Atmospheric pollution and its implications in the Eastern Transvaal Highveld

P D Tyson, F J Kruger and C W Louw

SOUTH AFRICAN NATIONAL SCIENTIFIC PROGRAMMES REPORT NO

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A report prepared under the auspices of the
National Programme for Weather, Climate and
Atmosphere Research (NPWCAR)

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Cover: A typical atmospheric pollution scene in the Eastern Transvaal Highveld at sunset during winter.

(Photograph: Division of Earth, Marine and Atmospheric Science and Technology, CSIR)

ABSTRACT

This report is a review of available information on the dispersion climatology, the degree of atmospheric pollution and the various impacts of that pollution on man and environment in the Eastern Transvaal Highveld (ETH) and adjacent regions. It was prepared for the information of the scientific community, for the authorities involved with the control and abatement of atmospheric pollution, and for all those anxious to see that the ETH and adjacent environments are not being despoiled by man's activities. The report concludes that climatic conditions in the ETH are highly adverse for dispersion of atmospheric pollutants. Relatively high levels of some pollutants occur under certain circumstances. These observations and the known adverse effects of these pollutants elsewhere in the world indicate a high risk for an adverse impact of atmospheric pollution in the ETH and adjacent regions. It is therefore imperative that the future planning and management strategies to achieve an acceptable level of atmospheric pollution be based on a conservative and cautious policy. Once damaged on a systematic and large scale, the environment will take a long time to recover.

SAMEVATTING

Hierdie verslag is 'n omvattende oorsig van alle beskikbare inligting oor die dispersie klimatologie, die graad van atmosferiese besoedeling en die verskillende impakte daarvan op die mens en sy omgewing in die Oos Transvaalse Hoëveld (OTH) en aangrensende gebiede. Dit is saamgestel vir die inligting van die wetenskaplike gemeenskap, vir die owerhede wat betrokke is by die beheer en bekamping van atmosferiese besoedeling asook vir diegene wat besorg is dat die OTH en aangrensende omgewings voldoende beskerming teen menslike aktiwiteite sal geniet. Die verslag kom tot die gevolgtrekking dat klimaatstoestande in die OTH uiters ongunstig is vir verspreiding van atmosferiese besoedelstowwe. Relatiewe hoë vlakke van sommige besoedelstowwe kom onder seker omstandighede voor. Hierdie waarnemings asook die bekende nadelige uitwerking wat hierdie besoedelstowwe elders in die wêreld het, dui op 'n hoë risiko vir 'n nadelige impak van atmosferiese besoedeling in die OTH en aangrensende gebiede. Derhalwe is dit noodsaaklik dat 'n konserwatiewe en versigtige benadering gevolg word in toekomstige beplanning- en bestuurstrategieë om aanvaarbare vlakke van atmosferiese besoedeling te verseker. Wanneer grootskaalse beskadiging reeds ingetree het, kan dit 'n geruime tyd neem om die omgewing weer te herstel.

ACKNOWLEDGEMENTS

As part of the preparation of this report, a workshop was held on 'The atmospheric pollution situation and its implications in the Eastern Transvaal Highveld' during 27-29 October 1987 at the Espada Ranch, Pretoria. It was arranged under the auspices of the National Programme for Weather, Climate and Atmosphere Research by the Foundation for Research Development of the CSIR. The following persons participated in this workshop and their valuable contributions are gratefully acknowledged:

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Chapter 2 on 'The dispersion climatology of the Eastern Transvaal Highveld' was written by Prof P D Tyson and Chapter 3 on 'Atmospheric pollution in the Eastern Transvaal Highveld' by Dr C W Louw. Chapter 4 on 'The environmental impact of atmospheric pollution in the Eastern Transvaal Highveld and adjacent regions' was prepared under the direction of Dr F J Kruger and in association with Prof J C A Davies (National Centre for Occupational Health, Department of National Health and Population Development); Dr B G Callaghan (Division of Materials Science and Technology, CSIR); Dr A J van der Merwe, Mr J C Schoeman and Dr L Korentajer (Soil and Irrigation Research Institute, Department of Agriculture and Water Supply); Mr D C Grey (S A Forestry Research Institute, Department of Environment Affairs); Dr P L Kempster (Hydrological Research Institute, Department of Water Affairs); Dr F M Chutter and Mr R W Skoroszewski (Division of Water Technology, CSIR); Mr D L Owen, Mr N Mönnig and Miss K A Baines (S A Forestry Research Institute, Department of Environment Affairs); Mr E Engelbrecht (Engineering Investigations Division, ESKOM); Dr C J Scheepers (Botanical Research Institute, Department of Agriculture and Water Supply); and Dr W P D Gertenbach (Kruger National Park)

The co-operative research effort on atmospheric pollution in the Eastern Transvaal Highveld has been managed by a steering committee under the chairmanship of Dr D van As (Isotopes and Radiation Department, Atomic Energy Corporation of South Africa Ltd). The success achieved so far has, in large part been due to his foresight, enthusiasm and leadership.

TABLE OF CONTENTS

1. INTRODUCTION

The powerhouse of South Africa is to be found in the greater Highveld in an area extending from about the Tropic of Capricorn in the north to about Bloemfontein in the south, from about the longitude of Zeerust in the west to east of Nelspruit. The Eastern Transvaal Highveld (ETH) itself is defined more narrowly as is indicated in Figure 1. The urban and industrial activities occurring in the area produce a large amount of pollution which is injected into an atmosphere as unfavourable for its dispersion as that found anywhere in southern Africa. Indeed the Highveld dispersion climatology must rate as among the most unfavourable anywhere in the world. This is a fact that has to be acknowledged and accepted in policy formulation and air pollution management strategies. In this monograph the most recent information on the nature of the dispersion climatology, the degree of atmospheric pollution and the impact of that pollution will be reviewed.

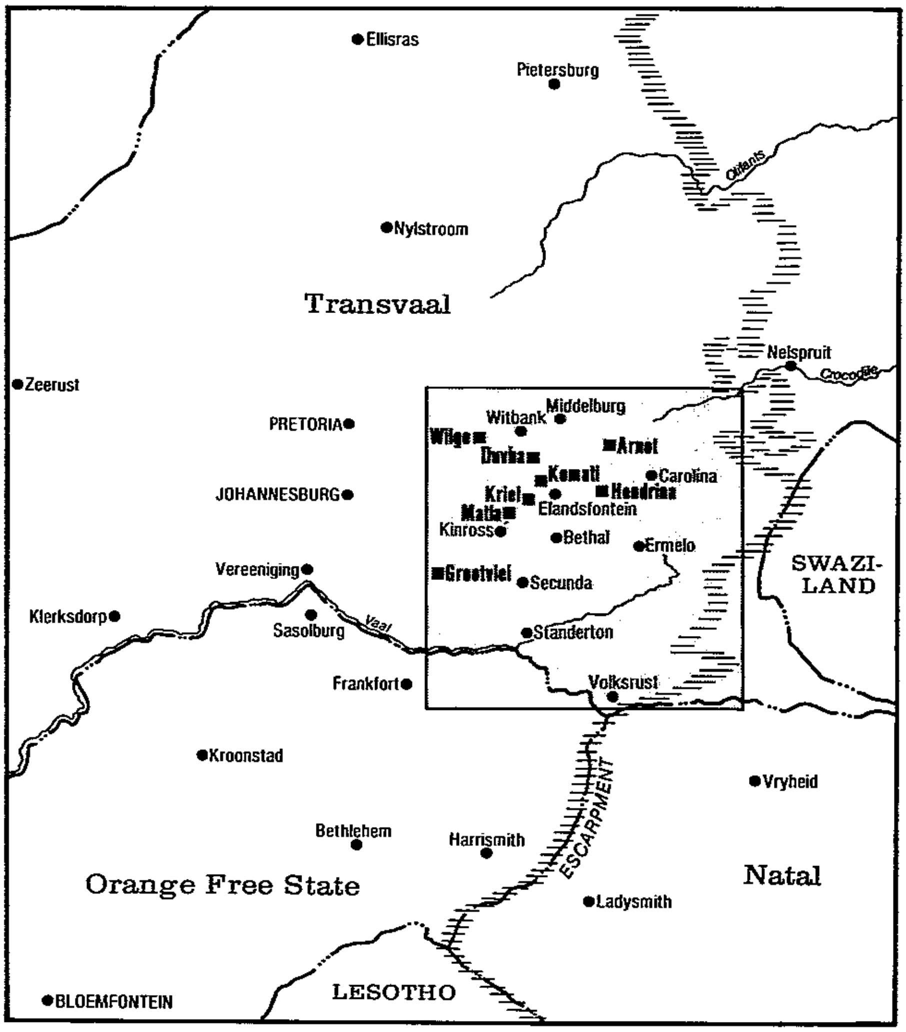


Fig. 1 *The Eastern Transvaal Highveld (dark shading) and adjacent regions likely to experience similarities in dispersion climatology.*

In dealing with the dispersion climatology, ventilation potential, synoptic and mesoscale atmospheric circulation patterns, effects of surface and elevated inversions and dispersion modelling will be among the topics considered. Atmospheric pollution will be examined by looking at the pollution sources and emission levels, ambient atmospheric concentrations and removal processes. Finally, the impact of atmospheric pollution on humans, structures, natural vegetation and agricultural crops, forests, surface waters and soils will be discussed.

The ETH is situated to the east of the Pretoria/Witwatersrand/Vereeniging urban complex at a mean altitude of about 1 700 m above sea level. It covers an area of some 30 000 km^2 of which it is estimated that 70% is covered by grassland where intensive animal husbandry is practised and the remainder used for crop cultivation and commercial forests. However, it is also the main coal producing region in the RSA where about 80% of the country's electrical power requirement is generated by coal-fired power stations. Besides some of the largest such power stations in the world, there are two major petrochemical plants, various smaller industries (e.g. ferro-alloy smelters, steelworks, brickworks, foundries, fertilizer plants, saw mills, paper mills and chemical works), a number of smouldering discard coal dumps, domestic fires, motor vehicles and veld burning from time to time, all of which are important sources of atmospheric pollution. An inventory by Els (1985) showed that for 1983/84 the average annual combined emissions of particulates, sulphur dioxide, nitrous oxides, carbon dioxide, carbon monoxide and hydrocarbons exceeded 125 million tons over the ETH.

The ETH is characterized by climatic conditions which are highly adverse for the dispersion of atmospheric pollutants, namely, high atmospheric stability, clear skies and low wind speeds generally associated with a high pressure system prevailing over the region. During winter, inversions of temperatures occur almost every night at the surface, while elevated inversions occur with high frequency. Moist unstable conditions and rainfall are confined almost exclusively to the summer period. The dry, highly stable winter period is obviously of greatest significance for accumulation of atmospheric pollution.

In view of the large pollution emissions and the high atmospheric stability characterizing the ETH, a curb was placed in 1975 by the Department of Health and Welfare (now the Department of National Health and Population Development) on the erection of power stations in this region. Since then the policy has been revised so that industries which are based on large-scale consumption of coal may be established in the area provided adequate control is applied to particulate and gaseous sulphurous emissions. At the time it was realised how important it would be to monitor and understand the atmospheric processes controlling the accumulation and dispersion of pollution and the daily, seasonal and annual pollution amounts. It was also recognised it would be necessary to compare atmospheric pollution levels with those found elsewhere. With these considerations in mind the Department of Constitutional Development and Planning contracted the Atmospheric Sciences Division, NPRL, CSIR (now the Division of Earth, Marine and Atmospheric Science and Technology, CSIR) to undertake a five year study (1979-1983) of the atmospheric pollution potential of the ETH. Industry likewise began initiating similar research. Towards the end of the period it was realised that a more comprehensive atmospheric pollution study would be needed to provide the necessary information for future atmospheric pollution control decision making, and for industrial and town development. The Departments of Health and Welfare, Environment Affairs and Constitutional Development and Planning then requested the FRD, CSIR to plan, initiate and coordinate such a study.

During 1983 a strategy was devised by a special steering committee to initiate a co-operative atmospheric pollution research programme in the ETH under the auspices of the National Programme for Weather, Climate and Atmosphere Research. The main goal of this strategy was to develop a predictive capability for the ETH with regard to

- the required efficiency of methods for controlling atmospheric pollution emissions,
- the atmospheric pollution levels,
- the impact of emissions on the local climate, inhabitants and the environment.

Appropriate proposals were encouraged from the local research community and subsequently evaluated in terms of scientific merit for financial support. This enabled the launching, in early 1984, of a co-operative research programme for the study of atmospheric pollution in the ETH. The participating organizations included the CSIR, universities, the Atomic Energy Corporation of SA Ltd., the Department of Environment Affairs (SA Forestry Research Institute), the Department of Water Affairs (Hydrological Research Institute), the Department of National Health and Population Development (National Centre for Occupational Health), the National Parks Board and industries (ESKOM, SASOL), as well as private atmospheric pollution consultants. Financial support for this co-operative research effort has been provided mainly by the Departments of National Health and Population Development, Environment Affairs, Water Affairs, CSIR and ESKOM.

In this monograph all existing knowledge concerning the atmospheric pollution of the ETH and its effects on people and land have been reviewed and synthesized to provide a state-of-the art publication that will be of use to the scientific community, to those concerned with atmospheric pollution control and management and to all those anxious to see that the ETH and adjacent environments are not despoiled by man's activities.

2. THE DISPERSION CLIMATOLOGY OF THE EASTERN TRANSVAAL HIGHVELD

2.1 INTRODUCTION

In any atmospheric pollution control programme modelling the accumulation and dispersion of pollutants is of the highest priority. Models are developed theoretically, tested against observed conditions and then modified to best account for local climatic conditions. Much effort had been directed towards understanding the dispersion climatology of the Eastern Transvaal Highveld (ETH). However, relatively little work has been done in developing models locally or modifying existing models for local use. Less has been done on using models operationally to develop an atmospheric pollution control strategy for the ETH. In this paper knowledge concerning the dispersion climatology of the ETH will be reviewed, as too will be the work done to date on modelling of boundary layer conditions and dispersion and transportation of pollution over the area.

The rate at which pollution will accumulate and disperse in the atmosphere is dependent entirely on the state of the atmosphere, particularly in the earth's boundary layer where thermal and mechanical turbulence are dominant processes. Once pollution has been released into the atmosphere, the determinants of its dispersion are meteorological. To asses atmospheric pollution dispersion it is necessary to have information relating to the general climate of an area, terrain characteristics and the nature of the diurnal and seasonal variation of the boundary layer. Of the boundary layer characteristics, stability and turbulence regimes and the nature of the low-level windfield are of the greatest importance.

Atmospheric pollution dispersion climatology is concerned with the average of factors such as the overall degree of disturbance of the atmosphere throughout the year (macro-ventilation characteristics and precipitation removal processes), the degree to which stagnation occurs and re-occurs (lack of ventilation, highly stable conditions and a high incidence of solar radiation) and low-level, surface-induced effects (micro-ventilation characteristics, occurrence of inversions, local winds and heat islands).

The chapter comprises three sections. The first deals with the general circulation of the atmosphere over the Highveld of southern Africa, with mesoscale circulations within the boundary layer and with regional and local effects. In the second section conditions prevailing over the ETH per se are considered. Finally, attempts to model pollution dispersion over the ETH will be reviewed.

2.2 GENERAL CONSIDERATIONS

2.2.1 Macroscale conditions

Over southern Africa as a whole the general circulation of the atmosphere is anticyclonic throughout the year above the 700 hPa level (i.e. above an altitude of approximately 3 000 m). In summer, nearer the surface at 850 hPa (approximately 1 500 m above sea level) a trough develops over central areas, but over the ETH the curvature of mean airflow remains anticyclonic (Fig. 2). At 500 hPa (about 5 800 m above sea level) the circulation is clearly anticyclonic. In winter, the mean pressure field is markedly anticyclonic throughout the troposphere. Such airflow is associated with frequent subsidence of air (Fig. 3). The subsidence produces adiabatic warming, drying of the atmosphere, increasing atmospheric stability, suppression of precipitation, the occurrence of dry spells and, most important of all in dispersion terms, conditions highly conducive for the formation of surface and elevated inversions. Examples of summer and winter continental anticyclones over southern Africa at the 850 and 500 hPa levels are given in Figure 3.

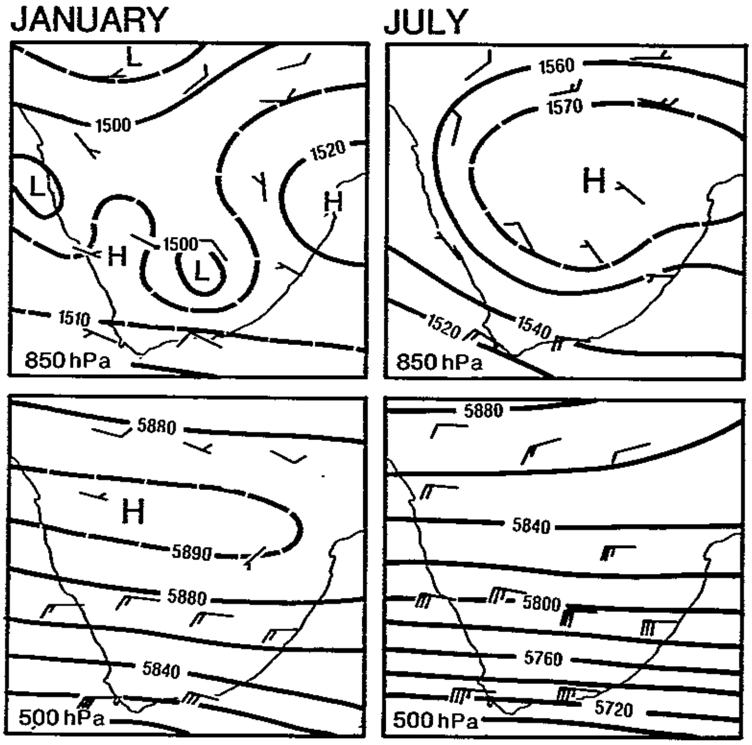


Fig. 2 *Monthly mean winds and contours of the 850 and 500 hPa surfaces (gpm) in January and July (after Taljaard, 1981).*

At Pretoria the frequency of anticyclonic conditions reaches a clear maximum in winter (May to October) (Table 1). Over the ETH the winter frequency of such conditions is likely to be somewhat higher and in summer much higher than over Pretoria. The dominant effect of winter subsidence is that, averaged over the year as a whole, the mean vertical motion is downward. In spring, summer and autumn the atmospheric flow field becomes disturbed, with the occurrence of mid-latitude westerly disturbances increasing and tending to peak in spring and autumn. Tropically-induced easterly disturbances peak in summer. A variety of weather disturbances bring rainfall. These disturbances are usually associated with strong winds and upward vertical air motion and their effect is to disperse vigorously accumulated atmospheric pollution. At the same time they may be associated with acid rain as pollution is washed out of the atmosphere.

The clear, dry air and light winds often associated with anticyclonic circulation of air over southern Africa in general, and the ETH in particular, are ideal for the formation of surface radiation inversions of temperature, surface drainage wind inversions and elevated subsidence inversions which form above the surface boundary layer of the atmosphere. The boundary layer is one in which surface-induced effects (notably friction, strong diurnal heating-cooling effects, pronounced variations in atmospheric stability and turbulence) are dominant. The boundary layer varies in depth by day and night and throughout the year. It may have depths varying from less than 300 m to much more than 1 000 m.

Taken over the year as a whole, surface inversions increase in frequency during the night towards the drier north-west parts of South Africa (Fig. 4) (Tyson et al., 1976). At midday ground inversions are seldom observed anywhere except over the Namib. In winter the depth of the inversion varies from much less than 300 m to more than 500 m over the plateau at around sunrise, which is the time of maximum depth and when the average strength of the inversion is about 5 - 6°C. In summer the surface inversion is about the same depth as that occurring on average in winter and has a strength of less than 2°C. Since these observations are based on fast-ascending radiosondes the depth of the inversion is probably overestimated and the strengths are likely to be underestimated.

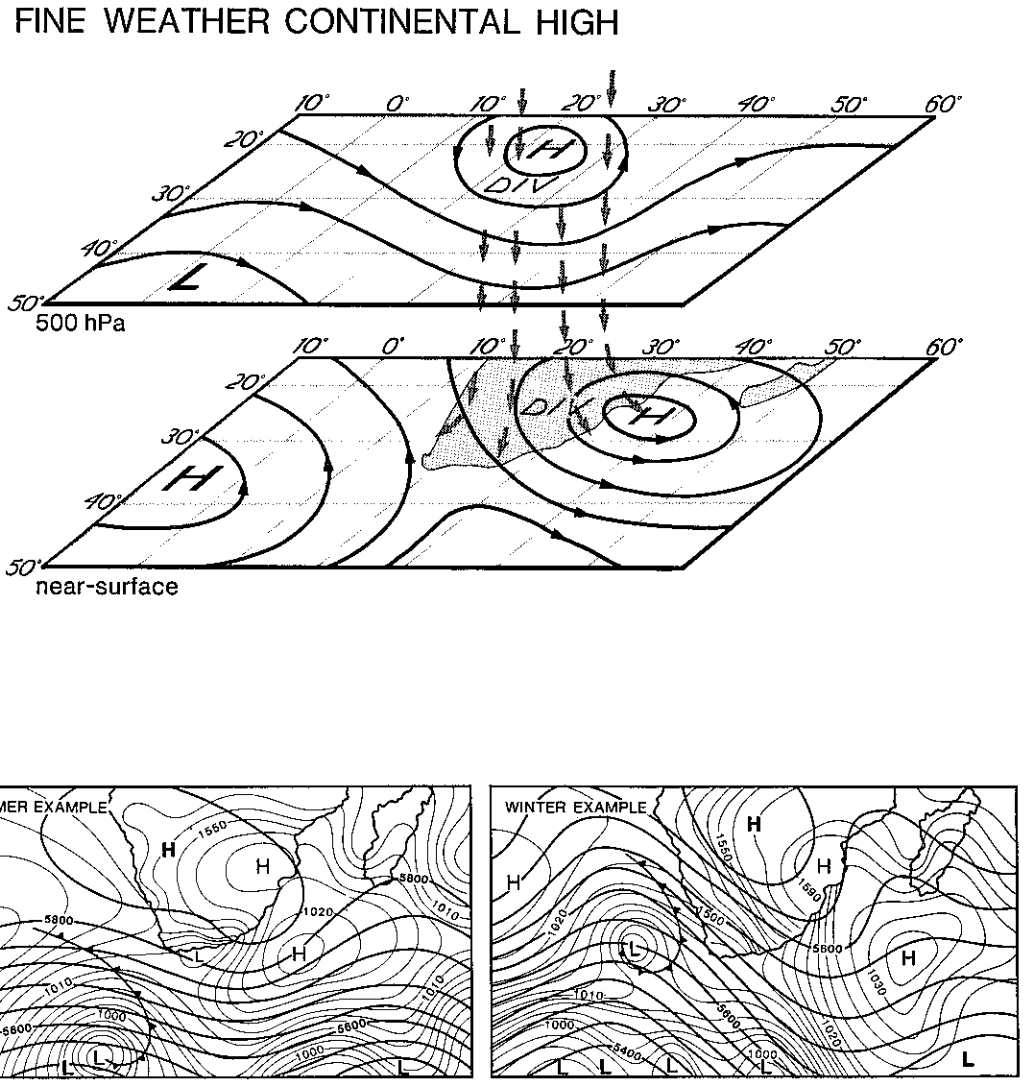
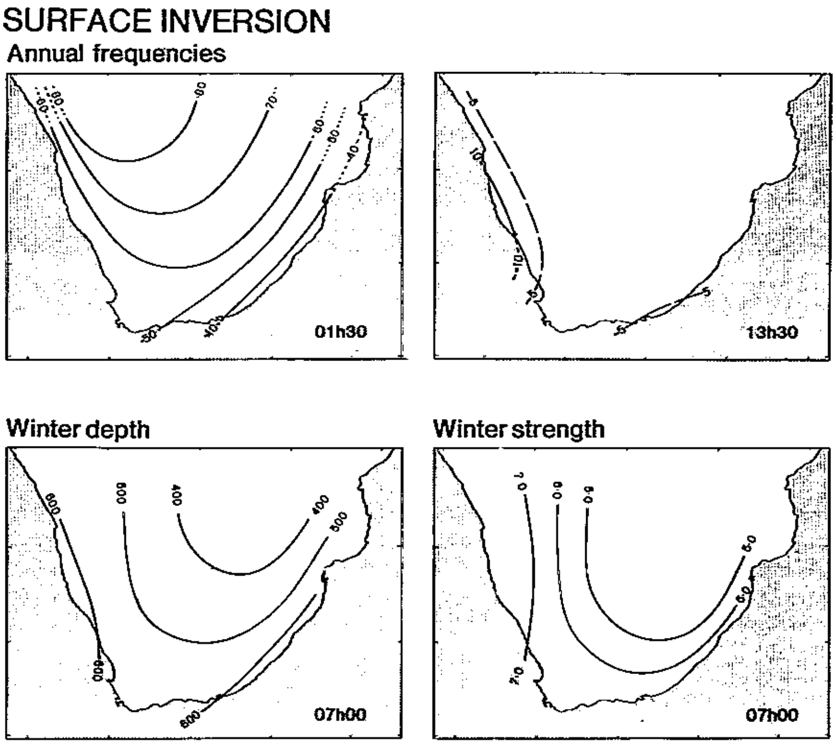


Fig. 3 *Upper: a schematic representation of the near-surface and 500 hPa fine-weather circulation associated with high pressure systems over southern Africa; Lower: summer and winter examples of such systems. Light lines indicate isobars at mean sea level (hPa) over the oceans and contours of the 850 hPa surface (gpm) over the land; heavy lines show contours of the 500 hPa surface (gpm) (after Preston-Whyte and Tyson, 1988).*

Table 1 *Frequency of occurrence of anticyclonic circulations over Pretoria (after Vowinckel, 1956). Note that over the ETH the frequency would be somewhat higher, especially in summer.*

	J	F	M	A	M	J	J	A	S	O	N	D
Percentage occurrence	18	17	19	25	38	79	79	72	65	38	19	11



SURFACE INVERSION

Annual frequencies

Winter depth

Winter strength

Fig. 4 *Upper: annual surface inversion frequencies (percentage) at midnight and midday; Lower: generalised winter, early-morning inversion depth, m, and strength, °C, over southern Africa (after Tyson et al., 1976).*

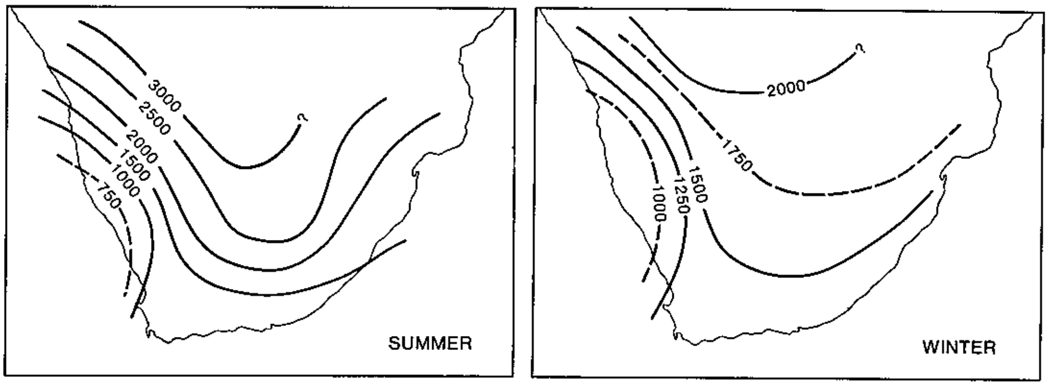
Subsidence of air in anticyclones generates elevated inversions, the first of which has a summer base height of 2 000 - 3 000 m (Fig. 5) above ground (Preston-Whyte el al., 1977). In winter, with stronger subsidence, the base height decreases to 1 500 m or less over much of the plateau. In both seasons the strength of the elevated inversion over the central interior of southern Africa is the order of 1° to 2°C. The seasonal variation of the base height and depth of the subsidence inversion is much less over Pretoria than Bloemfontein (Fig. 5, lower) and its frequency of occurrence consistently greater throughout the year (Diab, 1975).

In studies of atmospheric pollution climatology it is advantageous to combine circulation and stability effects through the use of stability wind roses (i.e. wind roses stratified according to the prevailing lapse rate of temperature). This has been done for a number of stations over South Africa (Tyson et al., 1979). The Pretoria and Bloemfontein annual results are instructive (Fig. 6). In central Pretoria, at night, almost all surface airflow is from an easterly quarter and is associated with stable or inversion conditions which occurred on 99% of occasions. In contrast, by day, most of the observed winds were associated with unstable air and occurred from the west through north-west to the north. A similar sort of pattern is to be observed for Bloemfontein, except that the local surface flow at night is from a different direction owing to the dictates of the topography in and around the city.

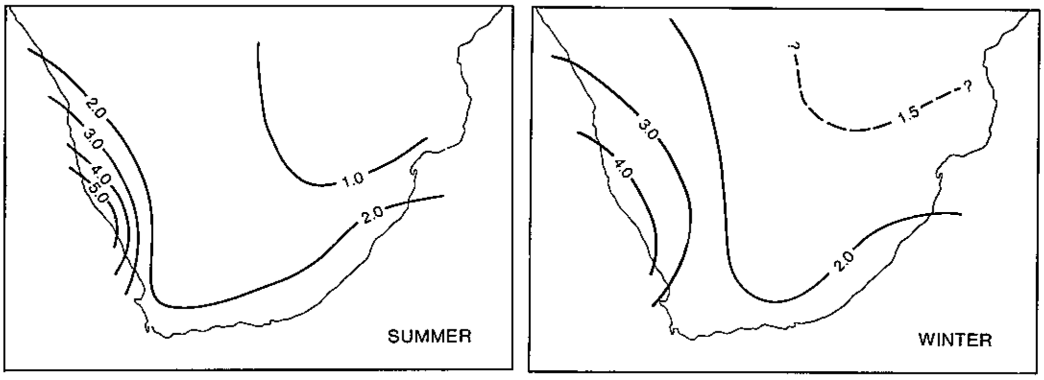
During the day as the stable boundary layer is eroded from below by convective heating and turbulence a mixing layer develops (Fig.7). This may or may not completely dissipate the surface inversion. Most often it does. Diab (1975) shows that maximum midday mixing depths vary between 1 000 and 2 000 m in winter to more than 2 500 m in summer over the plateau. Over the interior part of southern Africa, unlike over coastal regions, the seasonal variation of maximum mixing depths is pronounced. The Bloemfontein example in Figure 7 illustrates such a strong annual cycle. Mixing depths also show a

SUBSIDENCE INVERSION

Base height



Strength



Seasonal variation

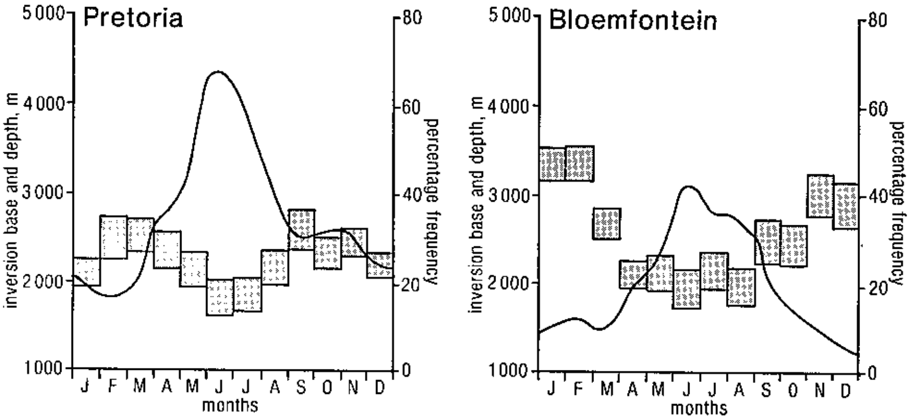


Fig. 5 *Upper and centre: the base height (m) and strength (℃) of the subsidence inversion over southern Africa in summer and winter (after Preston-Whyte et al., 1977); Lower: the seasonal variation of frequencies (solid line) and base heights and depths (shaded) of midday subsidence inversions at Pretoria and Bloemfontein (after Diab, 1975).*

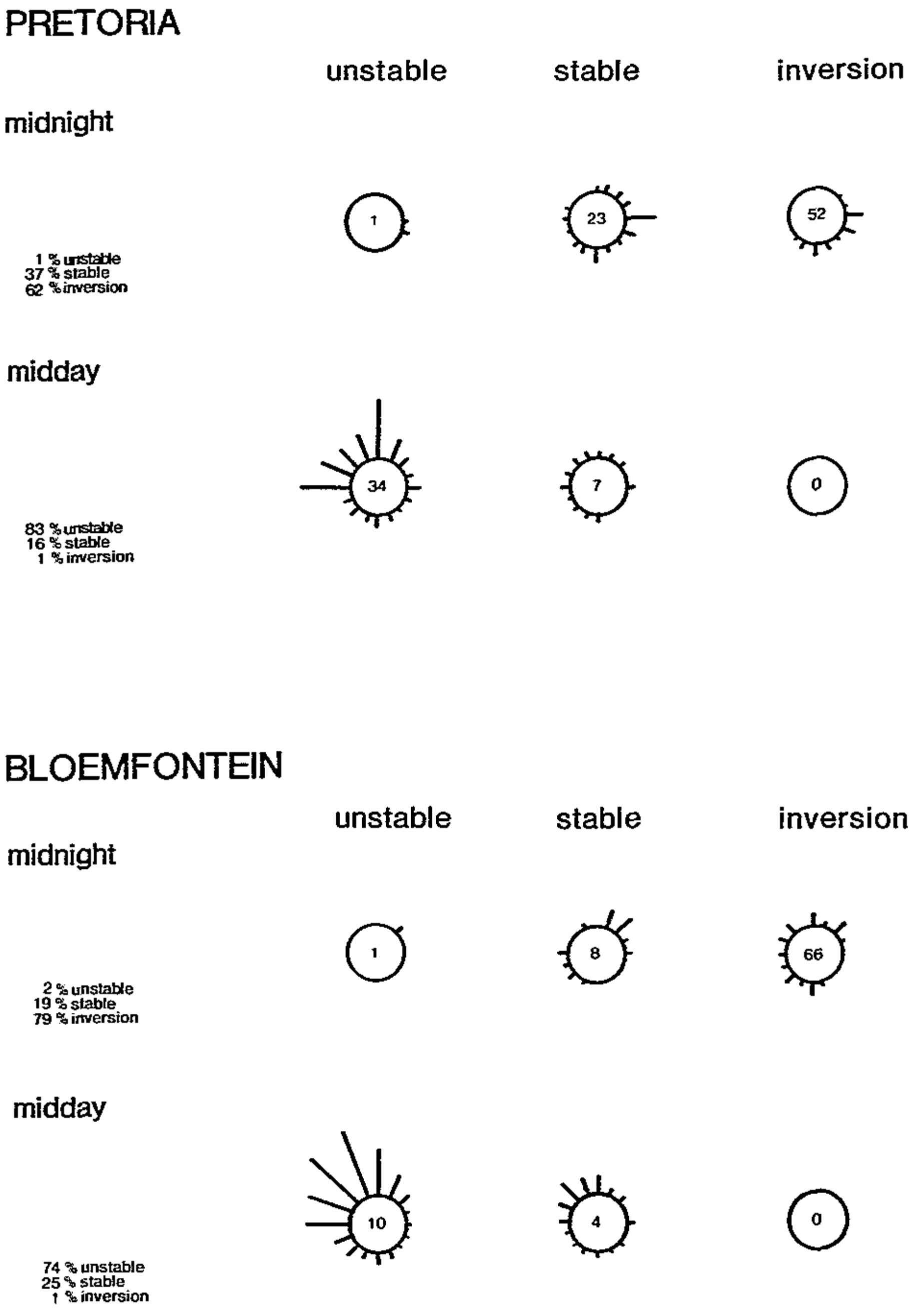


Fig. 6 *Midnight and midday stability wind roses at Pretoria and Bloemfontein (after Tyson et al., 1979).*

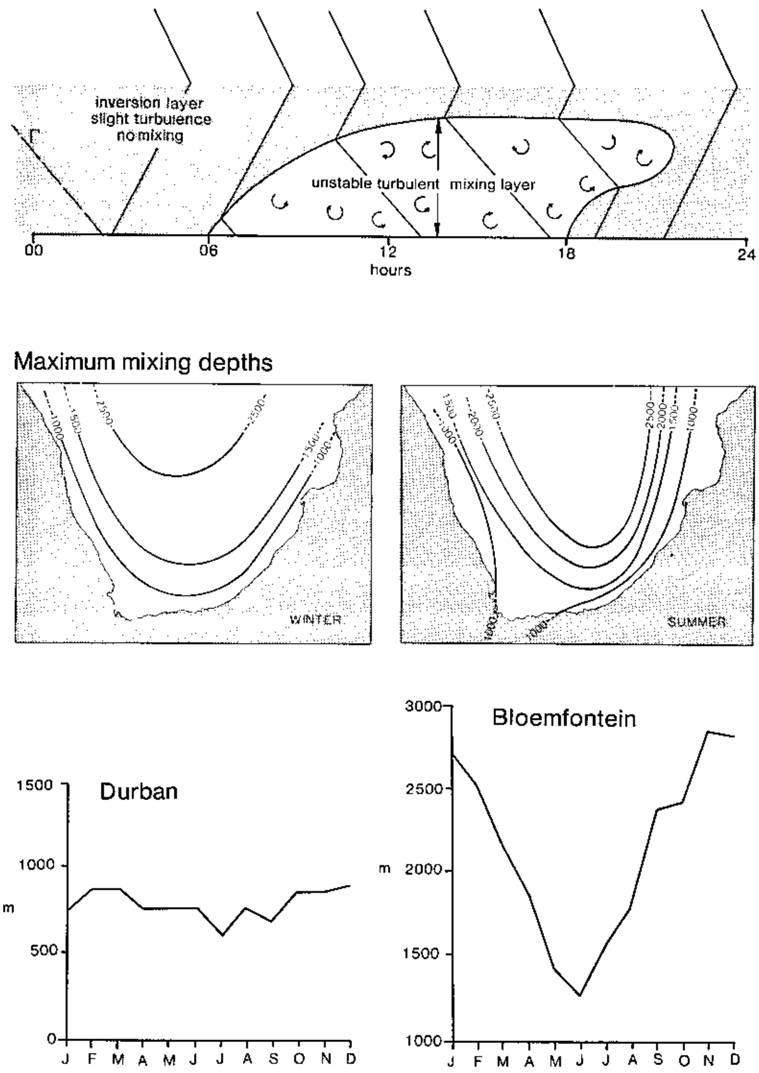


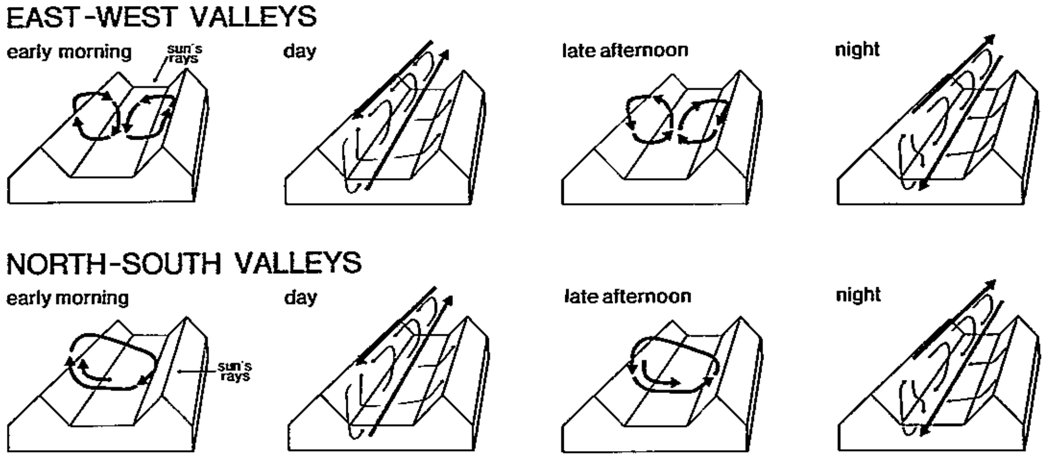
Fig. 7 *The daytime development of a turbulent mixing layer (upper), early-afternoon mixing depths (m) over southern Africa in winter and summer (centre) and examples of the annual variation of mixing depths at a coastal station (Durban) and inland plateau site (Bloemfontein) (adapted after Diab, 1975).*

strong diurnal variation and are usually zero for most night hours. By mid-morning they are usually only a few hundred metres deep. The probability that the winter mid-morning mixing depth will be greater than 500 m is exceedingly low (Diab, 1975).

2.2.2 Mesoscale considerations

Once terrain ceases to be flat and when the boundary layer becomes stable and inversion conditions begin to develop, cold air drainage into hollows and valleys is initiated. Valleys do not need to be deep for this to occur, though the deeper the topographic indentations the more pronounced does such down-slope and down-valley katabatic flow become. The development of local topographically-induced circulation is complex and depends on the geometry (depth and orientation) of valleys and the time of day or night (Fig. 8). Topographically-induced local winds have been studied extensively in South Africa (Preston-Whyte and Tyson, 1988). In valleys, the slopes of which receive roughly equal amounts of radiation throughout the day, and in the presence of clear skies and in the absence of strong synoptically-induced winds, early morning circulations tend to be up-slope in the early morning and down-slope around sunset

LOCAL WINDS (in valleys)



REGIONAL WINDS (below the Escarpment)

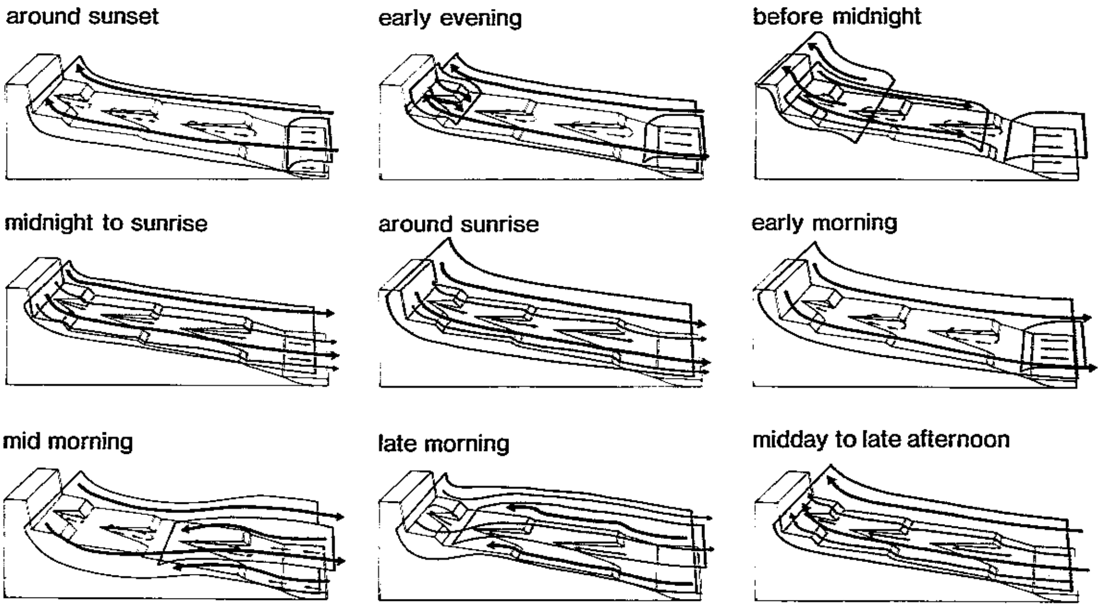


Fig. 8 *The diurnal variation of local wind systems. Upper: within valleys; Lower: on a regional scale between mountains (or escarpments) and plains (or the sea) (after Preston-Whyte and Tyson, 1988).*

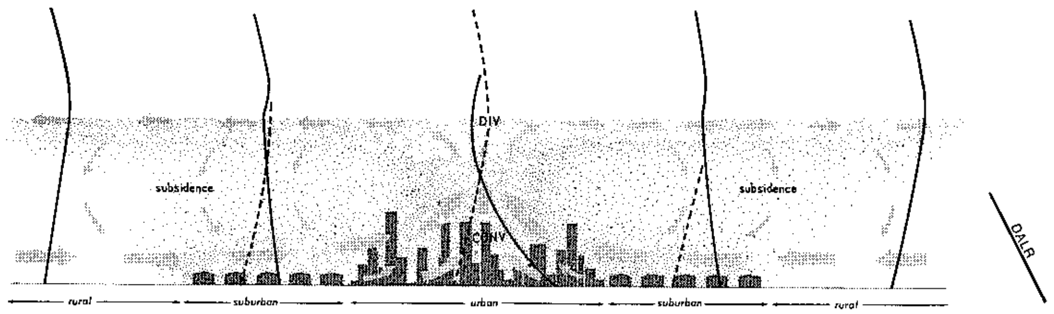
(Figure 8, upper). By day up-valley valley winds occur and conversely by night down-valley mountain winds may blow for more than twelve hours at a time. In valleys roughly at right angles to the rising and setting sun the situation is the same except that around sunrise and sunset unicellular flow up the warm slope and down the cold slope tends to occur. In all valleys return currents to the valley and mountain winds develop unless prevented from so doing by the strength of the synoptically-induced winds. A rule of thumb suggests that valley and mountain wind systems extend to the ridge lines of the valleys in which they occur. Clearly such circulations are major determinants of the low-level flow field, especially at night and in winter, and control to a large extent the transport of ground- and low-level emissions of pollution.

Regional topographically-induced circulations of a mountain to plain (or high ground to low ground) and plain to mountain variety occur on a massive scale in southern Africa. This is particularly so seaward of the Escarpment (Fig. 8, lower), but may also take place over the plateau, for example away from and towards the Lesotho massif by night and day respectively, or from the high ground of the Escarpment region of the Eastern Transvaal towards the lower-lying plateau of the Highveld to the west. In Natal the sequence of flow from the Drakensberg towards the sea by night and in a reversed direction by day is particularly clear and deep. Similar circulations have been shown to prevail between the Eastern Transvaal Escarpment and Lowveld (Held, 1985a).

Clearly the ability to model such winds in order to determine both the flow field in the horizontal and the variation of the local winds with height is essential. In Natal the mountain-plain wind is over 1 000 m deep and is known to transport pollution in an undiluted form for hundreds of kilometres.

Another phenomenon of the lower boundary layer exerting a considerable influence on the dispersion of atmospheric pollution is the urban heat island. Urban boundary layers and urban heat plumes form as a consequence of many processes, including the alteration of the energy balance of the atmosphere above cities and the injection of anthropogenic heat into the air. These factors acting alone and collectively produce distinctive urban boundary layers (Fig. 9). One of the most pronounced characteristics of urban heat islands is the occurrence of a lower frequency of surface inversions than in the surrounding rural areas, combined with a higher frequency of low-level elevated inversions at the top of the urban boundary layer. Consequently conditions favourable for fumigations of pollution are

Under calm conditions



With a wind blowing

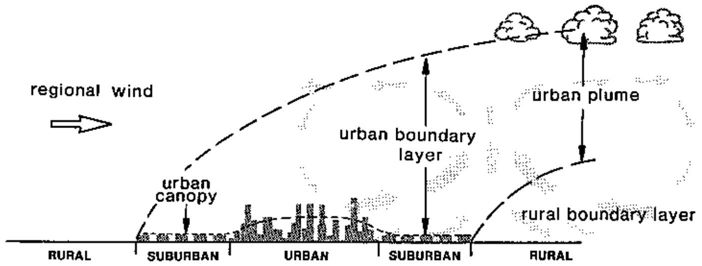


Fig. 9 *Upper: lapse rates and local air movement in urban heat islands in the absence of general winds to disturb the heat islands; Lower: the development of an urban boundary layer and urban heat plume and the downwind displacement of the urban circulation cell as the result of general wind.*

enhanced. Temperatures are always higher in urban heat islands and precipitation tends to be increased locally as a consequence of urban effects. In the absence of synoptically-driven winds, distinctive local winds may be induced within urban heat islands. Inwardly-directed flow converges and ascends over the central urban area and diverges and subsides over adjacent rural areas. Under the influence of a general wind not strong enough to obliterate the urban heat island, but merely to modify it, the urban circulation is displaced downwind in a bent-over urban heat plume such that the region of convergence tends to occur near the downwind limit of the heat island. More importantly, the upwind side of the subsiding aureole of air tends to occur over the urban centre. It is to be expected that these sorts of effects will be observed over cities such as Johannesburg, Pretoria and Witbank in the greater ETH area. Even smaller urban centres such as Middelburg and Ermelo will produce distinctive modification of the lower boundary layer of the atmosphere, mainly through a reduction of the surface inversion.

2.2.3 Local considerations

Buildings, cooling towers and other structures constitute an obstacle to airflow and induce local flow perturbations that add to the complexity of the wind field in the boundary layer. In the case of high-standing, flat-roofed structures maximum wind pressure occurs at a stagnation point on the leeward side. The sides, roof and leeward walls become characterised by increased flow in suction zones created by the separation of flow along building edges. Behind the structure in the cavity zone lee eddies and reversed and highly turbulent flow develop (Fig. 10). The disturbance of the wind profile is characteristic: a zone of maximum airflow occurs in the convergence region above the building with low-velocity reverse flow immediately above the roof and in the cavity zone. Downwind the velocity profile slowly adjusts to its upwind shape.

While clearly having few implications for large-scale transport and diffusion of atmospheric pollution, local flow around obstacles may exert important effects on urban dispersion and on the diffusion of plumes and the mixing of pollution in and around industrial establishments. Plume dispersion is a function of plume type and the prevailing atmospheric stability and turbulence (Fig. 11). Plumes vary from those that loop, cone or fan to those that loft in the unstable air above a surface inversion and those that fumigate with the development of a convective mixing layer beneath a prevailing or dissipating inversion. In the modelling of pollution dispersion, cognizance of plume types, the transition from one type to another and the frequency of occurrence of each type is essential. In general looping plumes in unstable air and fumigating plumes in stable air produce highest ground concentrations of pollution.

Having considered, in general, the most important factors affecting accumulation, transportation and dispersion of atmospheric pollution over southern Africa, it is necessary to direct attention, more specifically, to the atmospheric pollution dispersion climatology of the greater ETH region.

2.3 THE EASTERN TRANSVAAL HIGHVELD REGION

2.3.1 The flow field

An idea of the surface circulations of the atmosphere over the greater ETH region was given in Figure 2. It was also shown that the nocturnal surface inversion over the ETH is a few hundred metres deep and that during the day a mixing layer one or two thousand metres deep develops and reaches a maximum depth and intensity of mixing in the early afternoon. Surface wind fields likewise undergo alteration during the day and night.

During the day (06h00 to 18h00) mean winter surface wind roses for the ETH show a predominance of north-westerly winds, together with a secondary peak in frequencies from an easterly quarter (Fig. 12)

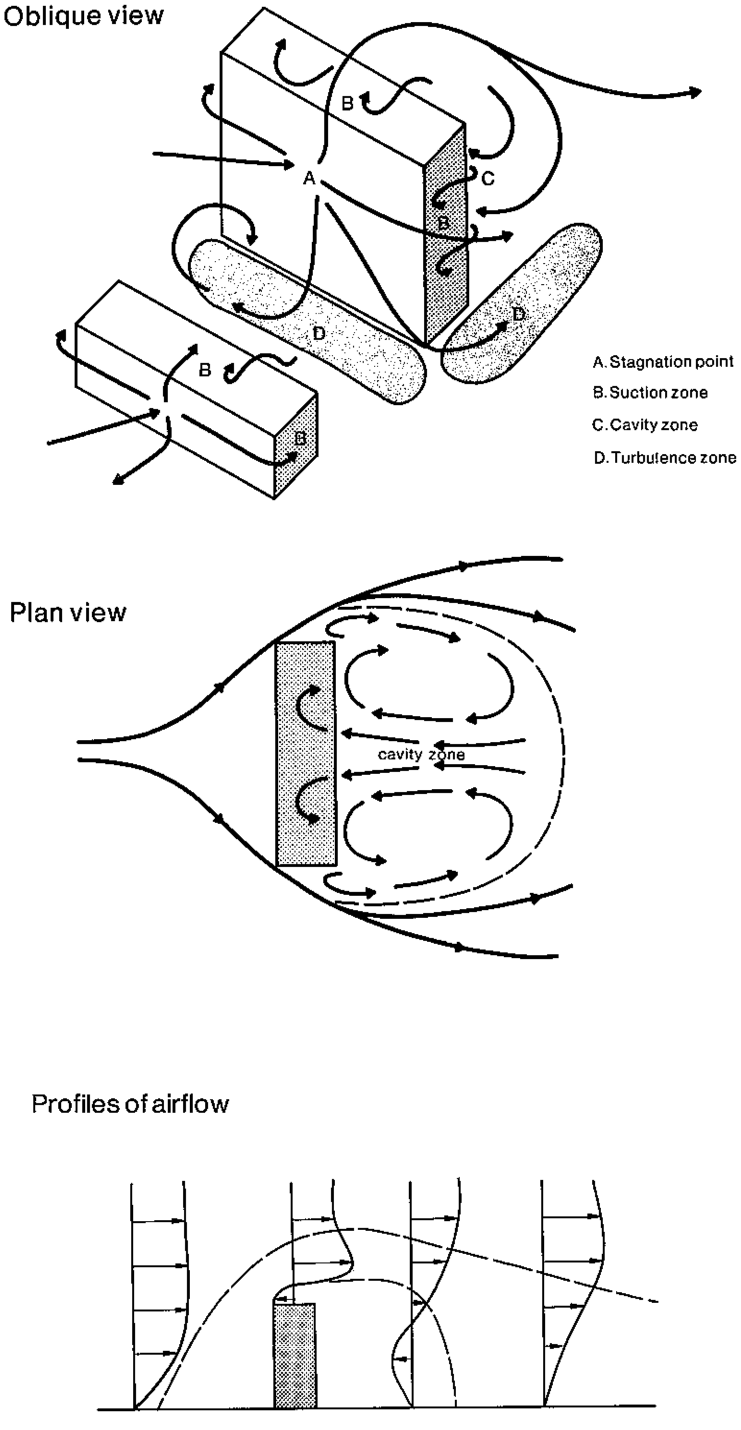


Fig. 10 *Flow patterns around local obstacles.*

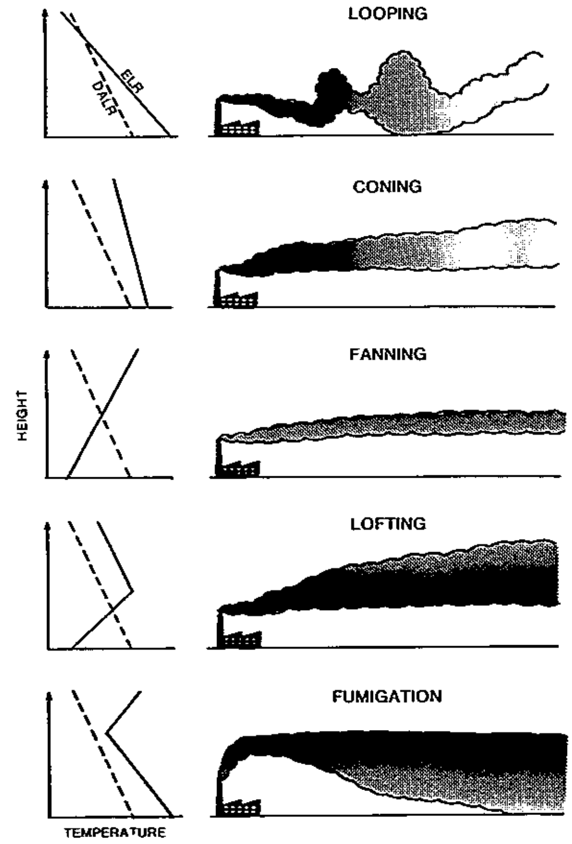


Fig. 11 *The effect of lapse rates on plume type. DALR signifies the dry adiabatic lapse rate; ELR the environmental lapse rate.*

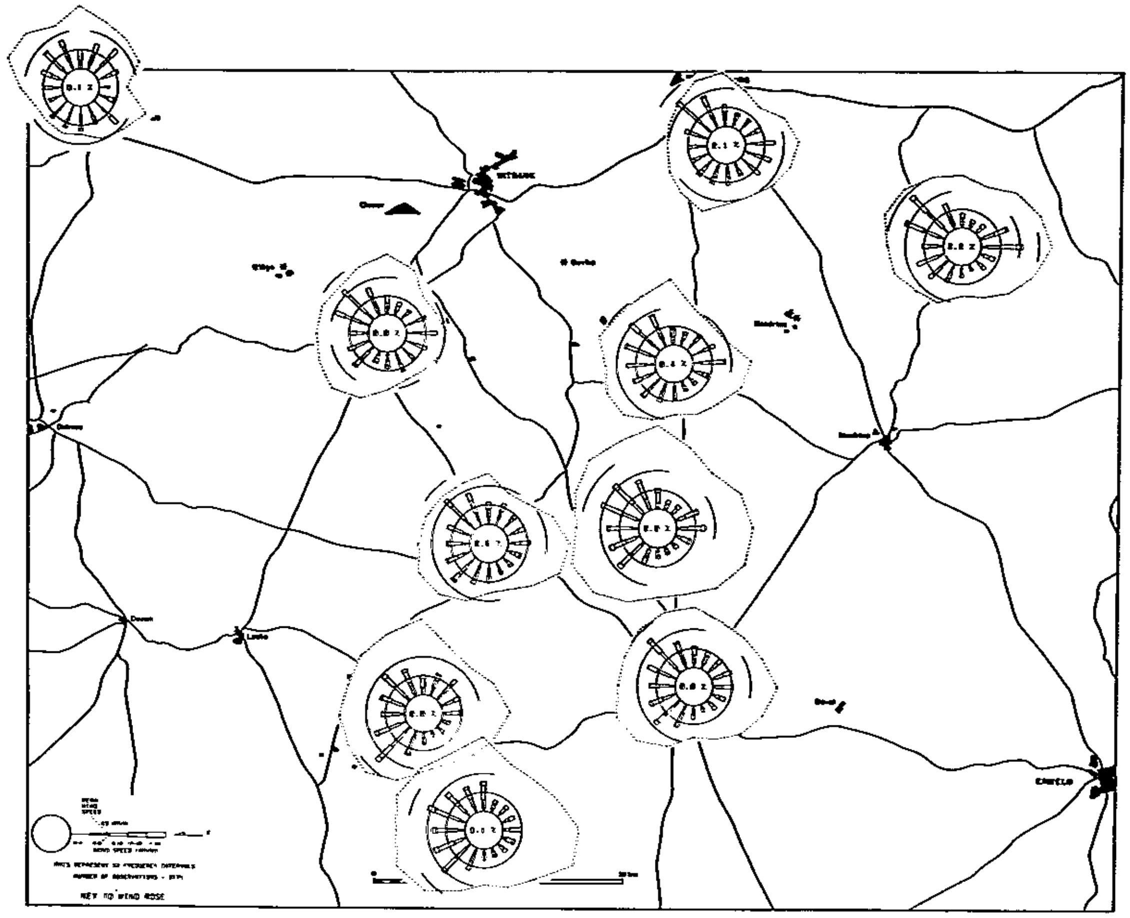


Fig. 12 *Winter, daytime (06h00 - 18h00) surface wind roses, 1979 - 1984, for the ETH (after Pretorius et al., 1986).*

(Pretorius et al., 1986). The north-westerly and strong south-easterly winds are of anticyclonic origin. Light winds with easterly and westerly components are local. South-westerly winds are cyclonic in origin and mainly associated with the passage of westerly weather disturbances. By night (18h00 to 06h00) the mean winter pattern of airflow shows a greater incidence of north-easterly winds, together with a marked increase in local light flow in the north-east to south-east quadrant (Fig. 13). The direction and speed of local winds are dependent on the detailed geometry of the surface topography and thus one finds that, in the south of the region, air drainage into the Vaal river basin imparts a more northerly component to the local surface winds. In other localities the air drainage may be north-easterly, easterly or south-easterly.

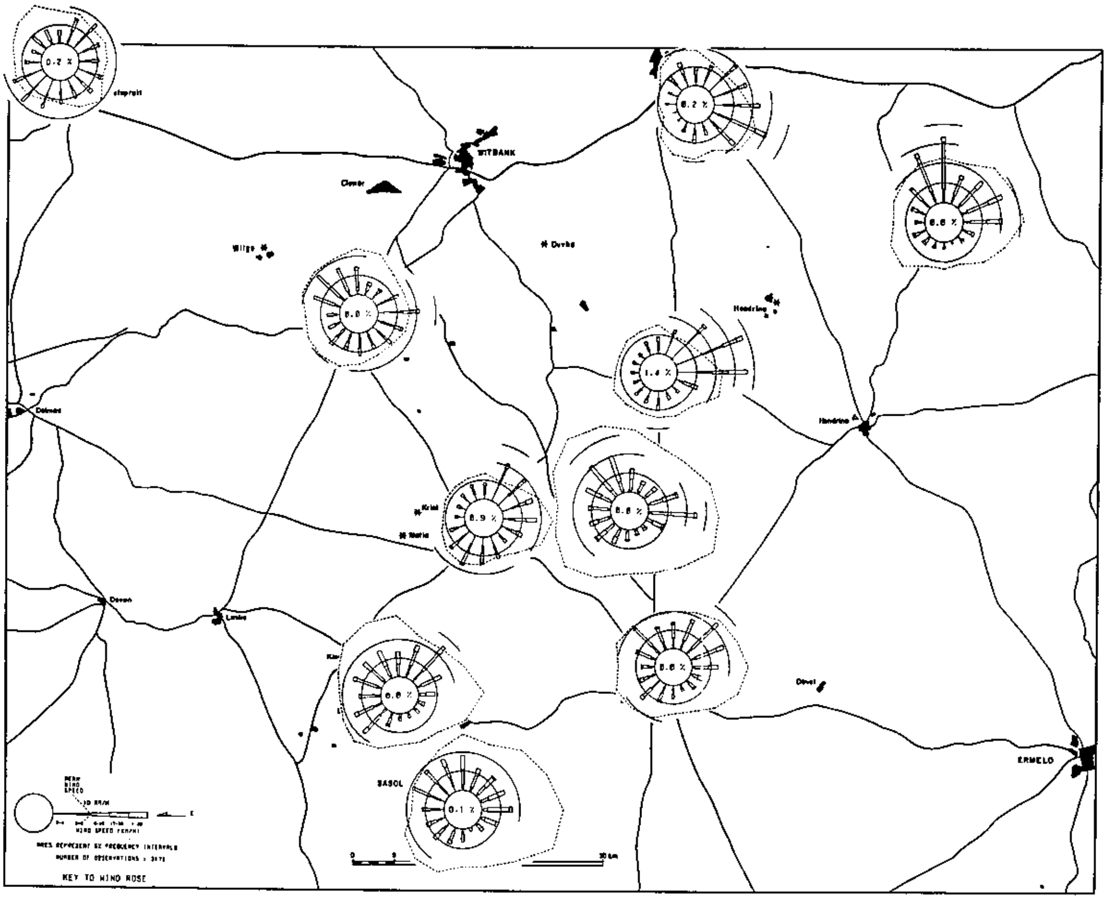


Fig 13. *Winter, nocturnal (18h00 - 06h00) surface wind roses, 1979 - 1984, for the ETH (after Pretorius et al., 1986).*

By day turbulent mixing within the boundary layer results in a more uniform velocity field than by night and surface wind roses give a reasonable approximation to conditions occurring in the first few hundred metres above the surface. By night the situation is very different as the lower atmosphere and that above tend to decouple at the top of the surface inversion. Under such circumstances the surface wind field may bear little relationship with that prevailing a few hundred metres above the ground. The 800 hPa pressure surface occurs about 350 m above the surface over the ETH and thus is a useful level from which to infer the circulation likely to occur at or near the top of the surface inversion layer. Such an analysis has been done by Tosen and Jury (1986b) on a monthly basis for the years 1969 - 1977. Aspects of the mean flow field are shown in Figure 14. Whereas the seasonal change in circulation over central and

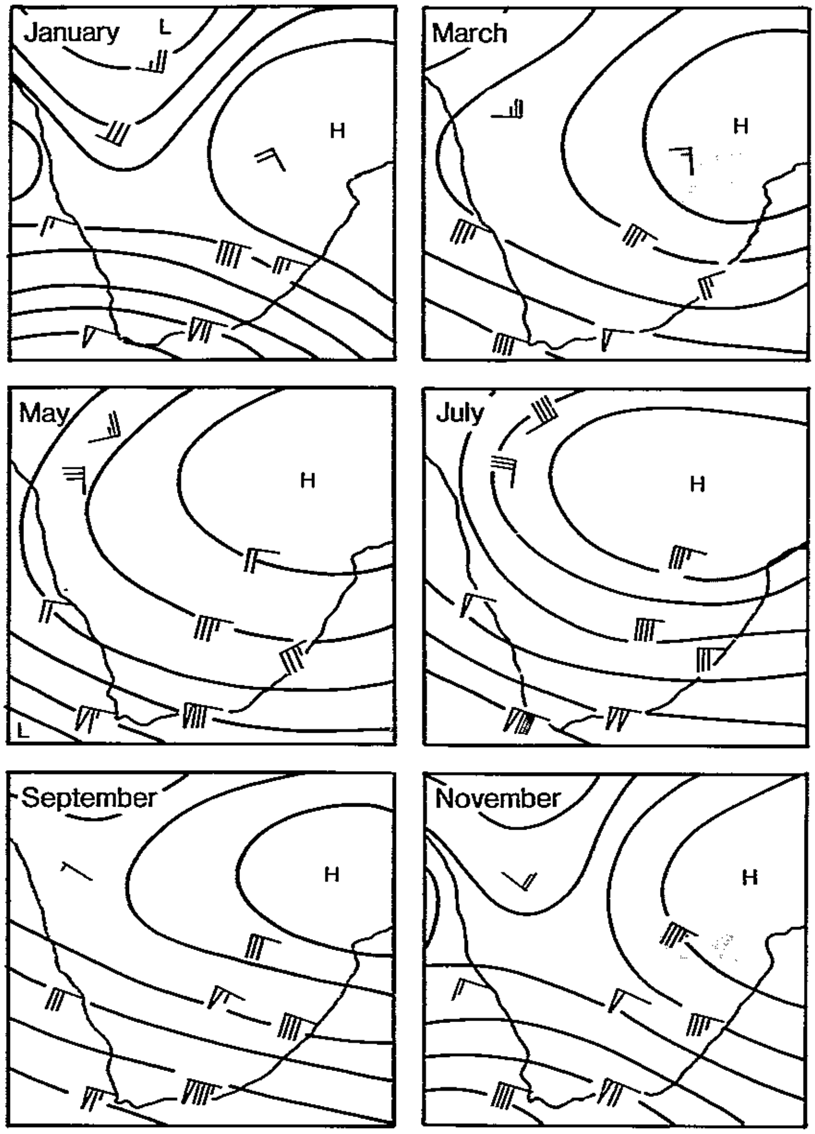


Fig. 14 *Mean 800 hPa winds and contours. The 800 hPa surface occurs at around 1950 m, i.e. about 350 m above the surface over the ETH (shaded) (after Tosen and Jury, 1986).*

western regions of southern Africa is apparent, it is evident that over the ETH, apart from an intensification in winter, the anticyclonic circulation over the area changes very little throughout the year. The implications for atmospheric pollution are obvious.

From month to month and year to year the circulation may vary appreciably (Tyson, 1986), but over long periods will revert to the patterns illustrated in Figures 2 and 14. Apart from surface-induced changes, the longer-period variability is clear in the surface wind roses shown above in Figures 12 and 13. Mean wind roses for long periods of observation are not available for levels above the surface and will only become a reality when doppler acoustic sounder data or tall stack anemometer data have been accumulated routinely for long enough. In the meantime doppler acoustic sounder data are available for case studies only (Earth Science Services, 1985). One such study included the month of July 1984, where at Elandsfontein wind roses at levels up to 750 m were obtained (Fig. 15). From this and other sets of observations it is clear that a pronounced wind shear exists between the flow near the ground and that above. In July 1984 at the 10 m level light easterly winds occurred both by day and night, but more so at night. At 60 m and above, south-easterly flow was completely absent at night and only stronger, synoptically-forced easterlies prevailed at heights exceeding 60 m above the surface during the day.

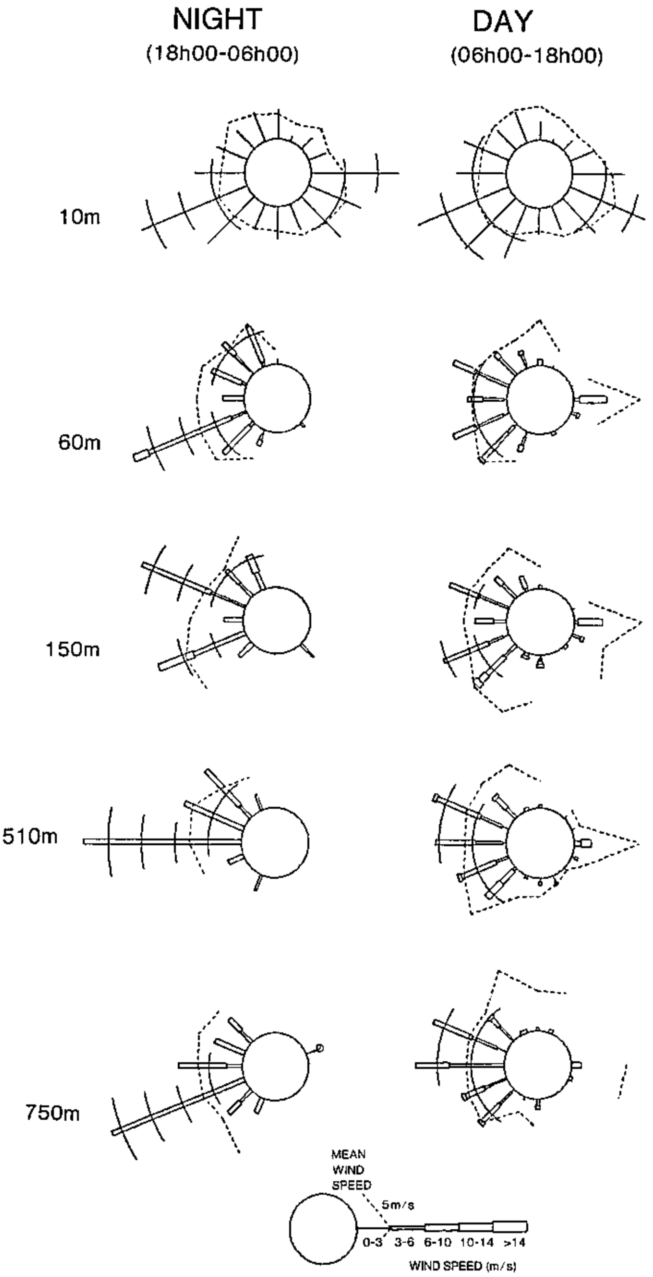


Fig. 15 *Wind roses derived from doppler acoustic sounder data, 1983 - 84 at levels from 10 to 750 m at Elandsfontein (after Earth Science Services, 1985).*

North-westerlies were relatively rare at the surface and much more common from a level of 150 m upward. The origins of winds of various directions are generally distinctive. The surface nocturnal easterly flow is a regional topographically-induced wind, whereas the south-easterly flow occurs with a ridging anticyclone to the south of the subcontinent. North-easterly and north-westerly winds occur with a continental anticyclone over the subcontinent and south-westerly winds with cyclonic curvature of airflow in systems originating in middle latitudes.

In fine clear weather the nocturnal surface flow is likely to be easterly. Above the surface layer airflow occurs most commonly from north-easterly to north-westerly directions. With weather disturbances of one kind or another the upper boundary layer winds are likely to be easterly to south-easterly or westerly to southerly. The low-level shear recorded in July 1984 has been observed frequently and is a distinctive feature of the lowest layers of the atmospheric boundary layer.

In general, the diurnal cycle of wind speed at the surface shows a midday peak at the time of maximum surface heating and instability. By night the stability of the lower atmosphere causes wind speeds to diminish near the ground. At the top of the boundary layer the opposite is the case. By day the turbulent eddies that effect the mixing of the boundary layer transfer momentum toward the surface and exert a frictional drag on airflow above the layer so causing a wind speed minimum. By night friction at the top of the stable layer is much less than at the surface, the stable layer tends to decouple from the air above and wind speed increases at or near the interface between the inversion and less stable air above. Winds for the ETH show these diurnal characteristics (Von Gogh et al., 1982; Pretorius et al., 1986).

Throughout the year low-level wind speeds vary with a clear annual cycle (Von Gogh et al., 1982; Tosen and Jury, 1986). February and March are the months of lowest average wind speeds and September and October are the windiest months. At this time of year surface mean monthly wind speeds at Elandsfontein (on a ridge and the most exposed site) exceed 22 km. h^{-1}.

Doppler acoustic sounder measurements at Elandsfontein show that, on average, highest wind speeds tend to be observed at or around the top of the inversion layer at about 200 - 300 m (Earth Science Services, 1985). Below this level the wind direction variability is at a minimum. Maximum direction variability occurs at heights of around 500 m where wind speeds are low. Thereabove, wind speeds increase and directional variability decreases.

The reason for the low nocturnal direction variability of flow in the inversion layer is to be found in the origin of the easterly regional wind that most often constitutes this flow (Fig. 16). The local drainage nature of the easterly surface winds was first proposed by Von Gogh et al. (1982). Clearly these winds are more than just local. Though very shallow, they appear to be regional and analogous to the deeper mountain-plain and plain-mountain winds observed over Natal (Tyson and Preston-Whyte, 1972) and over the Namib (Tyson and Seely, 1980). By night a shallow mountain-plain wind develops between the Escarpment uplands and the westward-sloping Highveld to the west. Below the Escarpemnt the flow will be down-slope toward the Lowveld. The evidence for the mountain-plain and plain-mountain winds between Escarpment and Lowveld is compelling (Held, 1985a; Garstang et al., 1985). By day the opposite is likely to occur. Observational evidence for light westerly component surface winds by day is evident in the wind roses of Figures 12 and the sections given in Figure 16.

Examples of regional easterly flow affecting three stations in the ETH show that the flow is confined to the lowest (steepest) part of the surface inversion layer (Fig. 16, centre) (Von Gogh et al., 1982). That such occurrences of regional winds are regular is shown in mean monthly time-height sections for August 1983 and June 1984 at Elandsfontein (situated on a rise some 120 m above the surrounding terrain and thus likely to give an underestimate of the depth of the mountain-plain flow). In both months, at a level of about 50 m, the reversal in direction of flow, at night and between day and night is striking. These examples are likely to be highly representative of winter, near-surface, stable, fine, clear-weather conditions. In summer the tendency for daytime, light westerly component, plain-mountain winds will increase and the nocturnal easterly flow will decrease. In winter the opposite will be the case.

The boundary layer wind structure and the transition to the airflow above may be uniform and regular. Often this is not the case and a pronounced multi-layered, highly sheared structure is evident, such as occurred in August 1983 (Fig. 17). During this month the average surface inversion depth was about 400 m. The topographically-induced easterly drainage flow off the Escarpment uplands was about 50 m deep at Elandsfontein during the night hours. Above the surface, from midnight to late afternoon the flow backed (i.e. azimuth decreased) from north-westerly to westerly. From late afternoon to midnight

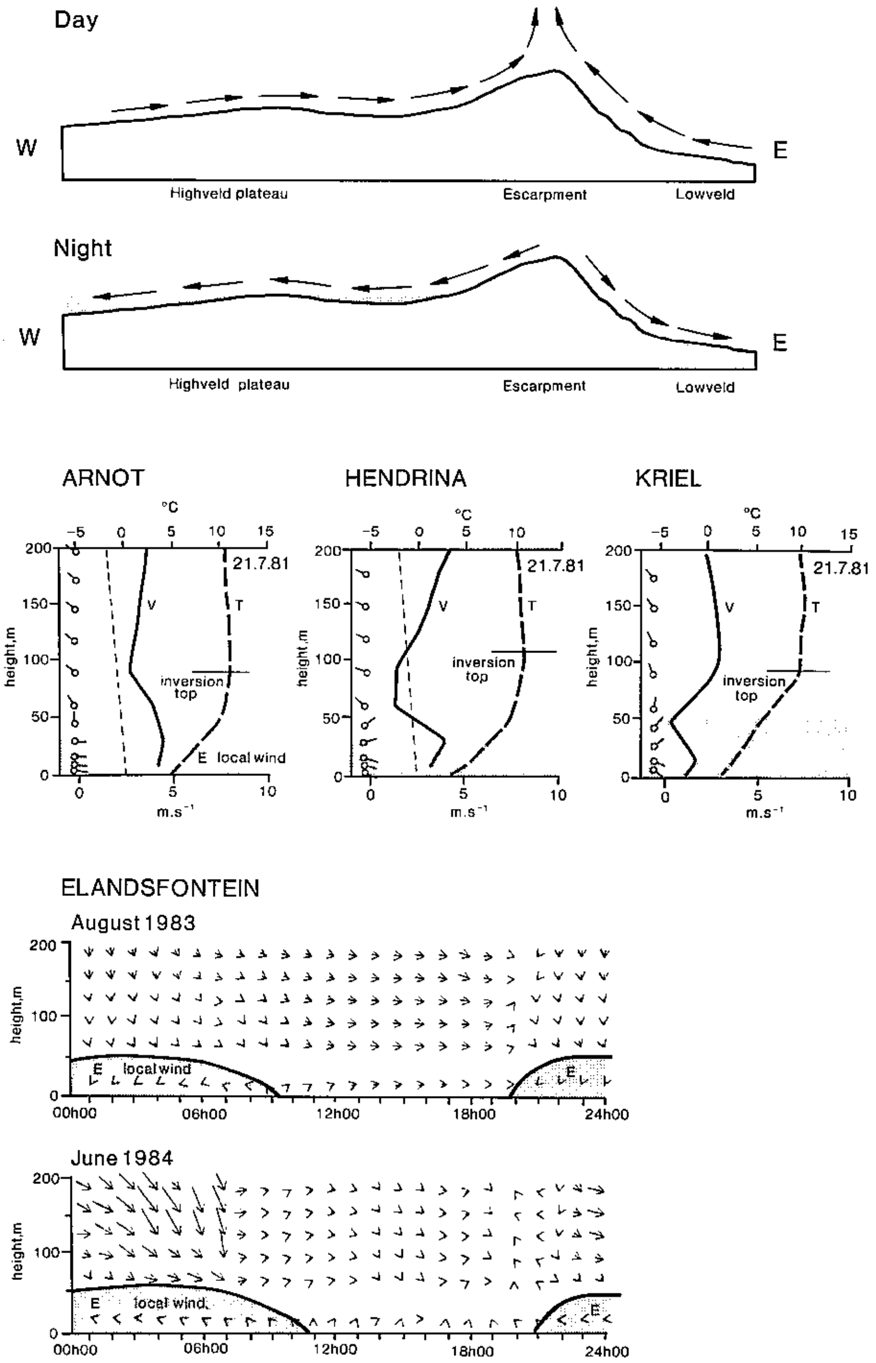


Fig. 16 *Profiles of wind speed (solid lines), wind direction (arrows) and temperature (broken lines) at Arnot, Hendrina and Kriel between 06h00 and 07h00 on 21 August 1981 (after von Gogh et al., 1982); Lower: August 1983 and June 1984 mean wind vectors illustrating mountain-plain and plain-mountain components at Elandsfontein (after Earth Science Services, 1985).*

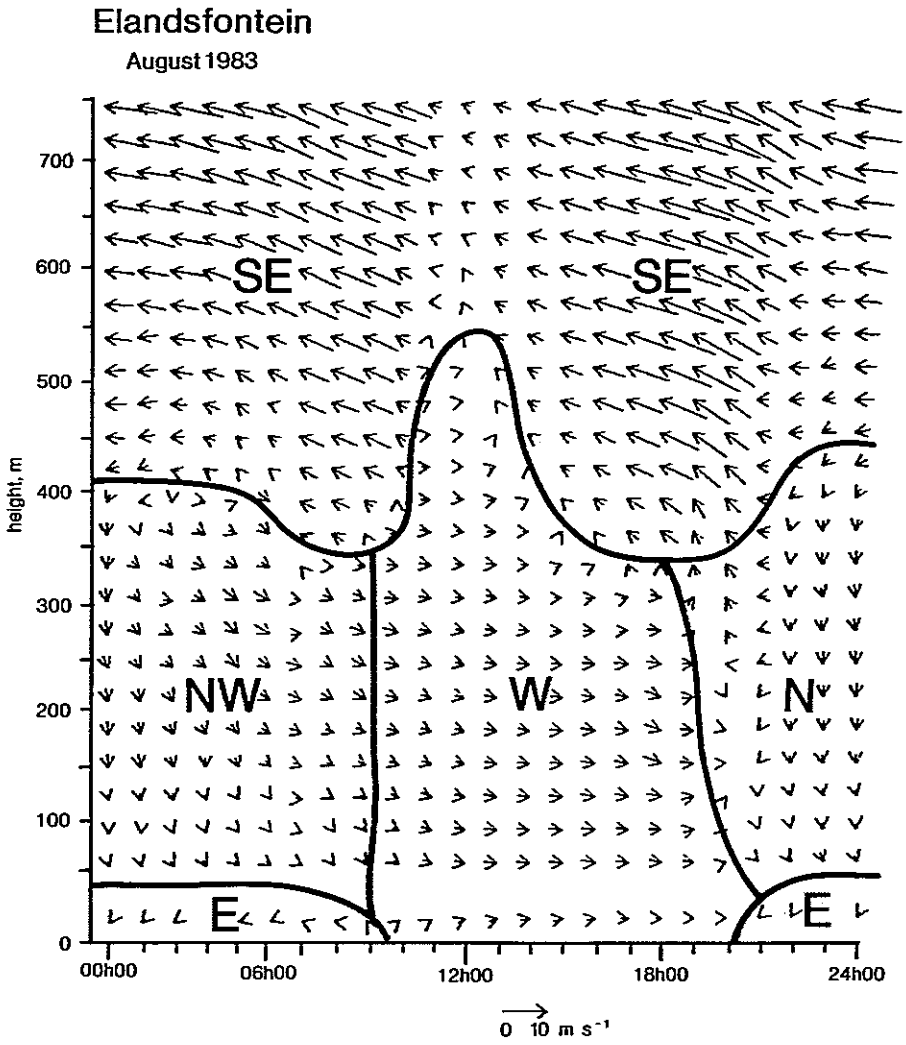


Fig. 17 *The mean diurnal variation of the boundary layer wind field, August 1983, at Elandsfontein (after Earth Science Services, 1985).*

the within-inversion layer flow veered (i.e. increased azimuth) to northerly and finally to north-westerly. This type of backing and veering was first ascribed to a thermal wind effect by Jackson (1956) and has since been noted (Von Gogh et al., 1982). More recently Tosen and Jury (1986) and Jury and Tosen (1987) have independently postulated the idea of a thermal wind effect to explain the upper boundary layer airflow and low-level wind maximum over the ETH. In winter with the drainage of cool air westward off the Escarpment uplands and into the Vaal river basin a cool pool of air develops over part of the ETH. In contrast, the air over the Springbok Flats area to the north-west is much warmer. The consequence is to induce a thermal wind component from the west or south-west within the inversion layer. This will cause westerly winds to increase in strength during the night. During the day, as convective heating and turbulent mixing erode and destroy the inversion and replace it with an unstable condition, the horizontal temperature field responsible for the thermal wind effect disappears and winds resume their alignment with the synoptic pressure gradient.

2.3.2 Surface inversions

As the surface cools by radiational loss of heat through the night, an intense inversion develops in the first few tens of metres. The drier the atmosphere the stronger the surface inversion is likely to be. Above the surface layer a further, less-intense inversion forms usually to a depth of a few hundred metres.

Above this in turn an isothermal layer usually occurs. The three elements of the stable nocturnal surface layer are clear at Matimba, Ellisras in the north-western Transvaal (Surridge and Swanepoel, 1987) as well as over the ETH (Von Gogh et al., 1982; Pretorius et al., 1986) (Fig. 18, upper).

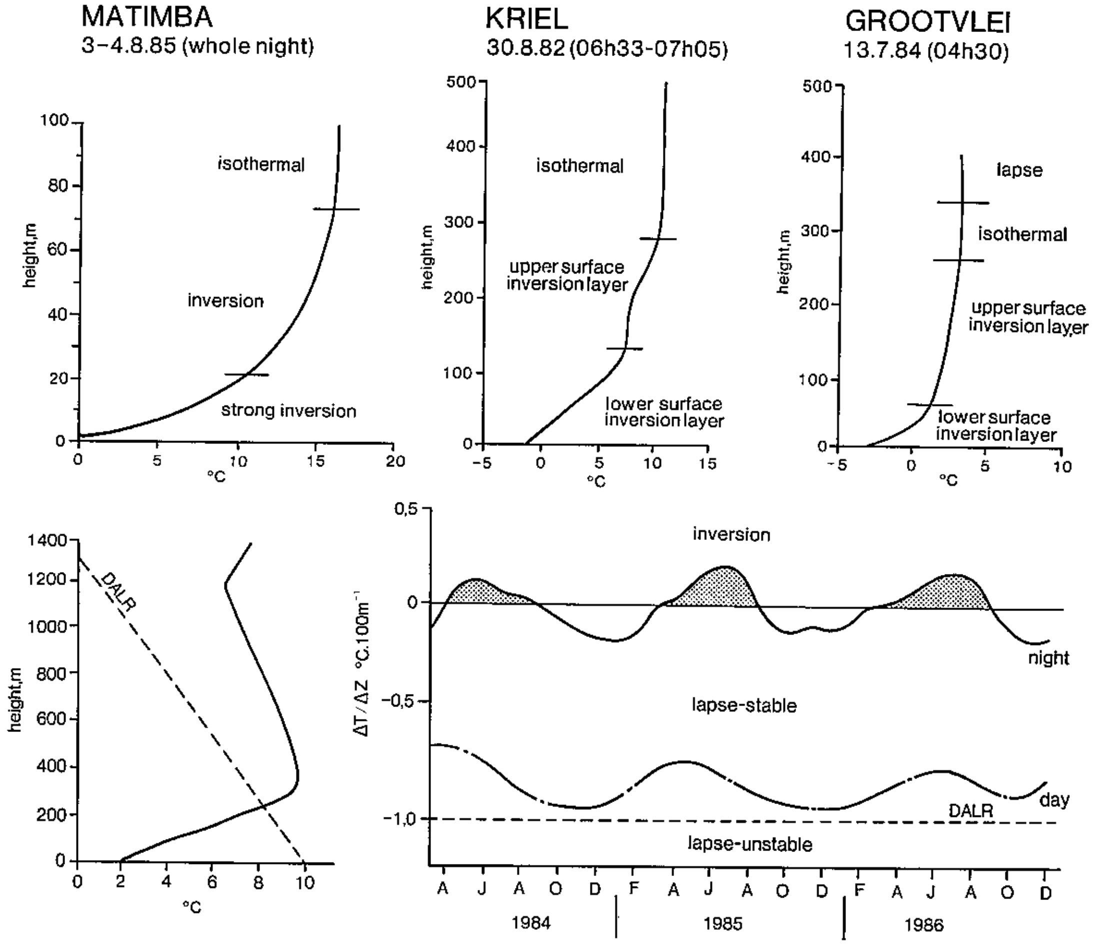


Fig. 18 *Upper: examples of surface inversion lapse rates at Matimba, Ellisras (after Surridge and Swanepoel, 1987), at Kriel and at Grootvlei (after Pretorius et al., 1986); Lower: an average profile for 450 winter aircraft flights over the ETH, and the annual variation of lapse rates between 850 and 750 hPa at Irene (after Tosen and Pearse, 1987).*

According to Von Gogh et al. (1982), using 1979 - 1981 data, mean winter early-morning surface inversions over the ETH vary from a maximum at Kriel of 8,3°C (range 2,8° - 14,8°) through a depth of 200 m (range 82 - 340 m) to a minimum at Arnot of 3,8°C (range 1,3° - 5,8°) through a depth of 115 m (range 30 - 230 m). By comparison the midnight data for Irene over the same period suggest an inversion of 4,4°C (standard deviation 2,3°) through a depth of 179 m (standard deviation 140 m) with a 91 per cent frequency of occurrence in winter. At Kriel 41 per cent of inversions had a strength in the range of 5 - 10°C during which occurrence they had a mean depth of 163 m, by comparison to the average depth of 200 m for all inversions. If the average depth of 80 - 90 m for the isothermal layer is added to the minimum depth, then it would appear that the stable boundary layer is of the order of 280 - 290 m over the ETH.

The most detailed set of inversion data for the ETH is that of Tosen and Pearse (1987). From 450 aircraft soundings (collected after sunrise) they show that the average inversion is 280 m deep with a temperature difference of 7° - 8°C between the near-ground and top of the inversion levels (Fig. 18, lower left). Such inversions occur on every four out of five nights. Only when the atmosphere is in a disturbed state (with cloud and strong winds) will the surface inversion not form.

Even in summer surface inversions occur, e.g. at Kriel through a mean depth of about 190 m with strengths in the range 0,2 to 3,0°C. Inversion frequencies are least in spring, when winds are strongest. In summer they may occur more than two out of three nights. Average summer surface inversion strenghts at Kriel appear to be about 2,5°C (Von Gogh et al., 1982).

Some idea of the diurnal and annual variation of low-level stability in the atmosphere may be gained from 850 - 750 hPa lapse rates over Pretoria (Tosen and Pearse, 1987). These lapse rates are between levels which straddle the mean height of the surface inversion. By day throughout the year, on average, the lapse rates are stable (Fig. 18, lower right). It is only on disturbed days, particularly storm days in summer, when they become unstable. A more detailed idea of the nature of the diurnal variation of lapse rates and stability may be gained from the example given in Figure 19. In winter, surface inversions develop from about 17h00 onward reaching their maximum strength and depth after 04h00. Following

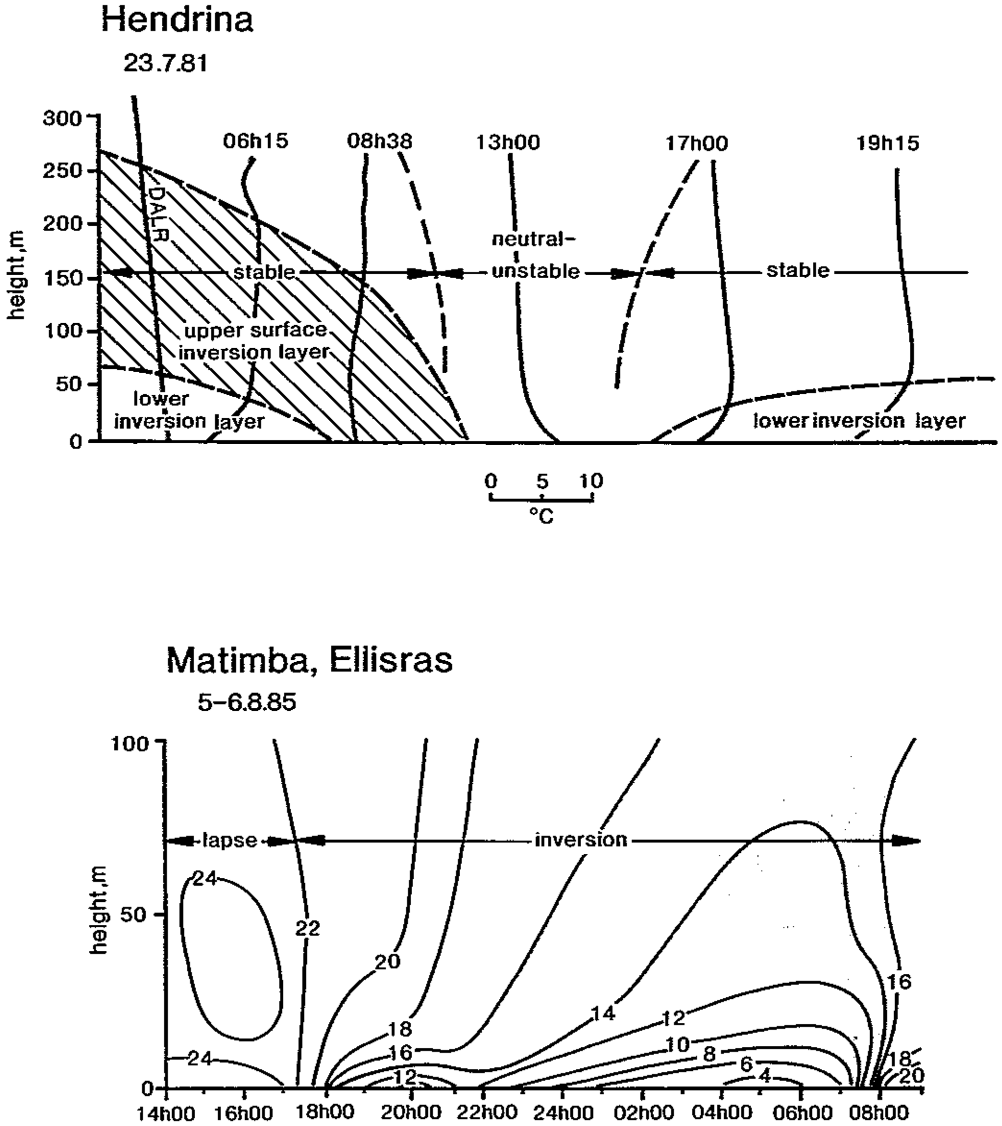


Fig. 19 *Upper: an example of the winter diurnal variation of lapse rates at Hendrina (after von Gogh et al., 1982); Lower: the development and deepening of the low-level surface inversion at Matimba, Ellisras (after Surridge, 1986).*

sunrise they dissipate rapidly by erosion from below through turbulent and convective mixing. In so doing they often deepen in the manner indicated by Tyson et al (1980). In general, as Surridge (1987) has shown, the steeper and stronger an inversion, the later it forms and earlier it dissipates (Fig. 20). Strong inversions show the most pronounced annual cycle of variation; weak ones have a less pronounced cycle and are more common. In winter the relationship between duration of an inversion and its strength is inverse and linear; in summer it is only the weak nocturnal inversions that are persistent and of long duration.

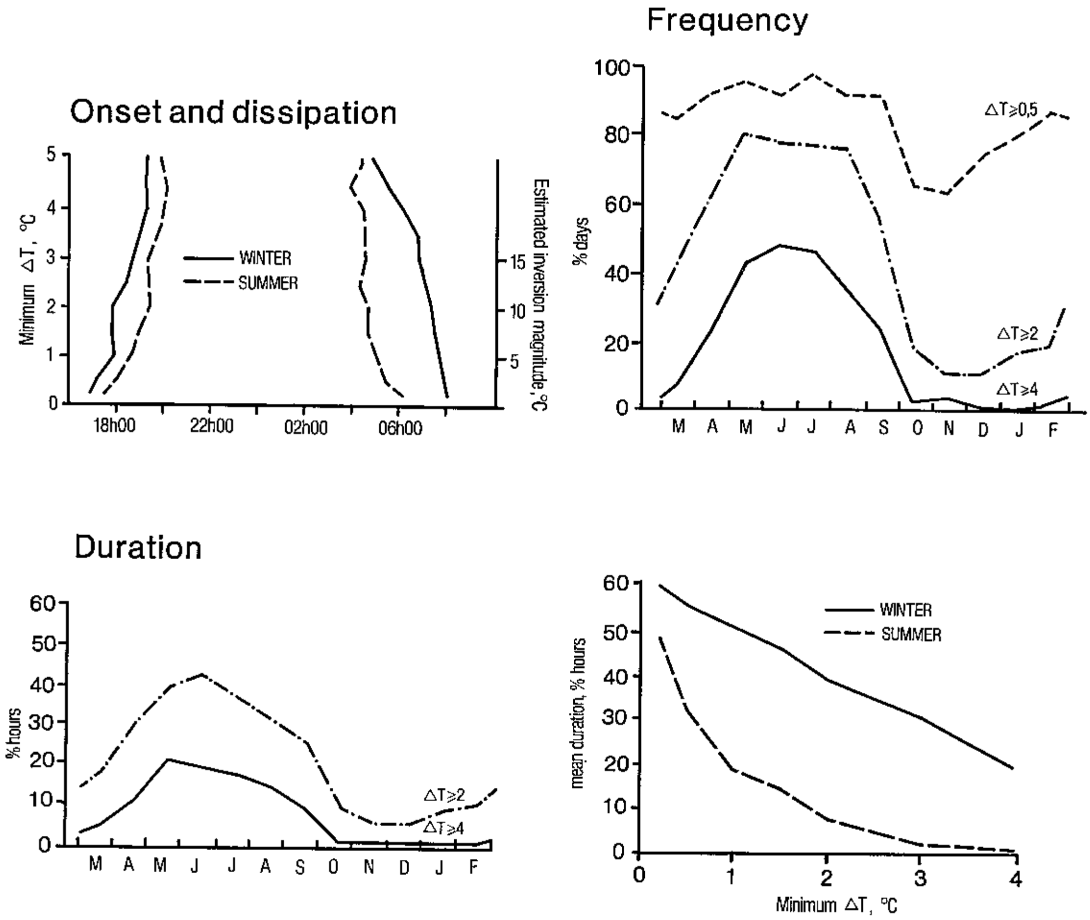


Fig. 20 *The diurnal and annual variation of surface inversion characteristics (after Surridge, 1987).*

Surface inversions may form abruptly and may deepen rapidly (Fig. 21), depending on the nature of the local advection of cool air. They are ubiquitous and at night their tops form a surface along which interaction with the flow above may take place. Frequently Kelvin and gravity waves are generated on the upper surface of inversions (see Fig. 21, upper right) and the consequent downward propagation of temperature disturbances may occur (Surridge, 1986). The top of the surface inversion layer is a surface of considerable importance in dispersion climatology.

Almost irrespective of wind direction, as the stable layer and the atmosphere above tend to decouple, as turbulence is rapidly damped in the stable layer and surface wind speeds decrease, so a low-level wind maximum develops just below, at, or just above the top of the surface inversion layer. The phenomenon was first recognised over the Highveld by Closs (unpublished) in 1978. Today it is apparent that within the less stable air above the inversion, and with low friction at the interface with the inversion, the mesoscale jet-like structure is a common feature over the ETH (Von Gogh et al., 1982; Tosen and Jury, 1986b and Pretorius et al., 1986) and indeed in many other parts of the world. Some examples of such low-level wind maximum occurring at or near the top of the surface inversion are given in Figure 22.

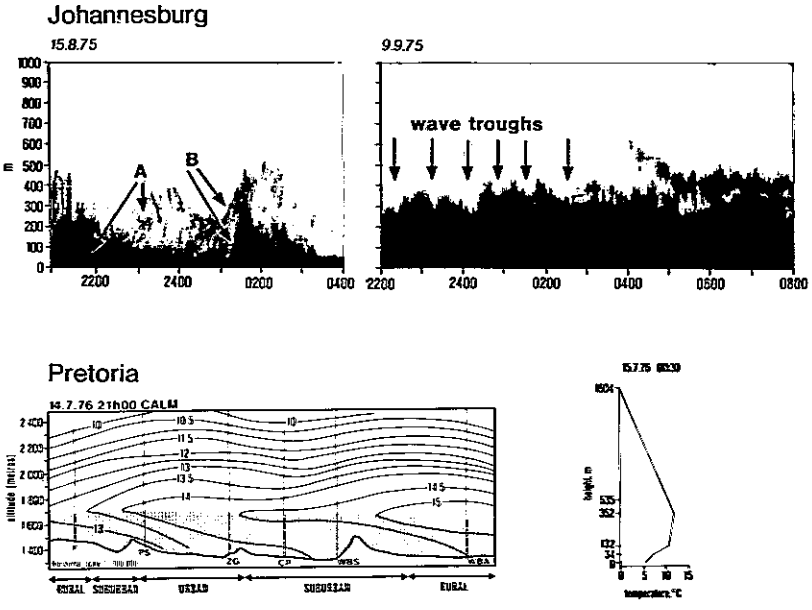


Fig. 21 *Upper left: acoustic sounder traces to show surface nocturnal inversions over central Johannesburg, showing the coupling between a double-layer structure (A) and a sudden deepening (B); Upper right: a uniformly deep 300 m inversion over Johannesburg exhibiting gravity and Kelvin wave ripples on its upper surface; Lower: a 300 m deep surface inversion blanketing Pretoria on a calm winter evening together with the Irene radiosonde sounding through the inversion.*

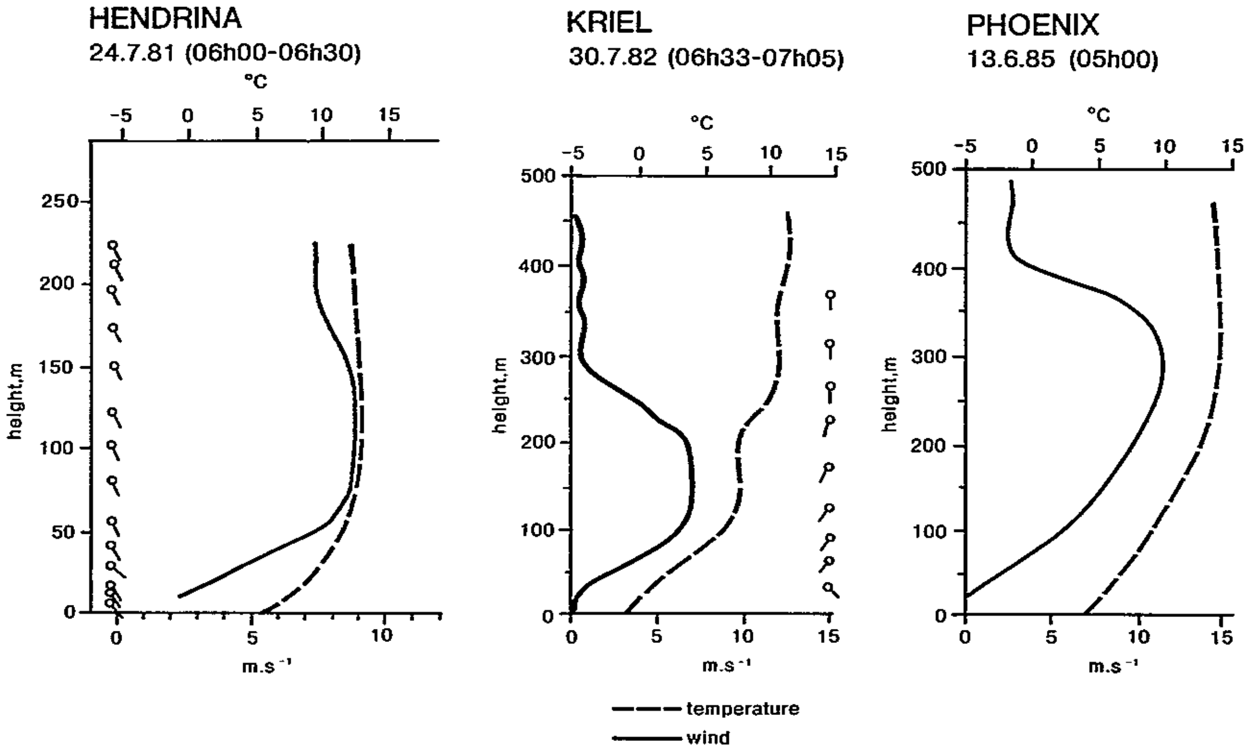


Fig. 22 *Wind profiles (solid lines) to show the occurrence of low-level wind maxima at the top of the surface inversion at Hendrina (after von Gogh et al., 1982), at Kriel (after Pretorius et al., 1986) and at Phoenix (after Tosen and Jury, 1986).*

Monthly averages obtained from doppler acoustic sounder measurements show that minimum wind direction variability at Elandsfontein occurs at about 200 - 250 m above the ground in the layer in which the low-level maximum is observed, whereas maximum directional variability occurs around 500 m where a minimum occurs in the wind speed profile (Earth Science Services, 1985). Above a height of 600 - 650 m wind speeds begin increasing steadily with height as local surface-induced effects begin to diminish and synoptic driving of the circulation becomes the dominant forcing. Tosen and Jury (1986b) show how, on average, the low-level wind maximum forms soon after inversion growth is initiated. Thereafter, as the inversion deepens, so the height of the wind maximum rises (Fig. 23). The height of the maximum is a function of the depth of the inversion, and the low-level maximum is almost entirely a nocturnal phenomenon (Fig. 24). With general winds having a westerly component the local thermal wind effect considered earlier causes a super-geostrophic acceleration of flow in the low-level jet, whereas with synoptic winds with an easterly component sub-geostrophic flow occurs in the low-level wind maximum (Tosen and Jury, 1986).

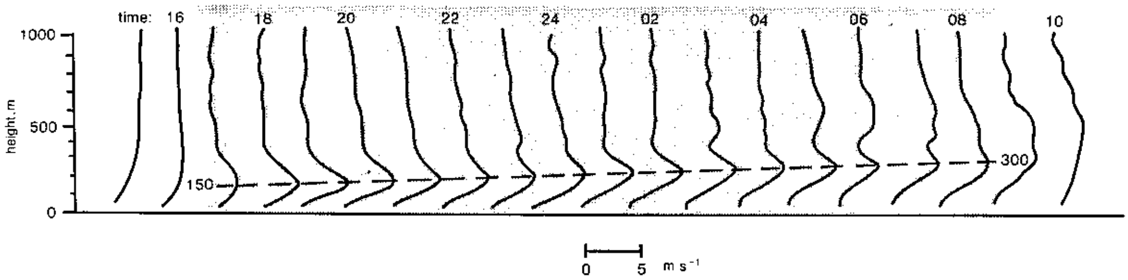


Fig. 23 *The nocturnal occurrence and development of the low-level wind maximum as shown by mean hourly wind profiles for June 1985 at Phoenix (after Jury and Tosen, 1987).*

Turbulence within the surface boundary layer may be assessed by determining the standard deviation of wind direction and the standard deviation of the vertical component of velocity. At night turbulence is at a minimum in the layer of the low-level wind maximum. At sunset turbulence collapses. With the onset of surface heating the following morning it increases rapidly, momentum is transferred down the velocity gradient and the low-level wind maximum is destroyed as the mixing depth penetrates to the top of the surface inversion and beyond. Within the mixing layer wind direction variability is at a maximum during the day. Maximum mixing heights over the ETH vary between 1 000 m in winter and 2 000 m in summer and since they are a measure of the lack of dispersion in the boundary layer they correlate inversely with measured amounts of ground-level pollution observed (Tosen and Pearse, 1987).

2.3.3 Elevated inversions

Elevated inversions may occur for a variety of reasons and on some occasions as many as five may be measured in the first 1 000 m above the surface (Tyson and Von Gogh, 1976) (Fig.25). They may occur at a uniform altitude, as is shown above Pretoria on a winter day, or may drape the topography as illustrated over Johannesburg.

Using Irene data for 1979 - 1981, Von Gogh et al. (1982) showed that elevated inversions occur on 60 per cent of all days at a mean height above ground of 1 700 m with a depth of just under 200 m and a strength of 1,5°C. They display little diurnal variation and almost always cap the midday mixing layer, if in fact the mixing layer penetrates to their height. Frequently the mixing layer does not reach the subsidence inversion with the consequence that beneath the elevated inversion a trapping layer develops in which pollution concentrations may increase.

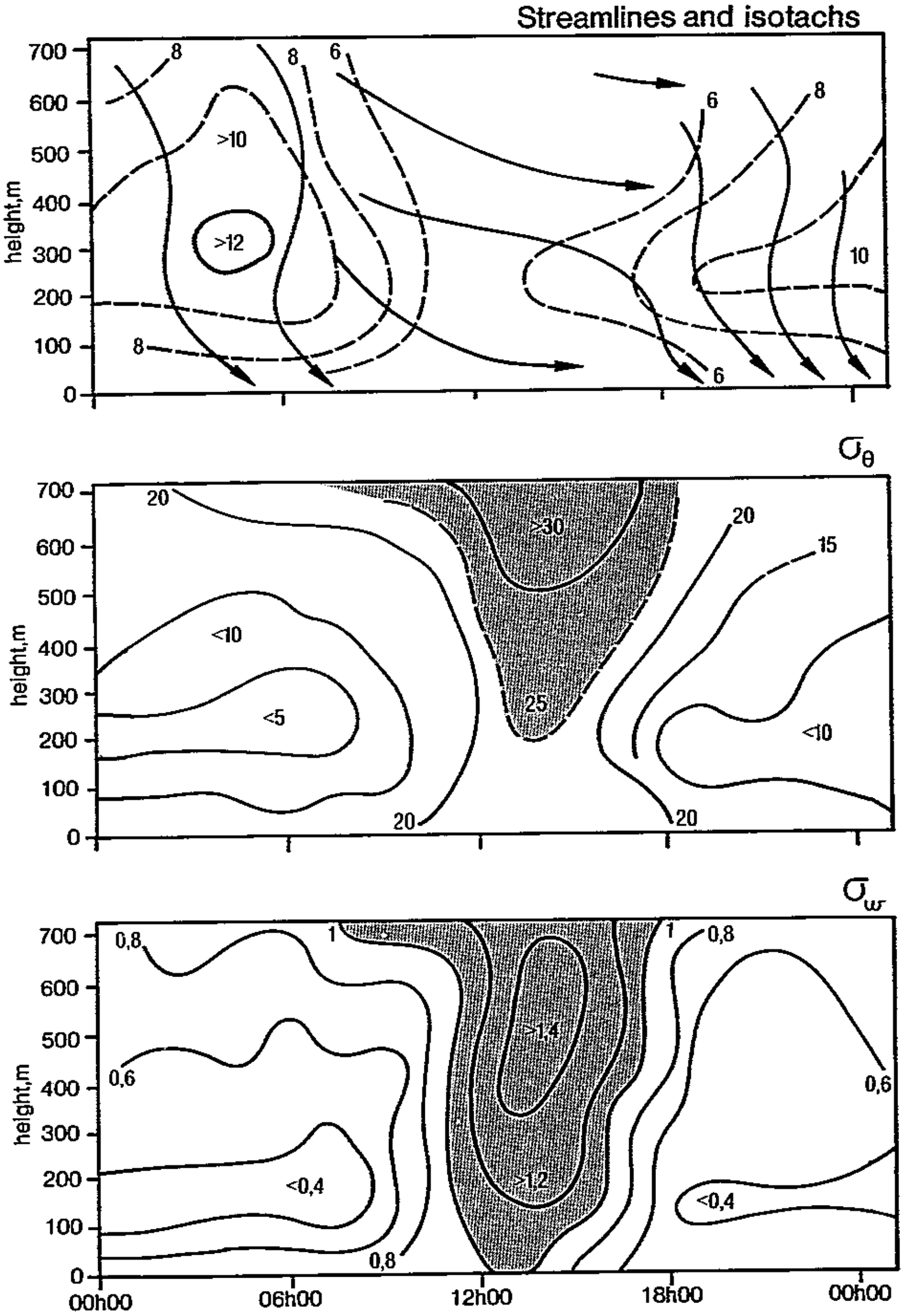


Fig. 24 *Mean doppler acoustic sounder data for August 1984 at Elandsfontein to show upper: streamlines and isotachs of airflow in near-surface airflow; centre: wind direction variability; lower: variability of the vertical velocity component (after Tosen and Jury, 1986).*

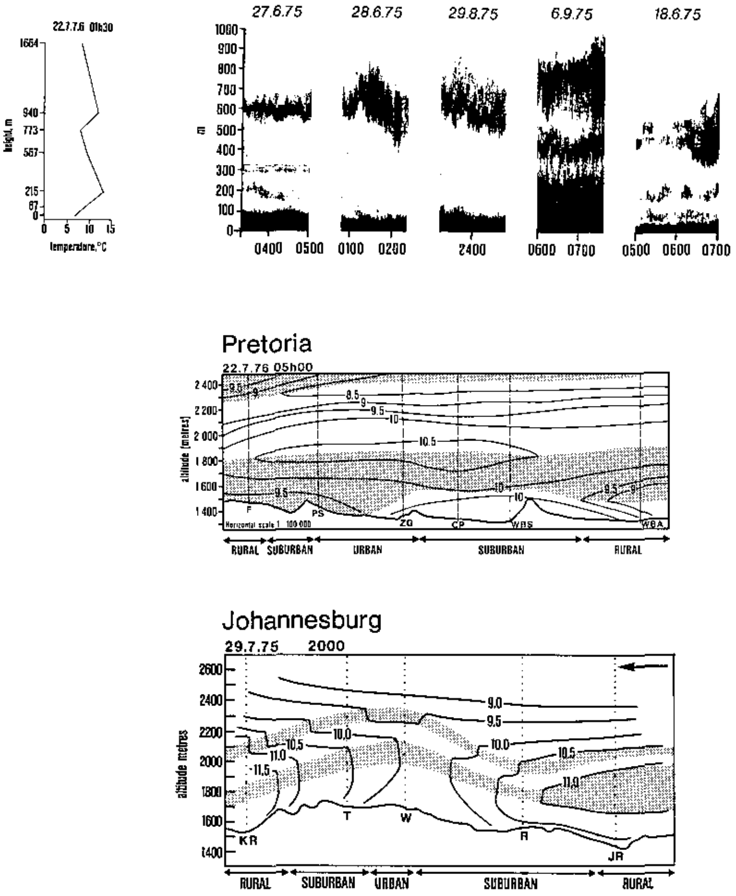


Fig. 25 *Upper: Pretoria (Irene) radiosonde profile and acoustic radar traces over central Johannesburg to show the occurrence of elevated inversions; Centre and lower: extended regional elevated inversions over Pretoria (von Gogh, 1978) and Johannesburg (Goldreich et al., 1981).*

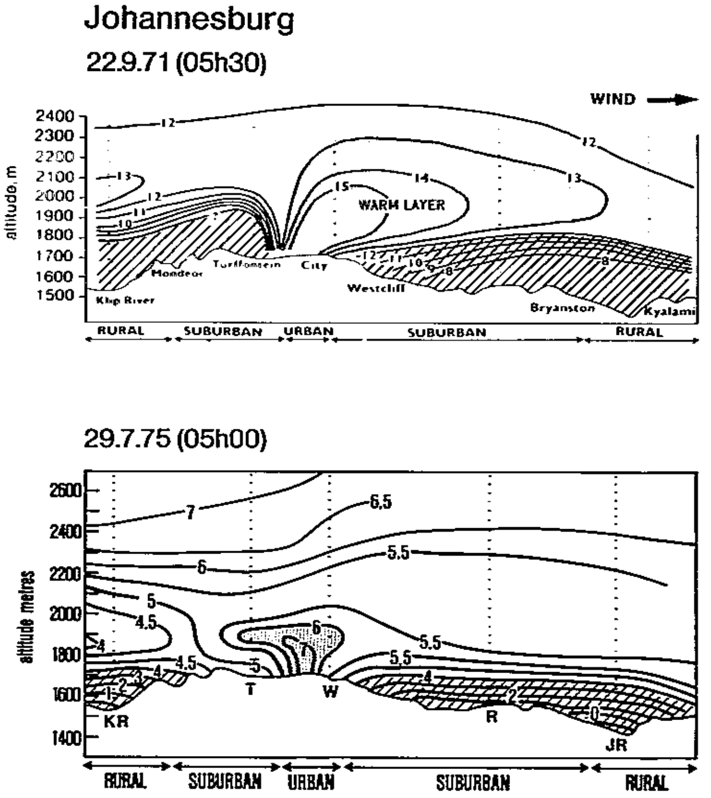
Elevated inversions occurring below 2 000 m represent 58 per cent of all such inversion events and are observed on 35 per cent of all days. Further analysis of Irene data for the years 1984 - 1986 by Tosen and Pearse (1987) gives a mean winter subsidence inversion at 1 550 m above ground level with a 78 per cent frequency of occurrence. Of the inversions observed, 60 per cent occurred at less than 1 550 m. By contrast, the mean summer subsidence inversion occurred at 2 600 m with a 40 per cent frequency.

From 450 aircraft ascents over the ETH the mean height of the subsidence inversion has been established as 1 300 m above ground (Tosen and Pearse, 1987), a figure entirely compatible with the Irene data, given the altitude difference between the localities. The mean depth of the aircraft-measured subsidence inversion over the ETH is 100 m.

2.3.4 Mesoscale and local effects

Urban heat islands

Urban heat islands are of common occurrence over Johannesburg and Pretoria (Tyson et al., 1973; Von Gogh, 1978; Goldreich, 1984). Often marked heat plumes may be observed (Fig. 26) in which the dispersion environment of the lower atmosphere may be substantially altered. Such plumes are linked to the occurrence of local winds (Goldreich et al., 1981) and may have an horizontal extent exceeding


Johannesburg

22.9.71 (05h30)

29.7.75 (05h00)

Fig. 26 *The occurrence of urban heat plumes over Johannesburg (after Goldreich et al., 1981).*

25 km. Surface inversions are of less frequent occurrence in urban areas. Such appears to be the case for Witbank (Pretorius et al., 1986). Commensurately, low-level elevated inversions are likely to be of greater frequency.

Sheltering and exposure effects

The sheltering effect of valleys may exert a noticeable effect on the dispersion climatology of an area by diminishing wind speeds and ventilation and by affecting the turbulence regime and stability cycle (Goldreich and Tyson, 1987). A good example is given by comparing wind roses in a Pretoria valley with those for Jan Smuts airport on exposed flat ground (Fig. 27). In addition to often setting up standing waves in the atmosphere, the Magaliesberg and associated ranges often exert a considerable sheltering effect, protecting the air in the valleys from disturbance and hence mixing by the winds of the general circulation. Comparing wind speeds alone, and all other things being equal, Pretoria has over five times the pollution potential of Jan Smuts. The incidence of strong winds in the Pretoria valleys is low in comparison to those experienced at ridge level at Jan Smuts Airport, particularly in winter when smog emission is highest and ventilation is most required. The effect of topography, ridge-top exposure and urban sheltering is further illustrated for Johannesburg in Figure 27 (Venter and Tyson, 1978). On the ETH, Kriel's location renders it susceptible to possible sheltering effects. In contrast, Elandsfontein is the most exposed site (Von Gogh et al., 1982).

Topographically-induced winds

Topographically-induced winds have already been considered. Shallow mountain-plain and plain-mountain drainage winds occur over the ETH. They also develop over the Escarpment slopes and Lowveld where diurnal wind reversals are more marked (Fig. 28), the winds are stronger and the systems deeper (Held, 1985a; Garstang et al., 1985). They exert an influence on the enhancement or suppression of cumulus convection and rainfall and have pollution implications as well. By night, should ETH pollution come to ground over the Escarpment, it will be advected in a highly stable layer of air draining eastward toward the Lowveld and westward into the Vaal basin. Any near-ground pollution emitted in the Escarpment region, on the slopes below the mountains or in the Lowveld will be advected towards Mocambique. By day the opposite will occur and advection will be toward and over the Escarpment, but in a deeper, more unstable and better mixed system. Over Natal the stable mountain-plain wind may transport pollution in visible plumes for distances exceeding 150 km. There is no reason to doubt that the same could happen to the east of the ETH.

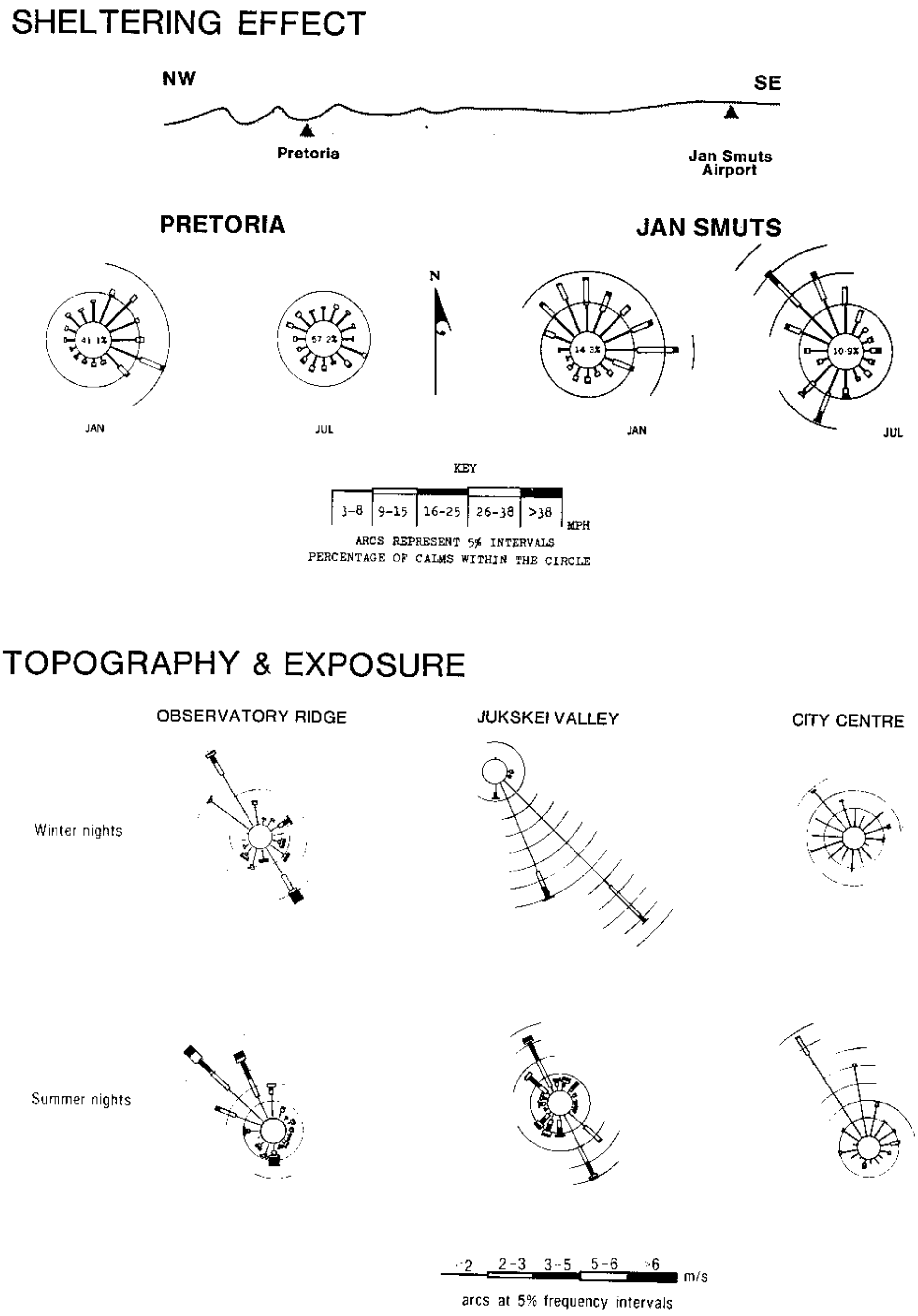


Fig. 27 *The effect of location and topography on airflow patterns and wind roses (after Tyson, 1974; Venter and Tyson, 1978).*

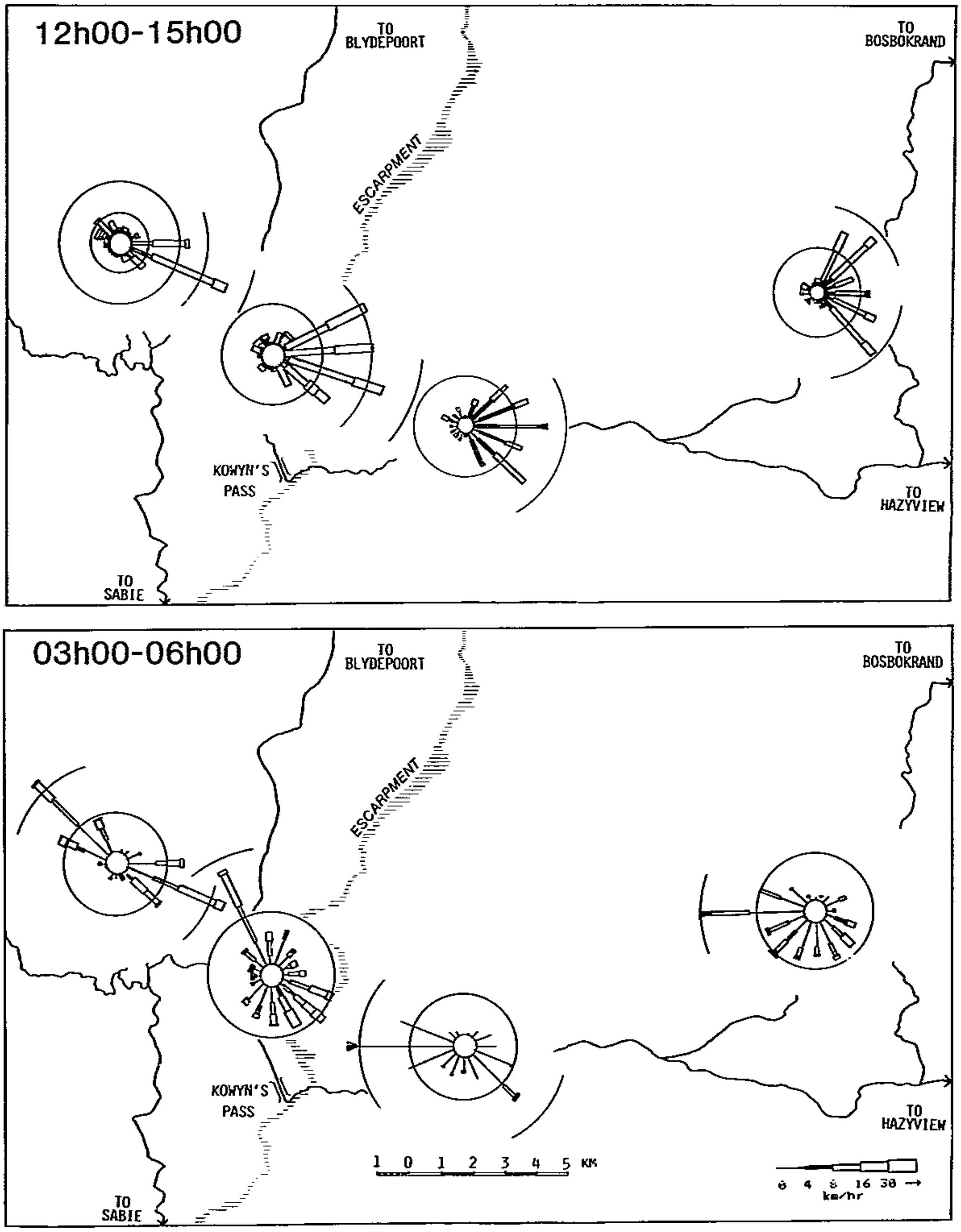


Fig. 28 *Mean daytime and nocturnal wind roses to illustrate plain-mountain airflow towards the Escarpment by day and mountain-plain airflow off the Escarpment by night (after Held, 1985a).*

Over the ETH itself, regional topographically induced mountain-plain and plain-mountain winds blow in the opposite direction to those over the Lowveld-Escarpment region (see before, Fig. 16). Together with local katabatic flow down slopes and mountain breezes along valleys, the mountain-plain drift of cool air forms frost hollows and causes large pools of cool air to form, as for example in the Vaal river basin, as Tosen and Jury (1986) have shown (Fig. 29).

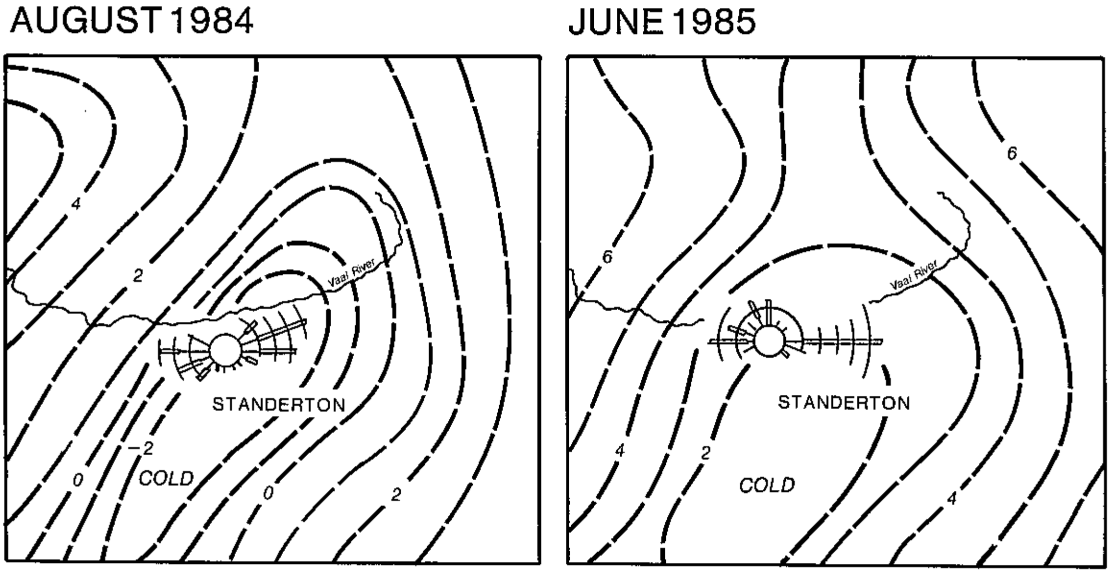


Fig. 29 *Mean minimum temperatures and wind roses for Standerton for August, 1984 and June, 1985 to illustrate the effects of katabatic drainage of cold air into the Vaal basin (Tosen and Jury, 1986).*

Airflow around obstacles

Little work has been done on the topic of airflow around obstacles, despite the fact that local obstacles and structures have a direct bearing on wind and temperature close to pollution sources. The effect diminishes with increasing distance from the source. Roughly speaking the region of flow disturbance around an isolated structure is at least twice the building height and extends downwind to five to ten times the height.

In the only investigation of the effect of a power station on the flow field around it, it was found that the effect was slight (Held, 1985b). A small tendency was noted for inversions to be steeper downwind of the power station in the sheltered area. No tendency for air to converge towards the plant as a consequence of the release of vast amounts of heat into the atmosphere could be discerned.

2.3.5 The effect of weather and climate on plume dispersion

In order to consider aspects of the plume climatology of the ETH, it is necessary to summarise the vertical structure of the winter wind and temperature fields (Fig. 30). In the lowest 50 m regional winds drain off the Escarpment uplands and steepest inversion profiles are observed near the surface. Pollution released into this air is trapped. The surface inversion extends to about 300 m at which height the relatively non-turbulent low-level wind maximum is observed. Pollution released into the slightly less stable inversion air is also trapped. If it reaches the top of the surface inversion it may be transported horizontally over great distances within the layer of the low-level wind maximum. Above the top of the inversion the air remains stable and the wind diminishes to a minimum in speed and increases to a maximum in directional variability. Pollution reaching this level will mix, but not completely, and will tend to stagnate by comparison to that at the top of the surface inversion. Pollution rising to the level of the subsidence inversion at a mean height of 1 300 m will not be able to rise further. Since the average height of the midday winter mixing depth is about 1 000 m, it is likely that over time a trapped layer will develop beneath the subsidence inversion. Evidence exists to suggest that there is an elevated layer of enhanced pollution concentration and that it may be a quasi-stable feature of the ETH atmosphere

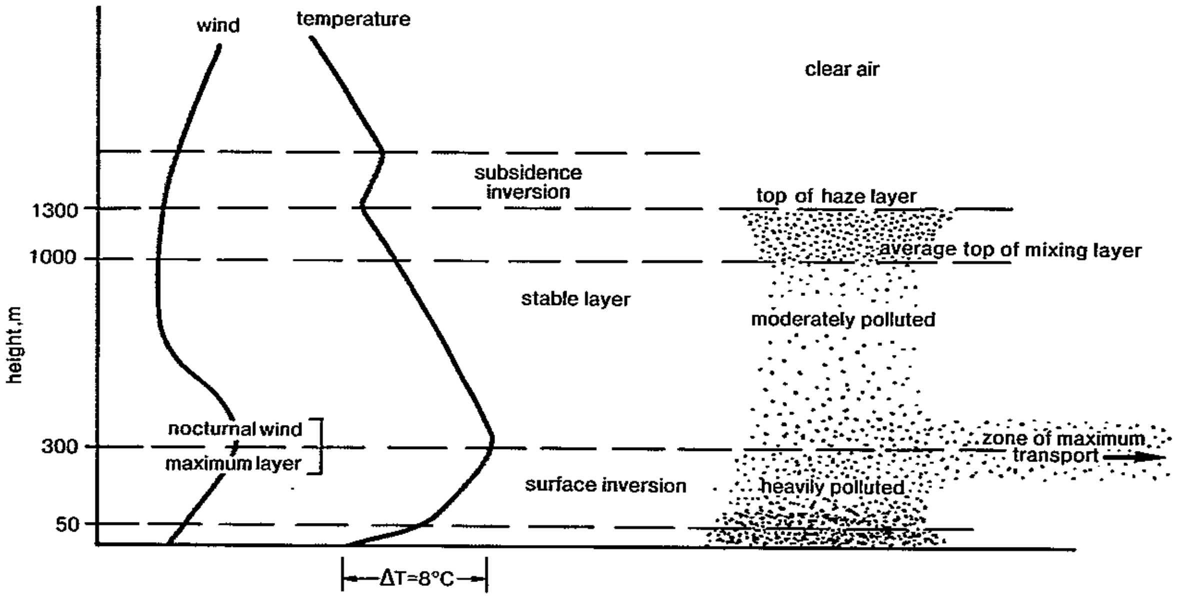


Fig. 30 *Mean winter temperature and wind profiles for the ETH and the major pollution accumulation layers.*

(Wells et al., 1987). Even under highly turbulent conditions the pollution in this layer does not appear to descend to ground level. The phenomenon needs further investigation. Notwithstanding, it is clear that the plume dispersion climatology of the ETH is highly adverse.

The height to which plumes rise over the ETH is dependent on the height of stacks and output of power stations. Plume rise from a 1 000 MW power station is likely to be the order of 180 m, whereas, from a 4 000 MW station it will be nearer 450 m (Tosen and Pearse, 1987). These figures must be read together with stack heights of the power stations in the determination of the final height to which pollution will rise. From day to day the plume rise and dispersion is a function of the inversions that occur and the prevailing windfield. Some examples of the work of Tosen and Pearse (1987) are given in Fig. 31. In the first case, a large anticyclone with weak pressure gradients and a low-level subsidence inversion was centred over the Transvaal. No plume could penetrate the strong subsidence inversion. In the second case, plumes from stacks less than 150 m high were trapped in the surface inversion, those from taller stacks reached intermediate levels and only one reached the high-level subsidence inversion. Lastly, an example of cyclonic airflow in a strong pressure field is given for a day on which a high-level subsidence inversion and a pronounced low-level, inversion-top wind maximum occurred. No plume from any station was able to penetrate the low-level wind maximum.

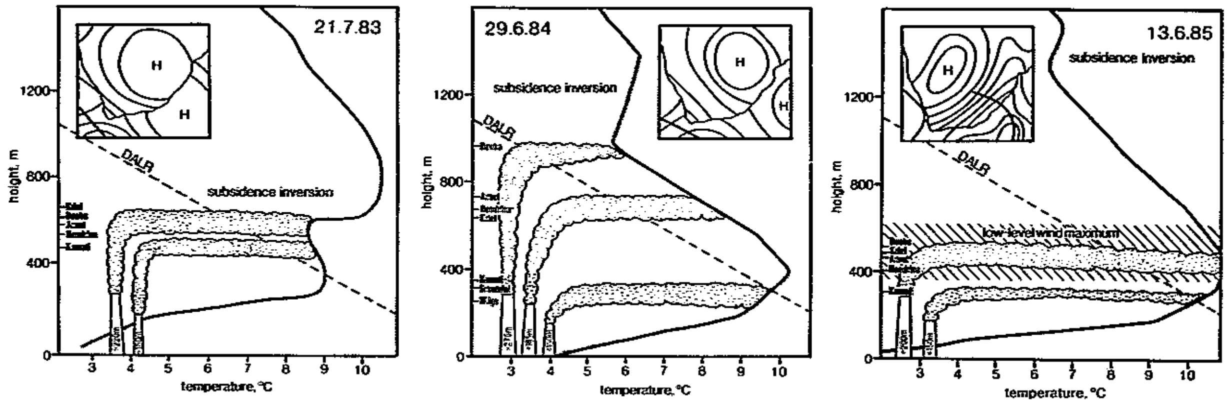


Fig. 31 *Examples of aircraft-observed plume characteristics under different airflow and temperature/ stability regimes (after Tosen and Pearse, 1987).*

If average conditions for plume observations for many aircraft flights are considered (Fig. 32), then it is seen that only from the 3 500 MW Duvha power station (with a stack of 300 m) will plumes regularly reach 600 m and very occasionally 900 m. On some occasions they barely clear the surface inversion. In the case of the Komati (1 000 MW), Wilge (240 MW) and Grootvlei (1 200 MW) stations (stacks equal to or less than 150 m) the mean plume height is below the top of the surface inversion layer. In observations between 1983 and 1985 no plumes penetrated the subsidence inversion, nor is it likely that in future stacks could be designed for this to happen. Again it must be said that the conditions for the dispersion of plumes over the ETH are highly adverse.

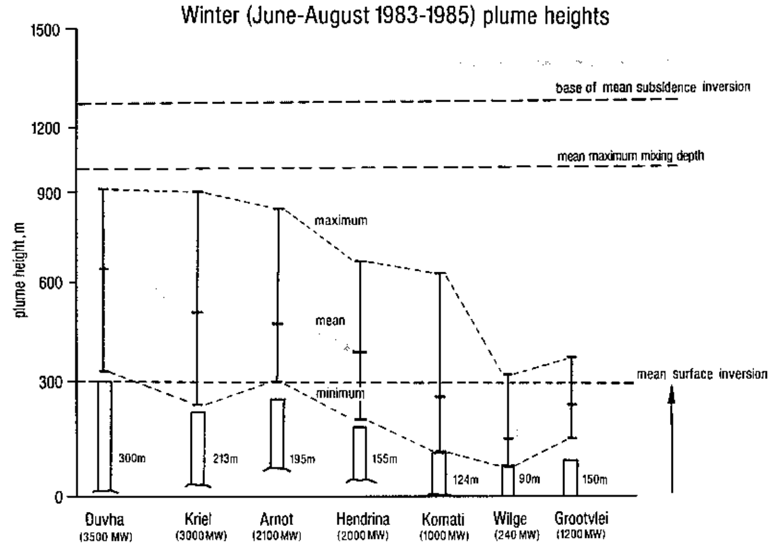


Fig. 32 *Mean June - August (1983/85) plume rise characteristics for ETH power station plumes and their relationship to the mean surface and subsidence inversions (Tosen and Pearse, 1987).*

2.3.6 Precipitation effects

The effects of moisture content of the atmosphere, rainfall and fog on pollution dispersion parameters and, indeed, on pollutants themselves over the ETH are not well understood. Clearly further research is needed in this respect.

2.4 MODELLING TRANSPORT AND DISPERSION

It would be inappropriate to discuss models in depth in a report of this kind. Instead they must be alluded to in such a way that users and decision-makers may be aware what models are available and how they may be used. Only mathematically-based models having a predictive capacity will be considered. Large-scale (subcontinental) air movement, regional topographically-induced flow near the surface, the development of the nocturnal stable layer, the extent and depth of urban heat islands, plume rise and pollution dispersion will be examined.

2.4.1 Macroscale airflow

It has been shown that air movement at about the level of the top of the surface inversion (800 hPa) is a significant feature of the dispersion climatology of the ETH. Such airflow, and that above, may be estimated with accuracy over large areas using a 15-level primitive equation model. The model is employed daily by the Weather Bureau and can be used to give derived divergence fields and vertical velocities. Though not yet capable of detailed sub-grid, mesoscale predictions, its power to predict regional patterns of circulation above the surface inversion layer is considerable.

2.4.2 Mesoscale circulations

Much work has been done on local winds, both generally (Atkinson, 1981) and particularly in South Africa. The prediction of wind profiles in valleys, even those that may be shallow (but not those that are more than tens of kilometres wide), by day and by night has long been possible (Tyson 1968a, 1968b). Closs and Venter (1980) have shown, using a technique developed by Mahrt and Swerdtfeger (1970), that it is possible to model the variation of wind speed with height in such a way as to predict the low-level, inversion-top wind maximum. For airflow within the first hundred metres, Tosen (1987) has used a standard power profile (calibrated so that the variation of the power to which the height ratio is raised varies with the Pasquil stability classes) to model the variation of wind speed with height. The establishment of how the power varies with stability is of great importance in modelling low-level pollution emissions.

The spatial variation of the windfield in the horizontal over the ETH has not been modelled adequately to date. Using an interpolative device, Smith (1978) described the windfield over Pretoria. Likewise, Scholtz et al (1978) used an interpolative scheme to specify the detailed surface windfield over Richards Bay. A similar approach has been used by Burger (1986) and Mulholland and Burger (1987) in order to interpolate the three-dimensional airflow beneath the subsidence inversion over the ETH. Topographic and thermal distortions were included, together with measurements from a 10 m mast network. The surface windfield was extrapolated upward using a few acoustic sounder observations. The most recent attempt at the interpolative specification of the windfield is that of Minaar (1987). Though mathematical, such approaches are descriptive and useful only for analytical work and as model data input. They have little prognostic value per se.

The best three-dimensional mesoscale model at present available is that of Pielke (1984). It has been applied successfully in land and sea breeze studies, heat island simulations, the examination of lake effects, forced airflow over rough terrain, the study of low-level jets, mountain and valley winds, the effect of horizontal gradients on heat flux, and lastly and most important of all, in transport and dispersion studies of atmospheric pollution. In the last-mentioned approach, topics such as trajectory analyses (Artz et al., 1985), terrain-induced circulations and pollution transport (Arritt and Pielke, 1984), regional-scale pollution dispersion by mesoscale circulations (Moran et al., 1986), plume fumigation and mixing layers (Segal and Pielke, 1983) and air quality under stagnant circulation conditions (Yu and Pielke, 1986) have been studied. In South Africa Diab and Garstang (1984) have used a two-dimensional form of the model to assess wind energy potential on the coast. No attempt has been made to use the model in atmospheric pollution work in South Africa.

2.4.3 Boundary layer characteristics

To date modelling of the boundary layer over southern Africa has related to the growth of the nocturnal stable layer (Surridge, 1986a; Surridge and Swanepoel, 1987) and to the extrapolation of the nocturnal boundary layer temperature inversion from near-ground observations (Surridge, 1986a). In addition, Surridge (1988a, b) has modelled the temperature profile and heat loss in the nocturnal stable boundary layer and successfully predicted the development and time-dependent depth and magnitude of the surface inversion under conditions of low atmospheric humidity.

Urban heat islands have been studied in greater detail and reviews are available (Tyson et al., 1973; Goldreich, 1984). An energy balance model was used to estimate the Pretoria heat island (Morkel, 1980) and a modification of the approach was used, with success, to model the Christchurch heat island in New

Zealand (Tapper et al., 1981). The degree and depth to which an urban mixing layer may develop over a city may be estimated (Leahey, 1969; Leahey and Friend, 1971). Likewise, the Pielke model has been used in heat island studies (Mahrer and Pielke, 1976; Hjelmfelt, 1982).

2.4.4 Plume rise

In the sixties measurements of plume rise and comparisions of observations with theoretical calculations showed that Highveld plumes rose to greater heights than predicted by the erstwhile models (Halliday, 1968, 1969, 1970). This result was confirmed by Venter (1977), when he applied the Briggs (1969) model for plume rise and that of Moore (1974) to the comparision of observed plume trajectories with those predicted by the models. Venter and Fourie (1981) have done further work with the Briggs model in order to ascertain the sensitivity of plume rise to changes in various atmospheric conditions.

2.4.5 Dispersion models

A comprehensive review of dispersion models has been provided by Zib (1977). Earlier, Venter et al (1973) had determined the diffusion parameters required to use the Sutton model in local Highveld conditions. No formal application of the model was attempted. The first attempt to use simple predictive models for atmospheric pollution control was that of Zib (1978, 1980a, b) who modified the Gifford-Hanna multiple source (urban area) grid model for local use. The model is easy to use, provided the appropriate source inventory is available, and may offer a good approximation to actual conditions (Stokes and Tyson, 1980). A Gaussian plume model for both individual and multiple sources was also prepared for local use (Zib, 1980c).

Attempts to use models for the prediction of pollution concentration fields over the Highveld include those of Fourie et al (1982) and Von Gogh et al (1984). Using a Gaussian plume model modified for complex terrain, incorporating standard Pasquill-Gifford stability categories, vertical dispersion co-efficients and using the Briggs method of determining plume rise, Pretorius (1982) has shown that long-term (annual) regional sulphur dioxide concentrations from power station sources alone are under-predicted by a factor of about three by the model. If other sources are included, the under-prediction drops to a factor of 1,3 (a result not dissimilar to that observed elsewhere in the world). The modelling of mesoscale advection, turbulent diffusion and removal of pollutants from multiple and area sources is being investigated using the Mesopuff II model (Scire et al., 1984; Fourie et al 1987). The model is time-dependent, Lagrangian and incorporates variable trajectories of airflow. Arising out of its initial predictions of sulphur dioxide concentrations from coal burning in the ETH in June 1984, some sensitivity studies are now being attempted. On the whole, however, few sensitivity or validation analyses have been done to date.

A simple trajectory model has been developed to delineate dispersion fields from individual and aggregated sources (Pretorius, 1982). The model has shown how recirculation of pollution in the lower boundary layer, as a consequence of low-level topographically-induced wind reversals, has an exacerbating effect on ground concentrations. Recirculation of this kind affects all stations except Elandsfontein. To date such studies have been done only for surface conditions using ground-level windfields.

Air pollution concentrations at the ground and at specified heights within the boundary layer, may be obtained using a numerical, dynamic sheared puff model for point sources developed by Mulholland (1980). The model incorporates wind shear and vertical diffusion and gives predictions that are generally too high. However, Mulholland's model appears to give results significantly better than those of similar

Gaussian puff models. Although the model could not allow variations of wind direction with height, important redistribution effects were seen to occur for direction changes with time. The integration of wind shear and vertical diffusion then spread material over much larger areas than predicted by the Gaussian approach.

A real-time atmospheric dispersion model, in which the u, v and w components of the wind (measured by anemometer-bivanes) are filtered to provide mean and turbulent components, has been developed by Burger and Mulholland (1987a). The model is a segmented Gaussian plume model and may be used with only one anemometer-bivane in which case the wind vector and diffusivity at that point is assumed to apply instantly throughout the field. The model is designed to be run on Apple II microprocessor, to be easy to use and to have clear output graphics. It gives results at least comparable with more complex models and offers acceptable predictions (Burger and Mulholland, 1987a).

A further interactive model is being used at Koeberg in the Cape (Mulholland and Jury, 1986). It makes use of sheared puffs, allows arbitrary variation of the wind vector with height and is based on interpolation of data from six telemetred masts within 20 km of Koeberg. The model has a grid resolution of 300 m over a 40 x 40 km area and runs at least three times faster than real-time on a HP3000 microcomputer. Although a low-level mast network is used, doppler acoustic sounding observations may be included to influence model wind vectors from mast-top height to heights exceeding 300 m. The model is particularly appropriate for South African conditions because of its ability to handle wind shear, both in speed and direction. It is thus able to cope with land/sea breeze situations, the shear that occurs at the top of topographically-induced surface flow and phenomena such as the nocturnal low-level wind maximum that occurs at the top of the surface inversion.

In a more sophisticated approach, Mulholland and Burger (1987b) have introduced a three-layer parameterization of the boundary layer, interpolation of sparse data into a rectangular computational grid and application of the continuity equation to construct a three-dimensional windfield. The model is designed to be user-friendly and offers a variety of meteorological input options ranging from wind velocity at one height with a specified extent of cloud cover, to winds and temperatures at several heights. From these the windfield, diffusivity profiles in the horizontal and vertical and mixing depths are determined and the dispersion model is run. Fixed or time-dependent boundary layer heights may be specified. The distribution of pollutants is simulated by the superpositioning of sequentially-released puffs in the Eulerian frame of the gridded area. Each puff is assumed to have a bivariate normal distribution in any horizontal slice. In the horizontal wind speed, direction and diffusivity vary in an organised manner; they may vary arbitrarily with height. First-order chemical reactions, washout in rain, dry deposition, the rise of bouyant plumes and sedimentation are accommodated. The model has been compared favourably to the Gaussian plume and Gaussian puff models and when tested over part of Durban gave excellent results. When run over an area 120 x 84 km on the ETH it gave acceptable results. Clearly it has potential and offers exciting prospects for future modelling of pollution in the complex atmospheric conditions characterising the ETH. Currently further models are being adapted and developed (Mulholland, 1987).

2.5 CONCLUSIONS

In winter over the ETH the synoptic, regional and local circulations of the atmosphere combine and interact to produce a set of conditions that are not conducive to the rapid dispersion of atmospheric pollutants. On the contrary, they favour the accumulation of pollutants in the atmosphere. The atmospheric pollution climatology is highly adverse from an atmospheric pollution point of view; it could hardly be more so. In summer, on average, conditions are better, but not perfect.

While much is known about the dispersion climatology of the region, much remains to be studied. One of the important points to emerge from this review is that observational work on the one hand, and modelling on the other, when done in isolation both have limitations.

To date, far too little cognizance of the needs of modellers has been taken by the empiricists in their collection of data. By the same token modellers and those doing observational work need to work together more often. Modelling must play a greater part in future in understanding atmospheric processes, in atmospheric pollution control and in management. Models need to be used in regional and site planning, in determining stack heights, in analysing pollution episodes, process scheduling and so on. The need for interaction between empiricists and modellers is clear. Equally clear, is the fact that research priorities need to be based on the acceptance of the future role of modelling in atmospheric pollution meteorology and climatology.

In order of priority, the following are particular research activities that need to be given attention:

- mesoscale airflow modelling;
- as joint second priority:
  - the study of turbulent transfer processes,
  - studies of the layer of air between the ground and the subsidence inversion;
- the application of existing dispersion models (including sensitivity and validation studies, and scenario simulation);
- the climatology of best- and worst-case atmospheric pollution situations;
- the development of new dispersion models (for dosage levels, long-range transport, black box studies and explaining aspects of atmospheric chemistry);
- studies of moisture effects (humidity, fogs, rainfall and washout);
- stability wind relationships (roses) in the vertical for upper air stations; and
- inadvertent weather modification studies.

Finally, it must be pointed out that for a successful understanding of the dispersion climatology of the ETH, it is vital that data collection, analysis and modelling proceed hand in hand in co-operative joint research. Only in this way will real progress be made. The prospect is exciting, a sound foundation has been established and the promise of success beckons.

3. ATMOSPHERIC POLLUTION IN THE EASTERN TRANSVAAL HIGHVELD

3.1 INTRODUCTION

The atmospheric pollution budget is determined by a number of physical/chemical processes occurring in the atmosphere (Watt Committee on Energy, 1984) (Fig. 33). In order to describe the budget it is necessary to obtain experimental information about emissions, ambient atmospheric pollution concentrations over time and removal processes, as well as the interrelationships between these budget components. This information is necessary for understanding source-receptor relationships between emissions from sources and pollution levels measured at given receptor sites.

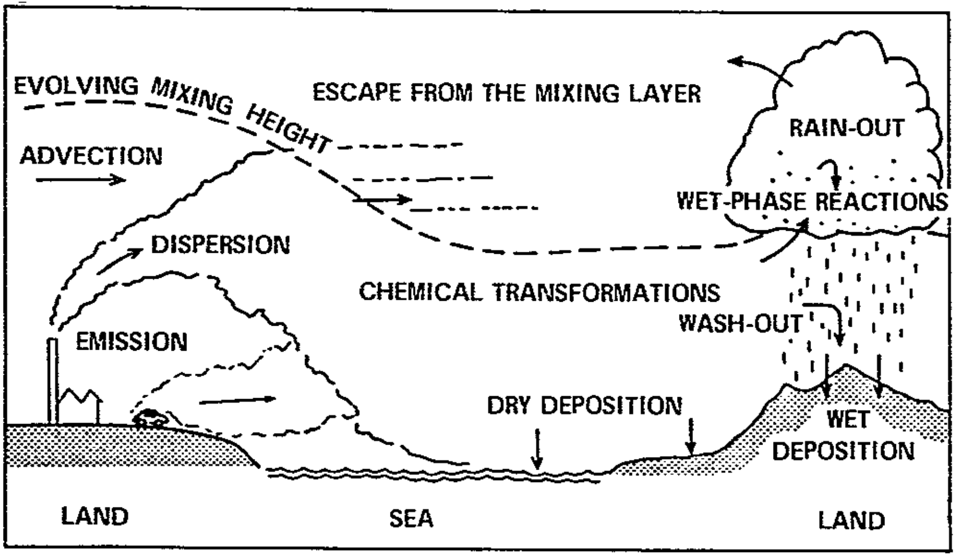


Fig. 33 *Processes involved in the pollution budget (after Watt Committee on Energy, 1984).*

3.2 EMISSIONS

3.2.1 Atmospheric pollution sources

Several sources of *primary* pollutants, e.g. particulates, sulphur dioxide, nitrogen oxides, carbon monoxide, hydrocarbons and carbon dioxide, exist in the Eastern Transvaal Highveld (ETH). Besides power stations there are two major petrochemical plants, various smaller industries (eg brick works, ferro/alloy works, steelworks, foundries, fertilizer plants, sawmills, pulp and paper- mills and chemical works), domestic combustion, motor vehicles, discard coal dumps as well as veld burning. It should also be pointed out that so-called *secondary* pollutants are known to be formed in the atmosphere as a result of sunlight-induced reactions occurring between nitrogen oxides and hydrocarbons. These include phytotoxic pollutants such as ozone and peroxyacyl nitrates (PAN).

Inventories of atmospheric pollution sources made during 1983 and updated during 1984 (Els, 1987) show the following overall emissions (tons per annum) in the ETH for 1984:

particulates	374 692
sulphur dioxide	1 038 556
nitrogen oxides	355 246
carbon monoxide	339 574
hydrocarbons	276 503
carbon dioxide	123 605 162

These figures were based on actual measurements and calculations drawing on applicable information in the published literature.

A further breakdown of the emissions (Table 2) shows that power stations are the major source of primary pollution in the ETH. The relative importance, however, of near ground-level sources such as domestic combustion, smouldering discard coal dumps and motor vehicles should not be overlooked, particularly in view of the weak atmospheric dispersion potential of the lower atmosphere of the region.

Table 2 *Emissions from various atmospheric pollution sources in the ETH (after Els, 1987)*

Source	Emission (tons.yr^{-1}), 1984*					
	Particulates	SO_2	NO_x	HCS	CO	CO_2
Power stations	(83,70) 313 646	(90,27) 937 492	(91,32) 324 435	(0,14) 386	(14,19) 48 178	(95,22) $117{,}7\times10^6$
Brickworks	?	(0,28) 2 888	(0,04) 156	(0,14) 397	(3,70) 12 594	(0,52) $0{,}638\times10^6$
Ferro-Alloy works	(6,18) 23 160	(0,13) 1 301	X	X	X	(0,31) $0{,}387\times10^6$
Steelworks/foundries	(2,82) 10 515	(0,00) 65	?	X	X	?
Sawmills	(0,55) 2 053	(0,05) 486	(0,17) 588	(0,32) 883	(1,53) 5 194	(0,26) $0{,}316\times10^6$
Paper and pulpmills	(0,01) 46	(0,00) 82	X	?	(3,50) 11 881	?
Petrochemical plants	(0,10) 382	(0,60) 6 193	?	(78,35) 216 629	X	?
Domestic/municipal combustion	(4,53) 16 976	(3,10) 32 255	(0,71) 2 546	(6,14) 16 976	(22,50) 76 394	(3,43) $4{,}241\times10^6$
Coal dumps	X	(5,24) 54 390	?	?	?	?
Motor vehicles	(1,04) 3 895	X	(7,00) 24 825	(14,91) 41 232	(54,58) 185 333	?
Other	(1,07) 4 019	(0,33) 3 404	(0,76) 2 696	X	X	(0,26) $0{,}323\times10^6$
TOTAL	374 692	1 038 556	355 246	276 503	339 574	$123{,}605\times10^6$

* i) Values in brackets indicate percentage of total emission for a given pollutant

ii) Values given are based on measurements, and calculations

iii) X Denotes relatively small emission

? Denotes that emission is not as yet known

Table 3 *Spatial distribution of atmospheric pollution sources and their emissions*

	Emission (tons.yr^{-1}), 1984						
Grid+ reference	No of sources	Particu-lates	SO_2	NO_x	HCS	CO	CO_2
2528DC	4	0,0	2 815,9	60,0	136,2	2 646,6	75 214,0
2528DD	8	53 184,2	18 472,4	8 159,8	7 196,3	48 738,2	1 648 979,0
2529CC	60	37 702,2	28 185,7	6 782,2	16 057,5	64 723,2	2 301 455,0
2529CD	31	29 794,7	161 925,2	53 252,4	6 315,4	33 208,1	19 959 950,0
2529DC	1	0,0	0,0	0,0	0,0	0,0	0,0
2529DD	3	43 206,1	88 549,1	22 128,6	0,0	9 113,4	10 934 570,0
2628AB	11	1 865,2	2 836,0	975,3	287,6	11 451,6	583 176,0
2628BA	3	767,1	1 326,4	1 037,7	2 025,8	7 615,9	185 602,0
2628BB	2	0,0	15,8	0,4	0,0	119,7	3 902,0
2629AA	9	0,0	20 553,9	0,0	0,0	0,0	0,0
2629AB	8	4 378,9	57 393,8	18 767,0	0,0	2 001,7	5 723 955,0
2629BA	4	39 859,7	72 644,8	26 881,2	12,2	2 412,7	10 212 540,0
2630AA	3	112,8	4,8	518,6	870,4	3 810,2	16 261,0
2628AD	28	7 357,8	13 655,1	7 382,4	15 268,6	73 020,6	1 960 395,0
2628BC	1	0,0	0,0	0,0	0,0	0,0	0,0
2628BD	1	10,8	20,5	1,6	10,8	48,7	2 705,0
2629AC	4	84 771,8	258 541,2	104 949,0	0,0	2 432,4	34 913 030,0
2629AD	1	160,5	305,0	24,0	160,5	722,3	40 097,0
2629BD	2	1,5	2,8	0,2	1,5	6,7	374,0
2629CA	10	21 714,5	168 771,6	64 064,8	218 806,0	15 011,8	20 133 430,0
2629DB	3	565,8	349,5	2 622,5	4 128,6	15 127,1	50 826,0
2630CA	5	25 292,5	106 794,5	18 867,1	0,0	19 584,7	8 146 695,0
2628DC	2	20 213,2	32 311,0	15 084,4	0,0	1 206,6	6 048 908,0
2629CC	4	747,6	1 065,3	1 697,1	3 084,9	13 140,7	171 095,0
2629CD	2	0,0	0,0	0,0	0,0	0,0	0,0
2630CD	3	74,8	4,6	32,6	81,7	447,9	31 108,0
2630DC	8	1 802,1	430,1	457,9	607,6	2 852,5	210 424,0
2630DD	7	778,2	1 331,4	280,3	216,9	3 080,4	210 618,0
2730BB	4	330,2	249,9	1 219,5	1 235,7	7 050,5	39 858,0

+ See Figs. 34 and 35. Area covered is 25°45' to 27°S and 28°15' to 31°E

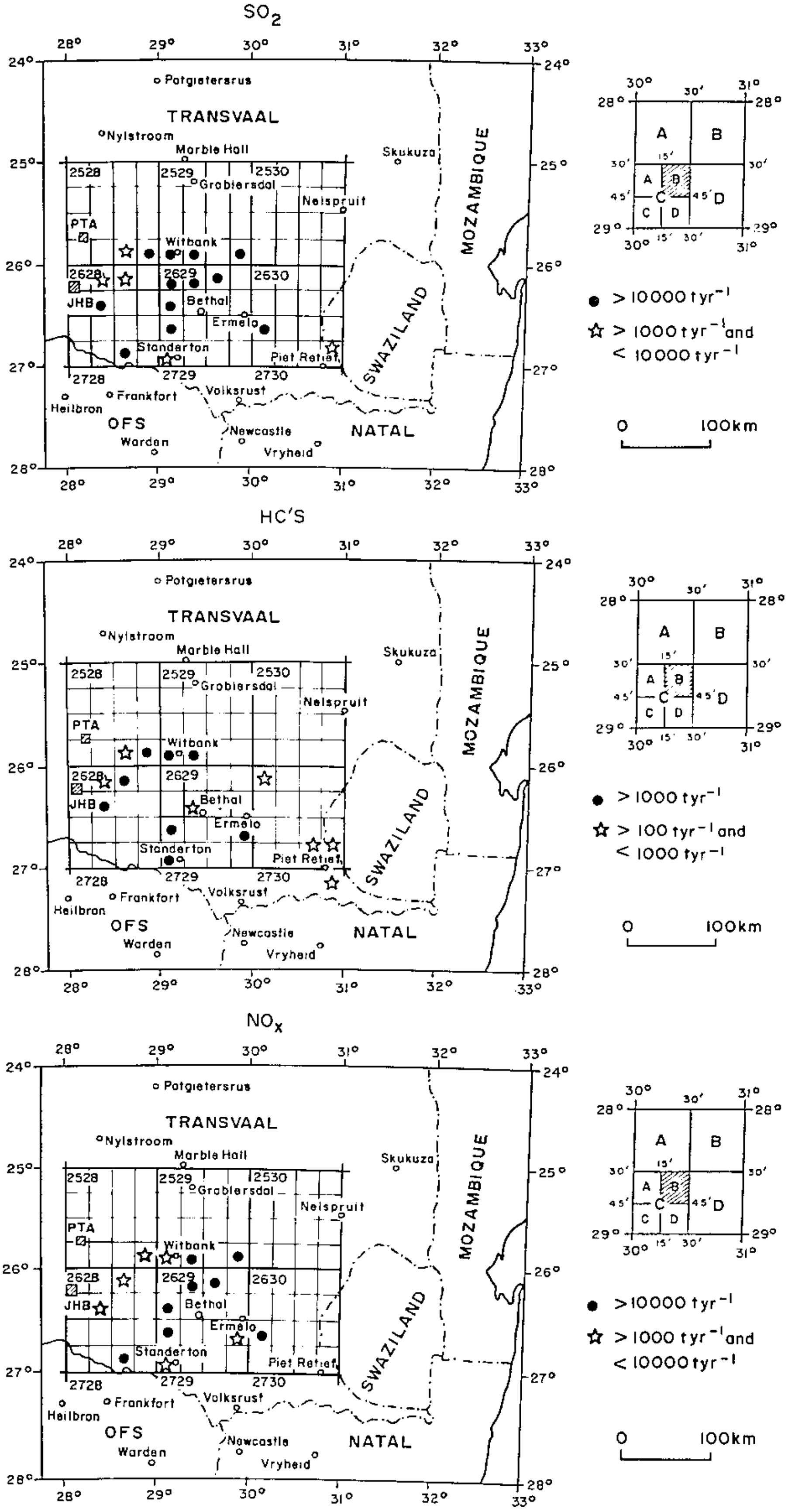
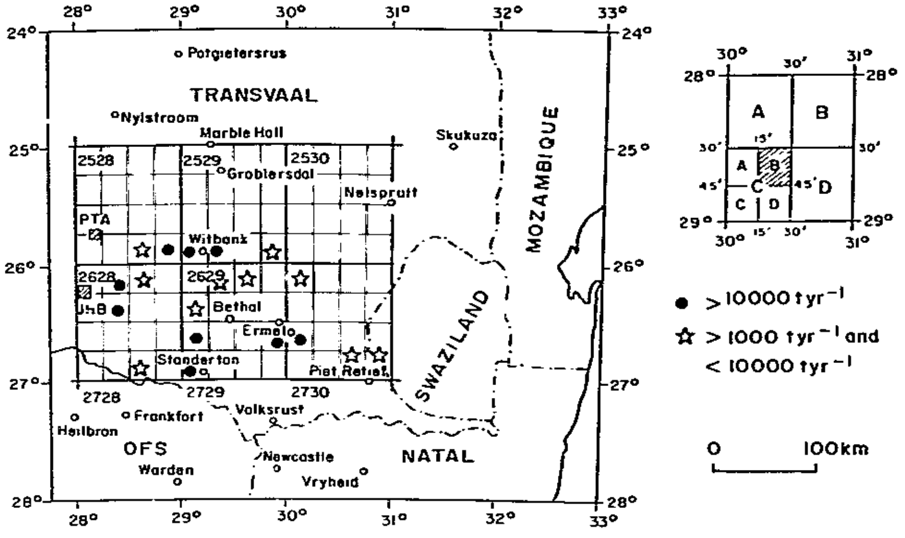
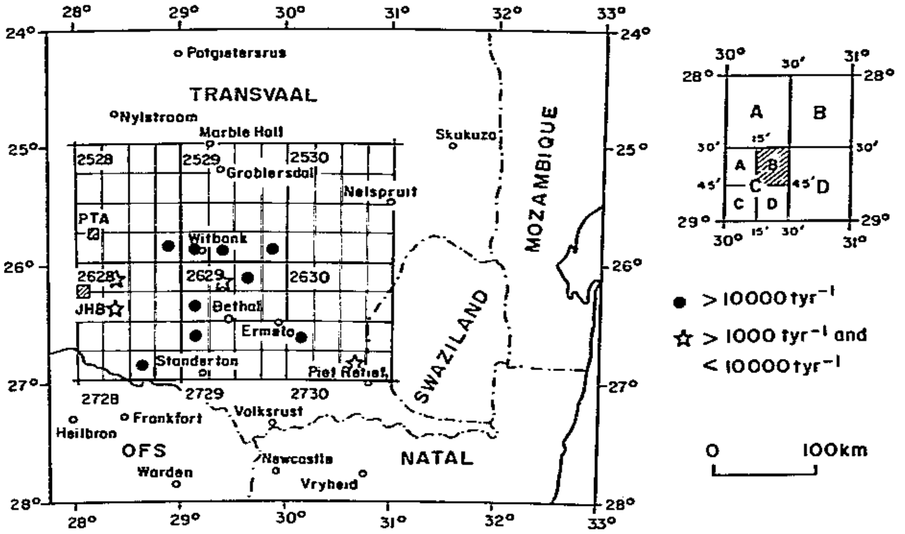


Fig. 34 *Spatial distribution of emissions in the ETH. Each square degree is (i) designated by a four-figure number made up of the values of the latitude and longitude at its NW corner and (ii) divided into sixteen areas, each 15'x15'. These are lettered ABCD. In the sketches (top r.h. corner) the hatched areas indicate 2830CB.*

CO



Particulates



CO_2

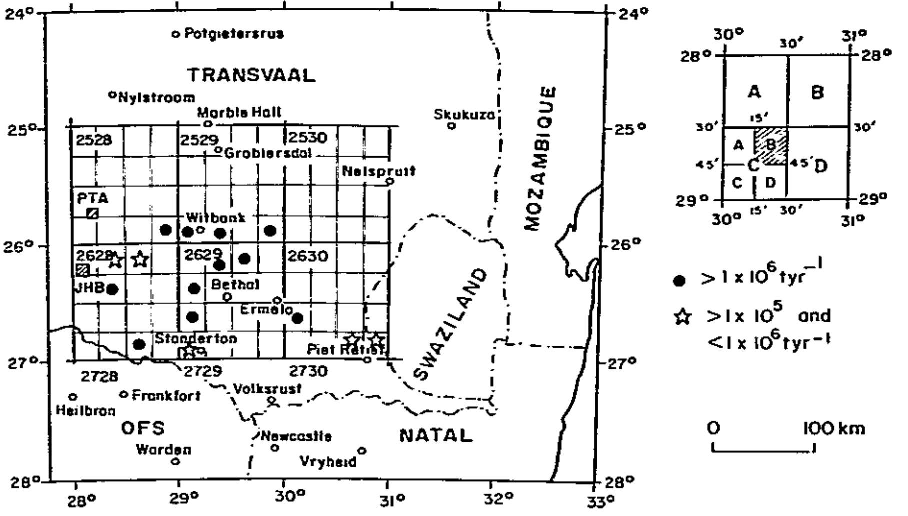


Fig. 35 *Spatial distribution of emissions in the ETH. Each square degree is (i) designated by a four-figure number made up of the values of the latitude and longitude at its NW corner and (ii) divided into sixteen areas, each 15'x15'. These are lettered ABCD. In the sketches (top r.h. corner) the hatched areas indicate 2830CB.*

It is also instructive to consider the spatial distribution of the various atmospheric pollution sources and their emissions (Table 3; Figs. 34 and 35). This shows that the larger emissions originate within a relatively small area of the ETH. A comparison of sulphur dioxide emission densities with those of other countries (Pechan and Wilson, 1984; Manson, 1985; Rentz and Weibel, 1984) shows that the projected figures for South Africa (Els, 1987) will be close to that for the entire USA (Table 4). Over an area exceeding a quarter of a million square kilometres in the Transvaal as a whole, sulphur dioxide emission densities are of the same order as those for West Germany and the Sates of Illinois and Missouri in the USA. If a narrower definition of the ETH is taken from 25°45' to 27°S and 28°30' to 30°30'E (30 000 km^2), then the emission densities are between about five and just under ten times greater and approximate the worst conditions found anywhere among the countries cited in Table 4.

Table 4 *Sulphur dioxide emissions from power stations (after Els, 1987; Manson, 1985; Rentz and Weibel el al., 1984)*

Country	SO_2 from power stations (tons.yr^{-1})	Area (km^2)	Tons SO_2.km^{-2} yr^{-1}
USA	15 816 000	9 362 626	1,69
- Ohio	2 120 000	106 759	19,86
- West Virginia	886 000	62 625	14,14
- Indiana	1 292 000	93 988	13,75
- Pennsylvania	1 262 000	117 406	10,75
- Illinois	1 037 000	146 067	7,10
- Missouri	1 094 000	180 476	6,06
- New Jersey	96 000	20 294	4,73
- Texas	356 000	692 367	0,51
Eastern Canada	726 000[a]	3 798 248	0,19
West Germany	1 800 000	247 968	7,26
East Germany	3 245 000	108 168	30,0
United Kingdom	3 500 000	244 000	14,34
South Africa	1 191 492	1 123 226	1,06
	1 751 492[b]	1 123 226	1,56
- Transvaal	1 131 492	262 499	4,31
	1 691 492[b]	262 499	6,44
- Eastern Transvaal Highveld	937 492[c]	30 000	31,25
	1 217 492[d]	30 000	40,58

Notes:
[a] Includes the provinces of Manitoba, Ontario, Quebec, New Brunswick, Nova Scotia, Prince Edward Island and Newfoundland.
[b] Future emissions from Lethabo, Tutuka, Kendal and Matimba included at 30x10^6 tons coal per year, and sulphur retention on fly-ash taken at 30%.
[c] All power generation (including SASOL plants) within the Eastern Transvaal Highveld.
[d] As (c) above but including future Tutuka and Kendal emissions.

3.2.2 Control of atmospheric pollution emissions

Atmospheric pollution emissions in the ETH are controlled by virtue of the Air Pollution Control Act no 45 of 1965. Controls are applied at most of the sources within this area. Although some R500 million has already been spent on atmospheric pollution control equipment, the pollution problem has not as yet been fully addressed (Odendaal, 1985). Significant progress has, however, been made in improving the situation. Some examples can be quoted (Odendaal, 1987) in this regard, e.g.

- particulate emissions from existing power stations are in the process of being reduced to meet emission guidelines set by the Department of National Health and Population Development (DNHPD). This will entail a capital outlay of about R100 million (at 1987 costs) as well as a running cost of some R11 million annually,
- nearly all the ferro/alloy ovens have now been equipped with dust arresting equipment,
- increased use is being made of permanent ovens in the manufacturing of bricks,
- combustion of sawdust and wood waste is being gradually phased out since these materials are now used to manufacture usable products,
- odorous gases emanating from the industrial complex at Secunda are now well under control (involving a total cost of about R166 million), and
- emissions from smouldering discard coal dumps can be expected to diminish through application of a recently devised method of smothering these dumps.

As far as the control of certain gaseous pollutants such as sulphur dioxide is concerned, use is made of tall stacks to disperse pollution. This approach is followed because of the extremely high costs that will be involved to remove sulphur from flue gases. It is estimated that at current rates and with existing technology using the non regenerative dry slurry process, de-sulphurization of flue gas from a 3600 MW power station would require a capital outlay of about R500 million as well as an annual running cost of some R100 million (Odendaal, 1987). Furthermore, the estimated costs of removing particulates using electrostatic precipitation with an efficiency of 99,8% at a 3 6000 MW power station would be about R80 million for capital, as well as some R8 million annually for operating costs (Odendaal, 1987). Thus, it is clear that before consideration can be given to the implementation of more stringent controls the relevant costs should be carefully weighed against those that are expected or predicted to result from detrimental effects to the ETH environment by atmospheric pollution emissions.

3.2.3 Future developments

The ETH has considerable potential for further development, especially for the establishment of new secondary and tertiary industries. Important contributing factors in this regard are the rich coal and mineral deposits as well as the availability of labour in this area. Moreover, according to recent predictions, the production of coal in South Africa will double itself within the next two decades and it can be expected to have a significant influence on industrialization in the ETH.

The types of new industries envisaged to be established within the ETH include energy suppliers (power stations based on fluidized bed combustion), integrated metallurgical industries (stainless steel and alloy manufacturing), petroleum production from torbanite and/or coal, and preparation of metal-related chemicals. It is expected that emissions from the secondary and tertiary industries will include large amounts of nitrogen oxides, halogens and hydrocarbons, all of which are precursors to the formation of photochemical smog, which includes highly toxic ozone.

Technology to control the emissions expected from new industries does exist, but needs to be further developed and refined. Advanced wet scrubbing systems would have to be used to curb the gaseous emissions from most of the metallurgical and chemical processes, but limitations of water availability may complicate matters. Refined bagfilter technology will be required for the control of particulates and aerosols. The role of electrostatic precipitators will diminish particularly when desulphurization of flue gases will be required at new power stations. Finally, there is scope for the further development of high temperature filters such as gravelbed filters and the use of stainless steel bag filters. Considerable costs will however be involved in fully developing and applying these technologies.

3.3 AMBIENT ATMOSPHERIC POLLUTION LEVELS

A knowledge of ambient atmospheric pollution levels is essential for the assessment of the air quality and exposure risk for man and environment. From 1979 ambient levels of a number of gaseous and particulate pollutants have been measured at several sites within the ETH (Fig. 36). Since its inception the monitoring network has been gradually expanded in order to allow a realistic assessment of the extent and intensity of atmospheric pollution within the region.

3.3.1 Statistical treatment of atmospheric pollution data

Atmospheric pollution data are not normally distributed (Georgopoulos and Seinfeld, 1982; Taylor et al., 1986). Consequently arithmetic means are not the most suitable parameters with which to describe the characteristics of such data. Instead frequency distributions and extreme statistics have been applied to describe the data. In addition, it must be pointed out that arithmetic means are of minimal value in the determination of potential effects of atmospheric pollutants on forests, agricultural crops and indigenous vegetation. Concentration and durations (doses) of the episode are more important parameters.

Although arithmetic means have limitations they nevertheless remain useful in some contexts and for allowing overall comparisons with published data from elsewhere. More importantly, ambient air quality standards are all based on arithmetic means.

3.3.2 Sulphur dioxide measurements

Monitoring of sulphur dioxide was carried out initially with Monitor Labs flame photometric analyzers and later with Monitor Labs ultra-violet fluorescence analyzers (Turner, 1987a, b).

The data set obtained for the period 1979 to 1986 (Pretorius et al., 1986; Turner, 1987a, b; Turner, 1988; Turner and Rorich, 1986) will be considered here. Due to technical problems experienced during the upgrading and expansion of the monitoring network a poor data yield as well as data of questionable quality was obtained during the periods April 1981 - March 1982 and April 1982 - March 1983. Despite this, some useful results could still be derived by applying appropriate statistical techniques.

*Ambient sulphur dioxide concentrations**

Measurements show that the range of annual mean sulphur dioxide concentrations, i.e. 3,4 - 15,9 ppb (8,8 - 41,3 $\mu g.m^{-3}$), recorded at different sites within the ETH during 1984 to 1986 (Turner, 1988) compares with those typical for urban areas (20 - 60 ppb), semi-urban areas (2 - 40 ppb) and rural areas (0,1-10 ppb) (ECE, 1986).

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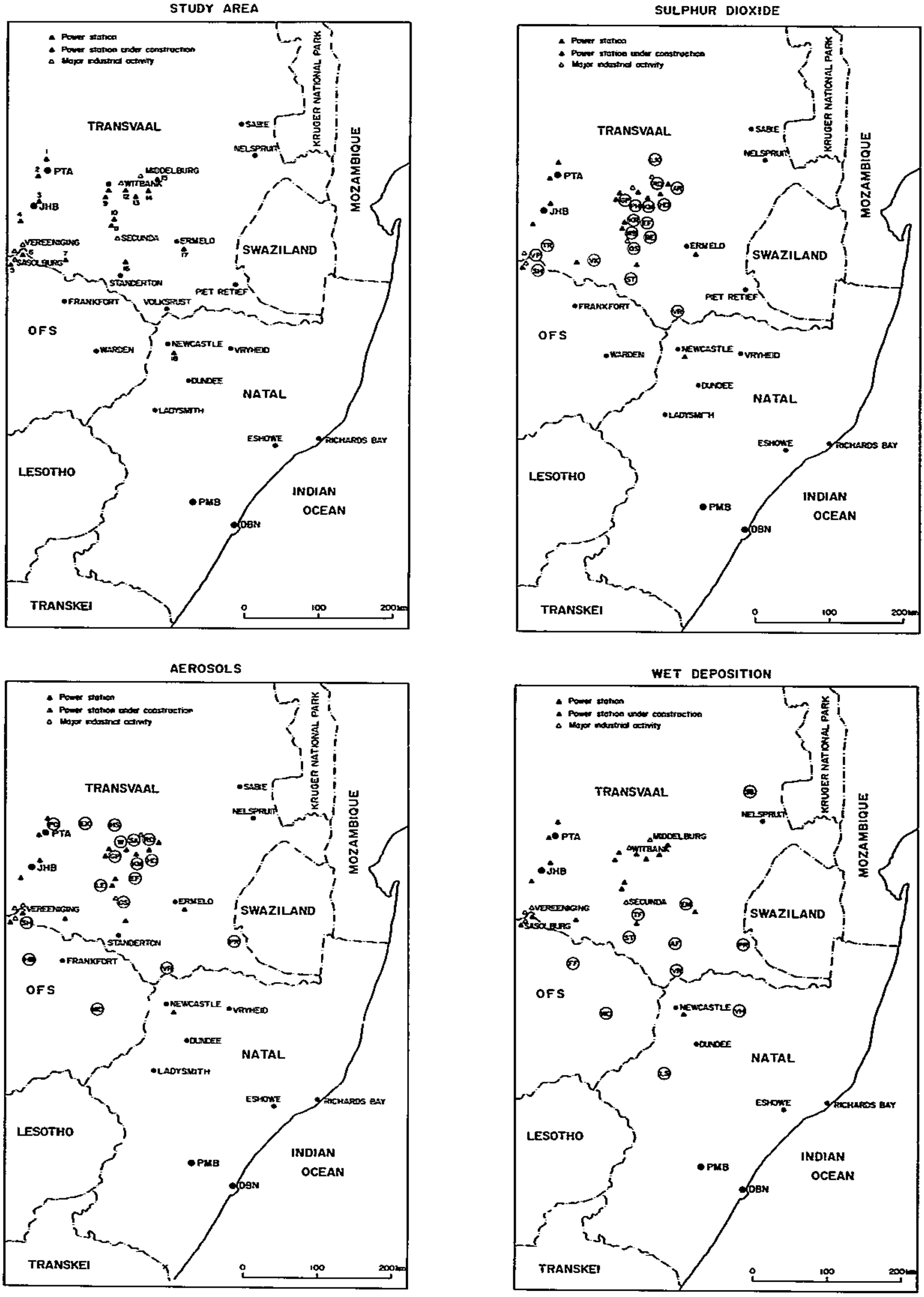
* Conversion used for sulphur dioxide: 1 ppb (v/v)=2,6 $\mu g.m^{-3}$


STUDY AREA

SULPHUR DIOXIDE

AEROSOLS

WET DEPOSITION

Fig. 36 *Study area and sampling sites. Power stations are: 1 = Rooiwal; 2 = Pretoria West; 3 = Kelvin; 4 = Orlando; 5 = Highveld/Taaibos; 6 = Lethabo; 7 = Grootvlei; 8 = Wilge; 9 = Kendal; 10 = Kriel; 11 = Matla; 12 = Duvha; 13 = Komati; 14 = Hendrina; 15 = Arnot; 16 = Tutuka; 17 = Camden; 18 = Ingagane. Sampling stations are: PO = Pretoria East/CSIR; EK = Ekangala; HS = Hartebeesspruit; LK = Lammerkop; SB = Sabie; W = Witbank; SA = SABC tower; RD = Rockdale; AR = Arnot; GP = Grootpan; PH = Phoenix; KM = Komati; HD = Hendrina; KR = Kriel; EF = Elandsfontein; LE = Leandra; WB = Wildebeest; BE = Bethal; OS = Oosskag; TP = Topfontein; EM = Ermelo; TR = Three Rivers; VP = Vaalpark; SH = Slangheuwel; VK = Van Kolderskop; ST = Standerton; AF = Amersfoort; VR = Volksrust; PR = Piet Retief; HB = Heilbron; FF = Frankfort; WD = Warden; LS = Ladysmith; VH = Vryheid.*

Table 5 *Exceedance of ambient air quality limits for sulphur dioxide set by Department of National Health and Population Development (after Pretorius et al., 1986; Turner 1987 b, 1988)*

Year	Number of exceedances Hourly	Daily	Annual
1979/80	4	0	0
1980/81	10[a]	5[c]	0
1981/82*	3	0	0
1982/83*	2	1	0
1984	2	1	0
1985	1	0	0
1986	16[b]	1	0

*Relatively low data yield obtained; results might therefore be biased.

[a] Eight of these exceedances occurred at Grootpan (Fig. 36) which is largely under influence of pollution from nearby smouldering discard coal dumps.

[b] Fifteen of these exceedances occurred at Komati (Fig. 36) which is largely under influence of pollution from the nearby Komati power station which has extremely short stacks.

[c] All of these exceedances occurred at Grootpan.

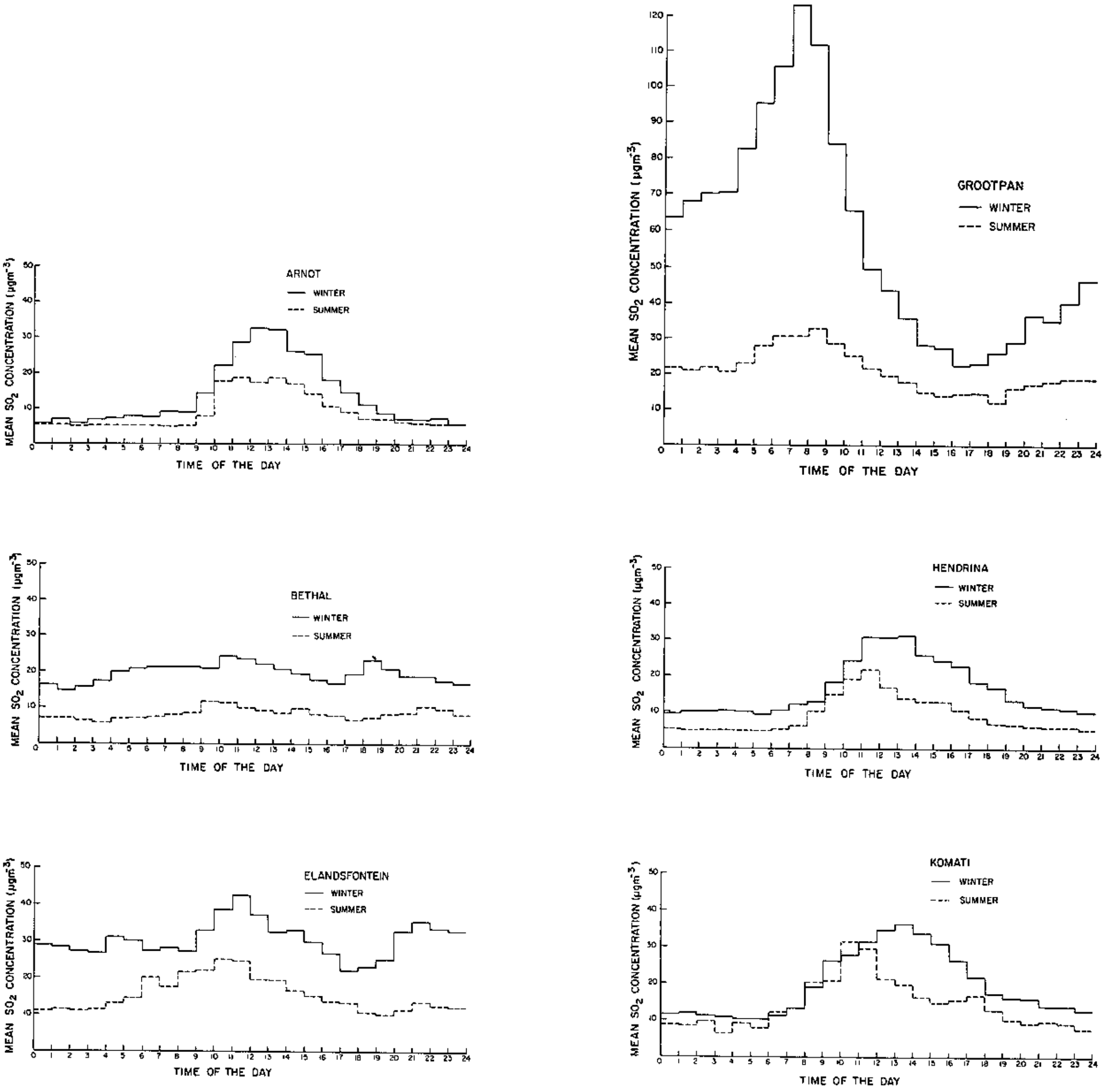


Fig. 37 *Examples of mean diurnal variation of hourly sulphur dioxide concentrations for summer and winter, 1979-1983 (after Pretorius et al., 1986).*

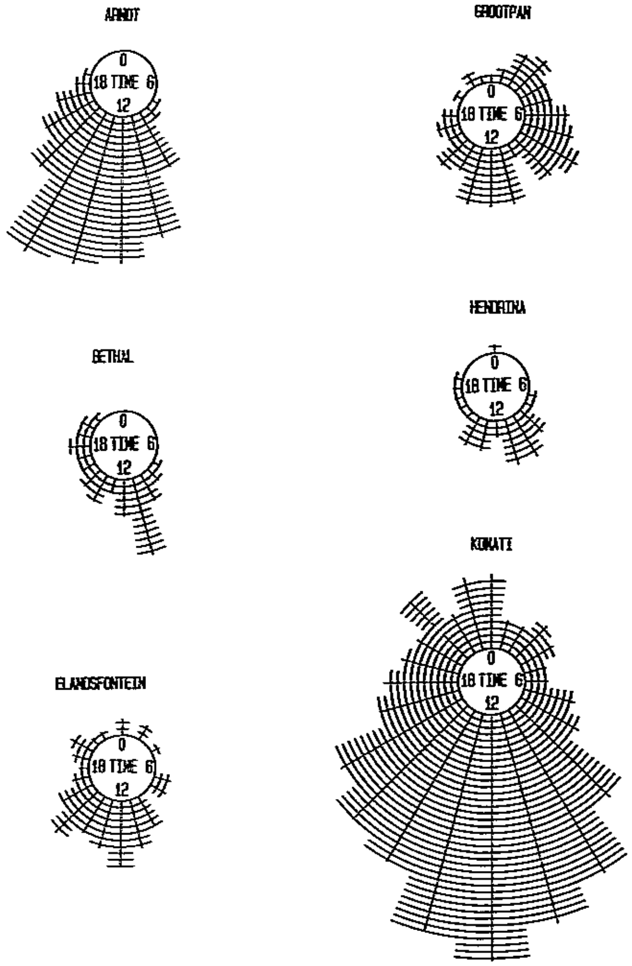


Fig. 38 *Examples of sulphur dioxide time-exceedance diagrams for 1985; 50 ppb (130 μg.m^{-3}) threshold level. Arcs represent units of 1 hour (after Turner, 1987b). Diagrams show the number of times the hourly mean concentrations of sulphur dioxide exceeded the threshold level for given hours of the day.*

A comparison of hourly, daily and annual mean sulphur dioxide concentrations with ambient air quality limits set by the Department of National Health and Population Development for the RSA (Table 5) shows that limits for hourly means were occasionally exceeded between 1979 and 1986. Limits for daily means were rarely exceeded. Annual means were never exceeded during the period of measurement. However, when considering directional sulphur dioxide concentrations, relatively high concentrations have been recorded (Pretorius et al., 1986). These were not randomly distributed, but were associated with winds from specific directions. This may well serve as an indication of possible future problems especially if such winds occur frequently.

Diurnal variations

Diurnal patterns of mean sulphur dioxide concentrations show that, for the majority of sites in the ETH, episodes of higher pollution concentration occurred during the midday period, whilst lower concentrations occurred during night time (Fig. 37). This finding was also supplemented by time-exceedance diagrams (Fig. 38) based on exceedances of an arbitrarily chosen threshold level of sulphur dioxide. The threshold of 50 ppb exceeds the noise level of the acquired data but is small enough for there to be a significant number of exceedances of the level.

These diurnal patterns are due to day-time turbulent mixing and the fact that during night-time the higher stacks ensure that plumes are lofted above the surface inversion layer. The sites at Grootpan and Elandsfontein do, however, deviate somewhat from the general diurnal patterns. This is due to the presence of significant low-level sources of sulphur dioxide i.e. from smouldering discard coal dumps in the near vicinity of both these sites and also the relatively elevated and exposed position of Elandsfontein, where plumes can impinge on the surface at any time of the day.

There is also some evidence from the 1985 and 1986 data (Turner, 1987 a,b) that post-dawn fumigations occur at a few sites, notably at Verkykkop (near Volksrust) and Vankolderskop (near Greylingstad). At present this effect does not appear to be significant. It also suggests that widespread fumigation does not follow the post-dawn inversion break-up, but this needs further study.

Seasonal variations

The seasonal variations of sulphur dioxide concentrations derived from 90% quantiles (the level below which 90% of all values occur) show greater frequencies of the higher concentration intervals during winter than during summer, when the depth of the mixing layer is much greater, thus diluting pollutants into a larger volume of the boundary layer. Other reasons for winter maxima are:

- a greater demand for electricity causing increased emissions from power stations;
- the pronounced influence of winter domestic coal-fired heating; and
- veld fires during the dry winter season.

Trends

Since the data for the winter months of the first four years of measurement were the most complete they were subjected to non-parametric trend analyses. It was found that the 90% quantiles of hourly sulphur dioxide concentrations indicated a highly significant increasing trend for the ETH region as a whole during the four winters of 1979 to 1983 (Table 6). This trend confirmed the impact of new power stations, e.g. Matla and Duvha, which were commissioned during the period of measurement.

Similar findings were obtained by analysing data for 1979/1980, 1980/1981 and 1984 by applying the technique of extreme statistics employing a threshold level of 50 ppb (130 $\mu g.m^{-3}$) sulphur dioxide (Table 7). A further analysis of the data for 1985 and 1986 indicated a possible leveling off of the increasing trend for the ETH region as a whole.

Source - receptor relationships

Establishing the relationship between source emissions and concentrations at given receptor measuring sites is important in planning an atmospheric pollution control strategy. One approach is to use sulphur dioxide wind roses based on arithmetic means (Fig. 39) or, alternatively, sulphur dioxide sector-exceedance diagrams based on exceedances of an arbitrarily chosen threshold level (Fig. 40). Both approaches revealed similar patterns of the rather localized influence of power stations at particular receptor sites. In some cases, the significant effects of smouldering discard coal dumps and industrial areas are apparent. The influence of low-level sources was found to be much more obvious during winter than during any other season of the year.

A further means of establishing the link between sources and receptors is to calculate approximately the ambient sulphur dioxide concentrations that may be expected at given receptor sites. Taking the estimated sulphur dioxide emission of about 830 000 tons per annum for 1983 (Els, 1987), a circular area with diameter of 125 km which includes all the major pollution sources, a sulphur dioxide decay rate of $3\%.h^{-1}$ (Newman, 1981), wind speeds of 10 to 50 $km.h^{-1}$, a mixing height of about 1 km and

Table 6 *Trend test for hourly sulphur dioxide concentrations for the period 1979-1982 using 90% quantiles (after Pretorius et al., 1986)*

a)

Site	90% quantiles for hourly SO_2 concentrations ($\mu g.m^{-3}$) for the four winter seasons			
	1979	1980	1981	1982
Arnot	21,0	21,0	26,0	44,0
Bethal	39,0	47,0	52,0	73,0
Elandsfontein	62,0	60,0	75,0	146,2
Grootpan	96,0	231,3	106,4	205,0
Hendrina	29,0	34,0	42,0	49,0
Komati	47,0	34,0	35,8	91,6
Kriel	26,0	57,3	39,0	62,6
Rockdale	18,0	36,0	47,0	18,0
Wildebeest	36,0	44,0	26,0	65,0

b)

Site	Ranks for the four winter seasons				
	1979	1980	1981	1982	S
Arnot	1,5	1,5	3	4	+5
Bethal	1	2	3	4	+6
Elandsfontein	2	1	3	4	+4
Grootpan	1	4	2	3	+2
Hendrina	1	2	3	4	+6
Komati	3	1	2	4	+2
Kriel	1	3	2	4	+4
Rockdale	1,5	3	4	1,5	+1
Wildebeest	2	3	1	4	+2

$\Sigma S = +32$; $z = (\Sigma S - 1)/\sigma_s = 31/8{,}72 = 3{,}56$; $p<0{,}01$

Table 7 *Trend for hourly sulphur dioxide concentrations for the period 1979-1986 using extreme statistics (after Turner, 1987 a, b; Turner, 1988; Turner and Rorich, 1986)*

a)

Site	No of hours per year SO_2 hourly concentrationsexceeded 50 ppb (130 $\mu g.m^{-3}$)				
	1979/80	1980/81	1984	1985	1986
Arnot	69,5	59,8	338,0	129,1	336,8
Bethal	14,4	40,2	20,6	46,1	117,7
Elandsfontein	110,7	158,9	828,7	74,2	275,9
Grootpan	256,4	846,8	174,2	104,6	89,9
Hendrina	25,7	26,4	76,6	38,7	74,8
Komati	63,3	59,0	265,0	349,0	712,0
Kriel	33,4	87,3	204,7	132,8	230,8
Rockdale	12,4	23,8	57,3	21,5	88,5
Wildebeest	11,6	13,7	31,2	64,5	78,7
TOTAL	597,5	1 316,0	1 996,3	960,5	2 005,1

b)

Correlation coefficients were computed for the data in (a) as a function of time using multiplicative models. These were subjected to the U-statistics method. From this the following trends for sulphur dioxide data were obtained for the period 1979-1986:

Arnot	M	Bethal	VW
Elandsfontein	N	Grootpan	-VW
Hendrina	M	Komati	S
Kriel	S	Rockdale	W
Wildebeest	S		

Where N = No significant trend indicated
VW = Very weak trend
W = Weak trend
M = Moderate trend
S = Strong trend
A negative sign indicates the trend to be negative

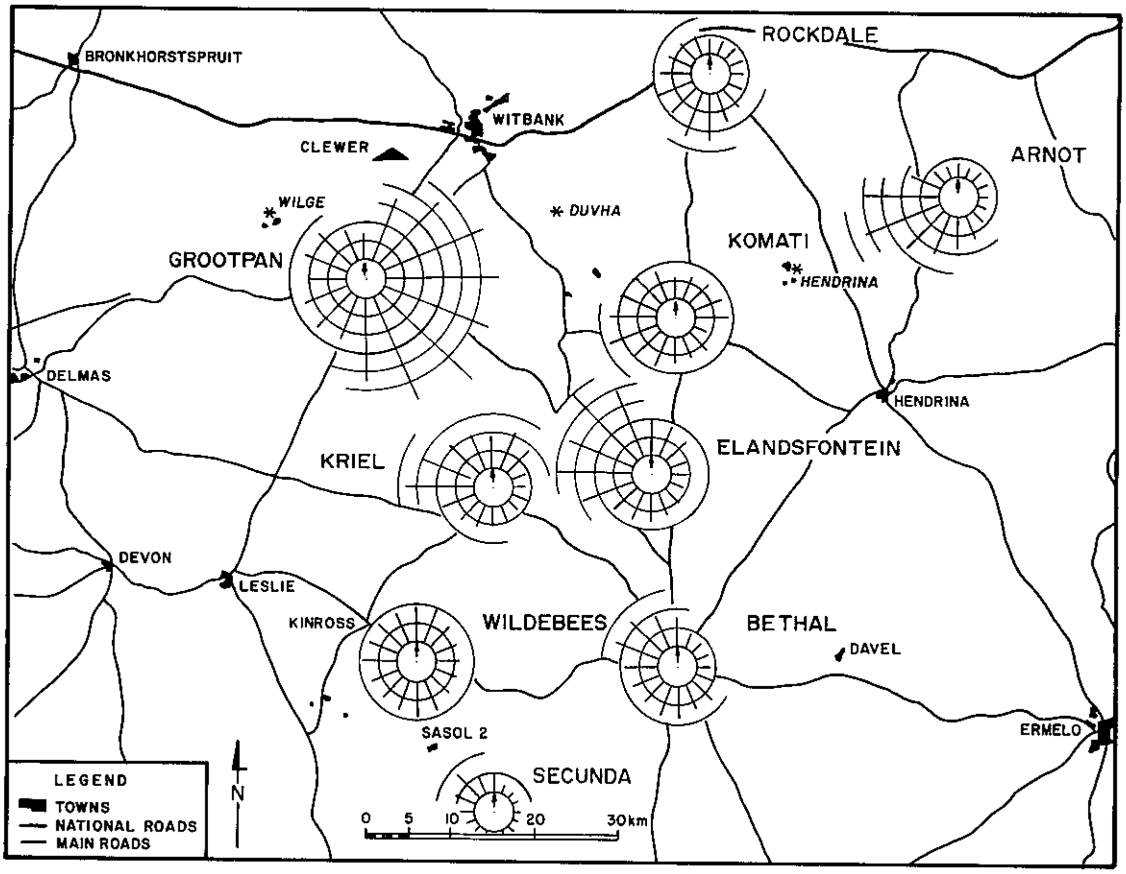


Fig. 39 *24-Hourly sulphur dioxide roses for 1979-1983 (49 months). The rose of Secunda is based on data from the last 23 months of this period only. Bars represent mean sulphur dioxide concentrations for each wind direction and arcs indicate 10 μg.m^{-3} concentration intervals (after Pretorius et al., 1986).*

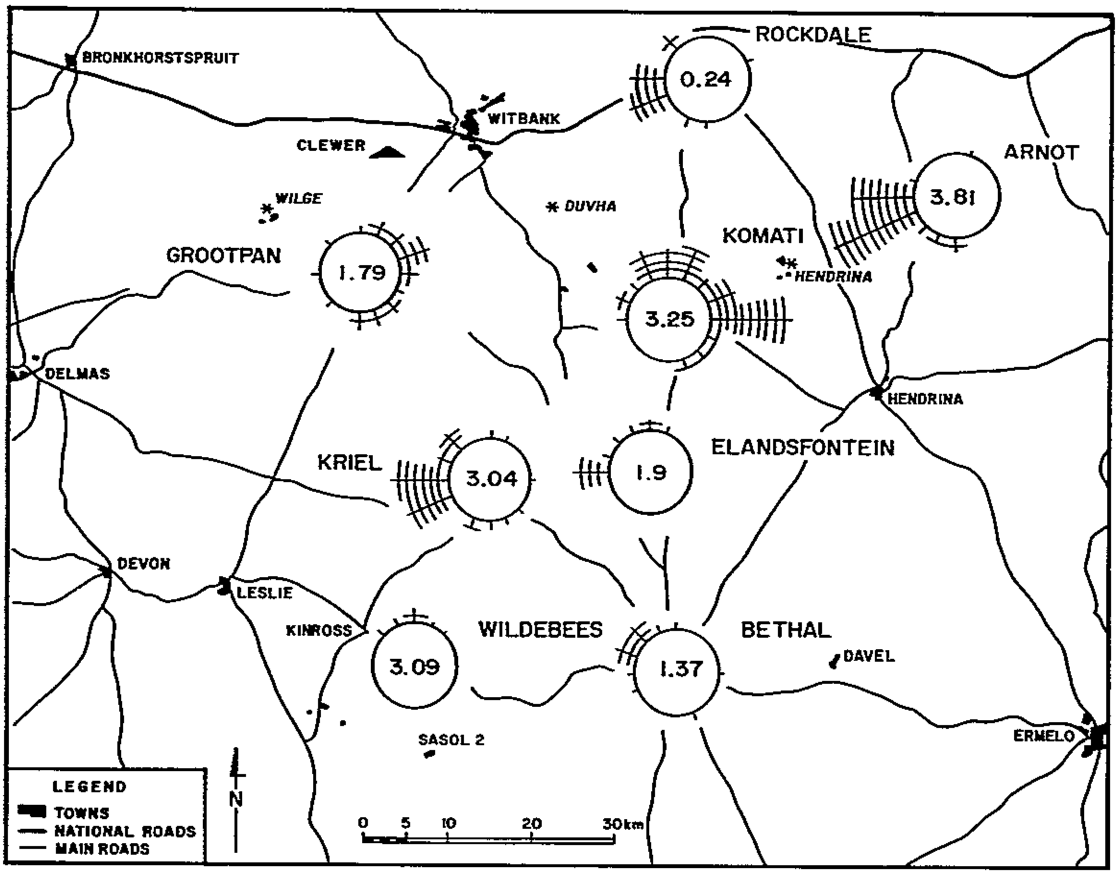


Fig. 40 *Sulphur dioxide sector-exceedance diagrams for 1985; 50 ppb (130 $\mu g.m^{-3}$) threshold level. Figures in the circles are for calms. Arcs represent 1% intervals (after Turner, 1987b). Diagrams show the percentage of the time that hourly mean concentrations of sulphur dioxide exceeded the threshold level for given wind directions.*

assuming negligible horizontal dilution, ambient sulphur dioxide concentrations between 14 and 56 $\mu g.m^{-3}$ (5,4 - 21,5 ppb) may be calculated for a site situated some 100 km downwind from the ETH centre. These concentrations are of the same order of magnitude as those measured most frequently in the ETH, i.e. 2 - 50 $\mu g.m^{-3}$ (0,8 - 19 ppb) (Pretorius et al., 1986). Thus, measured sulphur dioxide concentrations can be reasonably well accounted for in terms of known source emissions.

3.3.3 Nitrogen oxides measurements

Measurements of nitrogen oxides (Turner, 1987a,b) were made only at one site (Phoenix) during the second half of 1985. They showed that nitrogen oxides and sulphur dioxide were apparently largely co-sourced, a somewhat unexpected result due to the relatively large number of potential sources affecting the measurement site. The implication is that smouldering discard coal dumps which are situated close to the measurement site are major sources of ground level nitrogen oxides and sulphur dioxide.

3.3.4 Ozone measurements*

Measurements of ozone (Turner, 1987a, b) were also made only at one site (Phoenix) during 1985/86. Measurements showed that

- none of the daily mean values exceeded the level of 100 ppb (200 $\mu g.m^{-3}$) which is regarded as episodic in Scandanavian countries (Semb and Dovland, 1986),

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* Conversion used for ozone: 1 ppb(v/v) = 2$\mu g.m^{-3}$

- monthly mean values fell within the range of 5 to 30 ppb (10 - 60 $\mu g.m^{-3}$), which is typical of rural areas (Feister and Warmbt, 1987),
- none of the hourly, daily or monthly mean values exceeded the ambient air quality limits set by the Department of National Health and Population Development (DNHPD) for the RSA. During 1985 the means for the months of September (25,5 ppb), October (26,7 ppb) and November (26,2 ppb) did, however, closely approach the monthly ambient air quality limit of 30 ppb (60 $\mu g.m^{-3}$)set by the DNHPD.

Furthermore, observations made at Phoenix as well as Vaalpark (Vaal triangle area) showed that ozone concentrations exhibited a strong diurnal behaviour indicative of a chemically reactive atmosphere. This behaviour is characteristic of the formation and destruction of ozone due to human activities.

Thus, although ozone concentrations appear to be acceptable within the ETH at this stage, ozone should nevertheless be closely monitored in future in view of its inherent toxicity and reactive properties. For example, doses of ozone as low as 60 ppb per 4 h-day for a 6 - 10 day period have been reported to cause acute injury to *Pinus* species grown in the USA (Moore, 1987).

3.3.5 Aerosol measurements

Aerosols were collected at near-ground level (3 m above ground level) as well as at elevated levels (300 m above ground level) at a number of different sites in the ETH. Nucleopore filters were used to collect the samples which were subsequently analyzed for different aerosol species (i.e. sulphates, nitrates, chlorides and others) by ion chromatography.

The data set obtained for the period 1983 to 1986 (Snyman et al., 1987, 1986, 1985; Wells et al., 1987) will be considered here.

Origin and formation of sulphate and nitrate aerosols

These pollution species result from the conversion (oxidation) of sulphur dioxide and nitrogen oxides via a series of sunlight-induced reactions which occur in the free atmosphere and in clouds (Calvert, et al., 1985). Oxidizing pollutants such as ozone and hydrogen peroxide as well as reactive free radicals (notably the hydroxyl radical) and transition metals play a prominent role in these reactions.

The review of Wells et al (1987) suggests that the above-mentioned oxidation mechanisms will be strongly controlled in the ETH by increased solar radiation in summer and by reduced humidity in winter. Thus oxidation should be faster in summer and slower in winter. Some observations have, in fact, been made on aspects related to the conversion of sulphur dioxide to sulphate aerosol and these warrant further discussion.

Observations at a number of near-ground level sites showed that there was no clear overall seasonal trend in sulphate aerosol concentrations (Fig. 41). This was apparently due to the faster formation of sulphate aerosol during summer which roughly balanced the improved dispersion during summer. This result is to be expected on theoretical grounds and is in contrast to that for primary pollutants (smoke, sulphur dioxide, trace metals) which tend to show strong maxima in winter time.

The percentage particulate sulphur, i.e. the fraction of sulphur present in sulphate aerosol as compared with the total sulphur in sulphur dioxide and sulphate aerosol, can be taken as a measure of the extent of oxidation of sulphur dioxide to sulphate aerosol. At Elandsfontein (a near-ground level site situated near centrally in the ETH) particulate sulphur was found to average 12% but at Verkykkop (a high-level

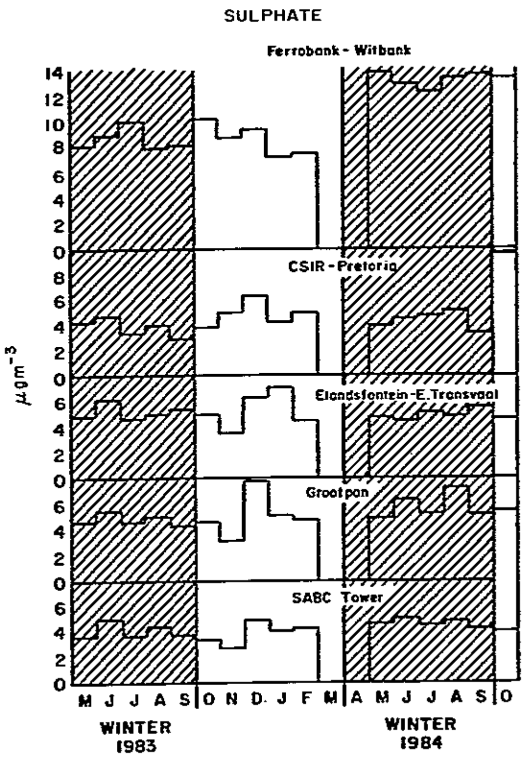


Fig. 41 *Seasonal variations in sulphate aerosol concentrations (after Wells et al., 1987).*

site situated some 130km away at a sufficient altitude to intercept higher level stratified pollution) a value of 33% was found. Comparable early summer values of 15 - 45% have been reported in the USA and Europe.

In addition, it has been found that peaks in percentage particulate sulphur often corresponded to high sulphate aerosol and low sulphur dioxide concentrations. This seemed to support the existence of a simple relationship of sulphate forming at the expense of its precursor, sulphur dioxide. There did not, however, appear to be a clear relationship between episodes of high sulphate and nitrate aerosol pollution and attendant concentrations of nitrogen oxides and ozone, which are inherently strong oxidants.

The above findings therefore indicate that the atmosphere of the ETH is fairly reactive in terms of the conversion of sulphur dioxide to sulphate aerosol particularly during the summer season.

Ambient aerosol concentrations

The situation for ambient atmospheric concentration of sulphate, nitrate and chloride aerosols at near-ground level sites is reflected in Figure 42. The results are ordered along the north-south axis of the ETH. The corresponding trends may relate to specific sources as well as to the three different meteorological regimes that apparently exist within the ETH (Pretorius et al., 1986). These recorded concentrations compare with natural and man-made pollution found elsewhere (Graedel et al., 1986) (Table 8).

The only known ambient air quality standards for aerosols are those which have been promulgated for sulphates in two different states of the USA. These are the rather stringent 24-hour standard of 12 $\mu g.m^{-3}$ for North Dakota (Angelo et al., 1984) and the more lenient 24-hour standard of 25 $\mu g.m^{-3}$ for California (California Air Resources Board, 1985). At all but one of the near-ground level

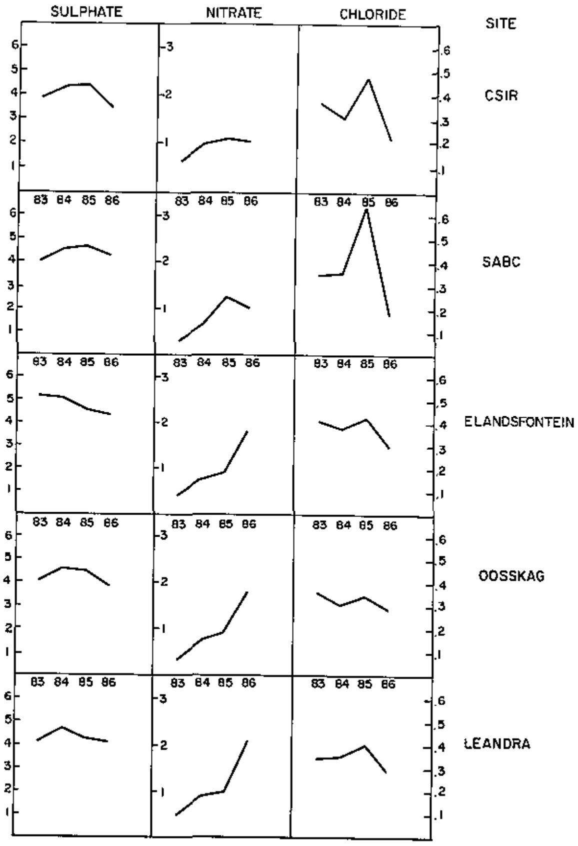


Fig. 42 *Sulphate, nitrate and chloride aerosol concentrations (µg.m⁻³) measured at near-ground level during 1983-1985. Measurements were made from May to October each year (after Wells et al., 1987).*

Table 8 *Natural and urban concentration ranges for sulphate, nitrate and chloride aerosols (after Graedel et al., 1986)*

Atmospheric regime	Aerosol concentration (µg.m^{-3})		
	$SO_4^=$	NO_3^-	Cl^-
Oceanic	0,1 - 3	0,1 - 1	1 - 10
Grassland	0,1 - 0,4	1 - 3	0,04 - 1,0
Desert	0,1 - 0,8	0,08 - 0,8	~0,1
Urban	1 - 40	1 - 10	0,2 - 3,0

measurement sites in the ETH the Californian standard was met. The exception was a site in an industrial area which had been under the influence of one particular local source. This source has in the interim been equipped with modern control equipment.

Aerosol concentrations at high-level sites

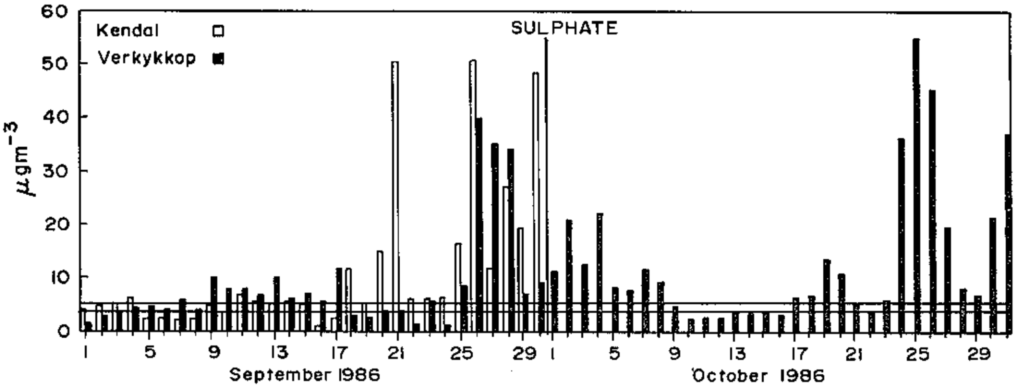
Measurements at Verkykkop situated approximately 300 m above the general terrain showed higher than normal aerosol concentrations (Table 9) as well as the occurrence of pollution episodes (Fig. 43) which were not observed at the near-ground sites. Measurements with a second high-level sampler installed

Table 9 *Atmospheric concentrations of sulphate, nitrate and chloride aerosols (µg.m^{-3}) at near-ground level and at about 300 m above ground level (after Wells et al., 1987)*

Month/Year	Site														
	Verkykkop			Volksrust Town			Kendal 1 (stack)			Kendal 2 (ground)			SABC (ground)		
	$SO_4^=$	NO_3^-	Cl^-	$SO_4^=$	NO_3^-	Cl^-	$SO_4^=$	NO_3^-	Cl^-	$SO_4^=$	NO_3^-	Cl^-	$SO_4^=$	NO_3^-	Cl^-
June 1985	3,9	1,5	0,9										4,5	0,7	0,7
July	3,3*	1,7*	0,5*										4,4	0,8	0,7
August	8,4	4,9	2,7										5,7	2,2	0,8
September	10,2	6,4	3,3										4,7*	1,1*	0,4*
October	5,7	3,4	1,7										3,5	1,3	0,2
November	6,9	3,6	2,0										3,2	0,7	0,3
December	6,9	3,0*	1,5*										3,5*	0,4*	0,3*
January 1986	5,8	1,5	1,0										3,2*	0,5*	0,1*
February	5,8	1,3	1,0										5,3	0,4	0,1
March	15,1	6,8	4,1												
April	9,4	3,3	1,2												
May	7,2*	2,3*	0,9*										5,2*	1,0*	0,2*
June	3,7	1,8	0,7	2,6	0,4	0,1							3,9	0,8	0,1
July	5,1	2,6	0,7	3,8	0,9	0,1							5,1	1,5	0,2
August	5,7*	3,8*	1,1*	3,8	0,7	0,1	3,7	1,7	0,3				4,1	1,0	0,2
September	8,8	5,9	2,5	4,0	0,7	0,2	11,6	5,8	1,1				3,9	1,1	0,2
October	13,4	6,7	3,7	3,9	0,5	0,1	8,0*	2,5*	0,2*				3,3	0,7	0,2
November	11,6	4,6	2,2	3,8*	0,4*	0,1*	9,7*	2,6*	0,8*	5,0	1,0	0,2	3,7	0,8	0,1
December	8,8*	3,2*	2,1*							6,4	0,7	0,2	4,9*	0,4*	0,1*

*Incomplete month's data

Ratios:	$SO_4^=/NO_3^-$	$SO_4^=/Cl^-$
Verkykkop	2,14	4,31
SABC	4,68	14,7



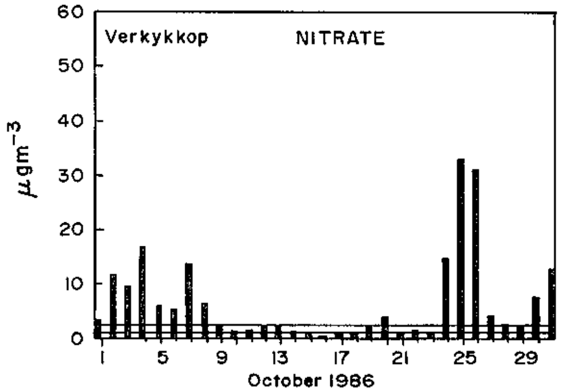


Fig. 43 *Sulphate and nitrate aerosol pollution episodes observed at high levels. Horizontal lines indicate upper and lower limits of mean concentrations recorded at near-ground level (see Fig. 42) (after Wells et al., 1987).*

at Kendal stack (situated about 275 m above ground level and some 165 km to the northwest of Verkykkop) supplemented these observations.

Careful consideration of the observed pollution episodes together with associated meteorological conditions indicated the possible existence of an elevated layer of polluted air in the ETH. The depth, geographical extent and shape of this pollution layer are largely unknown, as too are the pollution gradients in it. It is not as yet possible to predict how frequently or how long this pollution layer may persist. Some evidence exists to suggest re-circulation of polluted air from outside the present study area back into it.

It would appear that although tall stacks in the ETH may have succeeded in lowering ground-level pollution, environmentally significant pollution is now occurring in an elevated layer. Washout of such an elevated pollution layer or banking thereof against forested mountain regions could well lead to significant acidic deposition. Such deposition has been demonstrated to play a significant role in the decline of certain forests in the USA and Europe.

Source - receptor relationships

By doing the same calculations as in the case of sulphur dioxide and allowing for a 3%.h^{-1} conversion of sulphur dioxide to sulphate, sulphate aerosol concentrations between 1 and 29 µg.m^{-3} are suggested for sites situated 100 km downwind from the ETH centre. These concentrations are of the same order of magnitude as those actually observed in the ETH, i.e. 1-50 µg.m^{-3} (Wells et al., 1987). Thus, measured sulphate aerosol pollution may be reasonably well accounted for in terms of known source emissions.

3.3.6 Visibility

Nephelometer measurements of visibility at Elandsfontein frequently correlated well with airborne sulphate aerosol concentrations (Turner, 1987 a,b; Wells et al., 1987) (Fig. 44). Outliers on the correlation curves are probably due to other pollutants, humidity, windblown dust and veld fires.

Visibility at Elandsfontein during 1985 and 1986 was seldomly less than 19 kilometres and often better. Thus, the visibility at this site is not a special problem. Subjective experience elsewhere on the ETH, however, suggests that visiblity degradation presumably caused largely by sulphate aerosols could be a local problem in many areas but data are lacking.

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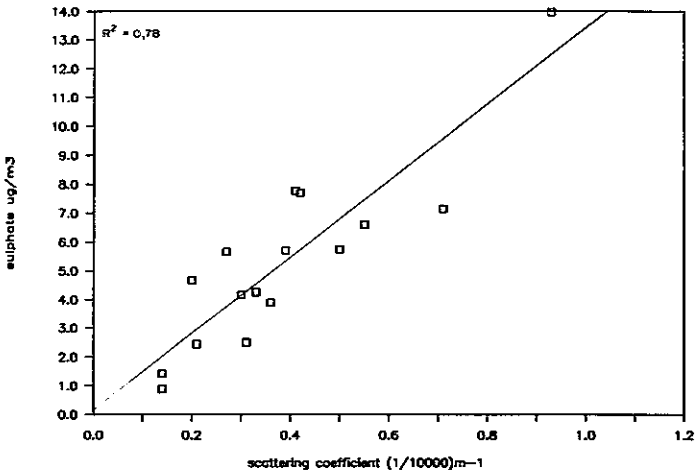

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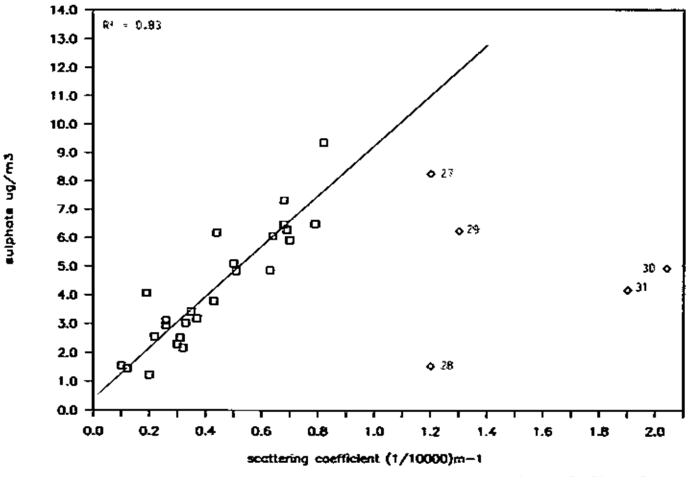

Fig. 44 *Relationship between sulphate aerosol concentrations and visibility denoted by scattering coefficient (after Wells et al., 1987). In the lower graph five days, i.e. 27, 28, 29, 30 and 31 October, are outliers.*

3.3.7 Other atmospheric pollutant species

The role of other pollution in the atmospheric chemistry of the ETH should not be overlooked (Wells et al., 1987). A case in point is the substance hydroxymethanesulphonate (HMSA), a strong acid, which results from the reaction of sulphur dioxide and formaldehyde in water. In the RSA increased emissions of aldehydes resulting from the use of alcohols in petrol could indeed contribute to the formation of HMSA. In addition, there is growing overseas evidence of substantial amounts of complex sulphur and nitrogen pollutant species whose full significance in terms of environmental impacts is still unknown.

A limited study made during March/April 1987 in the close vicinity of Secunda showed the presence of several volatile organic atmospheric pollutants (Van Niekerk et al., 1987). None of these were unexpected or rare compounds. Moreover, it was found that in general the organic pollution levels were within acceptable limits set by the DNHPD.

3.4 REMOVAL PROCESSES

It is essential that the processes controlling the pathways and fates of atmospheric pollutants (Fig. 33) are well understood as these will aid in assessing the potential impact of the pollutants on the environment. Processes of particular importance in this regard are the transportation and attendant chemical transformation of atmospheric pollutants, as well as the wet and dry deposition onto the earth's surface. Transportation of polluted air which has originated over the ETH can take place to adjacent regions such as Natal and Orange Free State, as well as to neighbouring countries such as Swaziland, Mozambique and Lesotho.

3.4.1 Wet deposition

Very fine particulates, in particular sulphate and nitrate aerosols, are removed from the atmosphere and transferred to the earth's surface by wet deposition processes such as washout and rainout (Fig. 33). These fine particulates comprise the major portion of wet deposition.

A network of sampling stations which monitor wet atmospheric deposition have been set up by different organizations (ESKOM, Hydrological Research Institute, Department of Water Affairs and South African Forestry Research Institute, Department of Environment Affairs) in the ETH as well as in the Northeastern Orange Free State, Natal and the forestry plantations at Sabie (Fig. 36). At the majority of stations wet deposition only was collected. Bulk deposition (including wet and dry deposition) was also observed at a number of sites.

Collected samples have been analysed for ionic species (eg nitrate, sulphate, chloride, etc) usually by ion chromatography (Mrozek and Dunn, 1986). In some cases spectroscopic and automated colorimetric methods were employed (Bosman and Kempster, 1985). Measurement of rainfall acidity (pH) was done as soon as possible after rain events. Precautions were taken to prevent biological decay and algae growth in samples prior to their analysis.

Rainfall acidity

The rainfall acidity (pH) recorded in the ETH and adjacent regions (Bosman, 1988; Gertenbach, 1986; Mrozek and Dunn, 1986; Van Wyk, 1987) is similar to that for north eastern North America and Europe (Fuhrer, 1984; Granat, 1987; ITF on Acid Precipitation, 1983; National Research Council, 1983, 1986; OECD, 1985; UK Review Group on Acid Rain, 1983, 1987) (Table 10). As has been found in these countries, the pH in the ETH and adjacent regions is lower than that recorded in areas which are relatively free from man-made pollution (Brunke, 1986; ITF on Acid Precipitation, 1983; Van Wyk, 1987) (Table 10).

These results do seem to indicate that acid deposition through acid rain is occurring in the ETH. Whether this necessarily constitutes an environmental problem is a matter which warrants further and more extensive investigation.

Table 10 *Rainfall acidity in ETH, adjacent regions and elsewhere in world (after Bosman, 1988; Brunke, 1986; Fuhrer, 1984; Gertenbach, 1986; Granat, 1987; ITF on Acid Precipitation, 1983; Mrozek and Dunn, 1986; NRC 1983, 1986; OECD, 1985; UK Review Group on Acid Rain 1983, 1987; Van Wyk, 1987)*

Country/ site	Year	Acidity (pH)
South Africa		
ETH		
Ermelo	1985/86	4,0
Standerton	1985/86	3,9
Amersfoort	1985/86	4,1
Piet Retief	1985/86	4,0
Volksrust	1985/86	4,2
Topfontein	1985/86	4,6
LOWVELD		
D R de Wet (Sabie)	1986	4,2
Punda Maria (Kruger National Park)	1983/84	4,8
OFS		
Frankfort	1985/86	4,1
Warden	1985/86	4,0
NATAL		
Vryheid	1985/86	4,2
Ladysmith	1985/86	4,3
NE North America		
Several sites	1980	4,2-5,0 *
Europe		
Several sites	1978/82	4,1-4,9 *
Sweden		
Several sites	1985	4,4
Switzerland		
Bern	1983	4,7
United Kingdom		
Several sites	1980/85	4,1-5,1 *
Pristine areas		
Sites in S & N Hemisphere	1982	5,0-5,3 *
Cape Point	1983/84	5,2
Jonkershoek	1986	5,1

* Ranges given are for mean values recorded at the different sites.

Wet (and bulk) deposition of ionic species

Wet deposition is derived from rainfall quality analysis by multiplying the concentrations of the various ionic species in rain water with the relevant rainfall. A comparison of the wet deposition of some ionic species in the ETH and adjacent regions (Bosman, 1987, 1988; Mrozek and Dunn, 1986; Van Wyk, 1987) with that for north eastern North America and Europe (Fuhrer, 1984; Granat, 1987; National Research Council, 1983, 1986; UK Review Group on Acid Rain, 1983, 1987) (Table 11; Fig. 45), shows that the hydrogen ion deposition values are similar, whereas sulphate, nitrate, and ammonium deposition

Table 11 *Wet deposition of ionic species in ETH, adjacent regions and elsewhere in world (after Bosman, 1987, 1988; Fuhrer, 1984; Granat, 1987; Mrozek and Dunn, 1986; NRC 1983, 1986; UK Review Group on Acid Rain 1983, 1987; Van Wyk, 1987)*

Country/ Site	Year	Wet deposition (kg.ha^{-1}.yr^{-1})			
		H^+	$SO_4^=$	NO_3^-	NH_4^+
South Africa					
ETH					
Ermelo	1985/86	0,60	18,17	9,17	3,27
Standerton	1985/86	0,75	19,06	11,35	4,88
Amersfoort	1985/86	0,53	15,89	9,53	3,41
Piet Retief	1985/86	0,60	17,85	10,46	3,98
Volksrust	1985/86	0,47	16,00	9,08	3,15
Topfontein	1985/86	0,31	24,00	4,00	-
LOWVELD					
D R de Wet (Sabie)	1986	0,68	27,99	1,96	-
OFS					
Frankfort	1985/86	0,44	14,04	7,14	2,79
Warden	1985/86	0,52	11,20	7,99	2,04
NATAL					
Vryheid	1985/86	0,48	13,98	8,07	3,01
Ladysmith	1985/86	0,40	10,69	5,35	3,49
NE North America					
Several sites	1980	0,20-0,97*	9,6-48,0*	12,4-32,9*	1,8-7,2*
Sweden					
Several sites	1985	-	9,6-33,6*	6,2-24,8*	-
Switzerland					
Bern	1983	0,17	15,98	12,0	5,69
United Kingdom					
Several sites	1980/85	0,09-0,98*	11,7-56,7*	4,3-27,7*	1,5-10,4*

* Ranges given are for mean values recorded at the different sites.

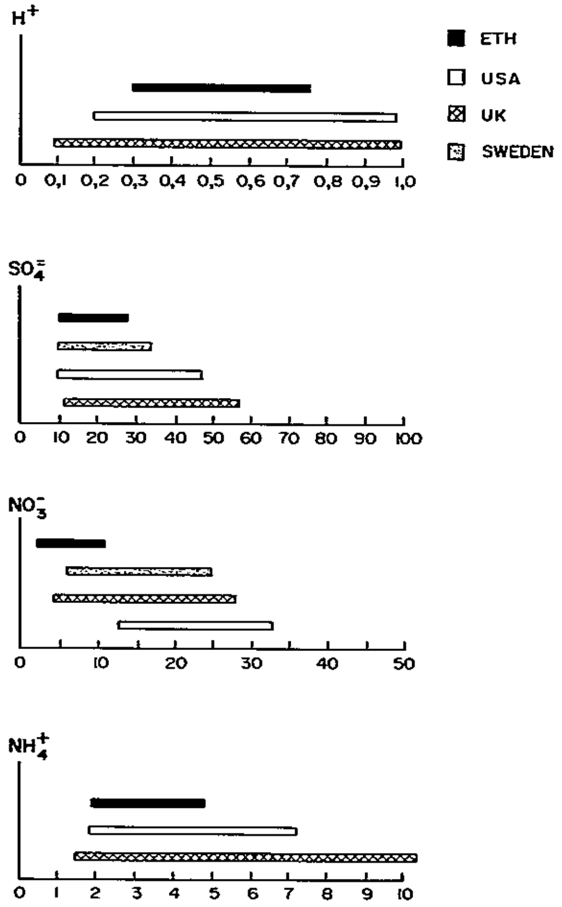

Fig. 45 *Ranges for mean wet deposition of ionic species (kg.ha^{-1}.yr^{-1}) in ETH and elsewhere (See Table 11).*

values are usually at the lower end of mean ranges reported elsewhere. An exception is, however, the relatively high sulphate depositions recorded in the eastern portion of the Vaaldam catchment at Topfontein and the forestry plantations at Sabie . At these two sites which may well be under the influence of local pollution sources the critical limit of 20 kg of sulphate ha^{-1}.yr^{-1} in wet deposition suggested in Canada to be required to protect sensitive aquatic ecosystems (Manson, 1985) has so far been exceeded. It is also of interest to note that at some of the sites within the ETH this critical limit was closely approached (Table 11).

It appears that the wet deposition occurring within the north eastern Orange Free State and northwestern Natal is similar to that occurring within the ETH (Table 11). This suggests that some export of pollution originating within the ETH is taking place.

Bulk (wet and dry) sulphate deposition loads recorded in the eastern portion of the Vaaldam catchment and mountain catchments near the ETH (Bosman, 1987, 1988; Van Wyk, 1987) are similar to those reported for localities in north eastern America (Barrie and Sirois, 1986; Henry and Brezonik, 1980; Mollitor and Raynal, 1983) (Table 12). Whether this is indicative of a local environmental problem or not depends, for example, on the further fate of the deposited sulphate in these catchments and on the results of investigations of the effects of acid deposition on indigenous vegetation.

Source emissions, aerosols and wet deposition

In order to further elucidate the role of wet deposition in removing atmospheric pollution, the relationship between sulphates deposited on a given surface area and those observed in the atmosphere

Table 12 *Bulk deposition of ionic species in ETH, adjacent regions and elsewhere in world (after Barrie and Sirois, 1986; Bosman, 1987, 1988; Henry and Brezonik, 1980; Mollitor and Raynal, 1983; Van Wyk, 1987)*

Country/ Site	Year	Bulk deposition (kg.ha^{-1}.yr^{1})	
		$SO_4^=$	NO_3^-
South Africa			
ETH			
Leeukop	1985/86	29	5
Charl Celliers	1985/86	35	6
Topfontein	1985/86	48	5
Hendrikspan	1985/86	32	4
Witbank	1985/86	28	6
Langspruit	1985/86	31	6
Swartkop	1985/86	24	5
LOWVELD			
D R de Wet (Sabie)	1986	30	2,4
Witklip (Nelspruit)	1983/87	61	1,5
OFS			
Springbok	1985/86	22	5
NATAL			
Cathedral peak (Winterton)	1984/86	59	3,8
NE USA			
Florida	1976/77	27	28
Adirondack region	1979/80	26	15
Eastern Canada			
Several sites	1979/82	10 - 83*	8 - 38*

* Ranges given are for mean values recorded at the different sites.

will be examined. For example, if some 70 ETH rain events per year are postulated, and in each a column of air 1 000 m deep over a surface area of 1 km^2 (100 ha) is swept clean of aerosols, then a deposit of 10 kg sulphate ha^{-1}.yr^{1} corresponds to an annual mean sulphate concentration in air of 14 μg.m^{-3}. This deposit is of the same order of magnitude as that actually observed in the ETH (See Table 11). Correspondingly, a deposit of 20 kg sulphate ha^{-1}.yr^{1} would imply an atmospheric concentration of 28 μg.m^3. These required atmospheric concentrations are much higher than the annual mean values of 4 - 5 μg.m^{-3} which have actually been measured at near-ground level sites in the ETH (Fig. 42). They do, however, match the relatively high peak values of 15 - 50 μg.m^{-3} observed at Verkykkop (Fig. 43) and postulated to exist in an elevated polluted atmospheric layer.

A second relationship that can be examined is the ratio of sulphate to nitrate in aerosols and wet deposition. According to measurements by the ESKOM network (Mrozek and Dunn, 1986), the annual ratio (by mass) of sulphates to nitrates deposited in 1985 in the ETH varied between 1,4 and 2,0 with a mean of 1,6. In contrast, this ratio varied between 3,8 to 5,0 in aerosols measured at near ground level. It is difficult to explain the ratios observed for wet deposition in terms of airborne aerosols measured at near-ground level. However, measurements at the high-level site at Verkykkop yielded sulphate to nitrate ratios which ranged from 1,8 to 2,1 and which are more consistent with those found in wet deposition.

These findings add to the suggestion that the elevated layer of polluted air probably resulting from high-level emissions makes a major contribution to the wet deposition of pollutant species within the ETH. It is, however, not possible at this stage to state whether the link between emissions from high-level sources (such as power station stacks) and wet deposition is linear or non-linear in nature, i.e. whether given reductions in the highlevel source emissions would result in proportionate or disproportionate reductions in the wet deposition of pollutant species.

3.4.2 Dry deposition

Gaseous pollutant species (such as sulphur dioxide) are removed from the atmosphere and transferred to the earth's surface by dry deposition processes such as adsorption and absorbtion. Depending on their size, particles are removed either by impaction or by gravitational settling.

Unfortunately, no accurate methodology exists for routine measurement of dry deposition. Consequently, an approach often used is to provide estimates of dry deposition from the product of near-surface concentrations of a given pollutant substance and the deposition velocity appropriate to the area of interest. The deposition velocity (V_d) is an experimentally derived parameter which is highly variable and depends upon the physical and chemical characteristics of the particular substance, the nature of the surface with which it is interacting and meteorological factors.

Evidence from observations and calculations have indicated that dry deposition may equal wet deposition over western Europe and north America (Record, 1983; Summers et al., 1986). In the ETH, with its often long dry spells and rainstorms of short duration, it would not be surprising if dry deposition were to play an even larger role than in overseas countries. In view of this, some estimates of dry deposition of sulphur dioxide in the ETH have been made. Values of V_d typically range from 0,5-1,0 $cm.s^{-1}$ for sulphur dioxide (Husar et al., 1978). If a value of 0,8 $cm.s^{-1}$ is assumed for Vd and if the range of annual mean sulphur dioxide concentrations, i.e. 3,4 - 15,9 ppb (8,8 - 41,3 $\mu g.m^{-3}$), recorded during 1984 to 1986 in the ETH (Turner, 1988) is taken, then the equivalent amount of sulphur deposited will be between about 11 and 52 kg. $ha^{-1}.yr^{-1}$. These deposition rates are considerably higher than those of 3,6 - 6,36 kg sulphur $ha^{-1}.yr^{-1}$ observed by the ESKOM network in the ETH for wet deposition (Mrozek and Dunn, 1986). Thus, even at relatively low atmospheric sulphur dioxide concentrations dry deposition of sulphur could exceed wet deposition of sulphur.

These estimates of dry deposition for sulphur indicate that dry deposition of gaseous pollutant species in the ETH should not be neglected. Moreover, dry deposition increases the pollution deposition load and hence enhances the possibility for the occurrence of detrimental effects to the ETH environment.

3.5 CONCLUSIONS

3.5.1 Emissions

Source inventory information indicates that relatively high sulphur dioxide emissions densities occur in the Transvaal and in the ETH. They are of the same order as those for other large industrial areas of the world.

3.5.2 Ambient atmospheric pollution levels

Atmospheric sulphur dioxide concentrations generally comply with local ambient air quality standards. However, isolated incidences occur when doses of sulphur dioxide (concentrations x time) associated with certain wind directions are high.

Sulphur dioxide pollution results mainly from sources within the ETH area. Relatively little net import of sulphur dioxide appears to occur from adjacent regions into the ETH.

Atmospheric sulphur dioxide concentrations currently displayed an upward trend for the ETH area as a whole up to 1984. Since then concentrations seem to have leveled off. Increases can be expected when new power station units at Tutuka (near Standerton), Kendal (near Witbank) and Majuba (near Volksrust) are commissioned (Eskom, 1987) between now and 1999. The situation should be monitored closely.

Ambient atmospheric concentrations of sulphate aerosols measured at near-ground level are similar to those observed in parts of the USA. Exceedance of the Californian ambient air quality standard for sulphate occurred only at one site in one of the industrial areas. There are, however, disturbing indications of the existence of an elevated layer of aerosols and other pollutants resulting from high level emissions (power station stacks). Pollution trapped in this layer may eventually have environmentally significant effects within the ETH and adjacent regions.

Limited observations have indicated that atmospheric ozone concentrations in the ETH are acceptable in terms of ambient air quality norms. It is, however, imperative that ozone should be monitored closely in future because of its inherent toxicity and reactive properties. Likewise other phytotoxic pollutants such as peroxyacyl nitrates should be regularly measured.

3.5.3 Visibility

Visibility degradation resulting possibly from aerosols and other pollutant species produced via photochemical reactions may be a problem in many areas within the ETH and needs further investigation.

3.5.4 Removal processes

Evidence suggests that an export of ETH atmospheric pollution takes place to adjacent regions (such as the Orange Free State and Natal). It is, however, not as yet known to what extent neighbouring countries such as Swaziland and Lesotho may be affected in this regard.

Wet and dry deposition processes remove relatively large amounts of pollutant species from the elevated pollution layer existing over the ETH. For example, wet deposit (rainfall) displays an acidity which is similar to that reported for north east North America and Europe. Also, relatively large amounts of sulphate aerosol are wet and dry deposited in the eastern portion of the Vaaldam catchment and the forestry plantations at Sabie. Furthermore, dry deposition of gaseous pollutants such as sulphur dioxide increases the pollution deposition load and hence enhances the possibility for the occurrence of detrimental effects to the ETH environment. Whether this situation is indicative of an environmental problem in the area and adjacent regions is a matter which warrants urgent investigation.

3.5.5 Source-receptor relationships

There seems to be a clear link between source emissions, pollutant concentrations measured in the atmosphere and pollutant species which are wet-deposited on surfaces within the ETH and adjacent regions. It is, however, not as yet possible to state whether this is a linear or non-linear relationship. An important factor in determining the relationship will be pollutant conversion and formation processes, for which favourable conditions seem to exist within the ETH atmosphere. A much better understanding is required of the chemical processes occurring within the atmosphere over the ETH before a sound information basis can be provided for the development of control strategies.

The current tall-stack policy appears to have been quite successful so far in avoiding unacceptably high ambient atmospheric sulphur dioxide concentrations at ground level near the sources. However, this policy leads to high-level pollution in the atmosphere and may well transfer the problem from being local to one of regional consequence. More stringent controls to safeguard the ETH and adjacent regions from possible medium and long- term effects of acidic pollutant species may be necessary in future.

There is evidence to suggest that there is every justification for the present policy of caution in controlling atmospheric pollution. The caution is wise, should not be relaxed and may need to be increased. New industries , particularly those that will involve large-scale combustion of coal, should be established in the ETH only if adequate control is applied to particulate and gaseous emissions. Furthermore, it appears necessary that the design of industrial plants to be erected in regions adjacent to the ETH should make provision for the retrofitting of equipment to control particulate and gaseous emissions.

3.6 RESEARCH NEEDS

From the above review and subsequent discussions between those involved in the ETH Workshop, it appears that further work is required on various aspects of the atmospheric pollution budget. These are briefly described and listed below.

Prediction: Modelling of all the stages of the atmospheric pollution process, including the governing meteorology and climatology, is of the greatest importance. To do this further information is needed on:

Source emission inventories

- Determination of chemical composition of emissions needed as an input to models predicting pollution dispersion
- Establishing variations in source strengths with time to enable prediction of future growth in emissions.

Physical-chemical dispersion modelling

- Development of pollution dispersion models allowing for physical as well as chemical changes during transportation of pollutants
- Development of models for quantifying source-receptor relationships
- Undertaking of tracer studies to validate models.

Atmospheric chemistry

- Studying of atmospheric chemical transformation processes involving pollutants
- Modelling of these processes to serve as an input to the development of realistic physical-chemical dispersion models to predict ground-level concentrations as well as deposition of pollutants.

Monitoring: Providing further information on levels and trends in space and time of atmospheric pollution emissions, concentrations and deposition loads is essential. In particular there is a need to undertake the following:

Geographical expansion of the present monitoring networks to

- establish the extent of transportation and the ultimate fate of pollutants,
- include suitable background sites (e.g. Kalahari Gemsbok Park; Karoo National Park) where realistic baseline (reference) data may be obtained.

Observation of additional variables such as

- various pollution species (i.e. peroxyacyl nitrates, ozone, nitrogen oxides, organic substances, etc),
- particulate pollutants, particularly over short-time scales,
- visibility,
- parameters pertaining to atmospheric stability,
- relative humidity.

Vertical profiling of pollution using

- balloon sondes,
- aircraft,
- plume trackers
- instrumented towers.

Dry deposition monitoring of

- gaseous pollutants (i.e. sulphur dioxide and nitrogen oxides),
- development of methodology,
- setting up of monitoring networks covering the ETH and adjacent regions.

Impact/risk assessment: The assessment of impacts of atmospheric pollution on humans and the environment is of immediate and pressing concern. Included in such impact studies there is a need to assess public perception of the severity of atmospheric pollution in the ETH and of the perceived effectiveness of legislative measures to control atmospheric pollution in the region.

4. THE ENVIRONMENTAL IMPACT OF ATMOSPHERIC POLLUTION IN THE EASTERN TRANSVAAL HIGHVELD AND ADJACENT REGIONS

4.1 INTRODUCTION

There is sufficient evidence to predict that atmospheric pollution from industrial sources and vehicular transport in the Eastern Transvaal Highveld (ETH) is likely to have measurable effects on the resources of the region. Ambient levels of pollution in the vicinity of industrial and power-generating sites as well as near low-cost, mass housing developments are at least episodically sufficient to cause damage of some kind to human health and to artificial or natural resources. Rates of deposition are clearly enhanced through much of the region, and rainfall acidity is markedly increased, as indicated earlier in this volume.

Levels of atmospheric pollution and rates of deposition have been assessed since 1979 at longest, and for relatively brief periods in most instances. Many species of pollutant have been inadequately monitored. Ozone, which is demonstrably phytotoxic at levels exceeding about 50 ppb (100 $\mu g.m^{-3}$) especially if exceedances are episodic (Campbell, 1987), has been monitored at only one station in the ETH, i.e. at Phoenix. Here, summer values of hourly average concentrations have reached 60-70 ppb (120 - 140 $\mu g.m^{-3}$), and winter values have reached 60-90 ppb (120 - 180 $\mu g.m^{-3}$) (Fig. 46). Sulphur dioxide is measured at many locations and has exceeded 35 ppb (91 $\mu g.m^{-3}$) on many occasions (Fig. 46). The highly phytotoxic peroxyacetylnitrate (PAN) (Kozlowski and Constantinidou, 1986a) will most likely occur in the atmosphere of the ETH (Louw, this volume), but the technology for monitoring PAN locally has only recently been developed. Gaseous pollutants interact among themselves and with other environmental factors causing stress and often have synergistic effects, increasing their impacts on organisms, structures, or processes of concern. Thus, the gaseous pollutants sulphur dioxide, ozone, nitrogen oxide and PAN will have more marked effects on vegetation, for example, when two or more are present than only one.

Over fifty per cent of the mere 3,1 million hectares of high-potential agricultural land of the country, and half of its forest resources are concentrated on the ETH and along its immediate periphery. Although the nature conservation areas in the ETH as such are relatively small, the greater region includes part of the Kruger National Park, the conservation areas of the Drakensberg, and several reserves administered by the Natal Parks Board. The major basins draining the ETH provide about 10% of the country's surface water resources, and if the Natal catchments are added then the sum amounts to 25% of the national total. By any standards, the natural resources of the area are vital to the economy, and the progressive development of mining and industry in the ETH adds to the sum total of resources potentially at risk from atmospheric pollution.

4.2. THE NEED FOR INFORMATION ON THE CONSEQUENCES OF ATMOSPHERIC POLLUTION

Knowledge of the effects of atmospheric pollution on resources of the ETH is poor or non-existent. Nevertheless, experience in the Northern Hemisphere and early signs from local studies indicate the need for timely evaluation of the likelihood of atmospheric pollution impacts, at least as a guide to their proper quantification. Decision makers concerned with the regulation and control of atmospheric pollution, or the development and conservation of natural resources, will need quantification of actual impacts and of risks of impacts under different development scenarios. They will need to make predictions of impacts under different conditions.

Their decisions and plans would need to be supported by the efficient deployment of data on the atmospheric pollution patterns and resources of the region, and useful and rapid application of

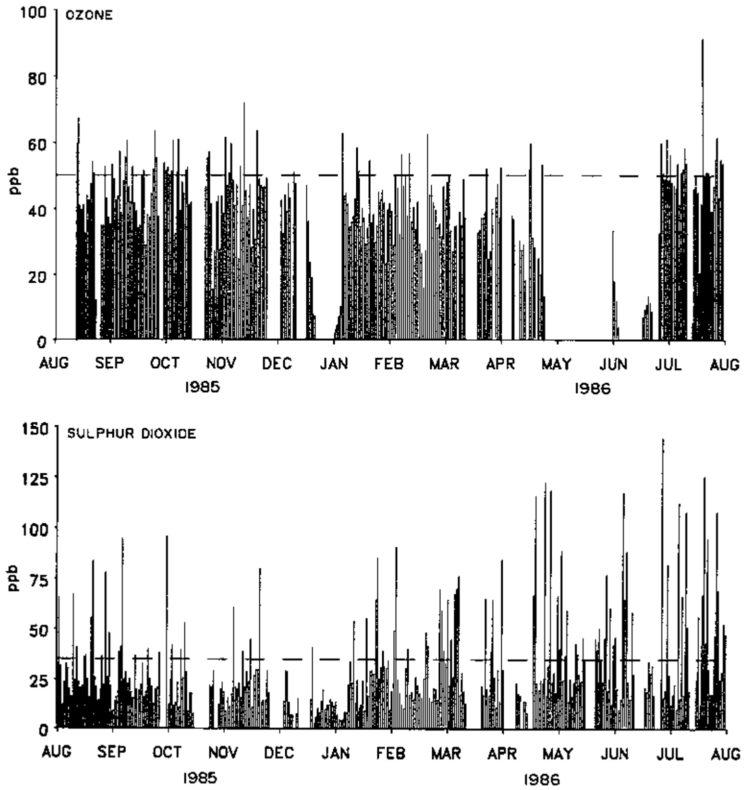

Fig. 46 *Daily maximum hourly concentration of ozone and sulphur dioxide at Phoenix, south of Witbank on the ETH. This was the only station on the ETH at which ozone had been monitored by 1988. Some effect on sensitive species of plants may be expected with periodic exposures to ozone at concentrations exceeding about 50 ppb and for sulphur dioxide at concentrations exceeding about 35 ppb.*

knowledge. Finally, environmental monitoring will be needed to assess trends in atmospheric pollution and its impacts, as well as to test predictions of these trends.

The question that ultimately needs to be addressed in an analysis of atmospheric pollution effects is whether the direct and indirect costs of such impacts will justify additional pollution control measures. Such measures would be costly and have their own environmental consequences, especially in the case of the very large power stations of the ETH, although technological development may reduce these disadvantages. Part of this question is that of whether the environmental impacts of atmospheric pollution are manageable at reasonable cost.

4.3 POTENTIAL FOR ATMOSPHERIC POLLUTION EFFECTS IN THE EASTERN TRANSVAAL HIGHVELD

4.3.1 Effects on human health

Experience in the Northern Hemisphere

There is general agreement that atmospheric pollution is a major environmental health problem in industrialized regions, and that a scientific evaluation of the health effects of atmospheric pollutants and the establishment of a dose-response relationship is needed (e.g. Anon, 1983). But great difficulties face the health specialist in making such an evaluation. The health effects of ambient atmospheric pollution are confounded by the effects of cigarette smoking, occupational exposure to pollutants, and exposures in the home.

Research focused on specific sensitive groups such as children is an appropriate method of avoiding the confounding effect of smoking, and making it possible to detect early or subtle effects. However, mobility among the target population may also confound any study, and would need control in any sample of children. Also, socio-economic effects such as nutrition, parental education, parental smoking, and many other factors may need to be taken into account. In addition, all studies must allow for the fact that the indoor environment may differ from the outdoor environment to which the measures of pollution normally apply.

Chronic health effects are unlikely to occur in conditions where ambient levels of atmospheric pollutants are below the present primary standards set for Europe and North America (Ferris, 1978). Studies among both adults and children have indicated that levels of atmospheric pollution considerably higher than those set in primary standards are necessary before any symptoms of morbidity may be reliably detected (Holland et al., 1978). For example, Holland et al. (1978), in a comprehensive review, were unable to find evidence for effects on health at particulate levels three times or more higher than the 75 $\mu g.m^{-3}$ for total suspended particulates (annual geometric mean). The only clear evidence for health effects was in cases where pollution levels were high, with annual mean daily smoke levels about 230-300 $\mu g.m^{-3}$ (total suspended particulate (Hi-Volume) equivalent 330-440 $\mu g.m^{-3}$), in the presence of sulphur dioxide at an annual mean of about 69 ppb (180 $\mu g.m^{-3}$).

Large-scale studies which cross cultural and linguistic boundaries need to be designed with special protocols to take such differences into account, and major investments in the quality control of observations are needed. A study of the effects of atmospheric particulates and sulphur dioxide on health of primary school children in 19 regions of the European Community, in which 22 337 children were sampled in a cross-sectional study of populations experiencing different levels of atmospheric pollution, produced contradictory results (Anon, 1983). Stringent efforts were taken to standardize the monitoring of ambient atmospheric pollution levels and the collection of health data. Any health effects detected in the range of atmospheric pollution encountered, i.e. smoke levels of 5-60 $\mu g.m^{-3}$ and sulphur dioxide levels of 7,4 - 61,5 ppb (20-160 $\mu g.m^{-3}$), could not be related to atmospheric pollution levels by way of a dose-response curve, nor was there evidence of any threshold effect. The effects varied by country and may have been due to cultural, linguistic and climatic differences, as well as to different welfare policies. Nevertheless, the confounding influence of indoor pollution and of other sources of variation in exposure or susceptibility, discussed above, was clearly demonstrated.

The overall conclusion was that, with industrial atmospheric pollution having been reduced by control to the levels observed, entirely different methods would be needed if future studies were to give meaningful results. The traditional epidemiological method for estimating the effects of atmospheric pollution on health needs to be replaced by methods involving direct estimates of individual exposure to atmospheric pollution. This should allow the investigation over time of cohorts of homogeneous populations living in the same climatic conditions but experiencing different individual exposure.

The effects of sulphur dioxide should be seen in the same light as those of particulate pollution but the mechanism of sulphur dioxide effects on respiratory function needs to be determined.

Research on atmospheric pollution effects on human health in South Africa

Coetzee et al., (1986) have compared a study group of children in Sasolburg primary schools with a control group from surrounding country towns. The levels of smoke and sulphur dioxide pollution differed clearly between the two areas.

No important differences were detected in respiratory illness, nor was there a detectable influence of passive smoking. However, all lung functions tended to be worse in the study area (Table 13).

Table 13 *Effects of atmospheric pollution on lung function and the incidence of respiratory illness in children living in the ETH*

Area of survey	Response relative to a control group in clean areas		Author
	Lung function	Respiratory illness	
Sasolburg	Inferior	No difference	Coetzee et al., 1986
Eastern Transvaal Highveld	No difference	Increased frequency of asthma in boys and chest colds in girls	Zwi et al., 1987

The Department of Community Health at the University of Cape Town has studied the effects of atmospheric pollution on human health. However, the quality of data is too poor to justify the conclusions reported.

Zwi and colleagues are presently studying health impacts in the ETH. Preliminary analysis (Zwi et al., 1987) of questionnaire data indicated that exposed children have increased frequencies of certain respiratory symptoms such as coughing and wheezing (statistically significant among girls only) and certain respiratory illnesses, i.e. asthma in boys and chest colds in girls (but not illnesses such as bronchitis and pneumonia). These reports were not supported by lung function tests, which revealed no significant differences between exposed and unexposed children. These results tend to contradict those of Coetzee et al. (1986; see Table 13). They were likely to have been confounded by maternal smoking, for example, which was significantly higher in the exposed than the unexposed group.

These studies reinforce the opinion in the report of the European Community study (Anon, 1983), that cross-sectional studies produce confusing and arguable conclusions.

Conclusion

At present it seems that long-term prospective studies are unlikely to demonstrate measurable effects on lung function at current levels of atmospheric pollution. Future atmospheric pollution control will make effects increasingly difficult to detect but with increasing pollution the situation could be quite different.

Future studies will need particularly careful design. Ambient atmospheric pollution levels cannot be taken as being uniform in the ETH and any study group of children will differ in their exposure from any other in a group of towns within the region. Direct measurement of dose-responses would be imperative in any definitive study of health impacts.

The effect of the indoor environment must be taken into proper account, especially in high-density housing areas where solid fuel is burnt.

Public concern centres around the issue of amenity of the area, and this issue should be addressed. Wells et al. (1987), for example, have emphasized that particulate haze is already affecting scenic views in the ETH.

4.3.2 Effects on buildings and other structures

Introduction

The corrosion rates of most metals are accelerated when exposed to polluted atmospheric environments. Other materials may also be affected, such as in the case of degradation of concrete by acidic pollutants, but the emphasis here is on metals.

The relative humidity of the atmosphere and diurnal fluctuations in temperature are important in determining corrosion rates. A relative humidity exceeding about 70% will support corrosion. Rainfall, the frequency with which falling temperatures cause the metal to reach dewpoint, and the proximity of water bodies, which are local sources of wind-borne moisture, are among the important factors determining relative humidity and the precipitation of water on the metal.

Atmospheric pollutants increase rates of corrosion, firstly by the hygroscopic effect of particulates deposited on surfaces, which increases the incidence and duration of wetting of the surfaces, and secondly by increasing the conductivity of the electrolyte involved in the corrosion process. In addition, many pollutants, such as chlorides and sulphates, break down the naturally protective corrosion products that may be formed under pollution-free conditions. Local climatic effects in the vicinity of pollution sources are important.

Apart from industrial sources, an important source of pollution is the use of coal as a heating and cooking medium in developing low-cost housing schemes. The impact of massive low-cost housing schemes with the attendant burning of fossil fuels results in rapid pollution of what would have been a rural area in a remarkably short space of time.

Resources potentially at risk to atmospheric pollution in the ETH are listed in Table 14. These have not yet been quantified.

Impact of atmospheric pollution on metals

Unpainted galvanized steel for roofing and side-cladding has been extensively used in South Africa and the ETH in particular for housing, commercial buildings and industrial buildings. There is a direct correlation between the protection provided by zinc coatings and the level of atmospheric pollution present, especially of the sulphur dioxide content of the air. Useful service life of this material has been nearly halved, from about 14-16 years to 8-10 years, in such areas as Pretoria. The useful life may be extended by using painted galvanized steel, at a cost, or replacement materials such as asbestos.

The extensive galvanized iron and steel fencing used on the farms of the ETH region will be affected in much the same way as roofing and side-cladding.

Power pylons are protected by inexpensive paint coatings or hot-dip galvanized coatings (approximately 80 µm or more of zinc). Atmospheric pollution will reduce the periods between maintenance for both of these coating types. Copper power lines passing close to smouldering discard coal dumps have been seriously affected due to corrosion caused by sulphur dioxide emitted by these dumps.

Polluted waters can cause rapid deterioration of pipework in water reticulation systems and dictate the use of alternate materials. Water treatment costs can also be affected and possibly irrigation equipment and pumps.

Atmospheric pollution mars paintwork, resulting in frequent repainting. Where paint is used for corrosion protection, atmospheric pollution may increase costs by requiring better surface preparation, more sophisticated or durable coating systems, and shorter maintenance intervals.

Table 14 *Economic sectors and resources potentially at risk to atmospheric pollution in the ETH.*

Sector	Components potentially at risk
Construction	Roofing, external door and window frames, side cladding, water reticulation schemes, low-cost housing schemes
Agriculture, farming	Housing, wind pumps, farming implements, irrigation systems, fences
Power generation and distribution, telecommunication systems	Power lines and pylons, substations and equipment (e.g. insulators), telephone lines, parabola antennae, construction materials of power stations
Transport	Bridges (steel and reinforcing steel), vehicles
Mining	Wide range, from buildings to vehicles

South African information

The CSIR corrosion group has conducted two four-year exposure programmes, followed by a 20-year programme now in its 15th year, to characterize the corrosiveness of the atmosphere in various areas of South Africa. None of the sites is in the ETH, the nearest being Pretoria and Sasolburg. Relevant results are summarized in Table 15. Because the climatic conditions and atmospheric pollution levels of the ETH resemble those of Vereeniging and Vanderbijlpark which are situated near Sasolburg, the level of corrosion in the ETH would be similar to that recorded at Sasolburg, i.e. higher than the relatively rural CSIR site in Pretoria but less than that of coastal areas (copper excepted).

ESKOM has carried out paint exposure programmes and the exposure of "climat" accelerated testing units. Neither provided quantitative results for correlation with the CSIR work. Another programme exposed zinc wire on several substrates, but it is too early for useful results.

Conclusion

Clearly atmospheric pollution effects on metals and hence on structures and other property in the ETH is potentially an important cost of development in the region. It is important that atmospheric corrosion sites be established in the ETH, particularly close to an atmospheric pollution monitoring site. The exposure programme should include metals, metallic coatings, and paint coatings.

4.3.3 Effects on soils

Introduction

The components of acid rain that can affect the chemical composition and productivity of soils include hydrochloric acid (HCl), sulphuric acid (H_2SO_4), nitric acid (HNO_3), ammonium sulphate ($(NH_4)_2SO_4$), ammonium nitrate (NH_4NO_3), and ammonia (NH_3). The strong acid sulphate and nitrate anions and the cations H^+ and NH_4^+, the latter normally rapidly oxidizing to NO_3^-, are the ions most strongly implicated

Table 15 *Metal corrosion rates, atmospheric pollution levels and climatic data for various sites in South Africa*

Site	Corrosion rate in μm.yr^{1} (based on 10 years' exposure)				SO_2 (μg.m^{-3})		Temperature °C				Relative humidity (08h00)	
	Steel	Zinc	Copper	Aluminium	Summer	Winter	Summer Max	Summer Min	Winter Max	Winter Min	Summer	Winter
Pretoria												
Church Square						32	28	17	20	6	73	76
CSIR	4,3	0,3	0,6	0,03		12						
Cape Town												
Foreshore	25,7	2,9	0,7	0,42		18	21*		13*		72*	83*
Durban												
Bayhead	37,1	2,3	0,9	0,55		62	24*		17*		80*	74*
Bluff	219,0	11,1	-	1,95								
Sasolburg	15,0	1,5	1,4	0,40								
Vereeniging							27	16	19	2		
Vanderbijlpark						26						
ETH												
Witbank						28						
Ermelo							24	13	18	1	78	82
Bethal					8	20	25	13	18	2	82	80
Arnot					9	13						
Elandsfontein					17	33						
Grootpan					22	60						
Hendrina					9	16						
Komati					15	27						
Kriel					11	18						
Rockdale					8	15						

* Daily average for the season

in effects on soils (Reuss et al., 1987). The H^+ ions in the soil solution tend to cause the dissolution of inorganic aluminium. In turn, the Al^{3+} ions displace cations such as Ca^{2+}, Mg^{2+}, Na^+ and K^+ from the exchange complex, in such a way as to cause a relatively larger increase in Al^{3+} ion concentrations than in base cation concentrations (Reuss et al., 1987). These processes of dissolution and exchange tend to buffer the acidity of the soil solution, depending on the level of base saturation. In naturally acid soils of low base status, small-scale inputs of strong acids have the potential for large-scale effects on the soils and on the surface waters maintained by drainage from these soils.

The potential impacts include soil acidification, increased loss of mineral nutrients required for plant growth, accelerated weathering of minerals, changes in soil biota, mobilization of aluminium and other heavy metals, and reduced cation exchange capacity (McFee, 1980). Precipitation of nitrogen, phosphorus, and sulphur may fertilize the site and enhance plant growth. Continued inputs of nitrate and sulphate may however induce nutritional imbalances and deficiencies of phosphate, molybdenum, calcium and magnesium, with detrimental effects to plant growth.

Whether or not the deposition of atmospheric pollutants affects soils depends on the rate of deposition, the site water balance, which determines the leaching ratio, processes of pedogenesis determined by vegetation, and the inherent sensitivity of the soil.

The sensitivity of a body of soil to the effects of atmospheric pollution will be related to its content of exchangeable bases, i.e. the percentage base saturation (McFee, 1980). This, in turn, is related to a combination of its inherent acidity (pH in water) and texture or cation exchange capacity. Sulphate adsorption capacity also plays a major role. Sulphate adsorption is evidently dependent on soil pH (Nodvin et al., 1968). Highly crystalline oxides of iron and aluminium have poor sulphate adsorption properties (Singh, 1984). Information of this kind has allowed various classifications of soils according to their sensitivity to atmospheric pollution impacts (e.g. McFee, 1980; Fernandez, 1983; Table 16).

Sensitivity of South African soils

Both published and unpublished information from the Soils and Irrigation Research Institute, as collated in the Land Type Surveys (Land Type Survey Staff, 1986a, 1986b, 1986c, 1986d) allow a broad classification and assessment of the susceptibility of South African agricultural soils to atmospheric pollution effects in terms of the criteria discussed above. Information from these surveys includes topsoil pH classes, topsoil textural classes, soil groups, and the percentage of acid soils within map units. Soil classes interpretable in terms of potential sensitivity to atmospheric pollution have been mapped for the ETH and adjacent regions, and this indicates extensive areas of soils potentially at risk (Fig. 47).

Strongly acid soils (pH in water less than 5,2) and moderately acid soils (pH > 5,2 but ≤ 6,0) dominate the entire ETH and adjacent regions (Pedology Staff, 1980; Fig. 47). In the data from these surveys, exchangeable bases correlated fairly well (r=0,6) with pH in the sandy topsoils, but the correlation weakened for loamy (r=0,58) and clayey topsoils (r=0,45). Strongly acid soils with a sandy topsoil, i.e. those most prone to impacts, are found between Pretoria and Witbank, but most of the other strongly acid soils have loamy or clay topsoils (Fig. 47).

Strongly acid soils in the study area as well as the moderately acid sands and loamy sands have less than 3 meq.100 g^{-1} of exchangeable bases (Table 17). Wang and Coote (1981), working in eastern Canada, concluded that soils with exchangeable bases less than 6 meq. 100 g^{-1} were sensitive to acid precipitation. It seems likely that most agricultural soils in the ETH are potentially at least as sensitive.

Even relatively small amounts of strong acids added to naturally acidic soils may have a major effect on the acidity of the soil solution and the flux of base cations out of the soil. This is despite the fact that

Table 16 *Parameters defining categories of sensitivity of soil to the effects of deposition of atmospheric pollutants.*

Parameter	Sensitivity class		
	Low	Moderate	High
Parent material	Carbonate-bearing limestone, dolomite, and metamorphic equivalents, calcareous clastic rocks, carbonate rocks interbedded with non-carbonate rocks	Non-carbonate-bearing volcanics, shales, greywackes, sandstones, ultramafic rocks, gabbro, mudstone, meta-equivalents	Non-carbonate-bearing granite granite gneiss, orthoquartzite, syenite
Soil depth, cm	> 25	> 25	< 25
Exchangeable bases, meq/100 g	> 15	6-15	< 6
pH, clayey soil	> 5,0	4,5-5,0	< 4,5
pH, loamy soil	> 5,5	5,0-5,5	< 5,0
pH, sandy soil	?	> 5,5	< 5,5
Cation exchange capacity, meq/100g	> 25	10-25	< 10
Clay content, %	> 35	10-35	< 10
Sulphate adsorption capacity as indicated by the combination of:			
organic matter	low		high
Al_2O_3 and/or $Fe_2O_3 + Fe_3O_4$	high		low

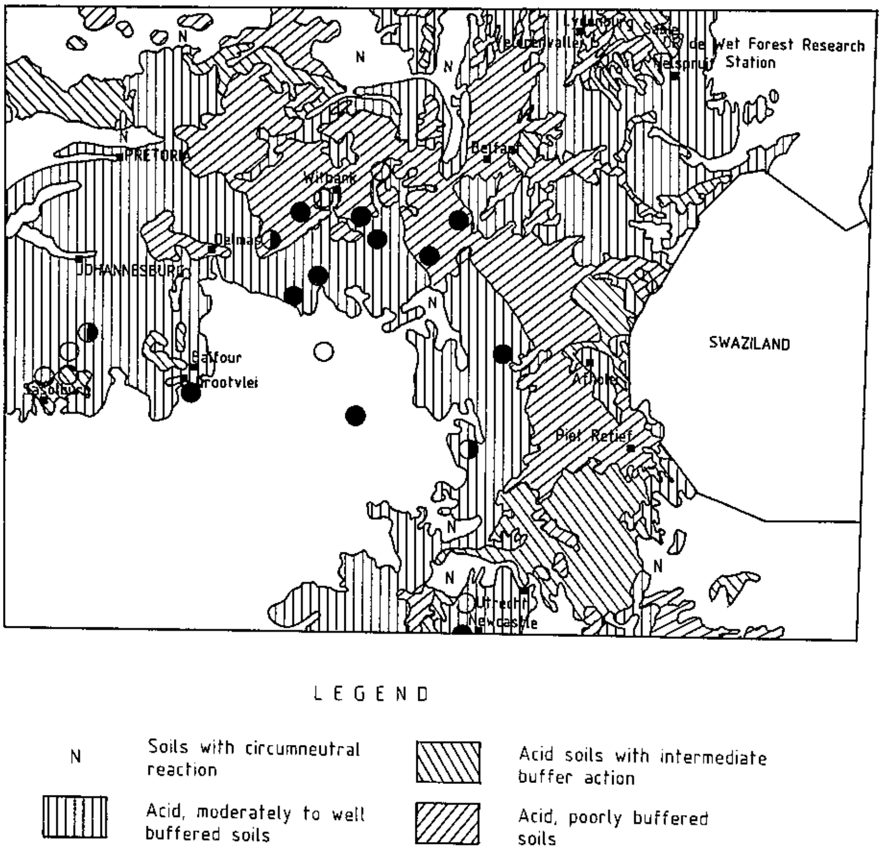

Fig. 47 *Distribution of acid soils with various degrees of buffering in the ETH (after Pedology Staff, 1980).*

Table 17 *Values for total exchangeable bases corresponding to pH and textural classes*

	Exchangeable bases for given pH and textural classes (meq/100g) pH in water <5,2			pH in water >5,2 - ≤6,0		
	Sand, loamy sand	Sandy loam, sandy clay loam, loam	Sandy clay, clay	Sand, loamy sand	Sandy loam, sandy clay loam, loam	Sandy clay, clay
Maximum	2,6	2,0	3,5	2,9	7,0	16,7
Minimum	0,2	0,4	0,1	0,2	0,3	0,6
Mean	1,2	1,2	1,2	1,3	2,7	4,7
Standard dev.	1,1	0,7	1,2	0,8	2,2	5,2
Number of samples	4	7	11	16	20	15

naturally acid soils contain exchangeable H^+ and Al^{3+} in amounts equivalent to millennia of acid deposition (Reuss et al., 1987). The key factors determining the magnitude of the response in such fluxes are the soil base status and sulphate adsorption capacity (Reuss et al., 1987). There is therefore some likelihood that the strongly acid soils of the ETH, where not under cultivation, may be significantly affected by current levels of deposition of atmospheric pollutants.

The net annual proton load (mainly H^+ ions) per unit ground area can be used to indicate the likely impact of current levels of acid deposition on these acid soils. Calculations of the net H^+ ion precipitation for

Table 18 *Annual $CaCO_3$ equivalent wet and dry deposition in kg.ha^{-1} plough layer of soil calculated by the method of Coote et al., (1981) using the wet deposition data of Mrozek and Dunn (1986)*

Region/ site	Wet deposition (μeq $H^+.l^{-1}$)				Wet deposition ($CaCO_3$ equivalent: kg.ha^{-1}.yr^{-1})	Estimated dry deposition ($CaCO_3$ equivalent: kg.ha^{-1}.yr^{-1})	Bulk deposition (wet plus dry deposition: kg.ha^{-1}.yr^{-1})
	[H^+]	[NH_4^+] x 1,15	[NO_3^-] x 0,7	Net [H^+]			
ETH							
Ermelo	99,6	33,8	16,7	116,7	37	15	52
Standerton	113,8	47,4	19,5	141,7	47	19	66
Amersfoort	86,7	38,1	18,1	106,7	33	13	46
Piet Retief	96,3	34,8	16,3	114,8	45	18	63
Volksrust	70,3	33,2	14,6	88,9	34	14	48
OFS							
Frankfort	84,1	35,7	16,3	103,5	28	11	39
Warden	93,5	28,3	17,6	104,2	29	12	41
NATAL							
Vryheid	65,1	28,3	13,2	80,2	30	12	42
Ladysmith	53,1	31,2	9,6	74,7	29	12	41

sites in the ETH and adjacent regions from data of Mrozek and Dunn (1986), following the methods of Coote et al., (1981), gave values for bulk precipitation of 39-66 kg.ha^{-1}.yr^{-1} (Table 18) and of the same order as the range of 20-40 kg.ha^{-1}.yr^{-1} estimated for eastern Canada (Coote et al., 1981). This estimate is tentative because of uncertainties about estimates of dry deposition, and the influence of soil and crop processes on nitrification, denitrification, leaching, and volatilization of ammonium and nitrate (Coote et al., 1981). Nevertheless, this calculated rate of deposition is about 35 to 70 times less than the equivalent acidification due to nitrification that occurs when a soil is ploughed and fertilized with ammonium. It is therefore unlikely that deposition of atmospheric pollutants will have an effect sufficiently marked to be distinguishable from those caused by normal tillage and fertilization. Deposition of atmospheric pollutants on cultivated soils of the ETH is unlikely to have economically significant effects.

Most forest soils in this region were under grassland or bushveld prior to afforestation. In general these soils are the products of pedogenesis over 20 million years, are highly weathered, low in buffering capacity and base status, but do not have highly developed podzol morphologies. Most South African forest soils can be classed as cation exchanging and this with the low base status indicates that they are close to the important pedological threshold associated with the release of free aluminium. Very few of the forest soils have been mapped. The few data available were used to assess possible impacts by classifying soils according to the scheme proposed by Fernandez (1983; Table 16).

From this it is inferred that certain forest soils may be sensitive to atmospheric pollution impacts. These are the soils with low clay contents (< 6%), poor nutrient cycling, mor humus, low base saturation (< 5%) and low pH in water (< 4,3). Such soils are found on the well-drained sands of the Zululand Coastal Plain, sands developed from the Black Reef Quartzite and Selati Formations in the ETH, and isolated pockets of soil on the Natal Group sandstones where colluviation is not the dominant process. The majority of forests soils are likely to be moderately sensitive. These are those weathered from Karoo sediments or dolerite, with high clay contents (> 20 %), reasonable base saturation (> 15 %), and with sufficient organic carbon in the A horizon (> 1,8 %) to afford some buffering.

Soils which are calcareous, have a high cation exchange capacity and base saturation, or are flooded at frequent intervals, are least sensitive to atmospheric pollution effects. Such soils are found in limited areas of coastal dunes and swamp forest in Zululand, on steep colluvial slopes derived from dolomite along the Eastern Transvaal escarpment, and on alluvial sites.

Conclusion

There are extensive bodies of acid and strongly acid soils in the ETH. For agricultural land the most sensitive soils are sandy, strongly acid soils underlain by coal-bearing sandstones and grits of the Vryheid Geological Formation. However, it may reasonably be concluded from the present levels of acidity from pollutants in precipitation of the ETH that acidification will be modest on agricultural soils and of little consequence where liming is practised. However, there is some likelihood that the strongly acid soils of the ETH, where not under cultivation, may be significantly affected by current levels of deposition of atmospheric pollutants.

Among the forest soils, those most likely to be sensitive have been noted above; evidence discussed later suggests that many soils within these broad categories are potentially sensitive to further acidification.

Research is needed on first the effects of acid precipitation on cation and anion exchange processes in South African soils and, secondly their sulphate adsorption characteristics. Available soil chemical and physical data (Reuss and Johnson, 1985) which characterise the buffering capacities of potentially sensitive soils of the ETH may be profitably used in mathematical process models to simulate the effects of atmospheric pollution at present at hypothetical intensities (e.g. Reuss et al., 1987). This would rapidly improve the assessment of the likely risks of atmospheric pollution effects on soils and hence surface waters and vegetation.

The distribution and types of soils in our forestry areas should be surveyed and mapped at scales of 1:10 000 to 1:20 000 to gain data for predicting impacts; special attention should be paid to humus form and clay mineralogy.

4.3.4 Effects on surface waters

Introduction

The effects of deposition of atmospheric pollutants on surface waters may be direct, through the influence of precipitation onto streams and lakes. However, the effect is principally secondary, through water reaching the streams after drainage through soil profiles (Reuss et al., 1987). The effect of atmospheric pollution on water quality and aquatic ecosystems is therefore determined in the first instance by the soil processes discussed earlier.

Recent simulation studies by Reuss and Johnson (1986) and Cosby et al., 1985) have shown that a marked decrease in surface water pH may be effected by relatively small changes in the ionic composition of soil solution which is in equilibrium with the surface waters. The model developed by Reuss and Johnson (1986) predicts that, even in soils with low exchangeable base status, the soil solution pH is only slightly affected by carbon dioxide partial pressures likely to be found in the soils (1-5% CO_2). In contrast, in surface water, pH values may vary widely with carbon dioxide partial pressure, depending on the alkalinity of the system. When the acid soil solution is transported into the fresh water it undergoes rapid degassing, to equilibrate with the carbon dioxide partial pressure in the atmosphere. This process results in increased pH in water with positive alkalinity, but has very little effect on pH if the alkalinity of the water is negative. In the latter case the transported soil solution remains acidic.

In these simulations, acid precipitation resulted in increased sulphate concentration in the soil solution and a decrease in solution pH of 0,2-0,4 units. This slight decrease may, however, be sufficient to cause a change in the soil solution from positive to negative alkalinity. This soil solution remains acid when degassed over the free atmosphere, as explained above. Hence, the process of acidification of surface water due to soil solution transport will commence as soon as sulphate concentration becomes sufficiently high to cause negative alkalinity in the percolate. The likelihood of this occurring depends on atmospheric pollution deposition, sulphate dynamics in the soil-plant system, and drainage, as discussed earlier.

The sensitivity of a water body to the effects of acid precipitation may be predicted from its alkalinity levels, i.e its acid-neutralizing capacity. Water bodies with alkalinities of 10 mg Ca.l^{-1} or less have been classified as highly sensitive to acidification, and those with 10-20 mg.l^{-1} as moderately sensitive (Altshuller and McBean, 1979).

The process of acidification in a freshwater system proceeds in several stages. Initially the acidity of water draining through the soil is neutralized or buffered in the soil, with consequent leaching of cations such as calcium and magnesium. As acidification proceeds, bicarbonate concentrations are reduced and replaced by sulphate. These dynamics of the system induce a threshold effect. Lakes undergoing acidification move relatively slowly down to pH 6, after which pH values correspond more directly to precipitation as the buffering capacity is exhausted (Dickson, 1975). In general, therefore, there is a latent period or lag phase between the onset of acidic precipitation over a catchment and the onset of water body acidification, which may last for several decades (Jacks, 1986).

Acidification of the water system may also be accompanied by mobilization of heavy metals from the soil body of the catchment. Aluminium especially is toxic to fish and other biota. This has manifested itself in fish losses from affected lakes in Scandinavia and North America, for example (Jenson and Snekvik, 1972; Schofield, 1976; Haines, 1981). Other less obvious but significant effects on the aquatic biota can be seen in the zooplankton (Roff and Kwiatkowski, 1977), phytoplankton (Kwiatkowksi and Roff, 1976), decomposer (Mackay and Kersey, 1985) and benthic invertebrate communities (Hendrey, 1976). Thus, acidification itself and the release of toxic metals both have an impact on the quality of water and the functioning of water systems.

A decline in water quality of this kind usually does not have any significance in terms of human health. For example, aluminium is not usually absorbed through the oral route (Jones and Bennet, 1986). However, the increased acidity may increase corrosivity (see earlier). This, in turn, may affect potability of water supplies.

The situation on the Eastern Transvaal Highveld

In terms of the alkalinity criteria discussed earlier, most of the rivers, dams and lakes of the ETH cannot be considered to be even moderately sensitive to acidification, having alkalinity values in excess of 20 $mg.l^{-1}$. Streams draining the basalt slopes of the Natal Drakensberg have high alkalinities, exceeding about 40 $mg. l^{-1}$ (Van Wyk, 1985). However, streams further north that drain granite catchments or catchments with substrates derived from other acidic igneous complexes have low alkalinities. Streams at Witklip, south-east of Sabie, have average alkalinities of 15,5 $mg.l^{-1}$, and those at Westfalia, north-west of Tzaneen, 8 $mg.l^{-1}$ (Van Wyk, 1985). In these cases, streams would be moderately to highly sensitive to acidification.

Pilot studies in the Vaal catchment (Kempster and Bosman, 1986; Bosman and Kempster, 1987) have indicated that atmospherically-derived sulphate is accumulated in the catchment during dry periods and that the sulphate is flushed into the streams during floods, resulting in a significant increase in the concentration of sulphates in the water. Exports in streams during dry months amounted to about 5% of depositions, but increased 100-fold with the onset of seasonal rains. This was not accompanied by an increase in stream acidity, however, most probably as a result of the alkalinity associated with the suspended clay particles in these turbid streams - a major contrast with the responses of the clear waters studied in the Northern Hemisphere.

Work currently under way in water systems of the escarpment zone near the boundary between the Transvaal, Orange Free State and Natal, with a control study in the Dullstroom area, has failed to detect any effects of acidification (Skoroszewski, 1987). Neither the composition of the benthic invertebrate community nor the chemistry of the streams suggest any deleterious effects. As historical data are not available for these streams the monitoring presently being undertaken will provide a useful baseline for assessment of future changes.

Conclusion

There is already evidence that sulphate concentrations of streams of the ETH have been affected by deposition of atmospheric pollutants. The economic significance of this has not been quantified, but the cost of water treatment may yet be affected. Upland streams are potentially at risk of acidification, but the real consequences of such potential effects cannot be predicted at present.

Clearly, any study of the effects of atmospheric pollution on surface waters should necessarily be closely linked with research on the soils of the catchments.

The rates of deposition over a range of catchments with differing soil buffering capacities need to be better quantified for proper evaluation of observed responses in water chemistry. In view of the possible risks to some upland streams along the escarpment it would be desirable to quantify the buffering capacities of these low-alkalinity waters accurately. Finally, investigation of present status and where possible the past history of biological and chemical conditions in the standing waters and wetlands in areas exposed to atmospheric pollution would usefully aid our understanding of the likely response of these ecosystems to continued pollution.

4.3.5 Effects on forests

Introduction

The evidence linking the extensive forest decline in Europe and North America to atmospheric pollution is reason for concern about the long-term productivity of South African forests, given the current and projected levels of atmospheric pollution from sources on the ETH (Louw, this volume). In 1986, an estimated 4 million ha of forests in West Germany alone were classified as affected by pollution (Anon, 1986). Where acute levels of atmospheric pollutants prevail through much of the year, as in the case of southern Poland and western Czechoslovakia, there is little question of the impacts of these pollutants on the forests. However, where levels are subacute, the real extent and the nature of the impacts on forests have been highly controversial (e.g. Morrison, 1984), and the debate has not yet been resolved.

Forestry in the Eastern Transvaal Highveld and adjacent regions

The South African forest and forest products industry, which it is estimated yielded 5,0 bn Rand to the Gross Domestic Product during 1987/88, is based on man-made forests of pine, *Eucalyptus* species, and black wattle *(Acacia mearnsii)*. Over 80% of these commercial forests occur on the eastern seaboard of the country, and at least 50% lie in a zone potentially affected by industrial pollution from the ETH (Table 19, Fig. 48). Additionally, there are 73 000 ha of pine plantations, mainly of *P. patula*, in Swaziland. This concentration is likely to increase, given the need for increased production of timber (Scharfetter, 1987) and the fact that the economics of transport forces the planting of forests within at most a few hundred kilometres of the major processing plants of Natal and Transvaal (Fig. 48).

In the region of concern, the most important commercial forest species are *Pinus patula, P. taeda,* and *P. elliottii* among the conifers, and *Eucalyptus grandis* and *Acacia mearnsii* among the hardwoods. *Eucalyptus nitens, E. elata, E. macarthuri,* and *E. fastigata* are species likely to be used on an increasing scale in the more frosty climates of the ETH.

Evidence of forest decline in the region

Despite the levels of atmospheric pollution recorded for the ETH and adjacent regions, there is no clear evidence of any decline in forest productivity or health ascribable to atmospheric pollution, nor any decline except for that associated with drought or disease, with a few exceptions. Schutz and Wingfield (1979) reported crown decline marked by needle shedding in stands of *Pinus taeda* 40 to 50 years old in the Sabie area in 1976. At the time of the investigation, affected trees were found scattered through the stands. Later, all trees in these stands were affected and the compartments were clearfelled of necessity (Schutz, 1987). Affected trees could be found on dolomites, shales, and quartzites. The decline could not be correlated with physical site factors, or directly to any disease, and was not evident among *P. elliottii* on the same sites. The conclusion was that the problem was associated with old age in *P. taeda.*

Table 19 *Extent of plantation forests in the forestry zones of the ETH and adjacent regions, classified by major species (after Anon, 1987). Data are thousands of hectares, and reflect the estimates for the year ending 31 March 1985.*

Species or category	Forestry zones				Total
	2 Sabie - Barberton	3,4 & 8 Highveld	7 & 9 Natal Midlands	5 & 6 Others	
Pinus					
P. patula	76,4	99,5	60,9	0,6	237,4
P. elliottii	53,8	18,4	20,2	44,2	136,6
P. taeda	34,6	15,3	21,8	4,5	76,2
Other conifers	3,7	3,0	1,3	5,2	13,2
Eucalyptus					
E. grandis	79,4	51,8	84,8	43,2	259,2
Other	6,9	56,5	3,1	3,9	70,4
Acacia					
A. mearnsii	0,2	57,2	57,5	9,1	124,0
Other hardwoods	0,7	1,3	2,8	0,8	5,6
TOTAL	255,7	303,0	252,4	111,5	922,6
Total as % of national total	22,9	27,2	22,6	10,0	82,7

More recently, decline in productivity in *P. patula* has been reported at Usutu in Swaziland (Morris, 1986). Declines in the second crop rotation of about 20% were evident on sites on gabbro, and about 13-14% on granites at higher altitudes, i.e. exceeding about 1300 m, but especially on sites lying above 1500 m. About half of the plantation area of 50 000 ha was affected. Morris (1986) ascribed these declines to deficiencies of phosphorus and potassium on the basic gabbros which arose through the depletion of organic phosphorus and exchangeable potassium by uptake into tree biomass, a depletion not operating under native grassland. The decline on the soils derived from granite was ascribed to the sequestration of nitrogen, phosphorus, and possibly calcium in the progressively accumulating needle litter.

Chlorotic flecking and mottling of conifer needles has been noted on conifers throughout South Africa for the past two decades or so. Pathogens could not be implicated in this syndrome (Lundquist, 1987; Moore, 1987). The recently invading pine needle aphid *Eulachnus rileyi* was hypothesized as a cause, but this explanation has been rejected after exhaustive experiments. The aphid evidently feeds on chlorotic tissue, rather than causing it (Marchant 1985). Chlorotic and necrotic mottling, flecking and banding in *Pinus elliottii* and *P. patula* in the ETH in the vicinity of Rosehaugh and from Belfast eastward is consistent in some degree at least with damage by ozone or sulphur dioxide, or their

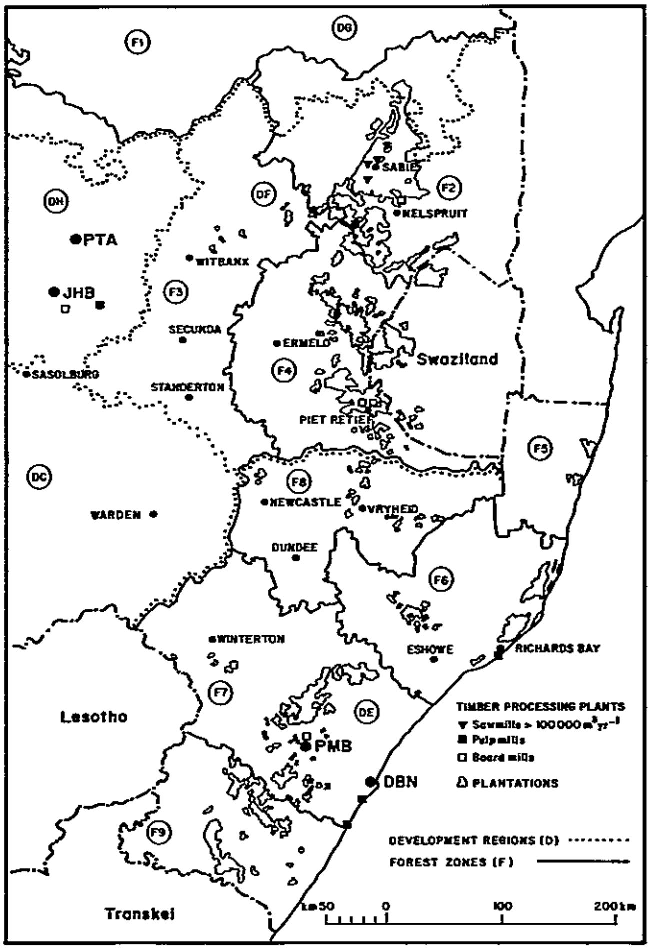

Fig. 48 *Map of the ETH and adjacent regions, showing forest zones, afforested areas, and major timber processing plants, as well as indicating sources of pollution.*

interactive effects, and may be caused by acid mist (Botha, 1987; Moore, 1987; Wessels, 1987; cf Skeffington and Roberts, 1985).

Potential for direct impacts on plantation forests

Forests are especially prone to atmospheric pollution impacts. There are several reasons for this, including the roughness of forest canopies (and hence their filtering effect) and the longevity of the trees and, often, their foliage (Keller, 1985).

Hypothetically, atmospheric pollution may impact directly on forests at several levels (Kozlowksi and Constantinidou, 1986a). Gaseous and particulate pollutants may affect leaf or needle tissues at the subcellular and cellular levels. Within the leaf, biochemical and physiological processes such as photosynthesis are rapidly affected. These effects carry through to the partitioning of assimilated carbon within the plant, to respiration (maintenance), growth of foliage, of stems and branches, of roots, and the production of secondary compounds. Reproductive processes such as the germination and growth of pollen are also affected, and through this or through changes in assimilation and partitioning of carbon, such variables as the number, size, and viability of seed are reduced. These effects may extend to the population level and the overall productivity of the forest stand.

The direct effects of atmospheric pollutants on trees may be observed from visible symptoms or physiological and growth responses. Damage to leaf tissues causes characteristic symptoms useful in diagnosis. Chevone et al (1986) and Kozlowski and Constantinidou (1986a) have reviewed the symptomatology of damage associated with the different species of pollutant. Such analyses provide a useful first approximation for the diagnosis of problems in the species of *Pinus* grown in the ETH. Pictorial diagnostic guides to the different syndromes are useful in identifying causes of injury (e.g. Skelly and Lambe, 1974).

Atmospheric pollution effects on foliage are detectable at much lower doses than those which cause visible damage. Gaseous pollutants, such as ozone and sulphur dioxide are absorbed through the stomata or through damaged cuticles. Effects on the leaf and its physiology may be biophysical, through responses in the stomata. Additionally, biochemical effects arise through direct uptake of pollutants in tissues or interactions with enzymes and proteins, and changes to cell membranes, especially where ozone is involved. These effects in turn affect physiological processes such as photosynthesis (Winner et al., 1985; Kozlowski and Constantinidou, 1986a). Effects on foliage become evident with prolonged exposure to ozone at concentrations of 50 ppb (100 $\mu g.m^{-3}$) and episodic exposures of 100 ppb (200 $\mu g.m^{-3}$). Responses to sulphur dioxide are observable at concentrations of 35 ppb (91 $\mu g.m^{-3}$) and less (Kozlowski and Constantinidou, 1986a).

As a rule, acid rain as such has little direct effect on trees at pH levels greater than 3,0 (Morrison, 1984; Chevone et al., 1986). Rainfall with pH less than 3,0 is unlikely to occur in forestry zones. However, acid mists with pH less than 3,0 are likely to occur (Unsworth, 1984; Chevone et al., 1986) and do have negative effects. Mist precipitation is especially frequent in the ETH and adjacent regions (Schulze, 1965).

Of the species of pollutant likely to be problematic in the ETH, the oxides of nitrogen are seldom directly implicated in damage to trees. With nitrogen oxides and acid rain, however, synergistic effects with other atmospheric pollutants have been found in some experiments (Chevone et al., 1986).

The various kinds of atmospheric pollution impact on any given tree affect rates of net photosynthesis, the leaf area of the crown, the relative allocation of carbon assimilated in photosynthesis to different organs, for example to roots and to shoots, and hence growth (Winner and Atkinson, 1986). Exposure of trees to atmospheric pollutants at subacute levels invariably causes changes in root:shoot ratios (Kress and Skelly, 1982; Hogsett et al., 1985; Mahoney et al., 1985; Winner and Atkinson, 1986). Atmospheric pollutants tend universally to reduce leaf and needle longevity (Schulze, 1987; Winner and Atkinson, 1986). Root growth may be directly suppressed, especially by ozone, so weakening resistance to drought and disease (Winner and Atkinson, 1986). These effects would tend to reduce forest productivity.

There often are marked synergistic interactions between species of pollutants. Thus, at low concentrations of sulphur dioxide and ozone, for example, no effects of any kind may be detected when plants are exposed to the pollutants individually, whereas responses are marked when exposed to both (Chevone et al., 1986; Kozlowski and Constantinidou, 1986a; see also papers in Winner et al., 1985).

Another important aspect of dose responses arises from the episodic nature of atmospheric pollution. The incidence of toxic levels of ozone in rural areas, for example, is markedly dependent on periodic weather conditions conducive to its entrapment and spread from sources (e.g. Chevone et al., 1986; Anon 1987), and the frequency and spectrum of doses varies accordingly. There is evidence at least from agricultural crop plants that responses to occasional high concentrations of ozone are more marked than to relatively constant, somewhat lower levels (Mehlhorn and Wellburn, 1987; Moore, 1987). This is evidently because of the interaction between ozone and ethylene released by plants under stress, at least in peas (Mehlhorn and Wellburn, 1987). Acclimation to low concentrations during prolonged exposure may explain the lack of response where concentrations do not fluctuate (Carlson, 1985).

Most evidence for the direct effects of atmospheric pollution on trees is from experiments in chambers, greenhouses, or in near-natural field conditions, i.e. involving the open-top chamber technique or chamberless pollution-gradient experiments (Winner et al., 1985). It is extremely difficult to use the results of many of these experiments to quantify the likely responses in nature. The experimental responses are often inconsistent, some species responding negatively, others positively, and some not at all. Responses vary within species, acccording to genotype, the physiological condition of the individual plant or of the organ, stomatal behaviour, and the doses of pollutant and the mix of pollutants (Chevone et al., 1986; Kozlowski and Constantinidou, 1986a). This variability is a confounding factor in experiments but also provides opportunity for managing atmospheric pollution impacts, through the selection of resistant species and genotypes.

Evidence relevant to species grown in forests of the ETH

In Table 20 the information is summarized from the literature on responses to atmospheric pollution of genera and species relevant to South African forestry. The literature contains nothing on the effects of atmospheric pollution on *Acacia mearnsii*; new research would be needed to evaluate possible impacts of pollution. No studies have been conducted overseas on the species of *Eucalyptus* grown commercially in South Africa. However, tests involving various Australian trees and exposure to 100 ppb (260 $\mu g.m^{-3}$) sulphur dioxide for three hours caused acute injury to the *Eucalyptus* and *Acacia* species in the trial; the *Eucalyptus* species were the most sensitive of all species included (O'Connor et al., 1974). Studies with various other species of *Eucalyptus* have shown them to be particularly sensitive to increased ambient atmospheric levels of sulphur dioxide, i.e. at 40 to 100 ppb (104 $\mu g.m^{-3}$ to 260 $\mu g.m^{-3}$) (Murray, 1984). The species grown in South Africa may be equally sensitive, although most plantations of these species are fairly remote from atmospheric pollution sources and so are more likely to be exposed to enhanced concentrations of particulate sulphate than to sulphur dioxide. Apparently, no research on the response of *Eucalyptus* spp to other atmospheric pollutants, singly or in combination, has been reported.

Fumigation experiments with both *Pinus elliottii* and *P. taeda* have shown that relatively low doses and concentrations of sulphur dioxide and ozone, respectively, reduce photosynthesis rates and, for ozone, increase respiration rates by up to 90% (Barnes, 1972; Kress & Skelly, 1982; Bennett, 1985; Hogsett et al., 1985). Physiological and growth responses were evident at ozone doses with seasonal six- to seven-hour means of 50 to 150 ppb (100 $\mu g.m^{-3}$ to 300 $\mu g.m^{-3}$), and sulphur dioxide at similar concentrations. In these studies, significant effects on growth were observed without any organ or tissue damage being evident. Declines in productivity in *Pinus taeda* have been correlated with variations in the levels of atmospheric pollution (Phillips et al., 1977; Johnson et al., 1981). Overall, *P. taeda* is rated as sensitive to ozone and sulphur dioxide, whereas *P. elliottii* is intermediate (Table 20). No work has yet been conducted on *P. patula.*

Fumigation and similar greenhouse experiments have demonstrated substantial intraspecific genetic variation in sensitivity to atmospheric pollution in *Pinus taeda* (e.g. Kress and Skelly, 1982; Krause, 1983). But in *P. elliottii* the studies have not provided evidence for heritable variation in sensitivity (Bennet, 1985; Hogsett et al., 1985).

In South Africa, Kelly (1986) has conducted fumigation experiments with *Eucalyptus grandis, Pinus elliottii*, and *P. patula* with exposure to sulphur dioxide at concentrations of 50, 100, 500 and 1 000 ppb (130, 260, 1300 and 2600 $\mu g.m^{-3}$) for different time periods. The effects were assessed as visible damage.

It was found that daily exposure for one or two hours (over 26 days) at the lower concentrations (50 ppb, 100 ppb) caused no damage to any of the species. *Eucalyptus grandis* showed damage after hourly

Table 20 *Relative sensitivity to the major gaseous pollutants of certain* ***Pinus*** *and* ***Euclayptus*** *species that are grown in South Africa. (after Chevone et al., 1986; EPA, 1986; Howe and Woltz, 1981; O'Connor et al., 1974; Skelly and Lambe, 1974.)*

Species*	Pollutant⁺					
	SO_2	O_3	NO_2	PAN	Fl^-	Cl^-
Pinus in general					S	
P. elliottii	I	I				S
P. taeda	S	S				S
P. radiata		S		S		
Eucalyptus in general	S					
E. robusta	S					
E. viminalis	S					

* No information is available for *Pinus patula* nor *Acacia mearnsii*.
\+ S = sensitive; I = intermediate; T = tolerant

exposures to 500 ppb for 26 days, and both *E. grandis* and *P. elliotii* were damaged by hourly exposures to 1000 ppb, for the same time period. *P. patula* was not affected. *P. patula* and *E. grandis* showed damage after a single 6-hour exposure at 500 ppb. *P. elliotii* showed slight damage after 6 hours, but only showed general damage after three successive weekly 6-hour exposures. Once damage was visible, subsequent exposures increased damage in all species.

There is therefore tentative evidence that the eucalypt was more sensitive than the pines, and that the two pines also differed from each other in this respect. The experiments were preliminary, with the same protocol problems as in the case of studies on beans discussed later. New experiments would be needed to allow firm conclusions to be reached.

The potential for indirect effects

Acid deposition in soils prone to further acidification (see earlier) causes the release of soluble aluminium and other heavy metals. For example, Bergholm (1985) measured a linear increase in aluminium ion concentration, from 0 to 0,5 mM, with a decline in pH from 4,9 to 3,5 units. Metals in solution, especially aluminium, interfere with rhizosphere processes and with root development. In coniferous trees, the principal effect appears to be on the rate of rootlet initiation, although the rate of mycorrhizal infection was depressed in some studies (Shafer et al., 1985; Schulze, 1987). Such effects would obviously interfere with uptake of water and mineral nutrients, and cause an imbalance between demand proportional to crown size and the supply from the reduced root system.

The effects of solubilized aluminium are not necessarily toxic. Growth of *Eucalyptus grandis* and other species of *Eucalyptus* may be enhanced by increased concentrations of soluble aluminium (Mullette, 1975). This may be because the aluminium is in the form of aluminium phosphate, which would increase the availability of phosphate to trees where soil phosphorus is otherwise not available for uptake by roots.

Recent work in Europe has indicated that it is not the concentration of aluminium itself which is important, but rather the ratio of calcium to aluminium ions (Schulze, 1987). The amount (length per unit soil volume) of fine roots and the density of root tips in spruce *Picea abies* was closely related to this ratio. There is also evidence that increasing nitrate concentrations in the soil depressed fine-root growth and root-tip formation (Schulze, 1987). The rates of mycorrhizal infection were not affected by these variations.

These effects on the rhizosphere carry through to the tree. For spruce, the foliar concentrations of magnesium and calcium was closely related to the ratio of ectomycorrhizal density to leaf area, increasing at higher ratios. The opposite held for foliar aluminium (Schulze, 1987). Similar relationships between fine-root quantities and canopy density and metabolism are evident for *Pinus taeda* (Gholz et al., 1984).

Reduced nutrient status of the soil may directly affect tree growth. Complexities arise because of changes in ratios of ions in solution, as well as through enrichment of soil nitrates, and responses in the root system. In trees, foliar concentrations of mineral nutrients tend to correlate with concentrations in soil solution (Van der Driessche, 1974; Schulze, 1985). High rates of deposition of atmospheric pollutants, especially of nitrates, fertilize the site. Leaching reduces the availability of cations, and this is reinforced by the tendency for conifers to take up nitrogen in the form of ammonium, leaving nitrates to contribute to acidification (Schulze, 1987).

Schulze (1987) has developed the theory to explain forest decline in terms of soil processes from proposals by Ulrich (1986). In soils prone to the process, pollution decreases the ratio of calcium to aluminium and this together with increased nitrogen supply reduces the amount of fine roots in the soil and the density of root tips. Root uptake of ions is reduced per tree, and this together with lower availabilities of cations in the soil solution reduces foliar concentrations, except for nitrogen. High nitrogen availability together with fertilization of the foliage (see earlier) evidently allows enhanced growth of foliage with concomitant dilution of cations such as magnesium, chlorosis, and reduced photosynthetic capacity. Feedbacks, such as between photosynthetic capacity, root development, and mycorrhizal infection, reinforce the system.

Regarding effects through the soil, Mciwes et al., (1986) have given explicit guidelines for the identification of soil forms likely to be affected by deposition rates experienced in South Africa. These are expressed in terms of routinely measured variables, such as pH and calcium:aluminium ratios. A brief analysis in these terms of unpublished data from C J Schutz for the sites planted to the major pine species indicates that a substantial fraction of these are possibly or probably already at risk of toxicity because of acidity or imbalance in the calcium:aluminium ratio (Tables 21 and 22). Data reported by Morris (1986) indicate substantial imbalances of the same kind in the Usutu soils. Insofar as the results of research on spruce can be transposed to plantation species grown in South Africa, the data do indicate that it is necessary at least to attempt to exclude acid rain effects on certain soils as a factor likely to affect productivity.

Atmospheric pollution effects on root development and carbon allocation may contribute to stress in trees through depleted capacities to capture mineral nutrients and withstand drought. Sulphur deposition has been shown to increase frost sensitivity in trees, and there is evidence that dry and wet deposition of nitrogen may do the same (Nihlgard, 1985; Unsworth and Crossley, 1985). Effects of this kind would be especially important in the ETH where periodic drought affects tree growth and the climate dictates the choice of species resistant to frost.

Table 21 *Classification of topsoils from the Sabie forestry area by pH in water, according to categories of susceptibility to acid toxicity established for West German conditions by Meiwes et al., (1986). (after data from Schutz, unpublished).*

Risk class and acidity	Frequency of sites for given species		
	Pinus elliottii	*Pinus taeda*	*Pinus patula*
unlikely, > 5,0	40	50	21
possible, 4,2 - 5,0	102	82	120
probable, 3,8 - 4,2	2	4	18
highly probable, < 3,8	0	0	0
n	144	136	159

Table 22 *Classification of topsoils from the Sabie forestry area according to the molar ratio of calcium to aluminium in solution, and according to categories of risk of damage to spruce roots established for West German conditions by Meiwes et al., (1986). (after data from Schutz unpublished).*

Risk class and molar ratio	Frequency of sites for given species		
	Pinus elliottii	*Pinus taeda*	*Pinus patula*
no effects, > 1,0	80	64	54
low risk, 0,3 - 1,0	20	34	33
high risk, 0,1 - 0,3	18	30	43
very high risk, < 0,1	26	8	29
n	144	136	159

Conclusions

Atmospheric pollution is merely one of many factors contributing to stress in forest trees. In South Africa the problem of discriminating between the effects of atmospheric pollution and those of other stress factors is compounded in several ways. Environmental relationships governing natural variation in forest productivity are hardly quantified, let alone any atmospheric pollution effects. Intermittent drought is known to reduce growth, but not by how much.

Many of the plantations were established fairly recently, now being in their first or second rotations. These new forests are themselves affecting the sites on which they grow, for example through acidification and leaching in some instances (Grey, 1987; Morris, 1986). Also, several new forest pests have begun to affect growth over the past decade or so, a further confounding factor (Van Rensburg, 1984). Although symptoms of atmospheric pollution damage may be found, and responses in growth determined experimentally, it will prove difficult to quantify effects on productivity in field conditions and to distinguish these from those of drought, pests and diseases, and silvicultural practice.

Despite the difficulties it is imperative to develop an adequate capacity to diagnose and predict the effects of atmospheric pollution on forests in the ETH. The first requirement is for the intensification of the precipitation monitoring network, with special emphasis on event monitoring, and establishment of at least one station to monitor gaseous pollutants at a forest site likely to be impacted by substantial gaseous pollution. Monitoring of mist precipitation and chemistry is especially important.

Reconnaissance studies are needed to quantify the already observed incidence of foliar symptoms in the ETH apparently ascribable to atmospheric pollution and to search for trends in growth independent of climate. The latter could, for example, be addressed through tree-ring analysis in conifer stands exceeding 40 years in age. Available survey data should be analysed to identify soils potentially at risk of acidification.

An urgent requirement is for information on the relative sensitivity to atmospheric pollution of the major forestry species. This needs appropriate fumigation experiments coupled with open-top chamber studies; the latter type of experiment would also aid in assessing effects of atmospheric pollution in the field.

Experimental studies of the responses of soils in different risk classes to deposition of atmospheric pollutants need to be conducted in conjunction with nutritional research to evaluate the likelihood of indirect effects, especially on rhizosphere processes. This work would best be conducted within the framework of nutrient cycling studies in the area of concern, with special attention to rates of pollutant deposition in fogs and dry deposition, and changes in litter cycling processes. Utimately information gained should be used in ecosystem process models to evaluate long-term effects.

4.3.6 Effects on agricultural crops

Introduction

Much of the discussion of the nature of atmospheric pollution effects on forests is of course broadly relevant to agricultural crops. The important difference is that deposition of airborne contaminants will be lower on crops than on forests. Crops are shortlived, and the indirect effects via the soil are unlikely to be problematic, due to the mitigating effect of agricultural practices (see earlier). There is ample evidence that some degree of impact on agricultural crops should be anticipated at the levels of atmospheric pollution recorded for the ETH; effects may be negative as well as positive (see, for example, papers in Winner et al., 1985).

The principal agricultural crops of the ETH are annuals and are produced under dryland conditions. Review of the literature (Winner et al., 1985) indicates that the major crop at present, maize, is relatively tolerant to current ambient atmospheric levels of sulphur dioxide. In general, maize is relatively sensitive to ozone and tolerant to nitrogen oxides, but further monitoring of these pollutants is needed for proper assessment of risk of damage. Literature indicates (United States EPA Research Management Committee, 1981, 1982) that the second most important crop, sunflower, is relatively sensitive to sulphur dioxide and nitrogen oxides and tolerant to ozone. Dry beans, which are also extensively produced in the area, are sensitive to all three pollutants.

Current work in South Africa

Presently, ESKOM is the only organization supporting work on atmospheric pollution effects on crops in the ETH. Investigations are limited to sulphur dioxide effects on dry beans, and involve the exposure of selected varieties of *Phaseolus vulgaris* to varying sulphur dioxide regimes in a non-filtered greenhouse. This initial work (Engelbrecht, 1987) involved concentrations of sulphur dioxide from 50 ppb to 100 ppb (130 to 260 $\mu g.m^{-3}$). Exposure times ranged from 30 minutes to two hours. An extreme treatment was also included, where concentrations were raised to 3 000 ppb (7 800 $\mu g.m^{-3}$), and exposures to 8 hours.

Responses in growth and yield to different sulphur dioxide doses proved complex, with significant reductions in biomass and yield of pods relative to controls at low exposures (50 $ppb.h^{-1}$), but increases at doses involving concentrations up to 100 ppb. Doses of 3 000 ppb for 8 hours caused severe damage to leaves and significantly reduced biomass.

Conclusion

The results from research on crop plants in South Africa are preliminary, and would need verification with stricter experimental protocols, including charcoal filtering of the greenhouse atmosphere, stricter controls, and sufficient replication. It is imperative to continue this research and to enhance the programme by conducting field experiments to test for responses under ambient conditions.

Once adequate monitoring data are available, especially for ozone and PAN, it will be necessary to conduct experiments with these pollutants, with emphasis on their synergistic effects, and no doubt with other species of crop. There is a pressing need to continue and expand the open-top chamber studies presently under way, to obtain field estimates of crop impacts.

4.3.7 Effects on natural terrestrial ecosystems

South Africa is distinguished by exceptionally variable climate regimes (McMahon et al., 1987), heterogeneous landscapes, and an unusually rich flora (Gibbs Russel, 1985). Thirty different major Veld Types (Acocks, 1975) occur within the region of concern. There is a therefore a marked degree of diversity in the natural biota and ecosystems, substantially greater than that found in the Northern Hemisphere countries where atmospheric pollution is a major concern. In South Africa, virtually nothing is known about the ecophysiology of native species of plants and animals, much less of their likely responses to atmospheric pollution.

Responses of native plants to atmospheric pollutants would be broadly analogous to those of crop plants. Native plant species will have marked inter- and intraspecific variation in sensitivity to atmospheric pollutants (e.g. papers in Winner et al., 1985). Atmospheric pollution impacts could potentially cause substantial modification to community composition and ecosystem functioning, could change the course of evolution within species, and cause a loss of biological diversity.

There is potential in using native plant species as indicators of atmospheric pollution effects. Lichens are an obvious example, since the nature of their responses to atmospheric pollution is well documented (e.g. Ferry et al., 1973). But other plant species are likely to be highly sensitive to sulphur dioxide or ozone (Botha, 1987; Moore, 1987). If these were identified they could be employed in a simple and cost-effective system for the detection of atmospheric pollution damage.

Obviously, atmospheric pollution effects are much more likely to be detected in plants than in animals, except perhaps in the case of aquatic ecosystems. The diversity of plant life in the ETH and adjacent regions, and our ignorance of the physiology and ecology of the species occurring there, present formidable challenges to anyone attempting to address the question of the effects of atmospheric pollution on our natural eco-systems.

The first requirement would be for basic studies on selected species, directed at providing sound knowledge for predicting atmospheric pollution effects. Species should be selected for study so that predictive hypotheses may be tested. One such hypothesis is that sensitivity to atmospheric pollution correlates with stomatal conductance (Western et al., 1985). Sensitivity may be related to shade tolerance (e.g. Umbach and Davis, 1984). Sensitivity is also postulated to be related to longevity of the foliage and the longevity of the individual plant (e.g. Keller, 1985; Westman et al., 1985). Species could be divided into functional groups on the basis of these criteria.

The determination of dose-response relationships of species selected to represent these different functional groups, complemented by ecophysiological work on natural environmental controls on stomatal behaviour, photosynthesis and growth, as well as anatomical and biochemical studies, could greatly increase our ability to predict the effects of atmospheric pollution and increase our understanding of the mechanisms resulting in damage.

Possible changes in the genetic constitution of plant populations and of plant communities would need attention. This question would also best be addressed through experimentation, involving greenhouse exposure trials of ecotypes within species, and field exposure of communities by means of chamber or pollution-gradient techniques (Winner et al., 1985). Possible adaptation to ambient atmospheric pollution levels in annuals and other herbaceous plants would need to be evaluated (cf. Bell, 1985; Westman et al., 1985).

Long-term ecological effects of the relatively low levels of atmospheric pollution deposition recorded for the ETH, especially at the ecosystem level, will present special research problems because of the complexity of the systems to be studied, as discussed earlier in relation to forests. Such research may also be guided by predictive hypotheses. For example, forests are likely to be more strongly affected than grasslands (e.g. Olson and Sharpe, 1985).

Studies of ecosystem-level responses to atmospheric pollution, at a small number of selected and well instrumented sites, would be needed if evidence for substantial effects at the level of the plant becomes available. Such work would best be conducted as an integral part of ongoing ecosystem experiments.

4.4 CONCLUSIONS

The null hypothesis that atmospheric pollution has had no measurable impact, needs to be tested for each of the kinds of resources potentially at risk in the ETH. Very little information is available that would allow reasonable approximations of the likely environmental effects of current levels of atmospheric pollution in the ETH, nor predictions for plausible pollution scenarios. Direct extrapolation from the knowledge generated by research in the Northern Hemisphere is severely constrained by several factors: the differing climate and atmospheric pollution regimes in the ETH, different social conditions, soil conditions that are often not encountered in the regions where research has been conducted, and species of plants and animals of virtually unknown biology.

However, with regard to the effects of atmospheric pollution on human health the evidence indicates that at present it is sufficient to maintain the standards confirmed by research in the Northern Hemisphere and applied in this country. Research to clarify the contradictory results of studies conducted to date in South Africa is required. It will be necessary to quantify the local variation in atmospheric pollution regime through the ETH, to identify areas where doses sufficient to affect health arise from local sources or through the influence of local climatic factors. The health effects of atmospheric pollution from non-industrial sources, usually very localized, would then warrant attention.

Whereas atmospheric pollution has and can be controlled so as to obviate chronic health problems, the impact of present levels on perceptions of the quality of life and of amenity values must be significant. This aspect needs evaluation, if decision makers are to take properly informed action on pollution control.

A sound basis for the evaluation of the impacts of atmospheric pollution will necessarily require additional research. Relatively simple studies can improve the basis of knowledge quickly, and these include inventories and surveys of resources crudely predicted to be sensitive to atmospheric pollution effects, as well as exposure trials and experimental determination of dose-response relationships among plant and animal species of concern. However, the quantitative understanding of the responses of species and natural or modified ecosystems to atmospheric pollution effects needed to predict responses in nature will not be gained rapidly or easily.

At this stage, there is a clear need for improvement to the monitoring network for gaseous, particulate and deposited pollutants, especially sulphur dioxide, ozone, PAN, and particulates. Monitoring must be designed to provide estimates of dosages to target components at corrosion exposure sites, and the sites for studies of effects on forest and natural ecosystems. There is a need to ensure the detection of levels and durations of high-pollution events or episodes, and to quantify the spatial distribution of atmospheric pollution in the area adjacent to the ETH. Table 23 summarises statistics that are needed for stations within the desirable monitoring network.

An additional exposure trial of construction materials within the ETH is needed next to an existing atmospheric pollution monitoring site, to provide plausible data on rates of corrosion within the ETH.

Forest soils need to be mapped and classified and then analyzed according to risk categories determined initially by criteria derived from Northern Hemisphere work, refined later according to the findings from local studies. Experimental studies of the processes of atmospheric pollution impact on soils should be directed at ionic exchange processes and sulphate dynamics, and should be related to risk classes; particular attention is needed for sandy, acid soils, especially where such soils have been afforested.

Bioindicator studies using natural species, such as lichens, and propagated plants should be used to evaluate the extent and relative severity of atmospheric pollution impacts. Such work would also provide baseline data for evaluation of trends in atmospheric pollution effects.

Reconnaissance evaluations of possible forest damage are needed, through surveys of the incidence of symptoms as well as through retrospective studies of growth trends. Experimental studies of exposure of plant species are required, involving both greenhouse and field studies and including the varieties of crop plants grown in the ETH.

There is a need to improve the understanding of the ecophysiology of agricultural crops, forest tree species and representative native species, with regard to stomatal behaviour, photosynthesis, carbon

Table 23 *Statistics of atmospheric pollution levels, needed to express exposures in terms of doses, here given for ozone. (after Moore, 1987)*

A) Long-term averages and sums
  1) M7 = 7-h seasonal mean (0900-1600 CST)
  2) M1 = seasonal mean of daily maximum hourly concentration
  3) TOTDOSE = cumulative sum of hourly concentrations

B) Peak-weighted exposure statistics
  1) P1, P7 = 1-h and 7-h seasonal maximum concentrations
  2) SUMxx = cumulative hourly concentrations above xx ppm
     where xx ppm = selected threshold level
  3) HRSxx = number of hourly concentrations above xx ppm
  4) TOTIMPACT = total impact
  5) PWCI = Phenotypic-weighted cumulative index
     PWCI (w(t),p) = [Ozone(t)**p x w(t)]
     where ozone = given hourly ozone concentration
     where w(t) = exponential weighting scheme

C) Other exposure statistics
  1) DAYBETxx = average number of days between episodes
  2) INDEX 1 = multi-component statistic
     = [M7 x HRS08**a]/[DAYBET08**b]
     where 08 = 0,08 ppm, i.e. the hourly ambient air quality standard (USA)

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balance and mineral nutrition, and responses to sulphur dioxide, ozone, and acidic precipitation. Finally, at a limited number of sites carefully selected in relation to exposure to atmospheric pollution and with respect to soil type and other site characteristics, ecosystem processes need to be quantified, especially those relating to nutrient cycling and limnology. This latter work should be integrated with ongoing ecosystems studies.

Decisions about the control of atmospheric pollution in the ETH will in most cases involve judgements about the probable impacts of calculated levels of atmospheric pollution, given different, hypothetical industrial development scenarios. This will require the effective marshalling of available data and knowledge. Ultimately any appropriate programme dealing with atmospheric pollution impacts must include the development and maintenance of effective data bases and other information systems, and the application of tested mathematical process models to simulate the effects of atmospheric pollution on the resources of concern.

5. CONCLUSIONS

Situated in the belt of the atmospheric circulation of the Southern Hemisphere that is dominated by recurrent, semipermanent anticyclonic cells, the region of the Eastern Transvaal Highveld (ETH) has an atmospheric pollution climate among the most adverse anywhere in the hemisphere, let alone in South Africa. This fact must be accepted and taken into account in future atmospheric pollution management strategies for the region.

5.1 The atmospheric pollution climate of the Eastern Transvaal Highveld

Subsidence of air in the dominant anticyclones that prevail over the region throughout the year, but most particularly in winter, ensures that the atmosphere is highly stable for most of the time. Surface inversions are about 150-300 m deep, are ubiquitous in winter and occur frequently even in summer. The elevated subsidence inversion occurs on average at a height of about 1200 to 1400 m above ground and is steep enough to preclude vertical diffusion of pollutants above this level on most days throughout the year.

Near-surface, stable, local winds, with little dispersion power and with the ability to transport pollution long distances, dominate the low-level wind field. At the top of the surface inversion, decoupling of the stable boundary layer from the less stable air above is associated with a wind maximum and a region in which horizontal transport of pollution is maximised.

Between the subsidence inversion and the top of the mixing layer, exists a layer in which pollution trapping produces a regional pollution hazard. This has not been recognized hitherto and needs further research. Other research priorities include mesoscale windfield modelling, and atmospheric pollution dispersion modelling.

5.2 Atmospheric pollution in the Eastern Transvaal Highveld

In the case of one of the primary pollutants, sulphur dioxide, emission densities observed in the ETH are comparable with some of the large industrial areas of the world. Most of this pollution results from power stations, but substantial contributions also arise from various smaller industries, discard coal dumps, domestic combustion and motor vehicles. Although significant progress has already been made in improving the situation, the atmospheric pollution problem has, for practical reasons, not as yet been fully addressed. Considerable costs will, however, be involved in the implementation of more stringent controls and these costs will have to be carefully weighed against those which are expected or predicted to result from detrimental effects to the ETH environment.

Actual ambient atmospheric levels of sulphur dioxide are usually within locally-accepted air quality limits. High levels of sulphur dioxide pollution may, however, be experienced with certain airflow types and pose possible environmental problems. In general, increases in sulphur dioxide concentrations can be expected when the new power station units at Tutuka, Kendal and Majuba are commissioned between now and 1999 and consequently the situation should be closely monitored.

Indications are that conditions in the atmosphere over the ETH are favourable for the formation of pollutants such as ozone and peroxyacyl nitrates which exhibit phytotoxic properties. Likewise, sulphate and nitrate aerosols occur and are the precursors of acid rain. Observations suggest that ozone concentrations over the ETH are acceptable in terms of ambient air quality norms. However, prolonged and extensive monitoring is needed to obtain a more realistic assessment of the situation. Ambient atmospheric concentrations of sulphate aerosols at near-ground level also appear to be within acceptable limits at present.

Reason for concern exists about pollutants which are accumulated in the middle layers of the atmosphere over the ETH. Some of this trapped pollution is deposited by wet and dry processes and may eventually cause detrimental effects in the ETH environment. For example, wet deposit (rainfall) in the ETH displays an acidity which is similar to that reported for north eastern North America and Europe where problems of fish population decrease and forest decline have been experienced. In addition, relatively large amounts of sulphate aerosol have been found to be wet and dry deposited in the eastern portion of the Vaal dam catchment and in the forests in the vicinity of Sabie. Furthermore, dry deposition of gaseous pollutants such as sulphur dioxide increases the pollution deposition load and hence enhances the possibility for the occurrence of detrimental effects to the ETH environment. Whether this situation constitutes an environmental problem under the climatic regimes and environmental conditions prevailing in the ETH and adjacent regions is a matter which warrants urgent investigation.

Deteriorating visibility resulting from aerosols and other pollutant species formed as a result of photochemical reactions, may be a problem in various areas in the ETH. Again further quantitative observations are needed in this respect.

The current tall-stack policy of atmospheric pollution control has apparently been successful in lowering ambient atmospheric pollution concentrations measured at ground level. This has been achieved at the cost of pollution accumulating in an elevated layer over the ETH. Some of this pollution subsequently falls out or is washed out with possible deleterious environmental consequences in and beyond the region in question. It seems that the present policy may have to be revised and supplemented with more stringent controls in future in order to safeguard the ETH and adjacent regions from detrimental medium- and long-term effects on the environment.

Every justification exists for the present policy that any new industries, particularly those that will involve large scale combustion of coal, can be established in the ETH only if adequate control is applied to particulate as well as gaseous emissions. Furthermore, it appears necessary that the design of industrial plants to be erected in regions adjacent to the ETH should make provision for the possibility of retrofitting equipment to control particulate and gaseous emissions.

5.3 The environmental impact of atmospheric pollution in the Eastern Transvaal Highveld

Where data are available for the ambient concentrations and the deposition of atmospheric pollutants, they indicate that conditions in the ETH are currently sub-acute, i.e. the pollution levels are unlikely to cause effects that are readily observable. Any effects on natural systems are likely to be masked partially by those of other environmental stresses such as drought. Incomplete understanding of the processes of pollution damage add to the problem of understanding the environmental impact of atmospheric pollution. The complicating effects of milieu and organismic variation are well illustrated by the difficulties encountered in epidemiological studies directed at determining the effects of atmospheric pollution on humans.

Sufficient reason for concern for potential effects on the environment exists in the presently observed levels of atmospheric pollution. Though control measures have succeeded in maintaining the levels below the thresholds of risk to human health, negative impacts on buildings and other structures are very likely. Research conducted elsewhere shows that plants are affected adversely at different levels of their functioning by the degree of atmospheric pollution currently recorded over the ETH. Some species and varieties are affected more than others. It is possible that adverse effects on foliage, on photosynthesis, on growth and on yield may become ecologically and economically significant in the future. Within the ETH, on the escarpment to the east and in regions to the south there are extensive areas of sandy or loamy, acidic soils that are prone to the effects of acid precipitation.

With this background, and given the experience, albeit often confused, of the industrial countries of the Northern Hemisphere, it will be prudent to address the task of quantifying present and future impacts of atmospheric pollution in the ETH as a matter of urgency. Despite the lack of evidence for the direct effects of atmospheric pollution on agricultural crops in this region, the size of the regional agricultural economy demands that the current work on crop plants should be continued and expanded. However, greater effort must be directed to the problems likely to occur with the forests of the region. Forest systems are inherently more sensitive to atmospheric pollution than are agricultural crops. Managing and ameliorating atmospheric pollution impacts on forests will be more difficult, with less opportunity for adjustment, than in agricultural crops, where pollution effects may often be overshadowed by cultural practices. In the pine plantations of the ETH, symptoms of foliar damage apparently consistent with atmospheric pollution effects, and not ascribable to pests and pathogens, were diagnosed only during the course of this review, though observers had noted the unusual condition of the needles for some time previously. A close evaluation of the situation regarding forests is needed immediately. At this stage, the work required for agricultural and forest crop plants should suffice to provide the basis for identifying atmospheric pollution effects on indigenous plants and ecosystems.

There are several requirements for adequate progress toward a proper appraisal of atmospheric pollution impacts in the ETH. The first is for improved monitoring of atmospheric pollution levels. More monitoring stations are needed in the areas adjacent to the ETH. Better data are needed for the rates of dry deposition of pollution. In the forestry areas where mist is prevalent adequate data on the incidence of mists and information on the chemistry of wet deposition of pollution on vegetation are required.

A rapid quantification of the extent and degree of damage symptoms in the forests must be attempted and followed by experimental work to establish the causes of the symptoms. Bioindicators, such as lichens, may be usefully studied to clarify geographical patterns of atmospheric pollution impact. If atmospheric pollution is clearly identified as the cause of presently observed damage on trees, retrospective studies of growth trends and experimental dosage trials will be required. The nature and likelihood of acidification and other atmospheric pollution effects on soils recognizably sensitive to airborne pollutants, and the likely extent and significance of these effects, need to be established. If atmospheric pollution effects on forest and agricultural crops are significant and bioindicators such as lichens have been affected by present levels of atmospheric pollution, then urgent attention will need to be paid to the likely effects on natural vegetation communities and ecosystems. This will require the integration of atmospheric pollution impact studies with current or new ecological programmes.

The results from local studies together with the knowledge gained from research overseas will need to be organised into predictive models which may be used to evaluate the impacts of future atmospheric pollution scenarios.

It is likely that the needs for industrial development will preclude the option of full atmospheric pollution control. Knowledge must, therefore, be used to adapt agricultural, forest, and conservation management practices so as to minimise the impacts of atmospheric pollution.

A final thought

Given the highly adverse atmospheric pollution climate, the relatively high levels of some pollutants occurring under certain circumstances, the known adverse effects of these pollutants elsewhere in the world and the high risk attendant upon the impact of atmospheric pollution in the Eastern Transvaal Highveld and adjacent regions, it is imperative that the future planning and management strategies to achieve an acceptable level of atmospheric pollution be based on a conservative and cautious policy. Once damaged on a systematic and large scale, the environment will take a long time to recover. This fact should never be forgotten.

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