure 1). The station is located at an elevation of 14 m in an extensive area of generally low relative relief. The North Sea is about

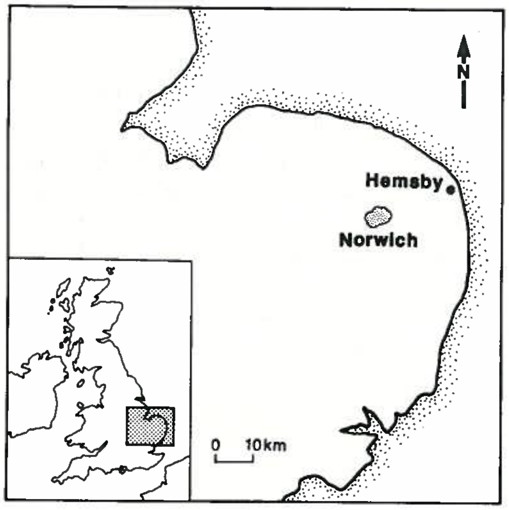

Figure 1. Geographical location of Hemsby

1·5 km to the east, and may affect the formation of inversions near the ground (see below). However, even for inversions associated with the ABL, the main controlling factor is the synoptic situation (Riordan *et al.*, 1986).

Observational requirements for lower tropospheric soundings have been set by the World Meteorological Organization (1970), but radiosonde data can contain errors from many sources. These errors are discussed by the World Meteorological Organization (1975, 1983). A fundamental problem is that it is difficult to establish the absolute accuracy of radiosonde data. The most serious errors occur in the humidity data, at temperatures lower than about −20°C, since humidity sensors have a very slow speed of response at temperatures where there is very little water vapour. Temperatures lower than −20°C are usually found at heights above 600–500 mbar. The data that are finally selected from the quasi-continuous radiosonde soundings can be subdivided into two groups:

(i) the 'standard levels', which are the levels at which the synoptic charts are drawn;
(ii) the 'significant levels' at which significant changes of temperature and humidity lapse rates or wind occur.

In this study, the significant temperature levels were used to identify the tops and bases of the inversion layers. If both groups were used, this would lead to an artificial creation of weak isothermal or inversion layers around the standard levels as the effective accuracy in the temperature measurements is poorer than 0·1°C (Milionis, in preparation). Besides the inversion layers, isothermal layers were also considered for the analysis and will hereafter be included in the term 'inversions'. Where consecutive inversions were found, they were merged together to give a deeper inversion. Consecutive inversions are adjacent inversion layers with different lapse rates. At this stage, it is worth noting that the UK Meteorological Office algorithm that selects the significant temperatures also merges inversion layers that are not consecutive, if the layer between them is less than 20 mbar in depth; this may help to explain the observed irregularities in dH (see below).

METHODOLOGY

In addition to the strength and depth, two more properties were taken into consideration in this study: (i) the difference in potential temperature between the top and the base of the layer ($d\theta$); and (ii) the difference in dew point temperature between the top and the base (dT_d). For inversions with different values of dT and dH, but the same value of $d\theta$, it can be shown that the minimum temperature which warm buoyant plumes must have, at the bases of these inversions, in order to penetrate them completely is the same.

Let us assume two inversion layers with bases at height h, but with tops at different heights, as shown in Figure 2. We assume that the difference in potential temperature ($d\theta$) between the top and the base is the same for both inversion layers. An air parcel that ascends will be able to penetrate inversion (1) completely, if its temperature when it reaches the top of inversion (1) is greater than or equal to T_t. The simplest case is to assume that the air parcel ascends following the dry adiabatic lapse rate. Then, if the ascending air parcel at height Z has temperature $T_p \geq T_t$, at height $Z + \delta Z$ it will also have $T_p \geq T'_t$ because the assumption that both inversion layers have the same value of $d\theta$ means that T_t and T'_t belong to the same adiabatic. Consequently, if the air parcel is able to penetrate inversion (1), it also will be able to penetrate inversion (2).

So, $d\theta$ is an important variable, particularly from the point of view of air pollution, since it denotes the ability of the inversion to inhibit vertical diffusion throughout its depth. It should be noted, however, that for

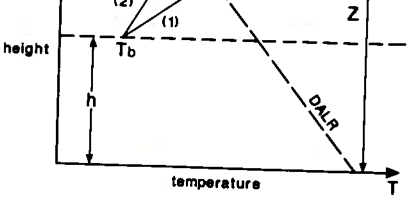

Figure 2. Two inversion layers (1) and (2) with different depths and strengths but same base-heights and potential temperature difference

inversions with the same value of dT and dH but very different base-heights, the one with the greater base-height may exhibit a slightly larger value of $d\theta$. This happens because, if the lower inversion layer is lifted adiabatically to the level of the upper inversion, its lapse rate will tend to approach the dry adiabatic lapse rate (DALR), producing a smaller value of $d\theta$. This is partly compensated by the fact that the pressure difference between the top and the base is smaller for the inversion with the greater base-height. It must be mentioned also that for two inversions with the same value of $d\theta$, the one with the smaller temperature lapse rate will be somewhat more effective in trapping pollutants, as it will stop the plume that does not have enough buoyancy to penetrate it completely within a smaller depth.

The value of dT_d was taken into consideration as it is a potential indicator of the physical origin of an inversion. Within anticyclonic subsidence inversions the dew point temperature decreases with height (Taylor and Yates, 1967), and in frontal inversions, depending on the type of frontal inversion, it usually increases (Byers, 1974).

The atmosphere was separated into layers of 50 mbar each, up to the 500 mbar pressure surface. Above 400 mbar, many inversions were found to be associated with the tropopause and, in the region between 400 mbar and 500 mbar, the number of inversions was too small to allow reliable analysis. For each layer the mean dT, dH, dT_d, and $d\theta$ were calculated. A simple index, given by the product of the mean $d\theta$ at the layer and the number of inversions in the layer, was utilized to combine the frequency and the severity of the inversions. This was done first by using all the data, and then repeated for data from midnight soundings and midday soundings separately, so that the effect of the diurnal cycle on the statistics of inversions can be examined.

RESULTS AND DISCUSSION

Figure 3 shows the vertical variation of the mean value of $d\theta$ for each layer. In order to avoid unnecessary complexity the standard deviations (SDs) are not drawn on this figure, nor in any of the figures that will be presented later. (The mean values for all variables and their corresponding SDs are given in Tables I–III.) It is apparent that $d\theta$ has maximum values at the consecutive layers 950–900 mbar, 900–850 mbar and 850–800 mbar. The same layers accommodate the maximum values of the number of inversions (Figure 4), and consequently the maximum values of the inversion index (Figure 5). However, examination of the vertical variation of dT_d (Figure 6), shows that there is a pronounced minimum at the layers 900–850 mbar and 850–800 mbar. This implies that inversions in these layers are mostly of anticyclonic origin. Above the layer 850–800 mbar the number of inversions rapidly decreases, and so does the inversion index, but dT_d increases. So, given that frontal inversions have roughly equal possibilities of being recorded at any height, it seems that the anticyclonic subsidence inversions have their maximum frequency in the layer 900–850 mbar. Above

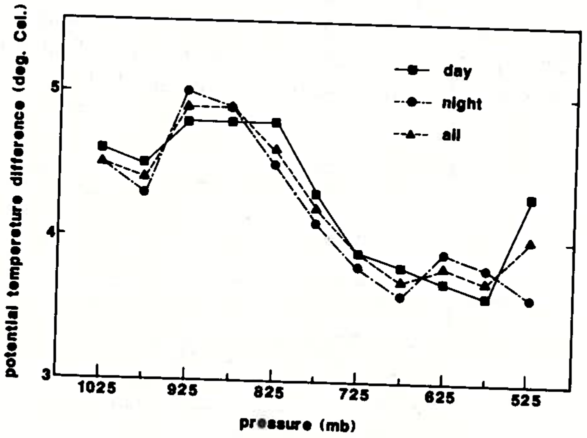

Figure 3. Vertical variation of the mean potential temperature difference in inversion layers

Table I. Vertical variation of characteristics of inversions (all cases)

Layer (mb)	Depth (m) Mean	SD	Strength (°C) Mean	SD	$d\theta$ (K) Mean	SD	dT_d (°C) Mean	SD
Ground–1000	218	153	2·5	2·1	4·5	2·8	−0·5	3·9
1000–950	233	151	2·1	1·8	4·4	2·6	−1·4	3·8
950–900	252	164	2·3	2·2	4·9	3·0	−2·6	5·1
900–850	255	159	2·1	2·0	4·9	2·8	−3·9	5·1
850–800	254	153	1·9	1·6	4·6	2·5	−3·6	5·0
800–750	237	147	1·5	1·4	4·2	2·2	−3·4	4·8
750–700	243	147	1·1	1·1	3·9	1·9	−2·7	4·9
700–650	235	153	1·0	0·9	3·7	2·1	−2·0	4·4
650–600	252	171	0·8	0·8	3·8	2·3	−1·3	3·9
600–550	230	123	0·9	1·0	3·7	2·0	−0·8	3·9
550–500	254	145	0·8	0·9	4·0	2·2	−0·5	3·8

SD = Standard deviation.

Table II. Vertical variation of characteristics of inversions(Midday inversions)

Layer (mb)	Depth (m) Mean	SD	Strength (°C) Mean	SD	$d\theta$ (K) Mean	SD	dT_d (°C) Mean	SD
Ground–1000	226	131	2·4	2·1	4·6	2·7	−1·0	3·9
1000–950	237	149	2·1	1·8	4·5	2·6	−1·3	3·6
950–900	260	178	2·2	2·2	4·8	3·1	−2·7	5·3
900–850	246	145	2·2	2·0	4·8	2·7	−3·8	4·8
850–800	261	157	1·9	1·7	4·8	2·6	−3·7	5·0
800–750	254	159	1·5	1·5	4·3	2·4	−3·7	4·8
750–700	242	124	1·2	1·1	3·9	1·7	−2·8	5·0
700–650	249	178	0·9	0·9	3·8	2·4	−2·0	4·6
650–600	231	156	1·0	0·9	3·7	2·2	−1·3	3·6
600–550	240	120	0·8	1·0	3·6	2·0	−1·0	2·0
550–500	288	164	0·8	1·0	4·3	2·7	−0·1	4·1

SD = Standard deviation.

Table III. Vertical variation of characteristics of inversions (Midnight inversions)

Layer (mb)	Depth (m) Mean	SD	Strength (°C) Mean	SD	$d\theta$ (K) Mean	SD	dT_d (°C) Mean	SD
Ground–1000	211	173	2·5	2·0	4·5	2·8	−0·1	3·8
1000–950	227	154	2·0	1·9	4·3	2·7	−1·5	4·0
950–900	245	148	2·4	2·3	5·0	3·0	−2·6	4·8
900–850	263	170	2·1	1·9	4·9	2·9	−4·0	5·3
850–800	248	150	1·8	1·6	4·5	2·4	−3·5	3·3
800–750	222	135	1·6	1·4	4·1	4·0	−3·1	4·8
750–700	244	168	1·0	0·9	3·8	2·0	−2·6	4·6
700–650	221	120	1·1	1·0	3·6	1·7	−2·1	4·1
650–600	272	181	0·7	0·7	3·9	2·4	−1·3	4·1
600–550	223	125	1·0	1·0	3·8	2·0	−0·7	4·4
550–500	217	113	0·9	0·8	3·6	1·5	−0·9	3·4

SD = Standard deviation.

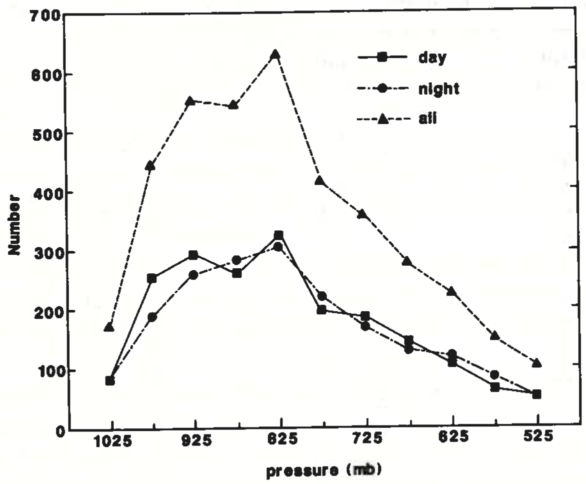

Figure 4. Vertical variation in the number of inversions in each 50-mbar depth atmospheric layer

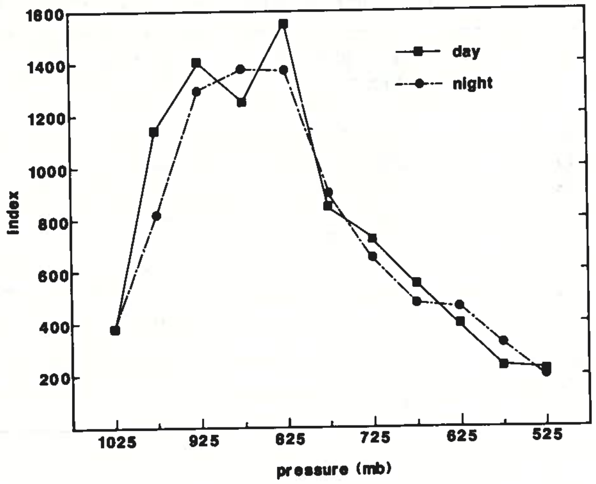

Figure 5. Vertical variation of the inversion index (see text)

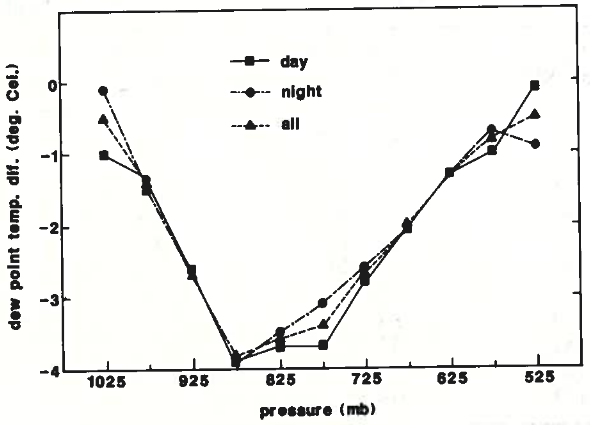

Figure 6. Vertical variation of the mean dew point temperature difference in inversion layers

800 mbar the frequency of anticyclonic inversions decreases, so that above about 750 mbar the great majority of the inversions are due to frontal surfaces, or advection.

Figure 7 shows the vertical variation of inversion strength. In all cases there is a general tendency for the strength to decrease with height, and this decrease is most pronounced from the layer 950–900 mbar to the layer 750–700 mbar. Figure 8 shows the vertical variation of inversion depth. Up to the layer 950–900 mbar there is an increasing trend, but above that layer variations are erratic, not only between adjacent layers but also between midday and midnight for the same layer. There does not seem to be any obvious physical reason for this erratic behaviour of inversion depth. The way that inversion layers are defined and recorded in the algorithm (see above) may be partly responsible.

A simple theoretical explanation can be given for the observed characteristics of the inversions. Let us assume that an air column of subsiding air is horizontally divergent on the whole. Convergence will take place at the top of the air column and divergence at the bottom; consequently there will be a level of zero horizontal divergence (LZD) where the vertical velocity will be maximized. As a result, the rate of warming of the subsiding air will be at a maximum for the air near the LZD, so that the lapse rate above the LZD will become relatively less stable, and below the LZD will become relatively more stable. The top of the subsidence inversion will then be below the LZD. The situation is summarized in Figure 9. In the real atmosphere the LZD is usually around 500–600 mbar (Holton, 1972), and subsidence, for a well-developed anticyclone, stops

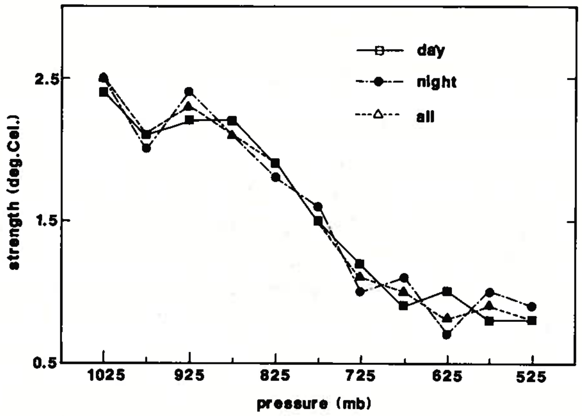

Figure 7. Vertical variation of the mean strength of inversion layers (see text).

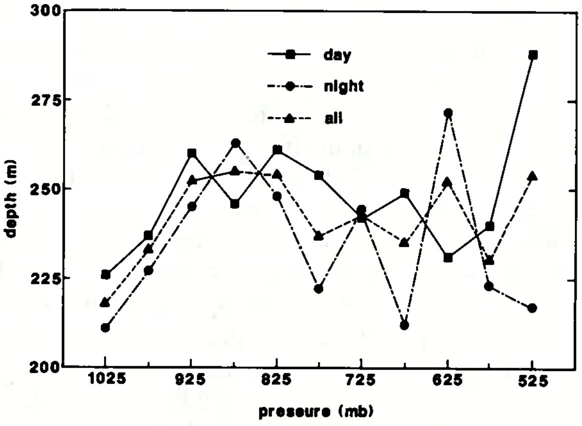

Figure 8. Vertical variation of the depth of inversion layers

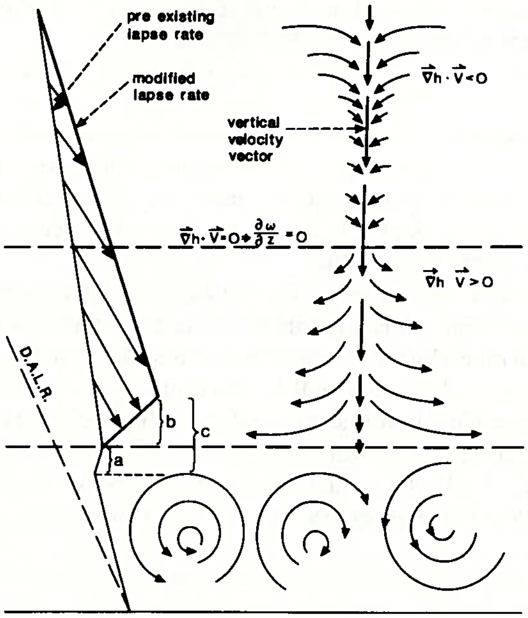

Figure 9. A simplified model for anticyclonic subsidence inversions. (a) Turbulence capping inversion; (b) inversion due to anticyclonic subsidence; (c) subsidence capping inversion. $\nabla h.\vec{V}$ is horizontal divergence

just above the ABL where turbulence does not allow subsidence. Typical heights of daytime convective ABLs are about 1000–1500 m (Smith and Hunt, 1977; Stull, 1988), which roughly corresponds to 900–850 mbar. So, subsidence inversions in well-developed anticyclones are confined so that their tops will be below the LZD and their bases at the top of the ABL. Our observations conform with these arguments. Certain assumptions have been made in this simplified theoretical explanation. First, it was assumed that the mean lapse rate before subsidence started in the hypothetical air column has no points of inflection. It was further assumed that the air parcels that converge at the top of the air column and then subside, belong to the same air mass. If these assumptions are not met, it is possible that the subsidence inversions may appear discontinuous.

In order to examine the effect of the diurnal cycle, a Chi-squared test was conducted for the difference in the number of inversions at midday and midnight in the various layers. It was only in the 1000–950 mbar layer that there was a statistically significant difference (5 per cent level) in the frequency of inversions (further details in Milionis, in preparation). Similar tests on the Z-statistic (Spiegel, 1988) for midday–midnight differences for $d\theta$, dT_d, dT, and dH for each layer show that, at the 5 per cent level; there are no significant differences for $d\theta$ and dT_d; a significant difference for dT in the 650–600 mbar layer; significant differences for dH in the 750–700 mbar and 550–500-mbar layers (further details in Milionis, in preparation).

To a certain extent, these observed characteristics can be explained in theoretical terms. In conditions of well-developed anticyclonic subsidence, the capping inversions at midday are caused not only by turbulence in the ABL, but also by subsidence. We shall call these inversions subsidence capping inversions hereafter. In the absence of anticyclonic subsidence, the capping inversions are caused only by turbulence that cools the air just below them owing to adiabatic expansion. These will be called turbulence capping inversions hereafter. The two types of capping inversions are shown in Figure 9. At midnight, as the ABL is stable, several types of turbulence may occur (Mahrt and Gamage, 1987). Although strong wind shears can sometimes generate mechanical turbulence of considerable intensity, on average, turbulence at midnight is much weaker than at midday. In the absence of anticyclonic subsidence, the capping inversion that is present during the day may disappear at midnight. When anticyclonic subsidence conditions are present, the subsidence capping inversions of midday are not expected to be destroyed during the night, but instead to extend further towards the ground and perhaps strengthen as turbulence weakens. We have noticed that, in a number of cases, usually

Table IV. Basic characteristics of midnight surface inversions at Hemsby

	dH (m)	dT (°C)	$d\theta$ (K)
Mean	179	2·2	3·9
Median	153	1·8	3·6
SD	141	2·0	2·6

SD = Standard deviation.

associated with calm conditions, these subsidence inversions, as they move lower during the night, are merged with the ground radiation inversions. This is reflected in the character of the corresponding dT_d profile, where dT_d is not a monotonic function of height but has a point of inflection. Below the height where the point of inflection is located, the inversion is due to radiation and above the point of inflection is due to subsidence. Such inversions have not been examined here as they are classified as ground inversions.

The statistically significant difference in the number of inversions at the 1000–950-mbar layer between midday and midnight can be explained by the absence of turbulence inversions at midnight and, to a lesser extent, by the fact that some subsidence capping inversions are merged with the surface radiation inversions at night and, hence, are not counted as elevated inversions. However, the most representative heights where capping inversions are expected to be found at midday correspond to the layer 950–900 mbar, as mentioned earlier, or 900–850 mbar. The proximity of the station to the sea is a local factor that also may be responsible for the midday–midnight difference in the number of inversions in the 1000–950-mbar layer. Owing to the induced sea-breeze circulation, at midday, parcels of relatively colder air may be advected over the land and an inversion layer may be formed.

There is no obvious physical reason for the significant differences found in the values of dH at the layers 750–700 mbar and 550–500 mbar, but in any case these layers are less important, particularly as far as air pollution is concerned.

It is worth noting that the layer 1000–950 mbar, where the frequency of occurrences is much lower at midnight than at midday, is the region where a stream of air moving at supergeostrophic speed is frequently found at night. This air stream is known as the nocturnal jet and there are several reasons for its formation (Blackadar, 1957; Garrat, 1985; Kraus *et al.*, 1985). Most frequently it is found just above the nocturnal surface radiation inversion. It is not our purpose to examine the surface inversions in detail here, but it is of interest to note some of their main characteristics. Table IV shows the values of some parameters for the surface inversions at Hemsby. The sum of the mean depth and the corresponding standard deviation is 320 m, so the nocturnal jet is expected to be found most frequently at heights lower than that. This means that, at midnight, in the region from about 300–350 m to about 500 m the conditions for the diffusion of pollutants in both the vertical (low value of inversion index) and the horizontal (strong winds) directions are favourable.

CONCLUSIONS

The atmosphere up to 500 mbar above Hemsby can be divided into three zones.

Zone 1. From just above the surface up to about 950 mbar. Elevated inversions that are found in this region are mainly turbulence capping inversions, or may be caused by local factors, such as, in the present case, the proximity to the sea.

Zone 2. From about 950 mbar to about 800 mbar. In this region the dominating type is subsidence inversions. It is the region where both frequency of occurrence and mean $d\theta$ value have their maximum values.

Zone 3. From about 800 mbar up to 500 mbar. This region is characterized by a rapid decrease of both frequency of occurrence and mean value of $d\theta$, and inversions are mainly of the frontal type. The standard pressure surface of 700 mbar seems to be a reasonable upper limit for the study of tropospheric inversion climatology.

The most conspicuous effect of the diurnal cycle is located at the 1000–950 mbar layer. Although at midday there is relatively high frequency of occurrence owing to the turbulent capping inversions, the frequency at night becomes significantly lower. This, combined with the fact that the nocturnal jet is usually found at the region just above the surface radiation inversion, has a direct consequence as far as atmospheric dispersion is concerned. During the night, releases of pollutants with effective emission height above the top of the surface radiation inversion, which from our data at Hemsby was at 199 m on average, have favourable conditions to be dispersed in both the vertical and horizontal directions. Unfortunately, only the highest and most efficient point sources will attain this effective height of emission.

Clearly it is worth considering the climatologies of elevated inversions at other locations, in order to assess the spatial character of inversion climatology, because of the implications for air pollution concentrations (discussed above). In this way, it may be possible to characterize inversion conditions near to large point sources of air pollution. This would be a considerable help in the assessment of the dispersion and transport of pollution.

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