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AEROPALYNOLOGY IN NORTH LONDON.

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ABSTRACT

AEROPALYNOLOGY IN NORTH LONDON

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This study investigates the abundance and dispersal of pollen in an urban area with a view to making accurate predictions of daily pollen counts. Two-hourly pollen counts of more than 60 different pollen types have been recorded over four complete growing seasons in the heavily urbanized area of North London and this data is interpreted in relation to meteorological conditions, local pollen source areas, topography and the urban morphology. The analysis and forecasting of airborne pollen concentrations has relevance within three subject areas. Hayfever sufferers are able to use the forecasts to avoid times of high pollen counts; and this is of particular importance as the incidence of allergic respiratory diseases is higher in urban than in rural areas, and the incidence is believed to be increasing. The research has relevance also for Quaternary palynologists as an increased understanding of modern day pollen dispersal can aid in the interpretation of fossil pollen stratigraphies, as well as to the dispersal of particulate pollutants in urban areas.

An initial investigation of pollen abundance illuminates seasonal, daily and two-hourly variations in concentration which are examined in detail in relation to both past and present meteorological conditions. Three pollen taxa (Gramineae, Betula and Platanus) are selected for further analysis to develop various models which are able to predict average daily pollen concentrations of these taxa two or three days in advance. The forecasting models are based upon a multiple regressional analysis of pollen counts and twelve meteorological variables and attain levels of explanation approaching 56%. An attempt is made also to predict the severity of the Gramineae pollen season by examining the average daily temperatures in the months preceding the start of the season.

This research is novel in the level of detail of the analysis of pollen concentrations as well as in attempting to predict pollen counts using a variety of methods, especially in the use of accumulated values of maximum daily temperature and sunshine hours.

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NOMENCLATURE.

The nomenclature in this thesis follows that of Clapham, Tutin and Warberg (1962) for vascular plants.

CHAPTER ONE

INTRODUCTION

1. BACKGROUND AND OBJECTIVES OF THE RESEARCH.

This research attempts to aid in the understanding of the processes of pollen dispersal in an urban area and to develop models forecasting pollen concentrations in advance. Pollen abundance and dispersal in urban areas may differ markedly from that of rural environments where most previous palynological studies have been undertaken and these differences will be considered in relation to the different dispersal environments and the location and strength of the pollen sources. Detailed consideration will be given to meteorological influences and the effect of the built environment on pollen dispersal, and to the location of the pollen sources relative to the sampling area.

Pollen concentrations have been monitored over a three year period, and these data used to evaluate the dispersal patterns particular to areas with few local pollen sources and a complex urban morphology. The pollen data are analyzed statistically with relevant weather data using multiple regression and time-series techniques to determine the influence of meteorological conditions on pollen dispersal. For several pollen types models forecasting pollen concentration are developed and these tested against data from a fourth years sampling.

The study of pollen dispersal in urban areas has been little considered in Britain since the work of Hyde, Williams, Davies and Hamilton from the 1940's through to the 1960's (Hyde, 1950, 1952a, 1952b, 1955, Hyde & Williams, 1944a, 1944b, 1945, Davies, 1962, 1965, and Hamilton, 1955, 1959a, 1959b). These works followed the invention of the Hirst spore trap, the first volumetric pollen sampler, and examined a wide range of problems concerning pollen abundance. However, due to the limited use of statistical techniques and computer facilities during this period, the analysis of the data advanced little beyond a descriptive approach which identified some of the main trends. The works did not explain the complex relationships between the meteorological variables and pollen abundance, or attempt any modelling of these processes. These earlier works concentrated almost exclusively on the abundance of grass pollen, even though other tree pollen types are also known to induce the hayfever (Davies, 1989).

As a result of this previous research the general temporal pattern of grass pollen abundance in a built-up area is well known, ie. that maximum grass pollen concentration occurs in the late afternoon on hot and dry days. However, the work of Davies in London (1965, 1969, 1973) left many unanswered questions concerning pollen dispersal, particularly on the day-to-day and diurnal variations in pollen counts and on the relationship between these and weather conditions. The influence of some meteorological variables (temperature and rainfall) on the daily grass pollen count has been examined in Britain by Hyde (1950) and by several authors abroad, for example Bringfelt (1980) in Sweden. However in London the precise relationship between both the daily and hourly pollen counts and meteorological variables such as wind speed, wind direction, humidity, cloud cover, and synoptic situation has not been fully evaluated. Little is also known of the ways in which these weather variables combine to produce high pollen counts.

Neither is much known of the temporal distribution of other pollen taxa, notably the allergenic tree types, which have both different flowering rhythms and source areas to grass pollen, factors which may influence the dispersal of these pollen types. The seasonal variation in pollen production by trees has never been fully investigated in Britain using volumetric sampling methods. The existence of cycles of high and low pollen production has been acknowledged since the work of Hyde (1950) and the work in Denmark of Andersen (1972). An examination of pollen abundance over four years may suggest whether or not the trends identified earlier are occurring in Britain today.

The developments achieved in the forecasting of pollen abundance in Scandinavian countries and in the United States may also be of relevance to palynological studies in Britain. Recent advances in the study of particulate pollution dispersal (Bringfelt, 1971) and in the application of statistical techniques to palynology (Moseholm *et al* 1987, Di Giovanni 1986, Di Giovanni *et al* 1989) also now enable a more quantitative approach to be taken to the study of pollen dispersal. Developments in contemporary palynology have been made across Europe, particularly in Scandinavia, and in the USA but there have been few new advances made in Britain since the early 1970's.

The main aim of this thesis is therefore to determine and then examine the controls which operate on pollen concentration in North London. Theoretically pollen concentration is governed by the meteorological variables which govern the production, release and transport of pollen grains, by the flowering phenology of plants and by the source area of the pollen relative to the sampling site. Any consideration of pollen dispersal must take account of these variables.

This knowledge will then be employed in the development of models to forecast average daily pollen concentrations based upon the meteorological parameters which prove to be of most relevance in determining pollen counts.

For the purpose of this thesis, the study of pollen abundance has been divided into three time periods. The seasonal, or year-to-year, variation is examined firstly as this will determine the potential pollen production on which further fluctuations are superimposed. The second consideration is the day-to-day pattern of pollen abundance and the third the two-hourly or diurnal fluctuation (variation within one day). The variations in pollen abundance within each of these time periods has relevance to the accurate forecasting of pollen concentration.

2. ORGANIZATION OF THE THESIS

This thesis has been divided into three main sections; the first being an introductory section and the second the presentation and analysis of this data. The third section develops this analysis towards the modelling of pollen concentrations.

The remainder of this first chapter comprises an introduction to the study area, where the topography, climate, urban morphology and the pollen sources of North London are considered, followed by an assessment of the relevance of a study of pollen dispersal. The second chapter is a survey of previous palynological investigations undertaken both in Britain and abroad relevant to this study. In Chapter 3 the research methodology of the study is then explained outlining the sampling procedures, the nature of the data and the analysis undertaken.

In the second section of the thesis, chapters 4, 5 and 6 present the pollen data and its statistical analysis to determine the roles of meteorology and plant phenology in influencing pollen concentrations. The examination of the pollen data has been divided into year-to-year or seasonal variations (Chapter 4), daily variations (Chapter 5) and diurnal trends (Chapter 6). Chapter 7 then considers in more detail some of the key problems encountered in the analysis.

Section three of the thesis expands the statistical analyses of chapters 4, 5, 6 and 7 to develop models which forecast pollen concentration in advance. Chapter 8 outlines the construction of these models, while their efficiency is tested in chapter 9 against data obtained from a fourth years sampling of pollen abundance. The relevance of the research to the interpretation of fossil pollen stratigraphies and to the study of the dispersal of particulate pollutants is considered in chapter 10, along with the applications in practice of predictive models of pollen abundance. The final chapter summarizes the main conclusions of the thesis and outlines suggestions for future research.

1.3 THE STUDY AREA.

1.3.1 Introduction to the Study Area.

The study of pollen dispersal is located in North-Central London, the area of the Borough of Islington, as it is typical of many densely-built urban areas. Features of an urban area that may influence the concentration of pollen include a dense, high-rise urban structure and a scarcity of local pollen sources. The study is located immediately to the north of central London, in preference to other inner London areas, to be as far as possible from the influence of rural environments, given the predominantly south-westerly wind-direction.

1.3.2 Topography

The topography around Islington is gentle and low-lying with altitudes ranging from 15m to 120m OD (Figure 1.1). The southern half of the study area comprises a gentle slope down towards the River Thames with areas around Highbury Fields elevated to 40m OD. To the north and west Islington is surrounded by higher ground reaching 120m on Hampstead Heath and 80m on the Highgate ridge with bordering slopes of 15% in gradient. There are no other breaks of slope or steep inclines within north-central London.

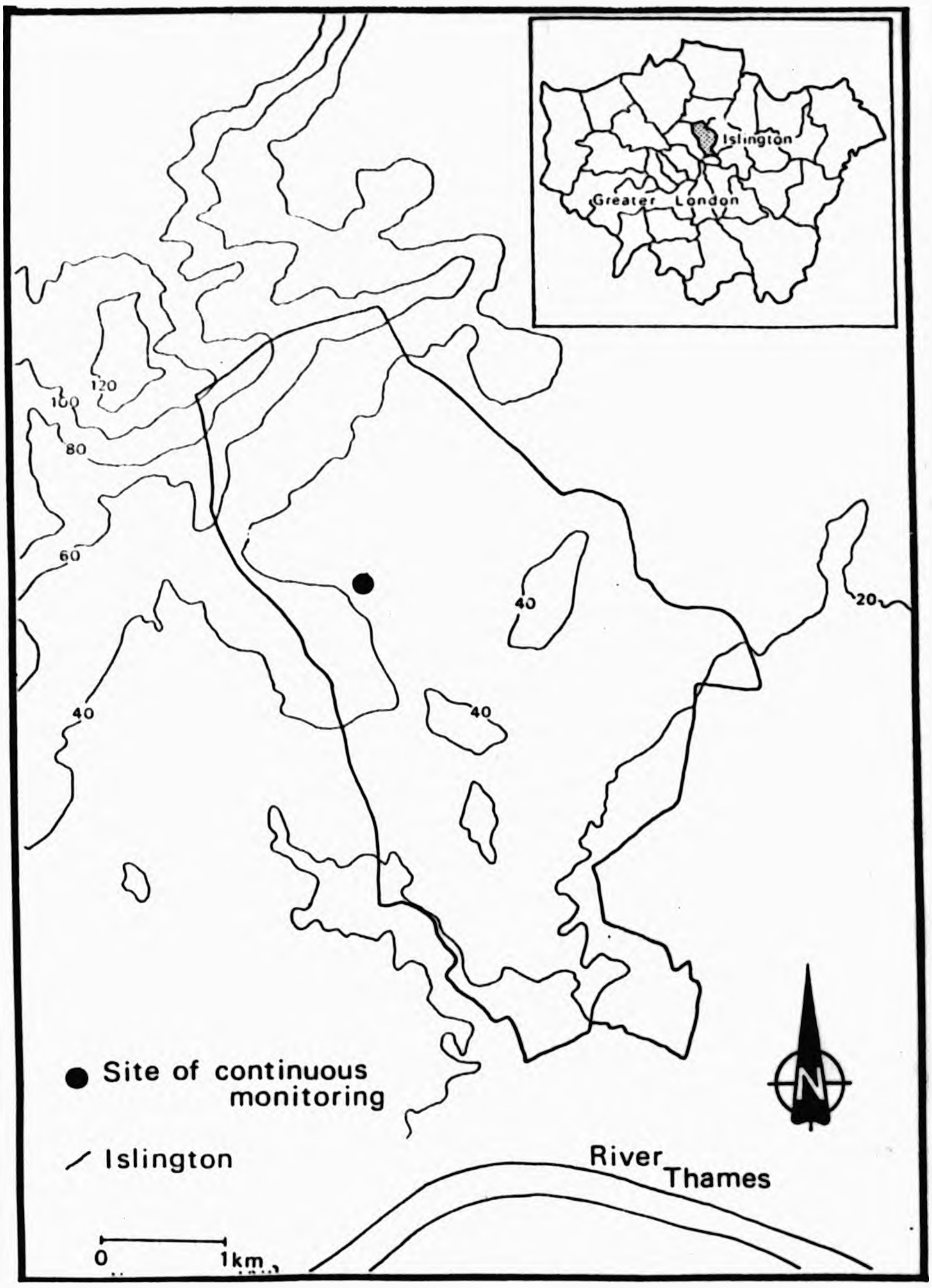

Figure 1.1 The location of the sampling site.

1.3.3 Climate

The climate of London is much influenced by the urban-heat island effect (Oke, 1973, Barry and Chorley, 1978) with the inner area being influenced by the amount of warmth escaping from centrally-heated buildings. The climate of north London is then influenced by its position in relation to the rest of the urban area (Figure 1.1). Winds from the south and west carry air that has traversed areas with deep street chasms and well heated buildings which heat and dry the air. This air is then significantly warmer and dryer than air flowing from the north and east which will have passed a shorter distance over a less well built up area.

Climatic variations also exist within the study area resulting from the local topography and urban environment.

Mean monthly temperatures in the southern part of the study area are about 2°C warmer than in the northern part because of the increased density of multi-storey buildings which radiate and conduct heat, and reduce wind speeds at ground level (Oke, 1973).

The average monthly sunshine figures for the years 1951-1980 for north London vary between 100 in early spring to 200 in July to 110 in September at the end of the growing season. Few differences in the amount of sunshine and cloud recorded exist within the study area.

The 1951 - 1980 average yearly rainfall in the centre of London is 480mm. However the higher land to the north and west of the study area is significantly wetter than the low lying areas. Rainfall figures recorded at Hampstead over the same period exceed those from the London Weather Centre (in the extreme south of the study area) by 20mm (The Islington Atlas). Although in London the winter months have the highest total rainfall, convection storms in summer ensure that those months experience the highest rainfall intensities with up to 23mm rain an hour.

The prevailing wind direction for the study area is from the west-south-west, a result of the eastward moving frontal depressions from the Atlantic. Between

February and August, north-north-east winds occasionally predominate and are associated with an outflow of relatively dry air from high pressure systems over Europe. However, the prevailing wind direction and wind speed at ground level will also be influenced by the urban morphology of the area, for winds in urban environments are often more turbulent than in rural areas.

In a city the size of London, atmospheric stability is greatly reduced compared to rural areas. In urban areas there are no strong diurnal changes in stability, and, as a result, marked temperature gradients and extremes of stability and instability are absent (Oke, 1978). The increased gustiness typical of cities and the modification of airflow in response to the urban structure also combine to reduce the potential for stable air profiles in the urban environment and to increase turbulence.

1.3.4 Urban Morphology.

The study area in Islington comprises densely built residential and commercial districts with buildings of 10-12m in height. These areas are dissected by a network of wide and narrow streets and a few open spaces of up to one hectare in size.

The alignment of deep canyon-like streets will influence the low level wind direction by funnelling winds along their length. Open spaces, such as Hampstead Heath, Highbury Fields and Finsbury Park (Figure 1.1) allow stronger winds to blow into the street system on their downwind margins, and hence may aid in the dispersal of pollen from these sources.

Individual buildings will also influence airflow around them, and hence the dispersal of particulates. Oke (1978) specifies how winds speeds are increased around and between buildings in the urban environment.

1.3.5 Pollen Sources.

Sources of pollen within 4km of the pollen sampling site have been identified and mapped and are displayed in Figure 1.2. Local pollen sources are comprised of three different vegetation types; parkland and gardens, trees planted along transport routes, and derelict and waste ground.

The small parks within the Borough of Islington consist mainly of mixed tree species and of grassland that is mown before pollination. To the south of the Borough Plane (Platanus spp.) and Lime (Tilia spp.) trees predominate with smaller amounts of Horse Chestnut (Aesculus hippocastrum). Sycamore (Acer pseudoplatanus). Ash (Fraxinus excelsior) and Oak (Quercus robur and Q. petraea). Plane and Lime trees were particularly favoured by urban tree planters because of their rapid growth, attractive appearance and resistance to damage by air pollution, so that in some areas together they comprise 80% of all trees (Figure 1.2).

To the north of the study area a wider range of trees has been planted. These include Poplar (Populus spp.) and some smaller species more suitable for gardens such as Birch (Betula spp.), Willow (Salix spp.) and Hornbeam (Carpinus betulus). Other species recorded in neglible amounts are Pine (Pinus sylvestris), False Acacia (Robinia pseudoacacia), Yew (Taxus baccata) and Rosaceae spp.

Trees planted along streets are less varied than those in parks and gardens. Again, in the south of the study area, Plane and Lime predominate, while to the north, Birch and Cherry (Rosaceae) may be found as well.

Areas of unmown grass are rare in north-central London as most parks and gardens are managed and the grass cut before flowering. However, grasses may pollinate in a few unkept gardens and on derelict land. The unmanaged open areas of Hampstead Heath to the north-west may also contribute grass pollen to the study area.

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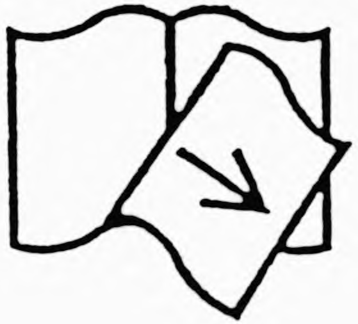


1.4. WIDER CONTEXT OF THE RESEARCH.

Although the prime focus of the research is to develop models of pollen concentration in an urban area, developments made in the understanding and forecasting of pollen dispersal will also be of relevance to the study of particulate pollution dispersal, the reconstruction of vegetation history through pollen analysis, and to the study of airborne pollen as an antigen.

A study of pollen dispersal will provide a useful analogy to the dispersion of some forms of particulate pollution as they will be affected by the airflow in a similar way. Many previous models have been constructed which model the dispersal of both particulate and gaseous pollutants. However, these have concentrated on dispersal from single points sources at known rates of emission, often at some height above ground level. Such premises do not apply to many pollutants, for example particulate emissions from vehicle exhausts, waste incinerators or general ground level dusts. These pollutants all disperse from area, ground level sources at unknown emission rates as does pollen.

Research into the dispersal of pollen as an example of particulate matter moving from rural into urban areas may also demonstrate how other forms of both organic and inorganic pollution spread. Examples of pollutants released in rural areas are herbicides and pesticides applied to crops, and fungal spores. The mechanisms that govern the dispersal of pollen will also influence the diffusion of these pollutants.

The study of modern pollen dispersal may also aid in the interpretation of fossil pollen assemblages where dispersal conditions are unknown. Although the urban situation in which pollen has been monitored, differs from the rural location of most fossil pollen studies, the interpretation of pollen dispersal is simplified by the discrete nature of the pollen sources.

The prominence of, and concern about, seasonal rhinitis attributable to pollen has grown considerably in the last two decades. The incidence of hayfever is believed by many to be increasing (Blenkinsopp & Blenkinsopp, 1989, Morley, 1989) and this rise is not accompanied by a corresponding rise in pollen concentrations. Recent surveys estimate that 10-20% of the population are afflicted by a pollen allergy (Davies, 1989), so that if the rising trend of suffering continues, more than a quarter of the population could suffer allergic reactions to pollen at some time in their life.

Previous research into modern pollen abundance in Britain has concentrated almost exclusively on the study of pollen from the Gramineae (Grass) family. Grass pollen accounts for approximately 35% of the total yearly pollen catch, occurring mostly during the months of June and July, and is acknowledged as being the main cause of seasonal rhinitis in Great Britain (Davies 1973). O'Rourke (1973) states that 80% of hayfever patients are allergic to Gramineae pollen. However, the proportion of the population allergic to arboreal pollen may be underestimated as the allergenic potential of these pollen types are not well known, even amongst doctors. Hide (1989) states that pollen from Betula, Corylus, Quercus, Platanus, Plantago and Compositae may induce an allergic reaction, and Fountain & Cornford (1991), working in New Zealand, have suggested that Pinus pollen may also cause hayfever or provoke cross-reactivity with other pollen types.

The examination of the seasonal rhythms of tree pollen production will be of relevance to rhinitis sufferers allergic to arboreal pollen types. Years of potentially high pollen production may be identified for the different tree taxa, and sufferers warned in advance so that they might avoid the highest pollen counts. The provision of an arboreal pollen count to the public and medicins might also allow the diagnosis of rhinitis in patients not previously thought to be affected by pollen. Awareness of the extent of tree pollen allergies may have been restricted in the past by the great variations in pollen concentration from year to year for a sufferer may not presume the symptoms experienced are indeed hayfever unless they occur every year. This thesis will therefore concentrate on examining the dispersal patterns of the allergenic tree pollen taxa along with pollen from the Gramineae family.

At present daily grass pollen counts are measured for release to the general public at approximately twenty sites throughout Britain. However, this count is an average pollen concentration from the preceding 24 hours, and as these counts vary markedly from day to day, a retrospective record is of little use to sufferers wishing to avoid high pollen counts. A forecast of the pollen concentration for the next 24 hours is issued, along with the count, in the form an informed, but subjective, estimate of a high or low count (above or below 50 grains M^{-3}) and whether this count will rise, remain steady or fall. This may lead to confusion amongst the general public as 50 grains M-3 is not a universal threshold below which nobody sufferers the symptoms of hayfever; many patients will suffer symptoms when pollen counts are as low as 10 grains M-3, particularly towards the end of a season when sensitivity has been increased by exposure to the pollen antigen (Viandder & Koivikko, 1978 and Connell, 1969). The severity of allergic symptoms may also not relate directly to the daily average pollen count as diurnal variation in the concentration may produce short-term peaks in pollen abundance not reflected in the daily count, but the allergic effects of which last for hours after the count has declined.

An accurate forecast of both the daily pollen count and the time and size of the peak two-hourly concentration may therefore be of benefit to rhinitis patients who wish to avoid times of high pollen concentration. If avoiding high pollen counts is impractical, sufferers would still have adequate warning enabling them to take suitable medication in advance.

CHAPTER 2

A REVIEW OF THE CURRENT LITERATURE.

The first published work to study the abundance of airborne pollen grains was undertaken through the 1920's to the 1940's by Gunnar Erdtman (Erdtman, 1928, 1929 cited in Erdtman, 1937, Erdtman 1943 and Nilsson *et al* 1978). Erdtman carried out a wide range of experiments using both depositional samplers and large volume air filters. He studied the airspora of both Great Britain and Sweden, as well as investigating the long distance dispersal of pine pollen by sampling aboard a ship in the mid-Atlantic (Erdtman, 1937). These works were contiguous with the development of the science of Quaternary palynology and were seen mostly as an aid to the interpretation of fossil pollen assemblages rather than being of significance in their own right.

Following from these studies, little interest or work in pollen dispersal resulted in Britain. In Germany, however, several papers were published investigating the role of meteorology in long distance dispersal (for example, Rempe, 1937 and Pohl, 1937), while, in Denmark, Tauber (1965 and 1967) examined pollen dispersal under closed canopy woodlands. These works, again targeted more towards Quaternary pollen studies, were the first attempt to provide a systematic model of pollen dispersal or deposition. Taubers first paper (1965) soon put paid to the previously held ideas of a uniform pollen rain. Instead he was able to demonstrate how significant quantities of pollen moved through the 'trunk space' of the woodland as well as being transported from the canopy up into the regional airflow. A third component of the pollen transport identified by Tauber was the pollen brought back to ground level by rainfall. Also investigated by Tauber, was the differential filtering of pollen types as they moved through the forest canopy. The implications of this work for the study of pollen dispersal are numerous, and in particular when the origin of pollen grains is considered. In Taubers model, most pollen carried through the trunk space will be local in origin, especially for large and heavy pollen grains. In contrast, pollen brought down to ground level by rainfall may have a distant origin, having been transported some way by the upper airflow. Although the study of pollen dispersal in a closed canopy woodland is not of immediate direct relevance to urban areas, an analogy may be made between the forest trees and buildings, in that both limit the upwards dispersion of pollen grains.

The work of Tauber was later supplemented by that of Solomon and Harrington (1979) and Solomon and Silkworth (1986). Solomon and Harrington compared recorded distance decay curves for pine pollen with figures derived atmospheric particle dispersion equations and found that these could not be fitted to the very marked decline in pollen deposition away from the pollen source. They suggested the application of step function equations to explain the spatial patterns recorded. These ideas were pursued by Solomon and Silkworth (1986) when they again investigated the decline in pollen deposition with distance from source, but in a mountainous region. The main conclusions of this study were that pollen deposition was high and variable within the source area, but that at distant sites the deposition was low and uniform, indicating a mixing of the pollen spectrum by local airflows. Once again, analogies can be made between modes of pollen transport in montane and urban areas.

Meanwhile in Great Britain, the development of the science of aerobiology concentrated mainly on the monitoring and explanation of patterns of pollen abundance. Two workers, based in Cardiff, began to monitor pollen on a regular basis in 1942, the results of which led to a series of six papers examining a range of aspects of pollen abundance, dispersal and the influence of weather conditions. These papers included studies of day to day variations in the grass pollen count (Hyde and Williams, 1944a), diurnal variations (Hyde and Williams, 1944b, 1945) and variations in pollen abundance at eight sites across Britain (Hyde, 1950). Hyde, together with another colleague, also produced the first comprehensive collection of photographs of fresh pollen grains, some of which were published in The Atlas of Airborne Pollen Grains (Hyde and Adams, 1958). However, much of Hydes work was limited by the use of depositional samplers, whose sampling efficiency is influenced by the settling velocity of pollen grains, as well as by wind velocity, wind direction and turbulence.

To improve on this rather limited method of sampling, efforts were made to develop a more accurate, anisokinetic spore sampler. The Hirst trap (Hirst, 1952) fulfilled these functions and has since become the standard pollen sampling machine in Europe. The first published records from the Hirst trap were from Hamilton (1955, 1959a, and 1959b) who re-investigated many of the same experiments that Hyde had covered in Cardiff, but with the volumetric sampler at St. Mary's Hospital in Paddington, London. Hamilton (1959a) also examined the abundance of other microscopic airborne particles recorded by the sampler, such as groups of algae, insect fragments, mycelial fragments, plant hairs and inorganic particles. The abundances of these organic particles have not been fully studied since.

The continuation of the sampling record at Paddington by Davies resulted in a number of papers investigating pollen abundance and dispersal in a large urban area (Davies, 1962, and 1965 and Davies *et al* 1963). Davies investigated the variation in abundance of pollens and fungal spores with height and in Londons parklands, concluding that great variations in concentrations could be recorded over very short distances. Following from this work, Davies also compared the airspora of London with that of Davos in Switzerland (Davies, 1969a, 1969b). A later development of Davies work was an attempt to forecast the start of the grass pollen season in London (Davies and Smith, 1973). Using accumulated temperature and rainfall data from four stations around London, the authors were able to forecast both the start and severity of the season. This important work was the first to consider the main controls on the flowering of grasses, namely the temperature and rainfall during the periods of pollen formation within the flowerheads; April and May.

However, whilst in Britain Davies was the only worker to investigate pollen abundance, many more developments were occurring abroad. In Denmark Andersen elaborated on the earlier works of Hyde (1951) researching the relative pollen production of deciduous tree types (Andersen, 1967, 1970, 1973) and the seasonal variations in pollen abundance (Andersen, 1974a, 1974b, 1980). Andersens work on seasonal variations was in close agreement with that of Hyde, whereby both recorded similar patterns for the same tree species, indicating that the same controls on pollen production operate both in Britain and in Denmark. In an investigation, perhaps aimed to be of more use to Quaternary palynologists than to aerobiologists, Andersen (1974a) also examined the wind conditions on pollen dispersal in a forest canopy from which a comparison to a urban street canyon situation may be made.

Following from these researches, a group of American aerobiologists started an investigation of pollen dispersal both from and within forests, (Raynor *et al*, 1974, 1975). Their main findings were in agreement with the theses proposed by Andersen, namely that most of the pollen released by the forest canopy falls in aggregates to the forest floor, and that only a small proportion is released into the airflow above the canopy. The same group of workers, as well as producing 'A Manual for Sampling Airborne Pollen' (Ogden *et al*, 1974), which is still the standard textbook for many sampling techniques, were also the first to start issuing systematic forecasts of pollen concentrations. Raynor and Hayes (1970) compared three different methods to predict daily ragweed pollen counts; climatology, persistence and a forecast based on the predicted weather conditions. With the latter method they achieved an accuracy of 67% which, when errors in the meteorological forecasts were taken into account, increased to 75%.

Most work on the modelling of pollen concentration since that of Raynor and Hayes has also attempted to forecast daily pollen concentration based on local weather forecasts. A more systematic way of doing this was developed for Stockholm, Sweden by Bringfelt (1980) who began by using correlation and regression analyses between recorded pollen counts and weather variables to establish the importance of individual meteorological factors. This work was then supplemented by that of Bringfelt *et al* (1982) using multiple regression analyses to forecast counts of Betula and Gramineae pollen based on the forecasts of as many as five meteorological variables as well as the potential pollen production as it varies through the season. An efficiency of 80% was achieved for Betula pollen counts, and 58% for Gramineae pollen counts.

A simpler regressional analysis, based on fewer meteorological variables and attaining a level of 56% accuracy, was performed by Spieksma (1980) using Gramineae pollen counts from the Netherlands. An alternative to the straightforward regressional forecasting of pollen concentrations was then proposed by Moseholm *et al* (1987) who suggested that, if pollen counts were autocorrelated, then a time series technique might also be employed. In their forecasting model a high level of efficiency was achieved, although they did conclude that the autocorrelation of the pollen counts was not significant and that it was due to an autocorrelation of the meteorological variables, a factor which a regressional forecasting model would indirectly take into account.

Since the work of Moseholm *et al* (1987) there have been no published developments in the forecasting of daily pollen concentrations. One unpublished work, however, deserves special consideration; that of Paul Dowding (1983, unpub.). Dowding, working in Dublin, Ireland, devised a model to forecast grass pollen concentrations at three hourly intervals based on a range of meteorological variables. The model differs from most previous ones in that it contains separate sub-models to predict the production, maturation and release of pollen from the grass flowerheads, as well as allowing for the carry-over of some pollen from one time period to the next. Based on the area/box models frequently used in air pollution dispersal research, this model is therefore based on the source strength of pollen emission which is calculated by the various sub-models, the results of which are then passed between columns of air as the pollen disperses from its source. However, this model has been devised entirely theoretically; its accuracy has never been fully tested and its applicability to a large urban area where many different climatic features are evident, is doubtful.

Besides the work of Davies, no recent research has considered the modelling of pollen dispersal with a view to the forecasting of daily pollen counts. Instead, many authors have considered the influence of meteorology of pollen concentration to elucidate on the controls that operate on pollen production, release and dispersal. Much of the work has been carried out abroad.

The diurnal variation of both arboreal and non-arboreal pollen, and the influence of both meteorology and phenological rhythms, has been considered by Kapyla (1981, 1984) in Finland. Kapyla concluded that the degree of influence of weather conditions varies between species; while some pollen taxa, in particular the non-arboreal types, have regular patterns of diurnal variation irrespective of the weather conditions, others mainly release their pollen in response to climatic controls. Markedly different patterns of pollen release to those recorded in Finland by Kapyla were observed by Galan *et al* (1989a, 1989b) in Spain, Mullins *et al* (1986) and Steel (1983) in Britain and by Spieksma (1983a, 1983b) and Spieksma & den Tonkelaar (1986) in the Netherlands indicating that although phenological patterns of pollen release may be important locally, on a regional scale climatic type and variation is important to the diurnal pattern of pollen release.

Other studies of pollen abundance have considered the role of single weather parameters. For example, McDonald (1962) and Dingle and Gatz (1966) analyzed the washout of pollen by raindrops, McDonald (1979 and 1980) the influence of seasonal variations in wind direction on the pollen spectrum of a coastal area, Spieksma (1983b) the influence on night-time pollen counts of temperature inversions and Steel (1983) the role of convection currents. These studies have all aided in the understanding of meteorological controls on pollen production and dispersal, and so may aid in the construction of dispersal models.

Day to day and seasonal variations in pollen abundance have also been given prominence in the work of Many European authors, although little attention has been paid to these phenomena in Great Britain. The work by Andersen (1974a, 1974b, 1980) has already been considered, but it has been complemented by that of McDonald (1980) who examined the importance of several meteorological factors on daily concentrations of grass pollen in Western Ireland. Daily variations in pollen abundances have also been considered by the Spanish authors Galan *et al* (1989a, 1989b) in relation to a range of weather conditions.

However, none of these works have led to new developments or approaches to the modelling of pollen concentrations. The most recent achievements in this field have arisen from workers concerned with the dispersal of modern day pollens an aid to the understanding of fossil pollen records and with those concerned with pollen dispersal from seed crops.

Prentice (1985), Di Giovanni (1986) and Di Giovanni *et al* (1989) have attempted to combine both source and receptor orientated approaches in the modelling of pollen dispersal. Adapting both gradient transfer theory and Gaussian plume models to simplified meteorological conditions typical of those under closed canopy woodlands, Di Giovanni (1986) and Di Giovanni *et al* (1989) tested the applicability of the models to both recent and Quaternary pollen data. However, one of the main problems encountered in this work was the multiplicity of pollen sources that occurs in woodland sites, even within the relatively small distances considered by the model. These 'hybrid' approaches to dispersal modelling do however provide a possible means of modelling where pollen sources are well defined.

Another recent work to apply a physical, source orientated model to pollen dispersal from a well defined source area was that of McCartney and Lacey (1991). These authors utilized a steady state advection diffusion model to examine the dispersal of oil-seed rape (*Brassica napus*) pollen downwind from a single field at distances up to 100 meters.

Recent progression in the field of aerobiology has arisen with the development of the International Aerobiology Association and the associated collaboration between researchers from many different countries. An important theme in the research undertaken by members of the Association has been the development of methods which forecast the start of pollen seasons (for example, Frenguelli, 1991 and Larsson & Nilsson, 1991) although interest in the modelling of daily pollen concentrations has fallen out of favour somewhat. Other key areas of research in aerobiology today include microbiology, phytopathology and the health impacts os other inhaled particles such as pollen and spore fragments. Nilsson (1991) provides a review of current research topics in aerobiology.

However, in contrast to the recent developments in the study of dispersion from single, well defined source areas, little attention has been given to pollen dispersal from diffuse or indistinguishable sources. That pollen grains recorded in large urban areas originate from many diffuse sources is widely accepted in the literature (Frankland in Davies and Smith, 1973 and Donini and Sutra, 1987) along with the hypothesis that cities greatly modify the dispersal environment for pollen (Steel, 1983). These suggestions, together with the fact that the majority of the population of Great Britain live in urban areas, that the incidence of hayfever suffering is greater in such areas (Ishizaki *et al*, 1987 and Weeke, 1989) and the incidence of hayfever is increasing (Blenkinsopp and Blenkinsopp, 1989) clearly indicates the need for further studies of pollen dispersal in urban environments.

CHAPTER 3

RESEARCH METHODOLOGY.

3.1 SAMPLING STRATEGY FOR THE STUDY OF POLLEN DISPERSAL.

3.1 The Pollen Sampler.

A Burkard sampler, designed to the specifications of Hirst (1952) has been used to sample pollen. This sampler is considered the international standard for sampling short term variations in the pollen concentration and for providing a volumetric pollen count (Davies, 1971).

The sampler draws in air through an orifice, 2mm x 14mm in size, which is directed into the main wind direction by a tail vane. Ten litres of air a minute are drawn through the orifice to approximate the rate of human breathing. Placed behind the air intake is a tape, made sticky with a mixture of petroleum jelly and 10% paraffin wax. This is attached to a drum that turns at 2mm/hour behind the sampling orifice so that each 24 hours sampling trace is spread over an area of 14mm x 48mm, with a sampling resolution of two hours. Up to seven days continuous sampling can take place without attention to the instrument.

The Burkard sampler has been chosen for this investigation of pollen abundance as it is the only widely used sampler that can provide both a short-term measure of pollen concentration and yet can operate over long periods (of up to a week) without attention. The sampler has been used extensively by previous authors across the world, although in the United States the Rotorod and Rotoslide samplers (Ogden *et al*, 1974) is also frequently used, this cannot be operated for more than a day or provide short-term measurements without constant attention.

3.1.2 Location of the Pollen Sampler

The Burkard sampler is located on the roof of a six-storey building in the centre of the study area (Figure 1.1). Pollen concentration will vary with height (Bryant *et al*, 1989 and Raynor *et al*, 1973) and so the pollen sampler is placed at an elevation where it is exposed to pollen from a wide area. The instrument is raised above the general roof level of the surrounding area to minimize the effects of pollen from the immediate environs and of low level particulate contamination. The sampler is exposed to an undisturbed wind flow from all directions. There are no large open areas within 500m of the pollen sampler and only a few scattered trees (Fraxinus excelsior, Aesculus hippocastrum and Platanus acerifolia) within 100m of it.

It is acknowledged that pollen concentrations may vary markedly over small distances (Donini & Sutra, 1987). A small pilot study undertaken in 1987 and 1988 investigated broad differences in pollen deposition across north London and concluded that the chosen site of continuous monitoring provides a representative sample of pollen abundance without excessive quantities of any pollen taxa, (Emberlin & Norris-Hill, 1991). Having conducted an extensive spatial survey of spore concentrations, Eversmeyer & Kramer (1987) concluded that a single volumetric sampler provides a representative measure of the air spora provided that consideration is given to the height of the sampler.

A sampler located at ground level therefore will provide a pollen count representative of only the immediate vicinity, whereas one at roof level represents a wider area. The pollen count taken just above roof height should then be representative of the pollen spectrum of this area of north London. The extent of this area will vary according to the predominant weather conditions but at a minimum is presumed to extend as far as the ridge of high ground at Hampstead (Figure 1.1) to the north and west, and to the centre of London to the south. The maximum extent of the catchment area is almost infinite with the possible long-distance dispersal of pollen (elsewhere described by Cour *et al*, 1981 and Wallin *et al*, 1991).

An additional reason for locating the pollen sampler at roof level is to reduce the risk of damage by vandalism and to remove it from the ground level particulates that might contaminate the sampling tape. London, in common with many other urban environments, is very dusty and if excessive amounts of dust are present the sampling tape becomes overloaded, both reducing the adhesiveness of the tape and obscuring the pollen grains held on it.

3.1.3 Pollen Counting Procedure.

The sampling tape is removed and replaced in the Burkard pollen trap once a week. The tape is then divided into 24 hour segments, each 48mm long, and mounted on microscope slides. The slide is warmed slightly to prevent the movement of particles on the tape, and is covered with a mixture of glycerin jelly and fuschin placed on a coverslip. The pollen grains are then sealed in the position in which they are impacted onto the tape, and hence the hour of sampling read off accordingly.

The mounted tape is then examined under a microscope. Following one of the pollen counting procedures outlined by Kapyla and Pettinen (1981) the sampling tape is divided into two-hour sections, each 4mm wide, and all the pollen grains in each section identified and counted. Pollen counts were carried out on a two-hourly interval to provide the maximum information possible concerning the temporal variation in pollen concentration. Counts of less than two hours duration (on an hourly interval for example) are believed to be less reliable (Ogden *et al*, 1974) giving an hourly figure of a two-hourly running mean concentration.

Pollen is identified under a magnification of 400 using the keys of Moore and Webb (1975), Hyde and Adams (1958) and Nilsson and Praglowski (1973). Pollen grains are identified to generic level where possible (for example, '<u>Betula</u>' which includes all species of birch) or to family level where this is not possible (for example '<u>Gramineae</u> which includes many different genera and species of grasses). Identification to species level, where feasible, (for example, <u>Plantago major</u> or <u>P</u>. <u>lanceolata</u>) has not been routinely undertaken. Over three years of sampling 65 different pollen taxa have been identified. Several indeterminable grains have been found and are recorded as such. The total count of each pollen type can then be calculated for each two-hour period by dividing the count by the volume of air sampled to result in a pollen count, or concentration, per cubic meter of air. The two-hourly pollen counts can then be averaged to obtain a daily count for each pollen taxa. All data are stored in a specially designed database on the University of North London's VAX mainframe computer.

3.1.4 Sampling Efficiency and Sources of Error

Gregory and Hirst (1957) report a trapping efficiency which averages 80% for the Hirst sampler, but this will vary according to the wind speed and particle size. Ideally, for isokinetic sampling, air should be drawn into an instrument at the same rate as the wind speed, but the Burkard sampler has a fixed rate of airflow. Gregory and Hirst report that under normal conditions sampling efficiency is 100% at wind speeds of 1 m/sec, but that this will decline with increasing wind speed. Wind speeds within London through the pollen season are generally in the range of 1 to 10m/sec with an mean wind speed of 2.1m/sec, so that errors due to anisokinetic sampling are likely to be small.

Few errors are likely to occur during the counting procedure as the entire microscope slide is scanned and so the problems of confidence limits on pollen concentrations are eliminated.

3.2 METEOROLOGICAL DATA USED IN THE ANALYSIS.

Meteorological data, to aid in the interpretation of pollen dispersal, have been obtained from the London Weather Centre which is located in the south of the study area, 4km from the pollen sampling site (Figure 1.1). Rainfall data, not being recorded at the LWC, have been obtained from the headquarters of Thames Water Authority, also in the south of the study area. Data from these sources are assumed to represent weather conditions over most of the study area, although on the high land to the north and west rainfall will be slightly higher. Data on the synoptic situation around London have been obtained from the weather log of Weather Magazine published by the Meteorological Office.

Hourly records of temperature, sunshine, cloud cover, humidity, rainfall amount and intensity, wind speed and duration, and weather situation and daily records of maximum and minimum temperature, rainfall, hours of sunshine, and synoptic situation are stored, along with the pollen data, in the database.

3.3 ANALYSIS OF THE POLLEN DATA.

3.3.1 The Nature of the Pollen Data

The pollen counts obtained from the Burkard sampler are in the form of a two-hourly count for each of the 65 different pollen taxa. This data then allows an analysis for diurnal variations, for day-to-day variations and for seasonal variations in the pollen count. For the day-to-day analysis the pollen counts are aggregated from midnight to midnight so that they may be used with the meteorological data which is divided and aggregated by the same method. For analysis of seasonal trends, the daily pollen counts are used as five day averages in order to eliminate the affects of short-term variations in the weather. The five-day average pollen counts may then be drawn up as a pollen calendar for each year.

Analysis of the pollen data has concentrated on the common and allergenic pollen taxa. These include Gramineae, believed to be the chief cause of hayfever in Great Britain, and Betula, Quercus, Corylus, Platanus, Urtica and Compositae, plants that are believed to produce allergenic pollen (Davies, 1989). Also considered as common pollen taxa, although there is little evidence to suggest that they invoke allergic reactions, are Acer, Pinus, Picea, Ulmus, Taxus, Alnus, Salix, Tilia, Castanea, Rumex, Sambucus, Rosaceae, Ligustrum, and Plantago.

Other more exotic pollen types are little considered in this study as their origin is indeterminable (they may originate from either natural vegetation or cultivated gardens) and their appearance spasmodic.

3.3.2 Definition of the 'Pollen Season'.

The length of each pollen season is also determined at this stage to define the time period for which further analysis would be performed. A closely defined pollen season is necessary to preclude resuspended pollen from the analysis. Several methods have been considered to delimit a pollen season, including a visual definition and the methods previously used by Mullenders *et al* (1972), Davies & Smith (1974), Pathraine (1975), Lejoly-Gabriel (1978), Viandder & Koivikko (1978), Nilsson & Persson (1981) and Driessen *et al* (1989, 1990).

The method adopted is that of Nilsson & Persson whereby the start of the season is defined as the time when the sum of the daily pollen counts reaches 2.5% of the total pollen sum and the close as the time when the sum reaches 97.5%. This is a simple way of including 95% of the total pollen catch, but it can, however, only be calculated in retrospect after the end of the pollen season.

3.3.3 Statistical Analysis of the Pollen Data

The pollen data are initially displayed graphically to determine the nature of the data and the obvious trends. Analyses of variance are then calculated between the pollen counts recorded under different categories of the meteorological variables to identify linear relationships. Where linear relationships are observed, the influence of individual meteorological variables is examined for both the hourly and daily pollen counts through correlation analysis. In order to distinguish the weather variables of greatest importance to pollen dispersal, partial and multiple correlation analysis is then performed.

Throughout the analysis the statistical packages of SPSSX and SPSS/Pc are used (Norusis 1986, SPSS/Pc 1987, SPSS/Pc Trends, 1987).

3.3.4 Models of Pollen Concentration

For further statistical analysis the pollen data are used in different forms to test through multiple regression analysis, which method of analysis explained most variance in the observed pollen counts and which of the meteorological variables accounted for this.

The data is firstly used as the raw pollen counts, then as logged counts, as normalized counts, as logged and normalized counts and as counts relative to the seasonal trend of the pollen season.

Raw Pollen Counts.
Hourly and daily pollen counts are used unaltered in the analysis.

Normalized Pollen Counts

Because of the wide variation in the total pollen sums recorded between the three years sampling (for example, the total Betula pollen catch varied between 318 and 5251 grains) the pollen counts are normalized to take account of this. The formula :-

$$np = \frac{p \times 1000}{\Sigma p}$$

where np = the normalized pollen count

p = the raw pollen count

Σp = the years total pollen count

is used following the methodology of Moseholm, Weeke and Peterson (1987). By this method, pollen counts from years of different pollen production potentials can be directly compared.

Logarithmically Transformed Pollen Counts

The use of parametric statistical tests necessitates that the data be normally distributed. As the pollen counts of all taxa recorded tend to cluster towards zero with very few exceptionally high values, the counts are also logged before use in the analysis.

Normalized/Logged Pollen Counts

The above two transformations are combined to produce a normal distribution of pollen counts with the affect of year-to-year variations in pollen production eliminated.

Smoothed Seasonal Curves

An alternative method of analyzing the pollen data is to use, not the absolute or transformed data values, but the deviation of the pollen count from the expected seasonal value. This method takes into account the potential pollen production as it varies through the season and can examine the effect of the meteorological variables in causing variations from this. Various methods of computing the seasonal curve are tested. By the method of least squares a polynomial curve is computed for each pollen season. The deviation of the observed pollen concentration from the corresponding value on the smoothed curve may then be regarded as either an exponential function or a product of powers function of the meteorological variables (the predictor variables).

Alternative Methods of Producing Smoothed Seasonal Curves

Another method of smoothing the daily pollen counts is the use of 5 and 10 day running averages. An alternative method tested is not to compute a smoothed curve in advance, but, instead, the seasonal variation is described by a second power expression of an accumulated meteorological predictor variable, for example temperature or sunshine.

For each of the pollen taxa studied in detail the above 'models' of pollen concentration are tested with the pollen data and meteorological variables in a stepwise multiple regression program to determine which provided the highest level of explanation for the observed variance.

Because of the observed delay in the response of daily pollen concentrations to sudden rises in temperature, the counts are analyzed with regard to some of the meteorological variables from the previous day.

The hourly and daily pollen counts are also analyzed using auto-correlation analysis to test whether the pollen data are in fact changing in response to external factors, or whether the counts are influenced more by their previous values.

CHAPTER 4

SEASONAL VARIATIONS IN POLLEN ABUNDANCE

4.1 INTRODUCTION.

Data on pollen abundance collected over three seasons in north London show marked seasonal variations. These differences must be considered before any conclusions are drawn from the examination of daily and hourly patterns as these will be influenced by the underlying seasonal trends. These differences will be analysed in relation to meteorological conditions and biological patterns of pollen abundance.

The seasonal variations in pollen abundance take two forms; pollen seasons can vary either in their timing or abundance. During the three years of pollen monitoring, the start of pollen seasons are observed to vary by up to three weeks, as for example did Betula pollen between 1987 and 1988. Pollen seasons may also vary in their magnitude between years. For example, in north London the total seasonal catch of Urtica pollen varied between 5182 grains in 1987 and 146 grains in 1989 (Table 4.1).

Variations between the timing and abundance of pollen between years derive from a combination of influences. The two main controls that operate are meteorological factors and the natural flowering rhythms of plants.

It is generally accepted that meteorological conditions affect the production and dispersal of pollen in several ways. The timing of flowering seasons and the quantity of pollen liberated are influenced directly by the contemporary weather conditions. For example, warm, dry weather will generally promote high levels of pollen production (Hyde 1950, Davies and Smith 1973) although prolonged dry periods may lead to decreased pollen production because of drought stress in the plants. In contrast, cool wet weather generally suppresses pollen production. Hyde (1952) also observes that the quantity of tree pollen production also varied according to the weather conditions of the preceding year, particularly conditions during the late summer when pollen is formed in the anther of the plant.

TABLE 4.1 CUMULATIVE YEARLY POLLEN COUNTS (SUM OF AVERAGE DAILY POLLEN CONCENTRATIONS).

	1987	1988	1989
Acer	48.36	59.08	65.18
Aesculus	57.34	45.26	41.94
Alnus	18.02	13.46	71.36
Betula	5251.96	318.43	2429.67
Carpinus	32.98	11.45	59.96
Castanea	226.15	56.78	25.47
Compositae	38.14	110.16	37.20
Corylus	32.06	16.34	24.73
Cruciferae	44.74	74.93	53.93
Fagus	4.13	7.66	74.86
Fraxinus	20.39	1128.93	88.55
Gramineae	3956.76	3471.48	2330.17
Pinus	184.08	813.35	1705.56
Populus	23.04	31.31	38.41
Plantago	69.11	36.65	32.45
Platanus	947.50	576.15	185.64
Quercus	991.53	614.23	1277.78
Ranunculaceae	11.72	9.28	3.86
Rumex	267.89	52.30	49.39
Salix	63.18	53.05	74.05
Sambucus	75.75	56.37	29.27
Taxus	118.70	167.21	422.22
Tilia	95.66	23.37	21.68
Ulmus	2.78	2.30	8.81
Umbelliferae	13.96	21.95	12.13
Urtica	5182.38	2443.43	146.00

However, other authors have noted that pollen production in many tree species may vary on a cyclical basis (Anderson, 1974b, Janzon *et al*, 1977, Nilsson & Persson, 1981, Hicks, 1985, Goldberg *et al*, 1988 and Atkinson & Larsson, 1990). Few works have investigated these variations and contradictory evidence emerges from the studies which have been conducted. Hyde (1952) concluded that Betula and Fagus vary over a two year cycle and that Quercus exhibited a five year one. Similarly Anderson (1974) reported that in Denmark quantities of Betula, Quercus and Fagus pollen vary on a biennial basis in phase with one another. The most recent work in Great Britain to investigate seasonal variations in pollen abundance concluded that no biennial rhythm in pollen abundance was evident (Bonny, 1980). However Nielson (1977) reports cycles for Quercus and Fagus in England of between five and seven years. These cycles seem to be an inherent physiological characteristic of the species, possibly related to nutrient exhaustion following abundant fruiting, or to the accumulation of photosynthesate giving energy reserves to initiate a major reproductive effort. These biotic rhythms occur regardless of prevailing weather conditions, although the immediate release and dispersal of pollen will be governed by meteorological factors.

The seasonal variation of pollen abundance and timing will be examined in north London to establish whether patterns of variation occur and whether they are in phase with the cycles proposed by other workers. These patterns will be interpreted in relation to both meteorological conditions and the flowering phenology of plants.

4.2 RESULTS.

The pollen calendars of the three years sampling are displayed for individual species as Figures 4.1 - 4.11. The pollen counts for each pollen taxa are plotted as five day average counts to smooth the curves and to eliminate the effect of short term variations in weather er conditions. The calendars then allow comparison of the years for variations in both the timing of the start and duration of pollen seasons and in pollen abundance. The three pollen seasons may also be examined individually.

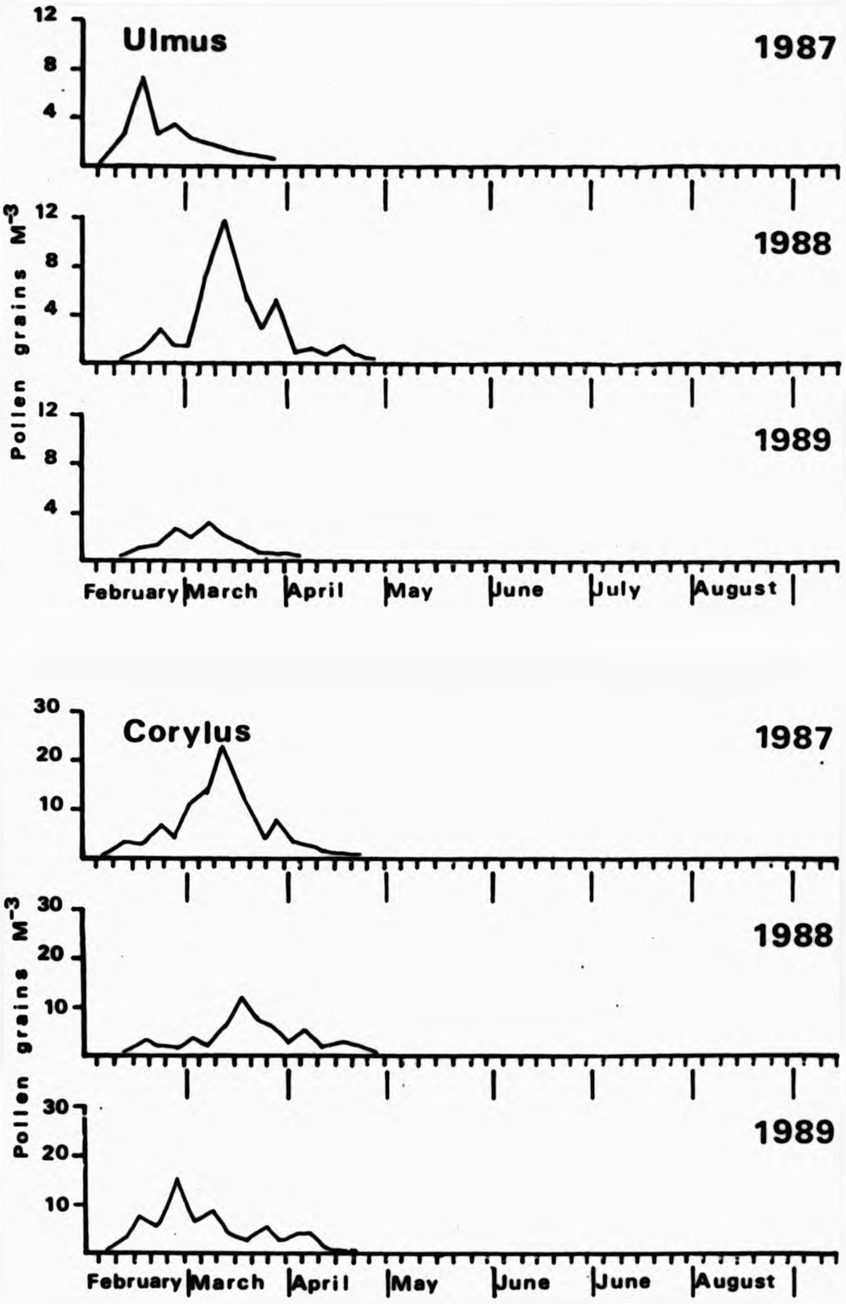


Figure 4.1 Five day average variation of Ulmus and Corylus pollen, 1987 to 1989.

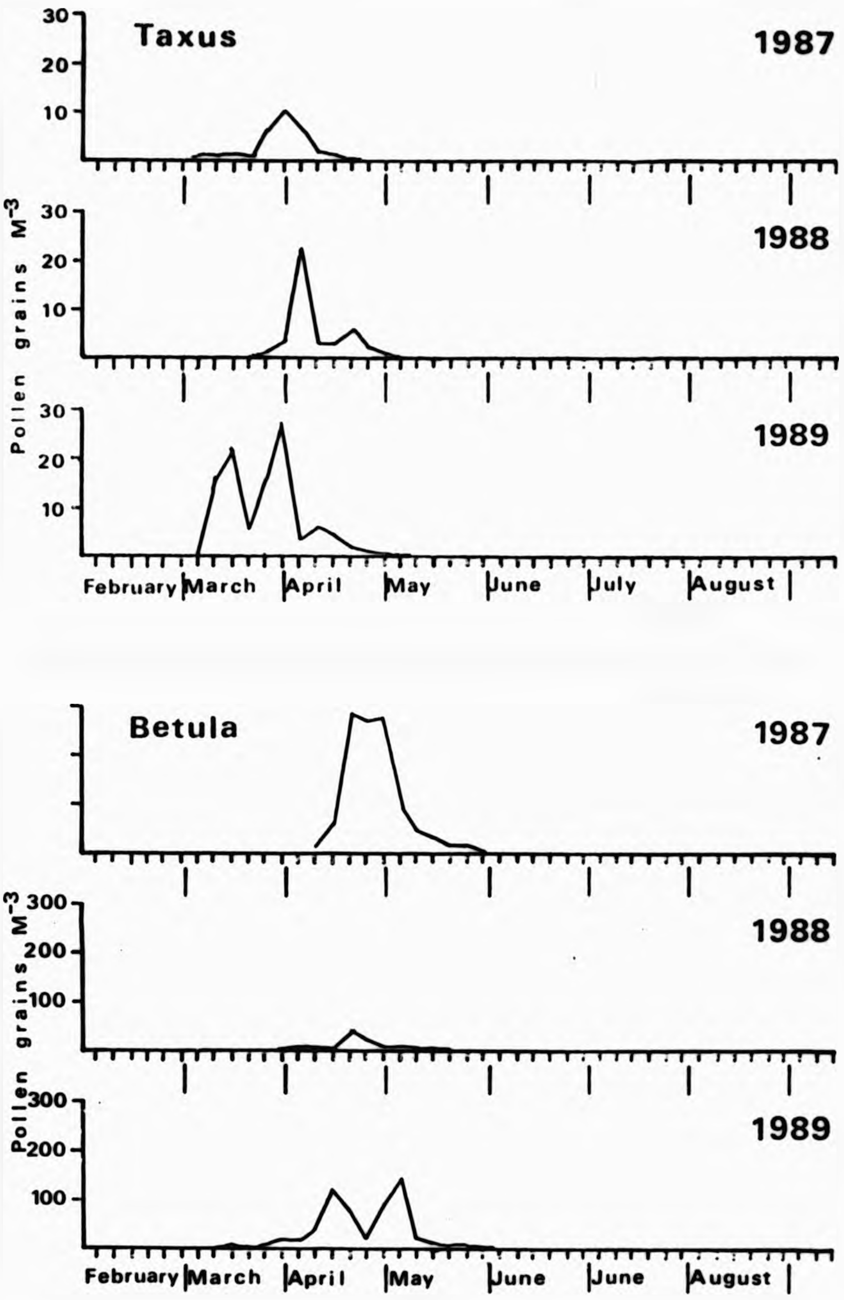


Figure 4.2 Five day average variation of _Taxus_ and _Betula_ pollen, 1987 to 1989.

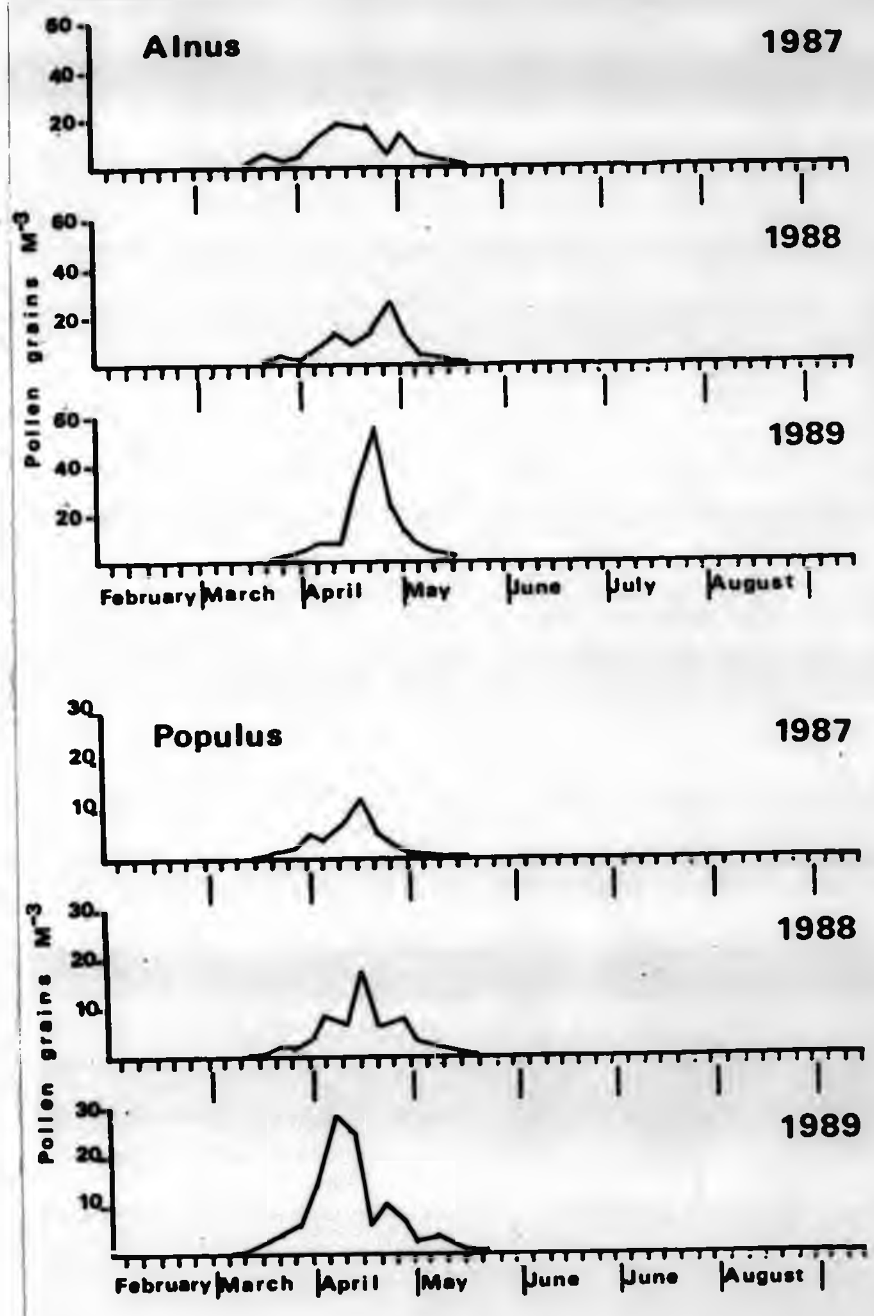


Figure 4.3 Five day average variation of *Alnus* and *Populus* pollen, 1987 to 1989.

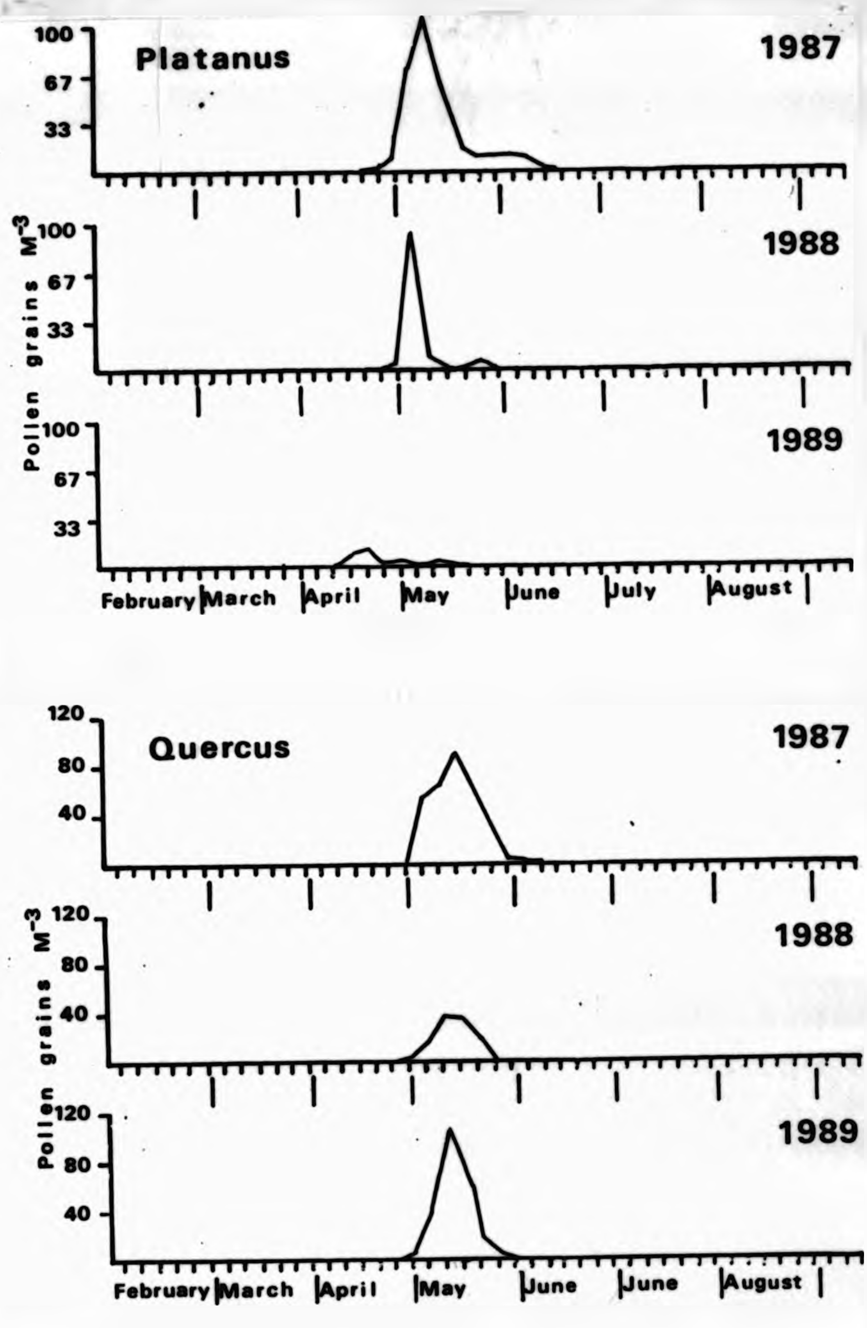
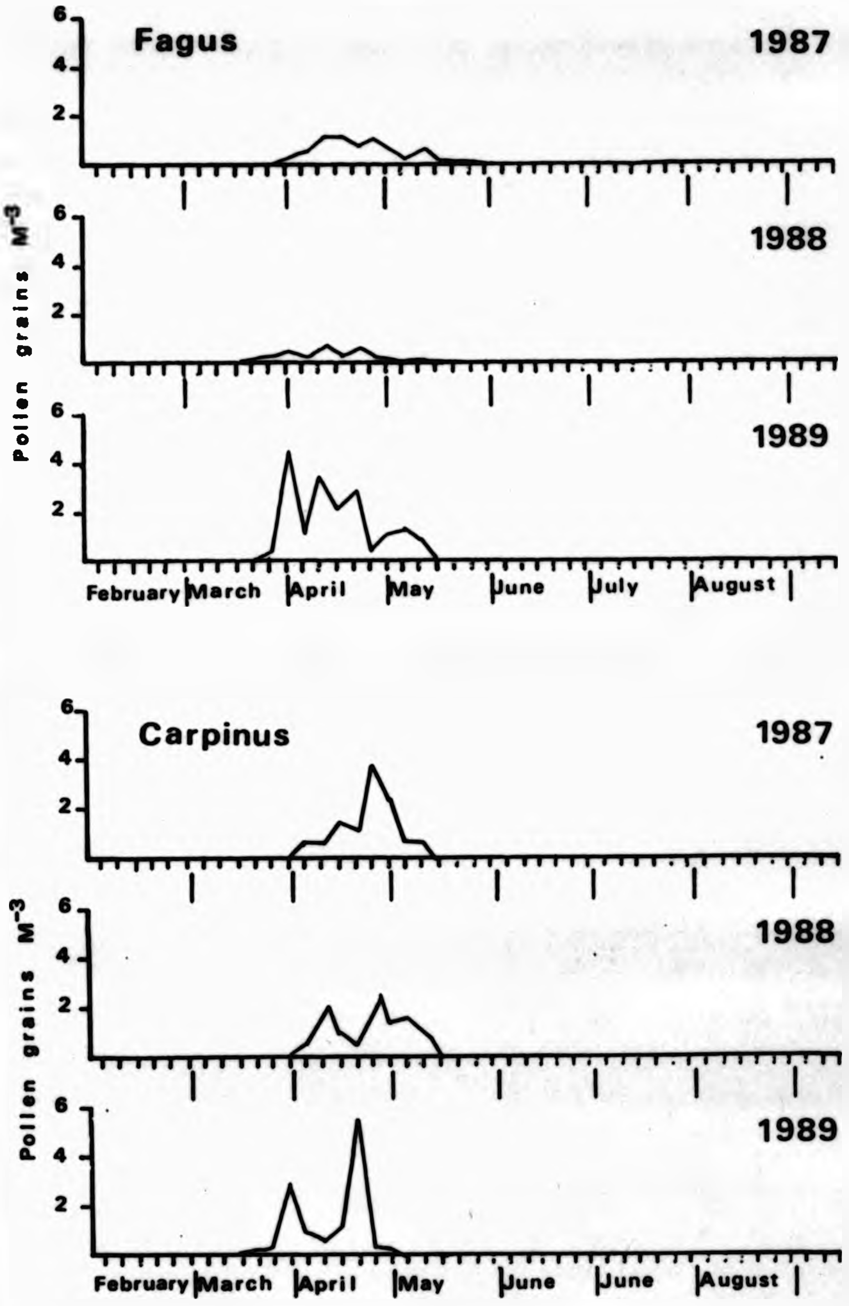


Figure 4.4 Five day average variation of *Platanus* and *Quercus* pollen, 1987 to 1989.



'igure 4.5 Five day average variation of *Fagus* and *Carpinus* pollen, 1987 to 1989.

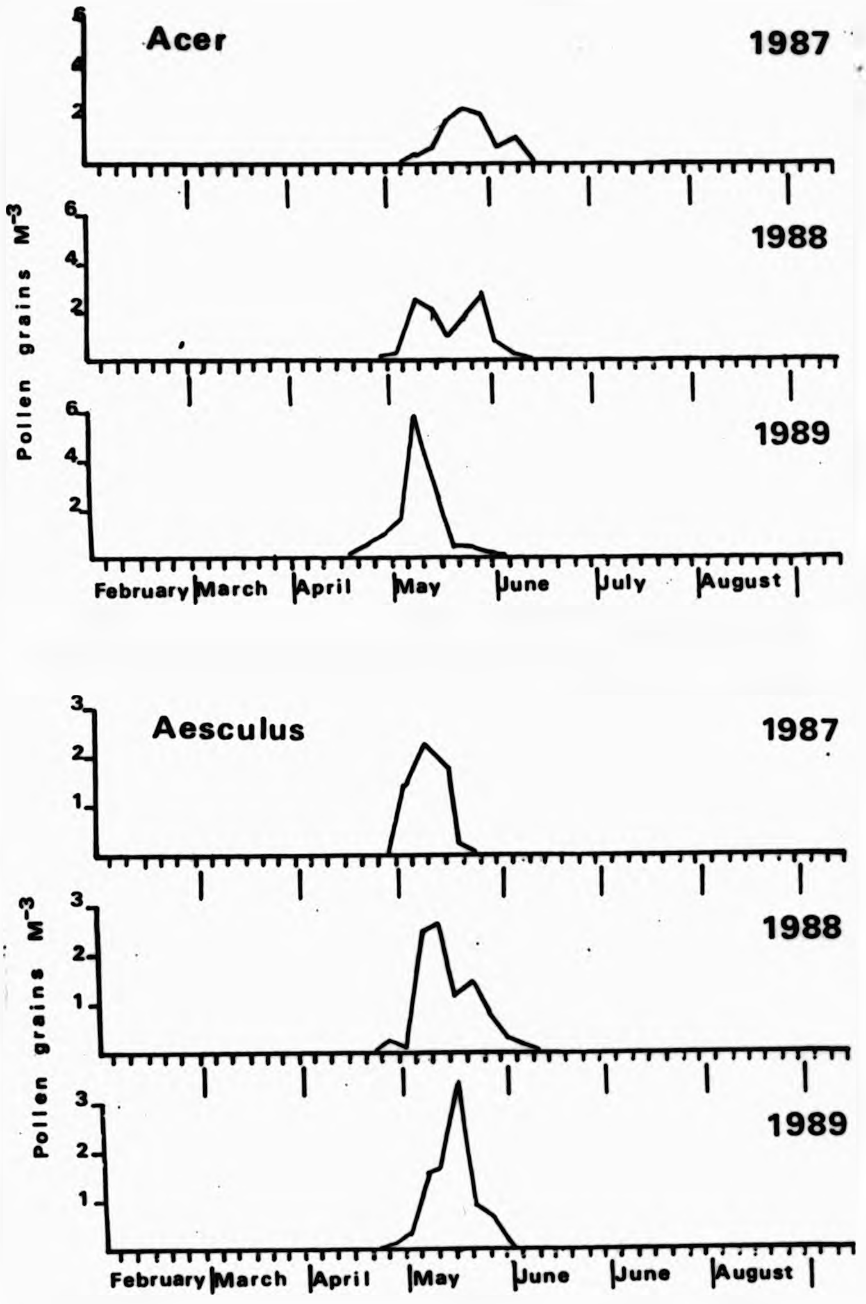


Figure 4.6 Five day average variation of Acer and Aesculus pollen, 1987 to 1989.

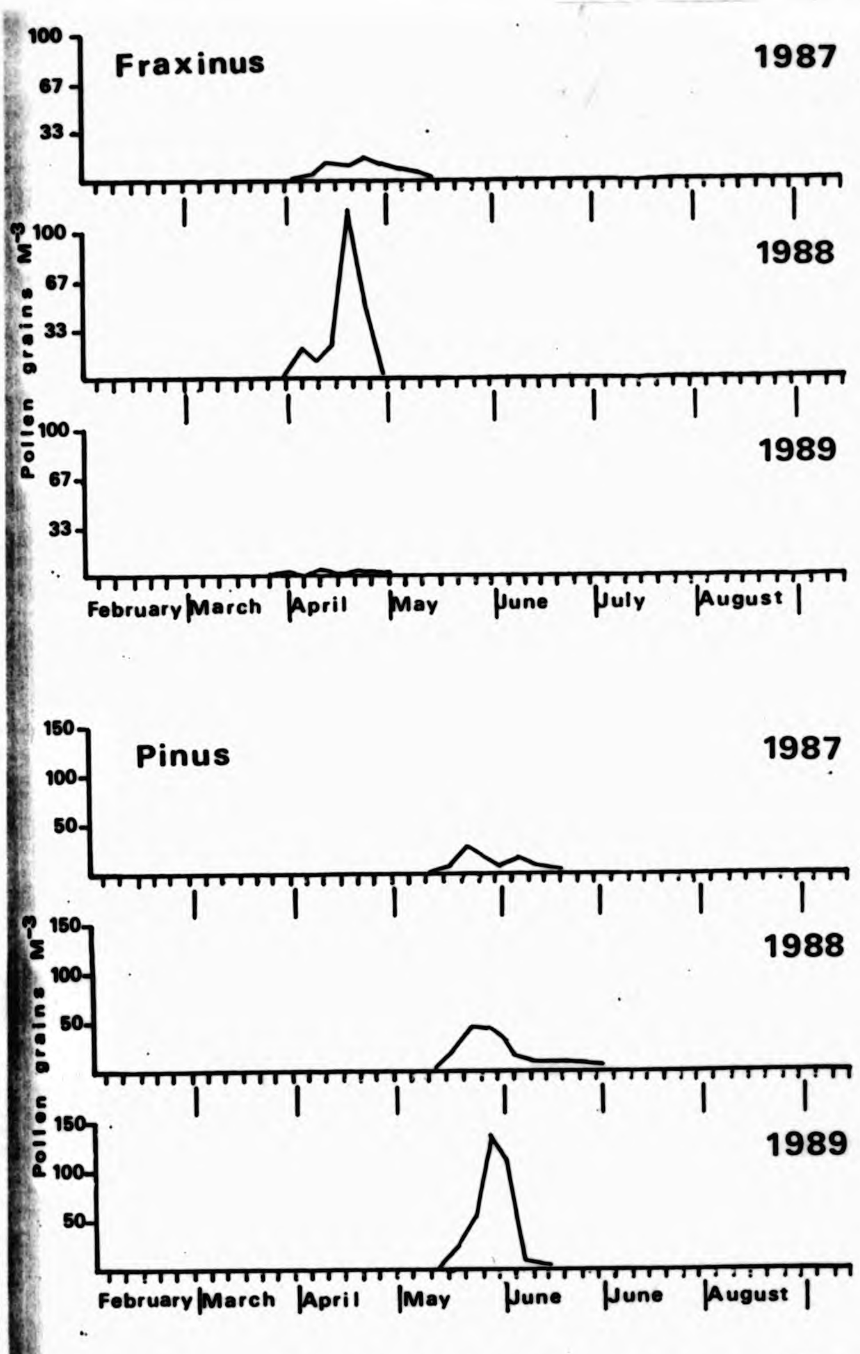


Figure 4.7 Five day average variation of *Fraxinus* and *Pinus* pollen, 1987 to 1989.

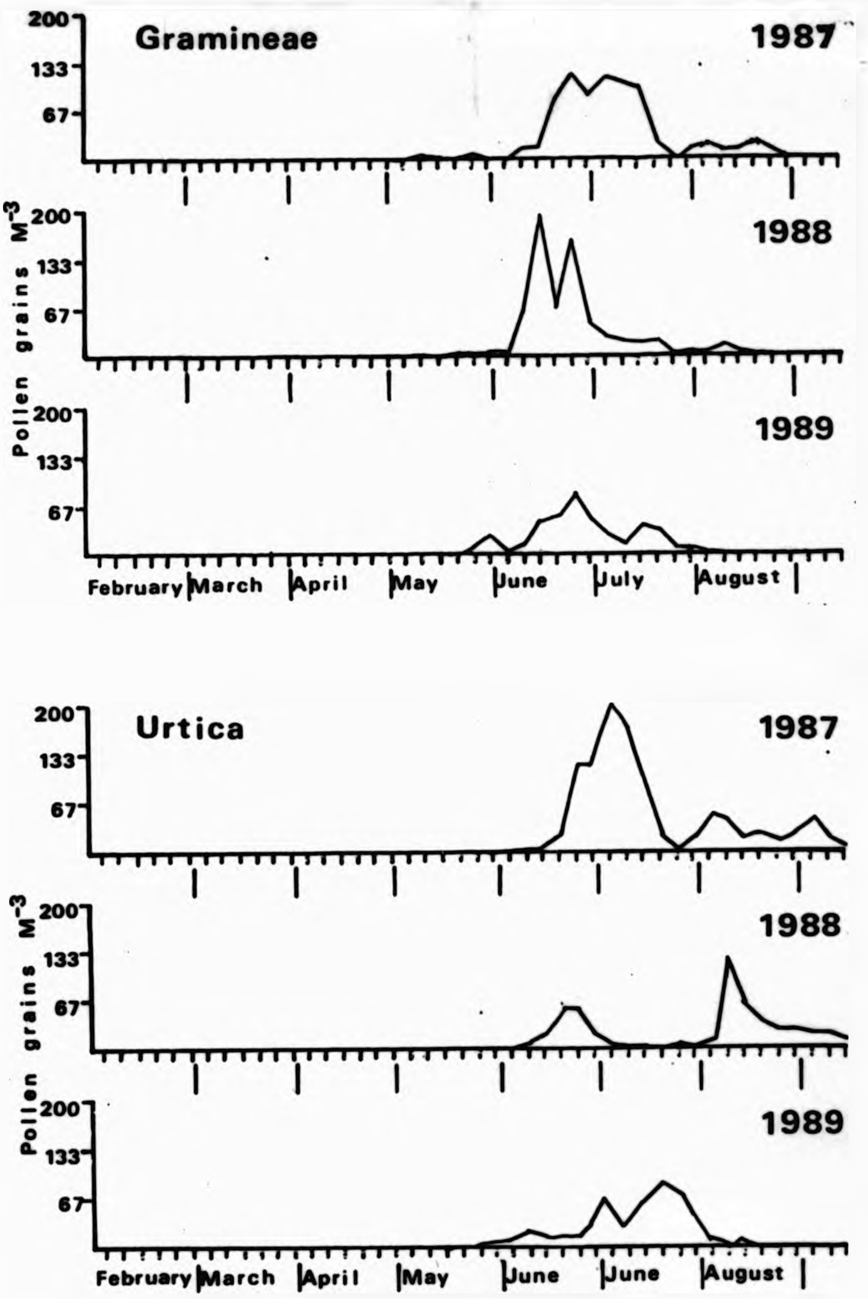


Figure 4.8 Five day average variation of Gramineae and Urtica pollen, 1987 to 1989.

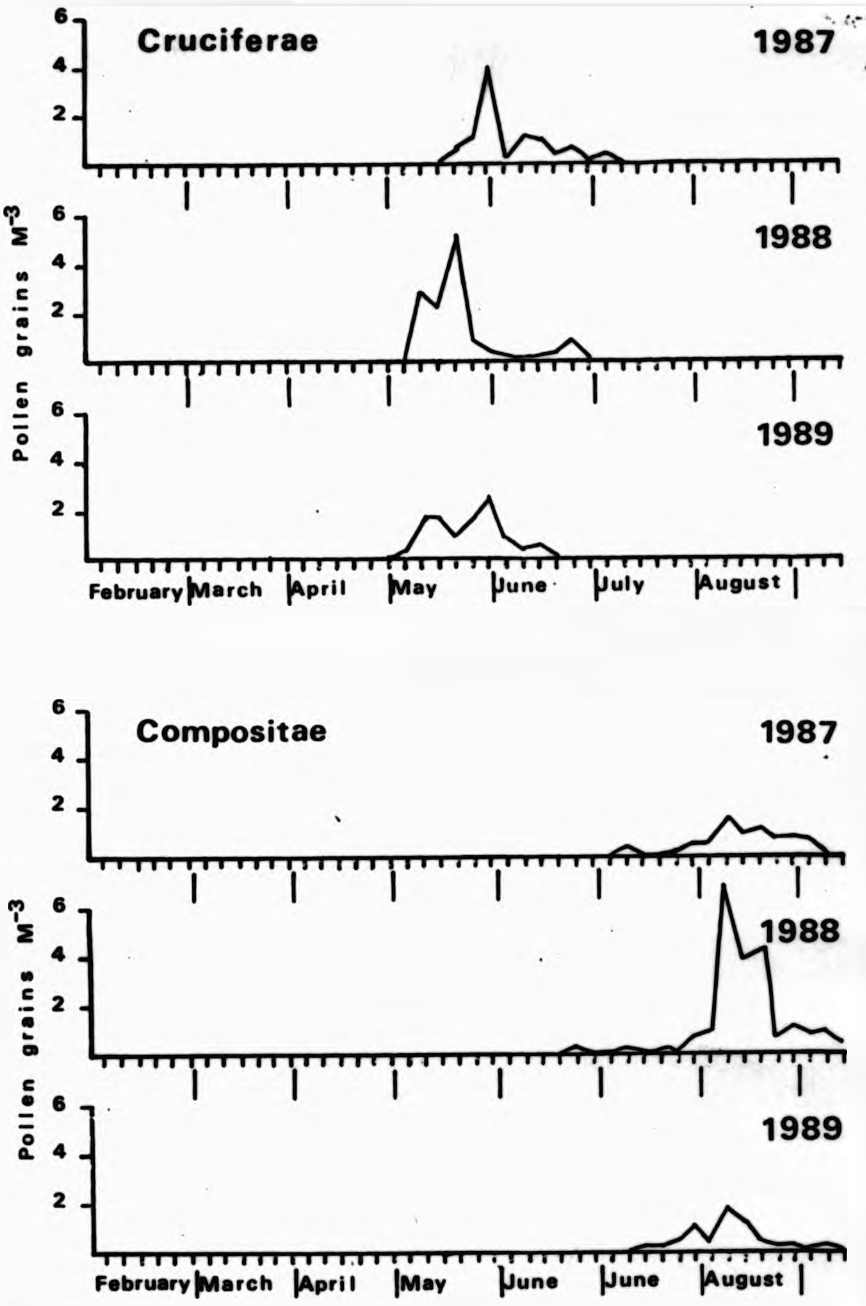
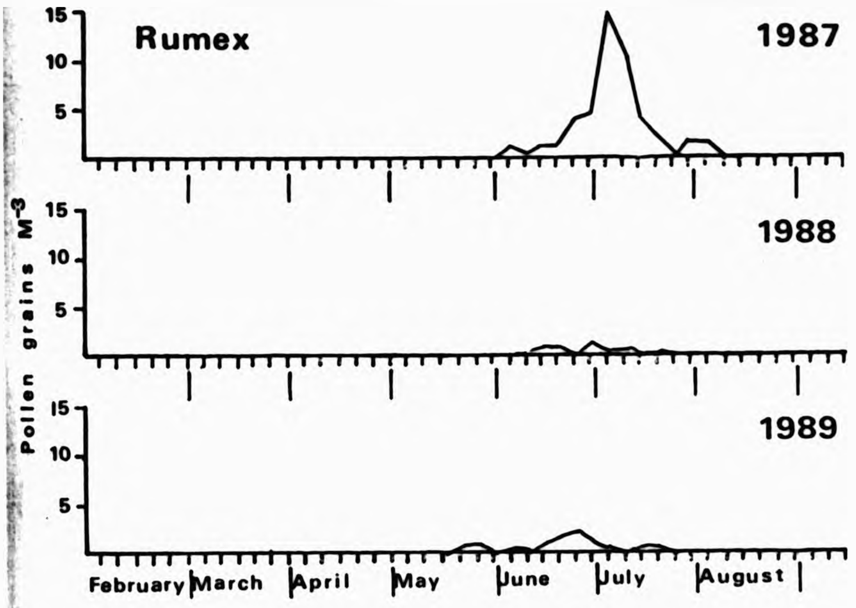


Figure 4.9 Five day average variation of Cruciferae and Compositeae pollen, 1987 to 1989.



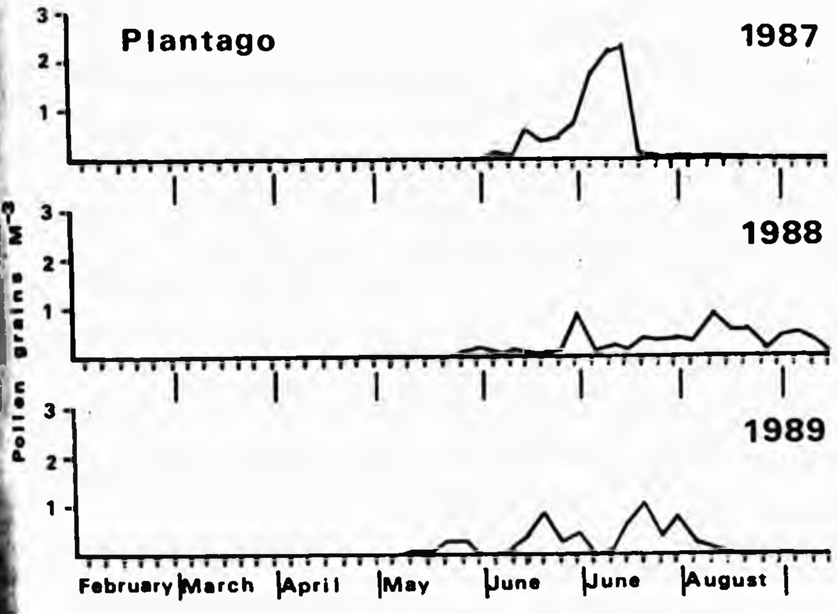


Figure 4.10 Five day average variation of Rumex and Plantago pollen, 1987 to 1989.

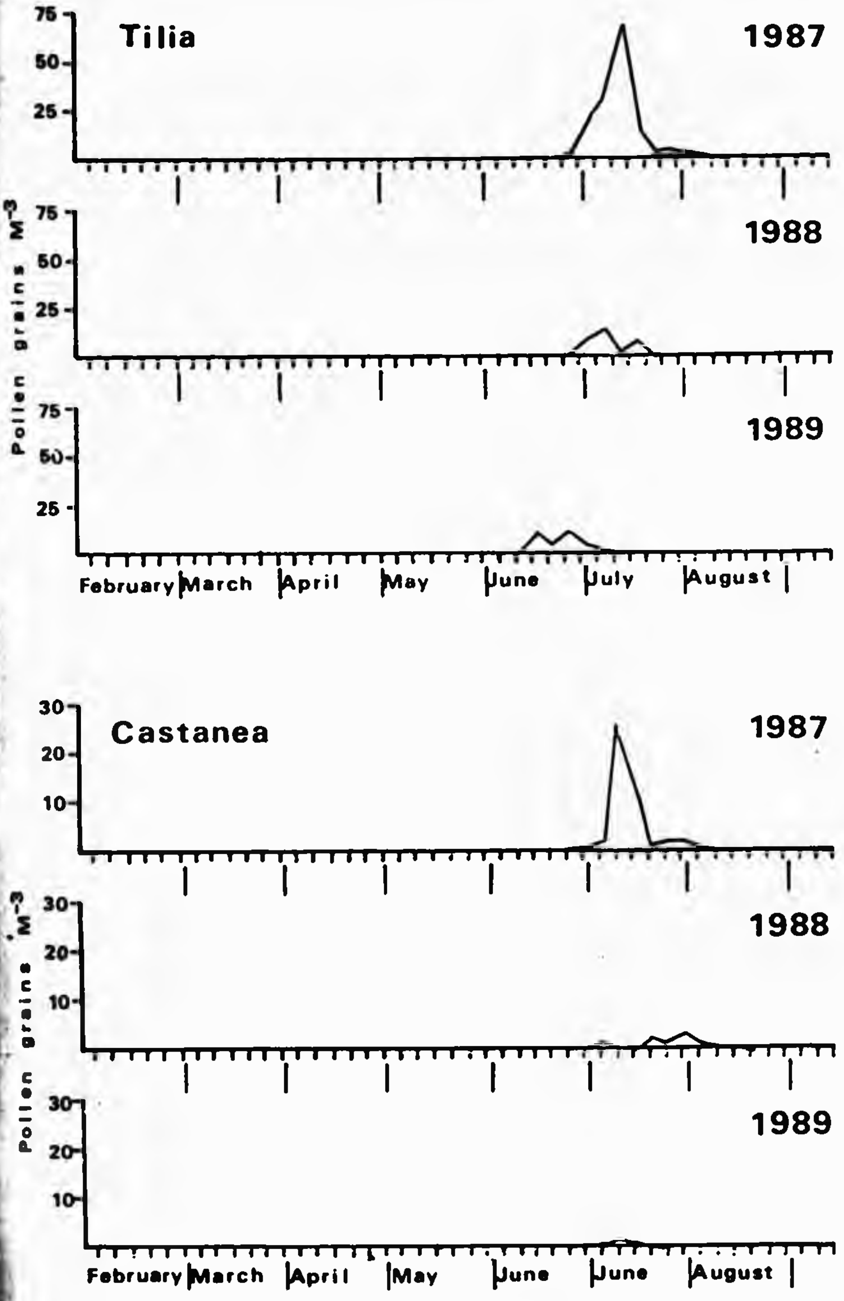


Figure 4.11 Five day average variation of Tilia and Castanea pollen, 1987 to 1989.

1987

The 1987 pollen season started in mid-February when trace amounts of Ulmus, Corylus and Taxus pollen were recorded (Figures 4.1 and 4.2). Concentrations of Taxus and Corylus rose to 9 grains M^{-3} and 17 grains M^{-3} respectively over a five day average in March, but then both counts declined following a period of cool, wet weather. The total arboreal pollen count rose at the end of March as the flowering of Alnus, Populus and Taxus coincided (Figure 4.3). Pollen concentrations were then steady until the warm sunny weather of mid-April when the level of Betula pollen increased dramatically (Figure 4.2). The peak daily concentration of Betula pollen was 373 grains M^{-3}. Platanus pollen however did not rise above a level of 10 grains M^{-3} (Figure 4.4). From the beginning of May, the Betula pollen count declined, while the counts of Quercus, Fagus, Carpinus, Aesculus, Acer, and Pinus increased (Figures 4.4 to 4.7). During May and June the total arboreal pollen count subsided an pollen from herbaceous species appeared for the first time. Gramineae and Cruciferae pollen were the first non-arboreal pollen to be recorded, with low levels present until the second week of June, when the Gramineae count rose dramatically to a daily peak of 118 grains M^{-3}, (Figure 4.8). The Gramineae pollen season lasted for five weeks, until mid-July. Throughout the months of June and July, the concentration of other herbaceous pollen taxa rose gradually (for example, Urtica, Plantago, Rumex, Compositae and Chenopodiaceae, Figures 4.8 to 4.10, mostly reaching maximum counts in early August. The summer flowering arboreal species, Tilia and Castanea (Figure 4.11), first appeared in the species spectrum in late June and were present until the end of July.

1988

The pollen production for most species in 1988 was considerably below that of 1987. The first pollen grains of the season appeared in early March, comprising mostly Corylus, Taxus and Fraxinus. Ulmus did not pollinate prolifically until mid-March, later than in the previous year (Figure 4.1). In mid-March through to early April Taxus, Salix and Corylus peaked in their pollen production, following which the total pollen concentration declined briefly, as it did in 1987. By mid April the Fraxinus pollen concentration reached 191 grains M^{-3} (24 hour average) in marked contrast to the negligible counts for this species recorded in 1987 (below 10 grains M^{-3}, Figure 4.7). In contrast to the high levels of Fraxinus pollen recorded, the concentration of

Betula pollen peaked at only 68 grains M^{-3} (24 hour average) in mid-April, compared to a peak daily count of 373 grains in 1987 (Figure 4.2).

The peak production of Platanus and Quercus coincided in the first half of May, as in 1987 (Figure 4.4). However, the counts for Quercus pollen were lower than in the previous year, peaking at only 37 grains M^{-3} (5 day average). During late May, the counts of these two species declined, while levels of Acer, Aesculus and Pinus rose to dominate the pollen count.

Late May also saw the start of flowering in some herbaceous species. Pollen from Gramineae, Urtica, Rumex and Plantago was present at low levels from the end of May through to early June, when concentrations started to rise as the weather became warmer and dryer. The peak Gramineae pollen concentration was recorded in the second week of June, with a daily count of 408 grains M^{-3}.

Late June also saw the emergence of pollen from the summer flowering trees, Tilia and Castanea. The maximum concentration of Tilia pollen occurred in early July, the same time as in 1987 although the pollen concentration reached only 1.5 grains M^{-3} (5 day average) in contrast to 7.2 grains M^{-3} in 1987 (Figure 4.11). Concentrations of Castanea pollen in 1988 were also lower than those recorded in the previous year.

Pollen from Urtica was present in the air from May, but did not reach its peak concentration until August; 122 grains M^{-3} averaged over a five day period. Compositae pollen also reached a peak concentration in early August at 6.8 grains M^{-3} (5 day average). Low levels of Gramineae, Urtica and Compositae pollen were then recorded through until mid-September.

1989

The start of the 1989 pollen season followed the same general pattern of the previous two years. The pollen spectra comprised low levels of Corylus, Ulmus, Taxus and Alnus until early March when first Taxus and then Alnus flowered in abundance (Figures 4.1 to 4.3). Corylus and Alnus pollen declined in mid March but the total arboreal count increased as the pollen production of Taxus, Betula and Fraxinus rose. By late March Fraxinus peaked in concentration but at a far lower level than in 1988 (Figure 4.7). Both Fraxinus and Alnus flowered two weeks earlier in 1989 than in the two preceding years.

Populus also flowered during this period producing the same low concentrations of pollen typical of previous years. The concentration of Betula increased in mid April (Figure 4.2) but then declined reflecting a period of cool, wet weather. At the end of April concentrations of Betula recovered to peak at 380 grains M^{-3} (24 hour average) in the first week of May. Minute quantities of other pollen types, for example Fagus and Carpinus (Figure 4.5) were also present in the spectrum. Quercus and Pinus pollen concentrations rose in early May, reaching a daily average maximum of 150 grains M^{-3} and 229 grains M^{-3} respectively in the middle of the month.

Herbaceous types began to appear in the pollen spectrum in early May and increased in abundance through the month. The Gramineae pollen season started 7 days earlier than in the previous year, in late May (Figure 4.8), but the total seasonal count was only 2330 grains, lower than in either of the two previous years (Table 4.1). Both the peak concentration and the total seasonal catch of Urtica pollen was also lower in 1989 than in 1987 or 1988 (Figure 4.8 and Table 4.1).

4.3 ANALYSIS OF SEASONAL VARIATIONS IN POLLEN COUNTS.

Differences between the pollen counts of the three years studied are investigated using the analysis of variance statistic. Because the pollen data are log-normally distributed, a log-transformation is applied to fill the requirements of normally-distributed data for analysis of variance statistics. The variance is then calculated between the daily pollen counts of each year sampled and differences significant at the 95% confidence level considered. The seasonal variations of each pollen taxa are displayed by Figures 4.1 to 4.11 in the form of a calendar for each year to show the differences in the timing and abundance of the pollen seasons. The results of the analysis of variance tests are displayed as Table 4.2. Differences in the timings of pollen seasons are investigated by the use of the start, length and finish of a pollen season. These parameters are defined using the methods of Nilsson and Persson (1981) as outlined in Chapter 3.

TABLE 4.2 ANALYSIS OF VARIANCE BETWEEN CUMULATIVE YEARLY POLLEN COUNTS.

SIGNIFICANT DIFFERERENCES

SPECIES	ALL	NONE	87>88	88>89	89>87	89>88	88>87	87>89
Acer					*			
Aesculus		*						
Alnus					*	*		
Betula	*		*			*		*
Carpinus				*	*			
Castanea			*					*
Compositae				*				*
Corylus		*						
Cruciferae		*						
Fagus					*	*		
Fraxinus				*			*	
Gramineae		*						
Pinus					*	*		
Populus		*						
Plantago		*						
Platanus				*				*
Quercus		*						
Ranunculaceae		*						
Rumex		*						
Salix					*		*	
Sambucus		*						
Tilia				*				*
Taxus					*	*		
Ulmus					*	*		
Umbelliferae		*						
Urtica	*		*	*				*

4.3.1 Abundance.

From an initial examination of the analysis of variance statistics, (Table 4.2) several groups of pollen taxa which vary with one another may be noted. The early spring flowering trees, namely Ulmus, Taxus and Alnus, show the same seasonal variation with a significantly higher abundance in 1989 than in 1987 or 1988 (Table 4.2). This variation may also be seen on the pollen calendars, Figures 4.1, 4.2 and 4.3. Also visible is a variation between the start of the pollen seasons between years. For example, Taxus (Figure 4.2) starts to pollinate in late March in 1987 and 1988, but in 1989 the pollen season starts almost 3 weeks earlier at the beginning of the month.

Other spring flowering trees that show similar seasonal variations are Fagus and Carpinus which produce pollen in April. As for the early flowering trees, a significantly greater abundance was recorded in 1989 than in 1987 or 1988. Another species, Pinus shows a similar variation, but releases pollen slightly later in May, Figure 4.7. Platanus and Fraxinus which flower together in late April, early May, both record significantly higher abundance during 1988 than in 1987 or 1989 (Figures 4.4 and 4.7).

The two summer flowering trees recorded in London, Tilia and Castanea, also show similar seasonal variations. Significantly higher quantities of these pollen types were recorded in 1987 than in 1988 or 1989. Other herbaceous species that flower at the same time, July also show similar variations :- Urtica, Rumex and Plantago.

Possible reasons for these synchronized variations include the occurrence of weather conditions favourable to high pollen liberation during the pollen season, conditions favourable to high pollen production during anther formation or the presence of cyclical patterns of pollen production.

However, some pollen taxa show no significant seasonal variation, Gramineae for example (Figure 4.8 and Table 4.2). Neither has Quercus shown any significant variation over the three years of sampling, even though Anderson (1974) observed a biennial rhythm of Quercus pollen production.

4.3.2 Timing.

Fewer variations in the timing of the pollen seasons, compared to their abundance, are evident from the pollen calendars, and the start of most seasons coincides within 10 to 15 days of the start in previous years. Exceptions to this are in the start of the 1989 Taxus pollen season (Figure 4.2) which started in the first few days of March, 15 to 20 days earlier than in the previous years. The 1989 Platanus season also started 15 days earlier than in 1987 or 1988 (Figure 4.4). The start of the Gramineae pollen season has also varied between the three years of sampling, with a progression forward from the 5th June 1987 to the 31st May 1988, to the 23rd May 1989 (Figure 4.8). The length of the season has remained relatively consistent, with a duration of approximately two months, so that the finish of the season has also moved forward accordingly.

The 1989 Tilia season was also earlier than in the previous two years (Figure 4.11). The pollen season commenced at least 10 days earlier than in previous years, and although only moderate levels of Tilia pollen were recorded (less than 2 grains M^{-3} 5-day average, Figure 4.11) the season was almost complete by the time maximum counts were attained in the previous two years.

4.4 DISCUSSION OF THE INFLUENCES ON SEASONAL VARIATIONS IN POLLEN ABUNDANCE AND TIMING.

4.4.1 THE INFLUENCE OF CONTEMPORARY WEATHER CONDITIONS.

During spring 1987 fairly high levels of arboreal pollen coincided with a mild, wet and sunny spring. Maximum concentrations attained by different pollen taxa were 277 grains M^{-3} of Betula pollen over a five day period (Figure 4.2), 106 grains M^{-3} of Platanus pollen (Figure 4.4), 4 grains M^{-3} of Acer pollen (Figure 4.6), 2 grains M^{-3} of Aesculus pollen (Figure 4.6), and 90 grains M^{-3} of Quercus pollen (Figure 4.4). Weather conditions were warmer (+2.6°C), sunnier (104%) and slightly drier in April than the 30 year average, (Table 4.3). Such conditions provide good opportunities for high pollen concentrations.

Spring 1988 recorded meteorological conditions similar to those in 1987, with mild, sunny and wet weather (Table 4.3). However, the pollen concentrations

TABLE 4.3 MONTHLY METEOROLOGICAL FIGURES FOR LONDON COMPARED TO THE AVERAGE FOR THE PREVIOUS 30 YEARS.

TEMPERATURE Difference from mean monthly temperature (°C)
SUNSHINE Percentage of average monthly sunshine hours
RAINFALL Percentage of average monthly rainfall

1986

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temp.	-0.7	+0.1	-0.1	-2.3	-0.9	+1.2	+0.5	-1.6	-1.8	+1.2	+1.9	+1.8
Sun.	78	95	112	92	88	110	95	90	108	112	117	125
Rain	121	108	100	149	108	33	108	116	41	129	106	111

1987

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temp.	-3.1	+0.4	-1.7	+2.6	-0.8	-1.9	-0.2	+0.2	+0.1	-0.2	-0.4	+1.0
Sun.	110	92	95	104	101	65	93	98	101	116	63	77
Rain	27	84	100	98	113	137	151	98	66	313	69	25

1988

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temp.	+2.1	+1.4	+0.5	+0.2	+0.9	-0.8	-2.0	+0.2	-0.4	+0.3	-0.3	+2.5
Sun.	112	184	79	99	103	78	85	111	102	106	139	84
Rain	210	68	140	68	88	86	149	105	50	100	26	16

1989

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temp.	+2.8	+2.9	+2.7	-1.7	+3.9	+1.6	+3.8	+2.5	+1.5	+1.9	+0.7	+1.5
Sun.	120	149	90	99	158	126	145	152	90	109	167	77
Rain	51	105	133	156	25	69	73	97	20	95	39	216

recorded were generally lower than those in 1987. Betula. for example, recorded only 36 grains M^{-3} as the maximum five day average count, Acer 2.7 grains M^{-3}, Aesculus 2.5 grains M^{-3} and Quercus 37 grains M^{-3}. The only exceptions to these lower counts were those for Platanus and Fraxinus. Platanus recorded concentrations similar to those in 1987 with a five day average of 94 grains M^{-3} (Figure 4.4). This peak lasted for only a short period and the total pollen count for year was lower than in 1987 (Table 4.1) Fraxinus recorded significantly higher counts in 1988 compared to 1987 (Table 4.2) attaining a maximum five day average count of 117 grains M^{-3} (Figure 4.7).

Concentrations of the summer flowering arboreal and herbaceous taxa were generally lower in 1988 than in 1987 or 1989, especially for species which pollinate in July. If the meteorological data for this period are examined, both June and July experienced temperatures and levels of sunshine lower than the 30 year mean (Table 4.3), conditions not conducive to high levels of pollen production. However, the lower than average rainfall in June may have offset the potentially low pollen production and resulted in counts similar to those of the previous year. In contrast July 1988 experienced rainfall 149% of and temperatures 2°C below the seasonal norm, which led to all pollen taxa recording lower counts than in July 1987. Following the onset of warmer, dryer weather in August, the counts of herbaceous pollen types rose quickly.

The spring of 1989 was exceptionally dry and mild with rainfall only 90% and temperatures 1.1°C above the 30 year average (Table 4.3). The early spring flowering trees, Corylus, Taxus and Alnus recorded fairly high concentrations (Figures 4.1, 4.2 and 4.3). The counts of other spring flowering trees rose quit rapidly in late March and early April. Betula. for example, recorded a five day average count above 100 grains M^{-3} by mid-April, but then a period of cold, wet weather suppressed all pollen counts (Figure 4.2). The coincidence of the height of the Platanus pollen season with this period resulted in the five day average count peaking at only 10 grains M^{-3} whereas in the two previous years it had attained more than 90 grains M^{-3} (Figure 4.4). Reduced counts of Fagus (Figure 4.5), Carpinus (Figure 4.5), and Fraxinus (Figure 4.7) were also recorded during this period of wet weather. Following the onset of warmer, dryer weather in early May, the pollen counts of most arboreal species responded rapidly to the favourable conditions with counts similar to previous years. The Betula count peaked at 142 grains M^{-3} (5 day average) within five days of the inset of warm weather, but the season soon came to a close as reserves of pollen became depleted, even though the weather conditions remained favourable. Other pollen taxa continued to record fairly high counts, Quercus (Figure 4.4), Aesculus (Figure 4.6) and Pinus (Figure 4.7) for example.

Meteorological conditions during the summer of 1989 were conducive to high pollen production with high temperatures and little rainfall (Table 4.3). The Gramineae pollen season responded to this with an early start in late May (Figure 4.8). The remainder of the season did not however attain the maximum levels or total counts of previous years reaching only 82 grains M^{-3} (Figure 4.8) over a five day average and a yearly total of 2330 grains (Table 4.1). The summer flowering tree taxa, Tilia and Castanea, showed a trend similar to that of Gramineae, their pollen seasons starting earlier than in the previous years, but only low pollen concentrations being recorded (Figure 4.11). Some herbaceous species also exhibited similar patterns, most noticeably Urtica, (Figure 4.8) and Compositae (Figure 4.9). These low pollen concentrations at times of weather conditions usually favourable to high pollen production may be a result of drought stress in the plants following three successive months with lower than average rainfall (Table 4.3). The lack of moisture available to the plants would limit their growth and pollen production capability. This phenomenon appears most markedly in the tall, leafy plants most exposed to the sun, Gramineae and Urtica for example, and least in low growing, fleshy plants such as Plantago which will be better shaded and more able to conserve supplies of water.

4.4.2 INFLUENCE OF METEOROLOGICAL CONDITIONS DURING THE POLLEN FORMATIVE PERIOD.

Several authors have noted that warm, dry weather during the period that pollen is forming within the anthers of a plant result in increased pollen concentrations during the pollen season. For the spring flowering trees, Hyde (1952) stated that this period is during the preceding late summer and early autumn, whereas for Gramineae, Davies and Smith (1974) believed the period to be April and May, the two months preceding the pollen season. This is also the time of pollen formation for the summer flowering trees and most other annual herbaceous plants.

Some indications of the relationships between annual pollen production and weather conditions during the time of pollen formation emerge from the data collected over three years in north London, especially for the arboreal pollen taxa. The autumn of 1986 was dry and sunny with rainfall 41% and sunshine hours 108% of the seasonal norm (Table 4.3). Correspondingly, the following spring, most tree pollen concentrations were high, in particular Betula (Figure 4.2) and Quercus (Figure 4.4). In contrast, the autumn of 1987 was cool and wet with rainfall 190% of and temperatures similar to the 30 year mean (Table 4.3). Most pollen counts were then low during the spring of 1988. There was however an exception to the generally low counts, as Platanus attained concentrations similar to those in 1987, (Figure 4.4). The autumn weather of 1988 was dry and sunny, but with cold periods (Table 4.3) and subsequently the arboreal pollen counts in 1989 were higher than in 1988. The reason why few 1989 pollen counts attained the maximum levels of the 1987 season might be the period of cool, wet weather experienced in late-April which suppresses the actual pollen concentrations, even though the potential for high levels existed.

If the meteorological conditions during the Gramineae pollen formative period are examined similar trends emerge. Davies and Smith (1974) reported that the temperatures recorded during the two months preceding the Gramineae pollen season would determine both the start and the total abundance of the season. They observed that during the years 1961-70 above average temperatures during April and May resulted in an early start to the season and an increased seasonal pollen catch.

Examining firstly the influence of meteorology on the timing of the Gramineae pollen season. The start of the Gramineae pollen season is shown on Figure 4.8 and the corresponding temperature data by Table 4.3. On initial examination of these data, the average temperature recorded during May appears more influential to the start date than does that during April. For example, during April 1987 the average daytime maximum temperature was 2.6°C above the seasonal mean and the Gramineae pollen season started on the 5th June. In contrast, in April 1988 and 1989 the average temperatures were +0.2°C and -1.7°C respectively and yet the Gramineae pollen season started in late May. If the average temperature during May are considered then a better fit with the pollen season start date is apparent than for the temperature during April. For example, the high temperatures recorded during May 1989 were followed by a start to the Gramineae pollen season at least seven days earlier than in previous years.

The influence of spring temperature on the seasonal abundance of pollen may be examined from Tables 4.1 and 4.3. Total seasonal Gramineae pollen abundance varied considerably between 1987 and 1989, however these data prove anomalous to the theories suggested by Davies and Smith, 1973. They state that if a pollen season starts early, then it will continue for longer and is more likely to be a severe season for hayfever sufferers, ie. that the total seasonal pollen catch will be high. This is clearly not so in London over the three years monitored as a negative relationship between the two variables is apparent. This is still true if other methods of defining the start of pollen season are used, for example the 50 grains M-3 threshold put forward by Frankland and Davies (in Davies and Smith 1973).

4.4.3 THE INFLUENCE OF RHYTHMS OF POLLEN PRODUCTION.

Some indications of the presence of rhythms of pollen production emerge from the sampling record, although sampling over a much longer period is necessary to confirm these patterns.

Annual variations in the abundance of Betula and Quercus pollen recorded in Islington support the theory of a biennial cycle of pollen production in these species with district peaks in abundance occurring in 1987 and 1989. The 1989 Betula pollen record attained high levels of almost 140 grains M^{-3} (Figure 4.2) as a five day average in spite of the cool and wet conditions that occurred during the season. Quercus pollen was recorded at maximum levels of 90 and 106 grains M^{-3} in 1987 and 1989, but at only 37 grains M^{-3} in 1988 (Figure 4.4). However, three years data are clearly insufficient to determine whether these are truly two year cycles. Other pollen taxa do not follow the trends reported by Hyde (1952) and Anderson (1974b) according to the sampling record. These authors suggested that Fagus would follow a biennial rhythm in phase with Betula, but this is clearly not so in London as negligible quantities of Fagus pollen were trapped in 1987 and 1988, but its abundance increased to a significantly higher level in 1989 (Figure 4.5 and Table 4.1). This single year of relatively high pollen production might be in keeping with the five to seven year cycle of pollen production proposed for Fagus by Nielson (1977) but clearly sampling over a much longer period would be needed to determine this.

Other arboreal pollen taxa do not display any discernible rhythm in their pollen productivity. Fraxinus pollinated prolifically in 1988 (reaching a maximum concentration of 117 grains M^{-3} over a five day period, Figure 4.7) but appeared in negligible concentrations in 1987 and 1989, even though weather conditions were favourable during its flowering season. This pattern suggests a possible cycle of two years or more, not in phase with Betula, Quercus or Fagus. The pattern of Platanus pollen abundance bears some resemblance to that of Fraxinus, with concentrations recorded during 1988 significantly higher than those in 1987 or 1989 (Table 4.2). However, the 1989 Platanus flowering season coincided with a period of cold, wet weather during the last week of April, which may have reduced the potential count for this year.

Pinus displays yet another pattern of pollen production. The concentrations recorded in 1989 are significantly higher than those in 1987 or 1988 (Figure 4.7) and those in 1988 are also slightly higher than in 1987 although this difference is not significant (Table 4.2). Jager (1989) could not establish a clear pattern of variation of Pinus in Vienna even over thirteen years.

Janzon *et al* (1977) observed marked variations in the pollen production of Alnus and Picea indicating that patterns of productivity may be evident in pollen taxa other than Betula, Quercus and Fagus, although these rhythms can not be identified over just three years of sampling.

The summer flowering trees, Tilia and Castanea, exhibit similar patterns of abundance. The concentrations recorded in 1987 are significantly higher than those in 1988 or 1989 (Table 4.2) in spite of the weather conditions in June and July of 1988 and 1989 which were more favourable to high levels of pollen production than those in 1987. To determine whether or not this is evidence of a cycle of pollen production of three years or more would need a sampling record over a much longer period. No previous authors have reported cyclical patterns of pollen production in Tilia or Castanea.

No regular patterns have been identified in the release of pollen from the Gramineae family or other herbaceous plants.

Anderson (1974b) states that in Denmark all the spring flowering trees with obvious cycles in pollen production were in phase with one another. However, little synchronization appears to exist in the London pollen record. Within the three years monitored, Betula and Quercus experienced years of peak abundance in 1987 and 1989, whereas maximum counts for Fraxinus and Platanus featured in 1988. Other species, such as Pinus, produced low quantities of pollen in 1987, and increased in abundance in 1988 and 1989. Anderson suggested that the synchronization of peak pollen years resulted from an important climatic episode that limited pollen production in one year so severely that all cycles were disrupted and recommenced from the following year. Such an event does not appear to have taken place in London.

4.5 IMPLICATIONS OF BIOLOGICAL RHYTHMS IN POLLEN PRODUCTION TO ALLERGY SUFFERERS.

No research has been conducted in Great Britain to determine the concentration thresholds at which susceptible people begin to experience allergic rhinitis due to tree pollens. Even the acceptance that allergic rhinitis can be provoked by such pollen taxa as Betula, Quercus, Platanus and Corylus is recent (Davies, 1989).

Research conducted in Finland by Viandder and Koivkko (1978) has established that a Betula count of over 80 grains M^{-3} at the start of the season and 30 grains M^{-3} at the end will invoke an allergic reaction in all those allergic to Betula pollen. Less pollen is needed to invoke symptoms at the end of the season as exposure to an allergen will further sensitize a sufferer. Based on these results, the thresholds of allergic response were exceeded in London for a period of thirty days in 1987 and for two separate periods of ten and seven days in 1989, whilst in 1988 the threshold was not reached at all. However, the relevance of the application in London of thresholds devised in Finland must be questioned as Betula pollen counts will be much higher there and arboreal-pollinosis more common. Nevertheless, the variation in Betula pollen from year to year, by a magnitude of as much as seven, does mean that people allergic to the pollen may not realise it as they may not suffer at the same time every year.

No threshold levels for other pollen types have been established, and so no comments on the frequency with which they are exceeded can be made. However, the fact that people do suffer allergic reactions to tree pollen means that threshold levels are being surpassed and so the identification of the patterns of abundance of these pollen type will be of importance to the sufferers.

4.6 SUMMARY.

Marked seasonal variations in pollen abundance have been shown to occur for several common arboreal pollen taxa, specifically Betula, Quercus, Fraxinus, Platanus, Pinus, Tilia and Castanea. Variations in abundance relate both to the influence of meteorological conditions on pollen production and to variations in the flowering phenology of trees. However, the seasonal variations of the non-arboreal pollen types such as Gramineae, Urtica, Rumex and Plantago for example are not marked and may be accounted for by the variations in the weather conditions between seasons.

The seasonal patterns of pollen abundance occurring in London agree, to some extent, with the patterns recorded in Denmark by Andersen, (1974b) and in Sweden by Goldberg *et al* (1988). They do not, however, agree closely with previous works on the seasonal variation of pollen abundance conducted in Great Britain by Bonny (1980) and Nielsen (1977) although the patterns identified by Nielsen may only become evident in the north London pollen record if sampling were to continue over a much longer time period.

Fewer variations in the timing of pollen seasons exist than for pollen abundance. No regular patterns in the timing of pollen seasons have been established and, instead, the variations relate to weather conditions preceding and during the pollen season. Warm and dry conditions result in an early start to a pollen season, while cool and wet conditions may delay or obscure the season.

CHAPTER 5

DAY TO DAY VARIATIONS IN POLLEN ABUNDANCE.

5.1 INTRODUCTION.

When the day to day variations of most pollen taxa are plotted over the three pollen seasons, large fluctuations are observable, (for example, Gramineae pollen, Figure 5.1). Such fluctuations have been commonly observed by other investigators, for example Hyde (1952) and Bringfelt (1982) who have considered them closely in relation to temperature and rainfall. However, many questions remain unanswered as to the exact role of meteorology in the release and dispersal of pollen grains, and especially in the influence of weather in producing high pollen counts. The identification of these weather conditions which may lead to an accurate forecast of a high pollen count is of particular importance to hayfever sufferers.

This chapter will therefore consider the day to day variations in pollen abundance. The variation in the behaviour of particular pollen taxa will firstly be considered in relation to meteorological conditions, followed by a discussion of the role of individual meteorological factors in causing day to day variations.

Several pollen types are selected for detailed investigation of daily patterns of pollen abundance. Pollen taxa are chosen on the basis of their abundance, allergenic potential and source area by the following criteria. A pollen taxon should firstly occur in abundance to enable a detailed consideration of the day to day variations, without being affected by spasmodic fluctuations in occurrence. Abundant pollen types are also more likely to fill the second criterion, that of allergenicity, than are types that occur only intermittently. The allergic potential of a pollen type is controlled by the protein content of the pollen wall, but this will cause hayfever problems only if the pollen occurs in sufficient quantity to sensitize those people exposed to the antigen. The third criterion for selection is that the pollen types chosen should provide a contrast in their source areas to allow consideration of different transport processes.

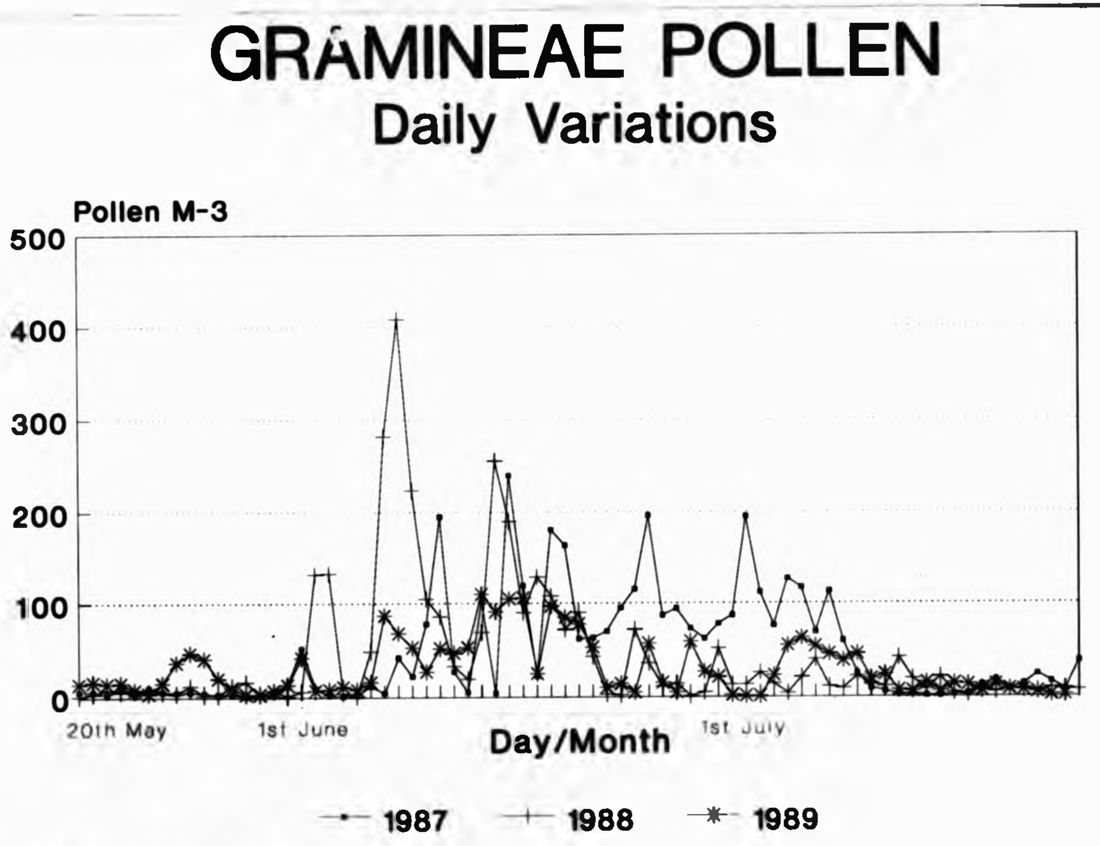


Figure 5.1 Daily Variation of Gramineae Pollen, 1987 - 1989.

The first choice of pollen taxon selected is Gramineae as it is the main allergenic pollen type in Europe (D'Amato & Spieksma, 1991), it is very abundant and it originates mainly from outside of London (Davies & Smith, 1973). Betula is also an abundant pollen taxon, it is a known allergen in Scandinavia (Johanssen 1975, Wallin 1991, and Hjelmroos 1991) and it is also thought to provoke hayfever symptoms in Great Britain (Davies, 1989). Betula pollen originates from both inside and outside the London urban area (Burton, 1983). The next choice of pollen type is Platanus which is particularly abundant within London and can provoke an allergenic reaction on a local scale (Davies, 1989). Platanus pollen originates almost totally within central London where it is planted as a street and park tree. Other pollen types recorded during the three years of sampling are excluded from this analysis as they derive from an uncertain origin or are not perceived to cause allergenic problems.

Twelve meteorological variables are used in this present work on the analysis of daily variations in the pollen count. They comprise daily maximum, minimum and average temperature, average relative humidity, hours of sunshine, rainfall, maximum and average cloud cover, maximum and average wind speed, predominant wind direction and synoptic situation.

Although other meteorological variables such as air turbulence, mixing height and air trajectories have previously are likely to influence pollen dispersal, these data are not recorded in central London and are not available for use in this study. Instead the stability of the lower atmosphere has been estimated by using Pasquil's (1962) stability categories which estimate stability by the use of wind speed and sunshine intensity during the day and wind speed and cloud cover over night. Stability of the atmosphere is classified as one of six classes from very stable through neutral to very unstable.

Due to the significant variation between the total yearly catches of Betula and Platanus pollen (Chapter 4), the daily pollen counts have been standardized relative to the total seasonal pollen catch following the methodology of Moseholm, Weeke and Peterson (1986). By this method pollen counts from years of different pollen production potentials can be compared directly. Because the daily pollen counts of the three taxa examined are log-normally distributed, they are also subjected to a log-transformation to satisfy the requirements of normally distributed data for the application of parametric statistical tests.

The logged, standardized pollen counts are then entered into an analysis of variance test to determine significant differences between the counts recorded under different meteorological conditions. Where linear relationships between the pollen counts and the meteorological variables are identified, Pearson product moment and partial correlations have also been calculated to identify the influence of each variable. Because of the inter-relationship between the meteorological variables, the data have also been processed through a stepwise multiple regression analysis to identify which parameters caused most variation in the pollen counts.

However, because of the marked seasonal variation in pollen abundance, the difference between the actual pollen count and the expected, potential value is also correlated against the weather variables. This method takes into account the potential pollen production as it varies through a season. Several methods of producing a smoothed seasonal curve of potential pollen abundance have been used, and the amount of variance in the daily pollen counts explained by the meteorological parameters in each model compared.

An initial attempt to produce a smoothed seasonal curve of potential pollen abundance followed the methodology of McCartney and Lacey (1991). Standardized pollen curves from the three years of sampling are centred relative to the period of maximum pollen production, and the standardized daily counts averaged over the sampling period. A seven day running mean is then taken of this curve, and a smoothed curve calculated for each year proportional to the total seasonal pollen catch. The 'average trend' is then subtracted from each daily pollen count and the difference analyzed in relation to the meteorological variables through Pearson product moment, partial and multiple correlations.

The 'T4253H' function within the SPSS/Pc statistical package (1988) is also used to produce smoothed seasonal curves of potential pollen abundance. This applies a compound data smoother to the pollen counts, firstly with a running median of 4, centred by a running median of 2, and then a running median of 5, centred by a running median of 3. The curve is then resmoothed using running weighted averages. The residual between the smoothed curve and the recorded pollen counts is then used in the analysis described above.

Further detrended pollen curves are produced by fitting standard mathematical curves (such as cubic and quadratic curves) to the pollen data of each season by the method of least squares.

5.2 RESULTS.

5.2.1 GRAMINEAE POLLEN.

An examination of the results of the analyses of variance between the daily pollen counts recorded under different categories of the meteorological variables reveals clear patterns of variation (Table 5.1). Gramineae pollen counts exhibit clear, significant and approximately linear relationships with the parameters of average daytime cloud cover, hours of sunshine, daytime humidity, daily rainfall and maximum temperature. For maximum temperature and hours of sunshine this is a positive relationship, whilst for the other variables it is a negative one.

These relationships can then be examined for significance using Pearsons Correlation coefficient (Tables 5.2 - 5.5). However, because some meteorological variables are interrelated (for example, sunny days will record low average cloud cover), the data are also subjected to partial and multiple correlation analysis, the results of which are displayed in Tables 5.2 - 5.5. Of the partial correlation coefficients of the model using logged and standardized Gramineae pollen counts, the variables maximum temperature and average humidity exhibited the most influence on the daily pollen counts. This influence is confirmed by the stepwise multiple regression analysis which entered these variables and the daily rainfall total and average wind speed into the equation. The interrelationship between all these variables is demonstrated by the relatively small increase in the Multiple R coefficient with the addition of subsequent parameters, ie. from an initial value of 0.58268 of the variation accounted for by the variation in humidity, an additional 0.06465 is gained by the inclusion of temperature and rainfall in the equation, despite the high, significant Pearsons correlation coefficients these display. Intercorrelation probably arises as rainfall is likely to cause high readings of relative humidity, which in turn is dependent on the air temperature, and hence the maximum daily temperature record. The influence of these variables on the pollen count is in agreement with the work of Hyde (1952b) who also recorded lower Gramineae

TABLE 5.1 ANALYSIS OF VARIANCE BETWEEN DAILY GRAMINEAE POLLEN COUNTS (LOGGED/STANDARDIZED) AND METEOROLOGICAL PARAMETERS.
(*denotes groups significantly different at the 95% confidence level)

AVERAGE DAYTIME CLOUDCOVER:
F. Ratio: 11.5987
F. Prob.: 0.0000

Group		Mean Pollen	N	Group 6	4	5	3	2	1
6	7.11 - 8.0octaves	.5213	36						
4	5.81 - 6.5	.8363	24	*					
5	6.51 - 7.1	.8417	26	*					
3	5.1 - 5.8	1.0752	37	*		*			
2	3.1 - 5.0	1.0888	48	*					
1	0.0 - 3.0	1.2762	19	*	*	*			

AVERAGE WINDSPEED:
F. Ratio: 2.5337
F. Prob.: 0.0303

Group		Mean Pollen	N	Group 6	5	1	3	4	2
6	12.0 - max knots	.6749	28						
5	10.01 - 12.0	.8634	32						
1	0.0 - 6.0	.9472	36						
3	7.01 - 8.4	.9624	38						
4	8.41 - 10.0	1.0072	28						
2	6.01 - 7.1	1.1120	28	*					

HOURS OF SUNSHINE:
F. Ratio: 8.6817
F. Prob.: 0.0000

Group		Mean Pollen	N	Group 1	2	3	4	5	6
1	0 - 0.75 hour	.6813	34						
2	0.76 - 3.0	.8099	26						
3	3.01 - 5.2	.9246	27	*					
4	5.21 - 7.5	1.0173	36						
5	7.51 - 11.0	1.0193	43						
6	11.01 - max	1.1324	24	*	*				

SYNOPTIC SITUATION:
F. Ratio: 4.0574
F. Prob.: 0.0020

Group		Mean Pollen	N	Group 6	2	5	4	1	3
6	LP over London	1.4704	3						
2	LP to NE	1.6127	23						
5	LP to NW	1.8586	54						
4	LP to SW	1.9687	11						
1	HP	2.2178	100	*	*				
3	LP to SE	2.2263	5						

TABLE 5.1 (Continued)

AVERAGE DAYTIME HUMIDITY:

F. Ratio: 17.1344
F. Prob.: 0.0000

Group		Mean Pollen	N	Group	6	5	3	4	1	2
6	80.1 - max %	.3579	24							
5	73.1 - 80	.8058	43		*					
3	65.1 - 69	.9117	29		*					
4	69.1 - 73	.9592	29		*					
1	min - 60	1.1975	27		*	*	*	*		
2	60.1 - 65	1.2416	38		*	*	*	*		

DAILY RAINFALL:

F. Ratio: 16.4369
F. Prob.: 0.0000

Group		Mean Pollen	N	Group	5	6	3	4	2	1
5	3.01 - 5.0mm	.4275	23							
6	5.01 - max	.4933	12							
3	0.51 - 1.0	.5024	19							
4	1.01 - 3.0	.7056	13							
2	0.01 - 0.5	.8784	52		*		*			
1	0.00	1.1722	71		*	*	*	*	*	

MAXIMUM DAILY TEMPERATURE:

F. Ratio: 17.0752
F. Prob.: 0.0000

Group		Mean Pollen	N	Group	1	2	3	4	6	5
1	min - 15.0°	.5759	33							
2	15.1 - 17.0	.7267	30							
3	17.1 - 19.0	.8039	42		*					
4	19.0 - 21.0	1.0432	29		*	*	*			
6	25.0 - max	1.1752	23		*	*	*			
5	21.0 - 25.0	1.3682	33		*	*	*	*		

WIND DIRECTION

F. Ratio: 19.2019
F. Prob.: 0.0000

Group		Mean Pollen	N	Group	3	2	4	1
3	181 - 270°	1.6600	69					
2	91 - 180	1.9174	15		*			
4	271 - 360	1.9781	50		*			
1	0 - 90	2.3085	56		*	*	*	

TABLE 5.2 ANALYSIS OF DAILY GRAMINEAE POLLEN COUNTS

MODEL: Logged/Standardized counts YEARS:1987-1989

PEARSON PRODUCT MOMENT CORRELATION COEFFICIENTS:

	Rainfall	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	-.4484	.5489	-.5628	-.4020	.4007	-.2080
N.	130	130	130	130	130	130
P.	.000	.000	.000	.000	.000	.009

FIFTH ORDER PARTIAL CORRELATION COEFFICIENTS:

	Rainfall	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	-.2056	.3032	-.2257	.0457	.0089	-.1851
DF.	123	123	123	123	123	123
P.	.011	.000	.006	.306	.461	.019

STEPWISE MULTIPLE REGRESSION:
Variables entered in the order:-
1. Humidity.
2. Max. Temperature.
3. Daily Rainfall.
4. Average Windspeed.
Multiple R = .65776
$R^2 = .43265$
Durbin Watson Test Statistic = .67958 (positive autocorrelation).
Residuals normally distributed, but positively correlated with the logged/standardized pollen counts.

Variation of residuals with predominent daily wind direction:

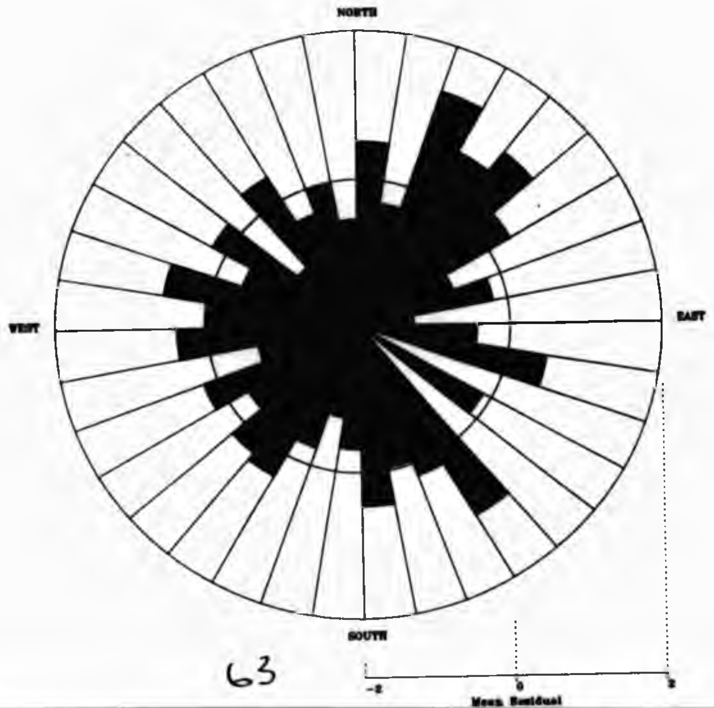


TABLE 5.3 ANALYSIS OF DAILY GRAMINEAE POLLEN COUNTS

MODEL: Quadratic curve (curvefit)   YEARS:1987-1989

PEARSON PRODUCT MOMENT CORRELATION COEFFICIENTS:

	Rainfall	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	-.4913	.6918	-.6456	-.4622	.4390	-.1971
N.	128	128	128	128	128	128
P.	.000	.000	.000	.000	.000	.021

FIFTH ORDER PARTIAL CORRELATION COEFFICIENTS:

	Rainfall	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	-.1974	.5748	.1126	-.2121	-.0512	-.0914
DF.	121	121	121	121	121	121
P.	.021	.000	.080	.008	.111	.332

STEPWISE MULTIPLE REGRESSION:
Variables entered in the order:-
1. Max. Temperature.

Multiple R = .68939
$R^2 = .47526$
Durbin Watson Test Statistic = .72589 (positive autocorrelation).
Residuals normally distributed, but positively correlated with the transformed pollen counts.

Variation of residuals with predominant daily wind direction:

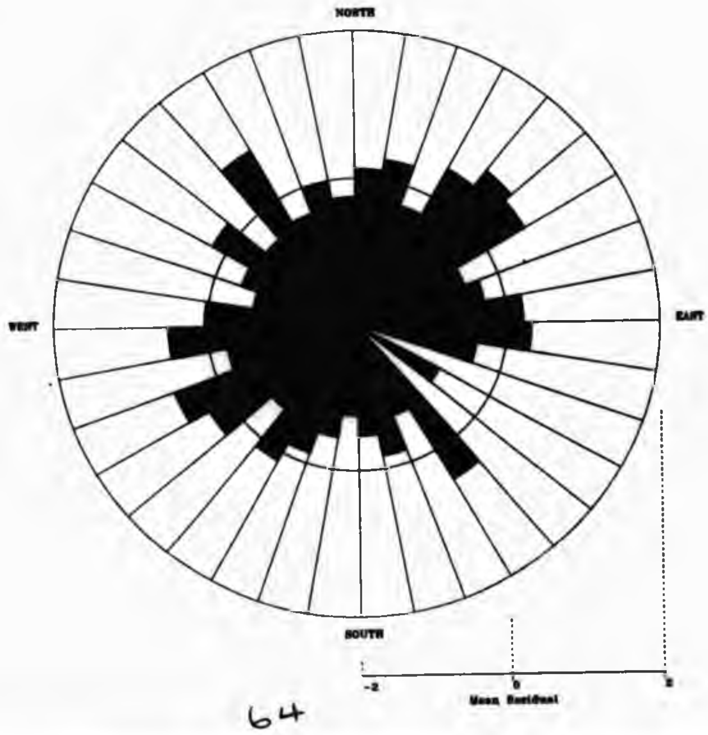


TABLE 5.4 ANALYSIS OF DAILY GRAMINEAE POLLEN COUNTS

MODEL: T4253H YEARS:1987-1989

PEARSON PRODUCT MOMENT CORRELATION COEFFICIENTS:

	Rainfall	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	-.4852	.6653	-.6028	-.4721	.4684	-.2672
N.	128	128	128	128	128	128
P.	.000	.000	.000	.000	.000	.007

FIFTH ORDER PARTIAL CORRELATION COEFFICIENTS:

	Rainfall	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	-.1028	.5263	.0782	-.2074	-.0693	-.0951
DF.	121	121	121	121	121	121
P.	.082	.000	.266	.009	.293	.301

STEPWISE MULTIPLE REGRESSION:
Variables entered in the order:-
1. Max. Temperature.

Multiple R = .61029
R^2 = .35286
Durbin Watson Test Statistic= 1.32096 (positive autocorrelation).
Residuals normally distributed, but positively correlated with the transformed pollen counts.

Variation of residuals with predominent daily wind direction:

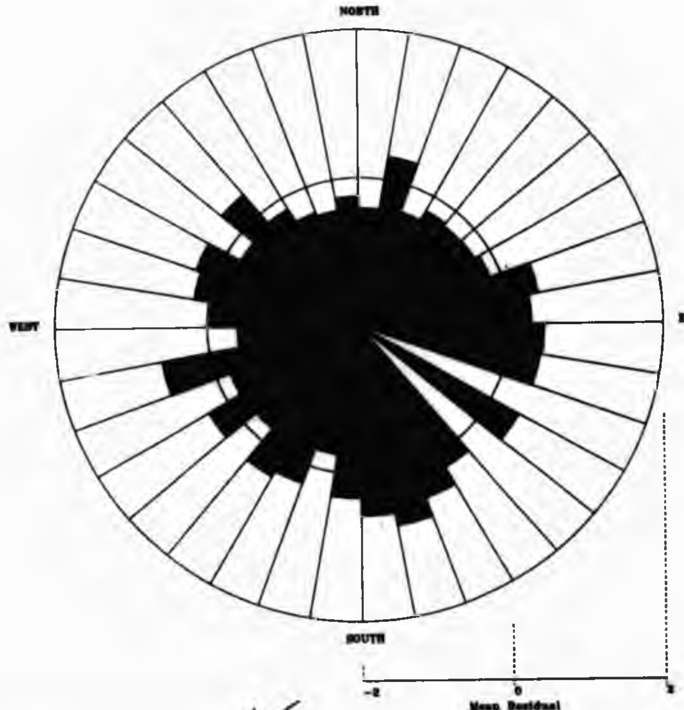


TABLE 5.5 ANALYSIS OF DAILY GRAMINEAE POLLEN COUNTS

MODEL: Counts detrended after McCartney & Lacey (1991)   YEARS: 1987-1989

PEARSON PRODUCT MOMENT CORRELATION COEFFICIENTS:

	Rainfall	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	-.2485	.5881	-.1726	-.3631	.2733	-.1615
N.	81	81	81	81	81	81
P.	.013	.000	.062	.000	.007	.075

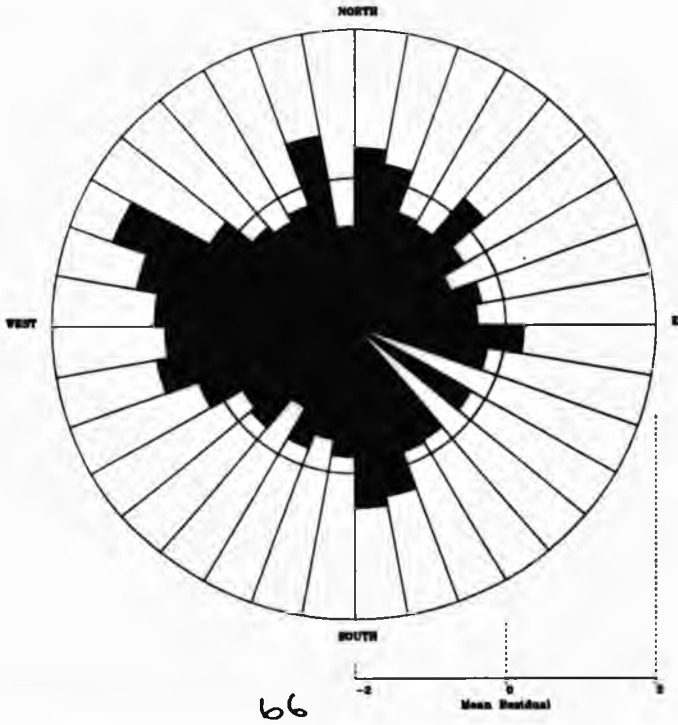
FIFTH ORDER PARTIAL CORRELATION COEFFICIENTS:

	Rainfall	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	-.0079	.5074	.0505	-.2280	-.1214	.0845
DF.	74	74	74	74	74	74
P.	.473	.000	.333	.024	.148	.234

STEPWISE MULTIPLE REGRESSION:
Variables entered in the order:-
1. Max. Temperature.

Multiple R = .58808
R^2 = .34584
Durbin Watson Test Statistic = .96176 (positive autocorrelation).
Residuals normally distributed.

Variation of residuals with predominent daily wind direction:



counts on days of low temperature and high rainfall. Higher counts were recorded on warm, dry days with low relative humidity.

However, if the results of the partial and multiple correlation analyses between the meteorological variables and the detrended Gramineae pollen counts are considered (Tables 5.3 - 5.5) then the parameter that appears to explain the most variation in the Gramineae pollen count is the maximum daily temperature. The importance of average relative humidity becomes slight when compared to the analyses using unsmoothed pollen counts and this variable is not entered into the multiple regression equations of the models using detrended pollen data. Maximum daily temperature is the only variable entered into these models and alone is sufficient to explain up to 56% of the variation in the daily Gramineae pollen count.

The relative unimportance of humidity in these models is in contradiction to previous works where it was considered as one of the most influential variables, (Hyde, 1952b and Galan *et al*, 1989a for example) although Cadman (1991) did not include it in her analyses of daily Gramineae pollen counts in South Africa.

The negative association between the Gramineae pollen count and daily rainfall has been considered by several previous authors who found it to be one of the most influential meteorological parameters (McDonald, 1962, Davies, 1969). However, in this analysis it is included in only one of the multiple regression equations (Table 5.2, logged, standardized Gramineae pollen counts) and there contributed only 2.2% to the increase in the level of explanation. This low contribution is probably explained by the intercorrelation between rainfall and the other meteorological variables: for example, in summer, rainy days are likely to have a lower temperature, a higher relative humidity, a higher level of cloud cover and frequently be windier than dry days.

The parameters of cloud cover, hours of sunshine and average wind speed do not significantly increase the level of explanation of any of the multiple regression equations. The lack of influence of wind speed recorded in London is in marked contrast to the work of Bringfelt *et al* (1982) in Stockholm where they found the average daily wind speed to be the most important meteorological variable in determining the daily Gramineae pollen count.

Likewise, the lack of influence of the hours of sunshine is in contrast to the work of Cadman (1991).

Although the parameters of wind direction and synoptic situation displayed high, significant F ratios in the analysis of variance tests (Table 5.1), these variables could not be entered into the multiple regression equation due to the nature of the data. It is unlikely, however, that data on the synoptic situation would greatly aid in the explanation of the daily variation due to the interrelation with other meteorological parameters. Anticyclonic situations in summer are generally characterized by low wind speeds, clear sunny skies, low rainfall and high temperatures. In contrast, cyclonic weather is generally rainy, windy and cloudy with mild temperatures, all parameters considered independently in this analysis. The position of a cyclone, relative to London, will however determine the wind direction, a variable also not included in the multiple regression analysis.

To determine the influence of wind direction relative to the other meteorological variables, the residuals of the multiple regression equations are plotted with the predominant daily wind direction. Tables 5.2 - 5.5 show how no consistent bias of the residuals of the multiple regression equations is evident relative to the wind direction. The absence of any residuals between 110° and 120° and between 130° and 140° is due to the fact that no days with a predominant wind from that direction occurred during the Gramineae pollen seasons of 1987 - 1989.

The slight positive correlation between the residuals of the multiple regression analyses using the detrended data and the dependent variable, the pollen count (Tables 5.2 - 5.5), suggests that the regression model needs the inclusion of another independent variable to fully explain the variation in the daily Gramineae pollen count. This variable might be a meteorological parameter not yet considered in the analysis or could possibly be due to the lack of an accurate method of forecasting the potential pollen abundance. As may be seen from Tables 5.3 - 5.5, the models using detrended Gramineae pollen counts explain only about 10% more of the variance in pollen concentration than does the model using absolute pollen counts (Table 5.2). The accuracy of forecasting potential pollen production might be improved by the inclusion of some further meteorological parameters, such as a value of temperature and rainfall lagged by

2-4 days to indicate the increase in potential pollen production following warm and wet weather.

5.2.2 BETULA POLLEN.

When the results of the analysis of variance tests between the Betula pollen counts recorded under different categories of the meteorological variables are examined, few clear patterns of variation emerge (Table 5.6). The only significant difference is between the categories of maximum daily temperature where a positive linear relationship between the maximum temperature and daily pollen count is evident. This result is confirmed by the Pearson product moment correlation coefficients (significant at the 95% confidence level) observed between the two variables for all the analyses of Betula pollen variation (Tables 5.7 - 5.10). If the partial correlation coefficients are considered (where the effects of the inter-relation between the meteorological variables are removed) then the daily maximum temperature remains as the only significant variable. As a consequence, it is the only parameter entered into the stepwise multiple regression equation, where it alone accounts for 26-36% of the variation in the daily Betula pollen counts (Tables 5.7 - 5.10). No other meteorological parameter exerts such a strong influence on the Betula pollen count, although concentrations recorded on wet days are significantly different from those on dry days with an F ratio of 4.1254 (F Probability 0.0000).

If the residuals of the multiple regression equations (Tables 5.7 - 5.10) are examined then a positive autocorrelation between the daily pollen counts is evident (Durbin & Watson test statistic 1.10124). As is observed for the Gramineae pollen counts, the standardized residuals are also positively correlated with the pollen count, suggesting that either another independent variable needs to be entered into the analysis, or that the models estimating the curve of the pollen season are not accurately predicting the pollen production potential. The variation of the residuals with respect to wind direction (Tables 5.7 - 5.10) shows no clear pattern of variation, suggesting that this variable is not an important influence on the daily Betula pollen concentration.

TABLE 5.6 ANALYSIS OF VARIANCE BETWEEN DAILY BETULA POLLEN COUNTS (LOGGED/STANDARDIZED) AND METEOROLOGICAL PARAMETERS.
(*denotes groups significantly different at the 95% confidence level)

AVERAGE DAYTIME CLOUDCOVER:

F. Ratio: 1.8117
F. Prob.: 0.1217

No two groups are significantly different at the 95% confidence level.

AVERAGE WINDSPEED:

F. Ratio: 0.9376
F. Prob.: 0.4622

No two groups are significantly different at the 95% confidence level.

HOURS OF SUNSHINE:

F. Ratio: 1.3610
F. Prob.: 0.2495

No two groups are significantly different at the 95% confidence level.

SYNOPTIC SITUATION:

F. Ratio: 0.5899
F. Prob.: 0.7081

No two groups are significantly different at the 95% confidence level.

AVERAGE DAYTIME HUMIDITY:

F. Ratio: 1.1170
F. Prob.: 0.3594

No two groups are significantly different at the 95% confidence level.

DAILY RAINFALL:

F. Ratio: 1.5894
F. Prob.: 0.1866

No two groups are significantly different at the 95% confidence level.

TABLE 5.6 (Continued)

MAXIMUM DAILY TEMPERATURE:

F. Ratio: 6.2354
F. Prob.: 0.0001

Group		Mean Pollen	N	Group	1	2	4	3	5	6
1	min - 10.5°C	.8777	11							
2	10.6 - 12.5	1.0210	9							
4	14.1 - 15.0	1.3151	20		*					
3	12.6 - 14.0	1.3464	14		*					
5	15.0 - 19.0	1.5892	11		*	*				
6	19.1 - max	1.6862	10		*	*				

WIND DIRECTION:

F. Ratio: 12.9740
F. Prob.: 0.0000

Group		Mean Pollen	N	Group	4	1	2	3
4	271 - 360°	1.4603	24					
1	0 - 90	1.4830	12					
2	91 - 180	1.9472	14		*	*		
3	181 - 270	2.1572	25		*	*		

TABLE 5.7 ANALYSIS OF DAILY BETULA POLLEN COUNTS

MODEL: Logged/Standardized counts YEARS:1987-1989

PEARSON PRODUCT MOMENT CORRELATION COEFFICIENTS:

	Rainfall	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	-.2348	.5091	-.1773	-.2048	.1932	-.0803
N.	76	76	76	76	76	76
P.	.021	.000	.063	.000	.047	.245

FIFTH ORDER PARTIAL CORRELATION COEFFICIENTS:

	Rainfall	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	-.0620	.4853	-.0887	.0044	-.0698	.1504
DF.	69	69	69	69	69	69
P.	.304	.000	.231	.485	.282	.105

STEPWISE MULTIPLE REGRESSION:
Variables entered in the order:-
1. Max. Temperature.

Multiple R = .50907
R^2 = .25915
Durbin Watson Test Statistic= 1.10124 (positive autocorrelation).
Residuals normally distributed, but positively correlated with the logged/standardized pollen count.

Variation of residuals with predominent daily wind direction:

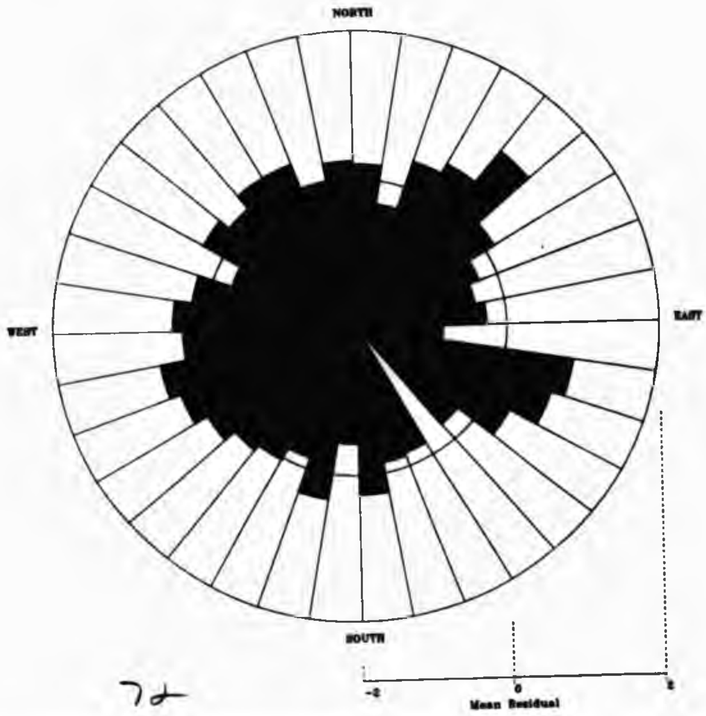


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TABLE 5.8 ANALYSIS OF DAILY BETULA POLLEN COUNTS

MODEL: Quadratic curve (curvefit) YEARS:1987-1989

PEARSON PRODUCT MOMENT CORRELATION COEFFICIENTS:

	Rainfall	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	-.3225	.4128	-.4012	-.2145	.1090	-.0256
N.	74	74	74	74	74	74
P.	.000	.000	.000	.081	.174	.131

FIFTH ORDER PARTIAL CORRELATION COEFFICIENTS:

	Rainfall	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	-.0414	.3014	-.0647	-.0074	-.0224	-.0014
DF.	67	67	67	67	67	67
P.	.131	.021	.321	.435	.211	.432

STEPWISE MULTIPLE REGRESSION:
Variables entered in the order:-
1. Max. Temperature.

Multiple R = .54110
R^2 = .25526
Durbin Watson Test Statistic = .72589 (positive autocorrelation).
Residuals normally distributed, but positively correlated with the transformed pollen counts.

Variation of residuals with predominent daily wind direction:

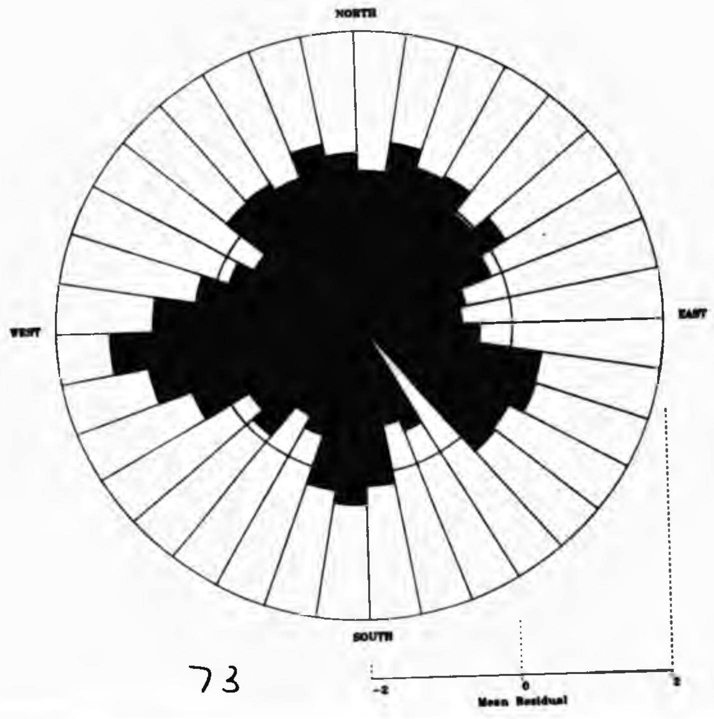


TABLE 5.9 ANALYSIS OF DAILY BETULA POLLEN COUNTS

MODEL: T4253H YEARS:1987-1989

PEARSON PRODUCT MOMENT CORRELATION COEFFICIENTS:

	Rainfall	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	-.1256	.3128	-.2914	-.1245	.1211	-.0854
N.	74	74	74	74	74	74
P.	.104	.002	.010	.121	.114	.301

FIFTH ORDER PARTIAL CORRELATION COEFFICIENTS:

	Rainfall	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	-.0842	.3045	-.1489	-.0081	-.0076	-.0172
DF.	67	67	67	67	67	67
P.	.348	.012	.187	.474	.478	.217

STEPWISE MULTIPLE REGRESSION:
Variables entered in the order:-
1. Max. Temperature.

Multiple R = .51247
R^2 = .23678
Durbin Watson Test Statistic = .94873 (positive autocorrelation).
Residuals normally distributed, but positively correlated with the transformed pollen counts.

Variation of residuals with predominent daily wind direction:

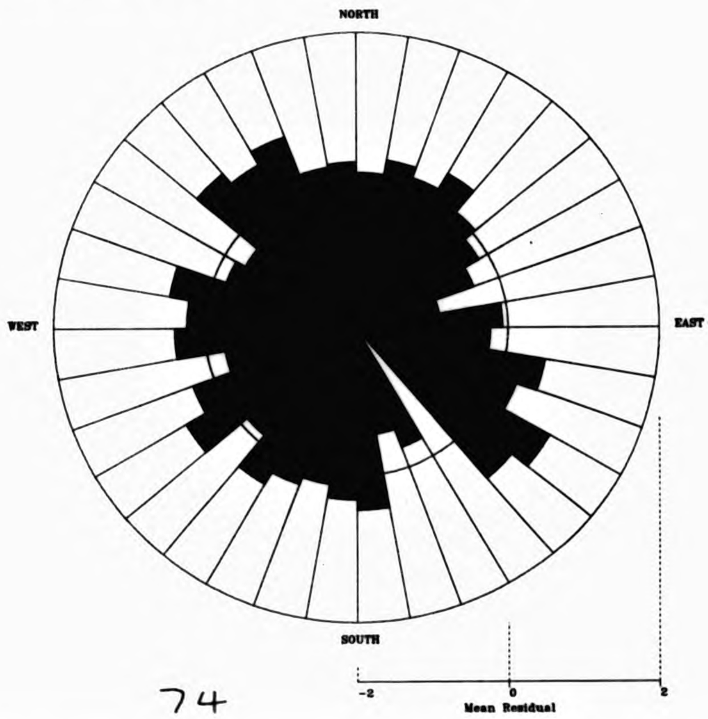


TABLE 5.10 ANALYSIS OF DAILY BETULA POLLEN COUNTS

MODEL: COUNTS DETRENDED AFTER MCCARTNEY & LACEY (1991) YEARS:1987-1989

PEARSON PRODUCT MOMENT CORRELATION COEFFICIENTS:

	Rainfall	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	-.0745	.4127	-.3512	-.2584	.2475	-.0945
N.	74	74	74	74	74	74
P.	.301	.000	.004	.021	.034	.328

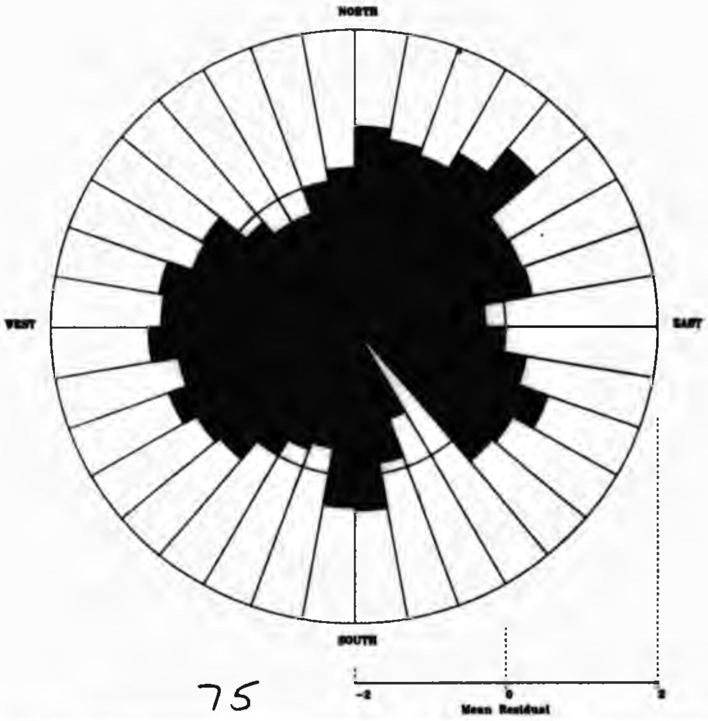
FIFTH ORDER PARTIAL CORRELATION COEFFICIENTS:

	Rainfall	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	-.0745	.3471	-.1760	-.0145	-.0081	-.0164
DF.	67	67	67	67	67	67
P.	.376	.015	.101	.374	.417	.408

STEPWISE MULTIPLE REGRESSION:
Variables entered in the order:-
1. Max. Temperature.

Multiple R = .55247
R^2 = .25478
Durbin Watson Test Statistic= 1.02478 (positive autocorrelation).
Residuals normally distributed, but positively correlated with the transformed pollen counts.

Variation of residuals with predominent daily wind direction:



5.2.3 PLATANUS POLLEN.

The results of the analysis of daily variations in the Platanus pollen counts and their relationship to the meteorological variables display some marked contrasts to those of Betula or Gramineae pollen.

The analysis of variance test between Platanus pollen counts recorded under different categories of the meteorological variables reveal significant differences in respect of the variables of wind direction, synoptic situation and average daytime humidity (Table 5.11).

However, none of these variables display linear relationships and when the Pearson product moment correlation coefficients are examined, no correlations significant at the 95% confidence level are evident (Table 5.12). The highest partial correlation coefficient is between the logged and standardized pollen count and the average daily humidity, which at -0.1881 has a probability of only 0.062 (Table 5.12). In the multiple regression equation for this analysis none of the meteorological variables are entered.

In contrast to the results of the other pollen taxa considered, Platanus pollen displays a positive relationship with the daily rainfall total, although nowhere is this coefficient significant at the 95% or 90% confident level. This may result from the increased turbulence associated with rainstorms whereby more pollen is raised from street level to roof-top level where it is recorded by the Burkard sampler.

A distinctive feature of the results of the analysis of daily variation in the Platanus pollen count is the low level of variation that can be accounted for by the meteorological variables. The highest R^2 coefficient derived from the analysis of counts relative to a smoothed quadratic curve (Table 5.13) but could only account for 18% of the variation in the counts. This low level of explanation suggests that the meteorological variables under consideration are not those of importance to Platanus pollen dispersal. Small scale air movements around the urban fabric may play an increasingly important role compared to the predominant wind direction and wind speed in the London area than for the other pollen taxa considered. A more accurate forecast of Platanus pollen dispersal would then require measurements of mixing height and turbulence.

TABLE 5.11 ANALYSIS OF VARIANCE BETWEEN DAILY PLATANUS POLLEN COUNTS (LOGGED/STANDARDIZED) AND METEOROLOGICAL PARAMETERS.
(*denotes groups significantly different at the 95% confidence level)

AVERAGE DAYTIME CLOUDCOVER:

F. Ratio: 0.3241
F. Prob.: 0.8968

No two groups are significantly different at the 95% confidence level.

AVERAGE WINDSPEED:

F. Ratio: 0.3819
F. Prob.: 0.8595

No two groups are significantly different at the 95% confidence level.

HOURS OF SUNSHINE:

F. Ratio: 0.3743
F. Prob.: 0.8646

No two groups are significantly different at the 95% confidence level.

SYNOPTIC SITUATION:

F. Ratio: 3.9080
F. Prob.: 0.0035

Group		Mean Pollen	N	Group	1	4	2	5	3	6
1	HP	1.2564	14							
4	LP to SW	2.1091	15							
2	LP to NE	2.1743	9		*					
5	LP to NW	2.3882	21		*					
3	LP to SE	2.5508	12		*	*				
6	LP over London	2.6008	2		*	*				

DAILY RAINFALL:

F. Ratio: 0.2691
F. Prob.: 0.8969

No two groups are significantly different at the 95% confidence level.

TABLE 5.11 (Continued)

AVERAGE DAYTIME HUMIDITY:

F. Ratio: 2.9479
F. Prob.: 0.0183

Mean Group		Pollen	N	Group	4	6	3	2	1	5
4	69.1 - 73.0%	0.2645	4							
6	80.1 - max	0.7193	29							
3	65.1 - 69.0	0.8902	10							
2	60.1 - 65.0	0.9905	12							
1	min - 60.0	1.2035	7		*					
5	73.1 - 80.0	1.2170	11		*					

MAXIMUM DAILY TEMPERATURE:

F. Ratio: 2.4427
F. Prob.: 0.0429

No two groups are significantly different at the 95% confidence level.

WIND DIRECTION:

F. Ratio: 41.8924
F. Prob.: 0.0000

Mean Group		Pollen	N	Group	4	1	3	2
4	271 - 360°	1.2061	21					
1	00 - 90	1.2727	11					
3	181 - 270	2.3364	32		*	*		
2	91 - 180	2.8665	9		*	*	*	

TABLE 5.12 ANALYSIS OF DAILY PLATANUS POLLEN COUNTS

MODEL: Logged/Standardized counts YEARS:1987-1989

PEARSON PRODUCT MOMENT CORRELATION COEFFICIENTS:

	Rainfall	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	.0914	.0424	-.1270	.0191	.0388	.0784
N.	73	73	73	73	73	73
P.	.221	.361	.142	.436	.372	.255

FIFTH ORDER PARTIAL CORRELATION COEFFICIENTS:

	Rainfall	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	.1508	.0819	-.1881	.0614	-.0373	.0808
DF.	66	66	66	66	66	66
P.	.110	.253	.062	.310	.381	.256

STEPWISE MULTIPLE REGRESSION:
Variables entered in the order:-
No variables were entered into the equation.

Multiple R = n/a
R^2 = n/a
Durbin Watson Test Statistic= n/a

Variation of pollen counts with predominent daily wind direction:

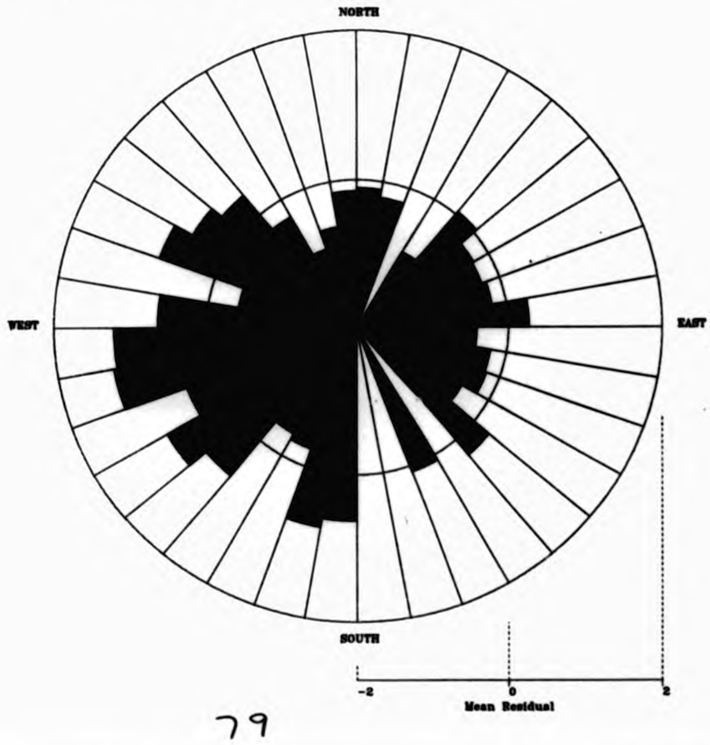


TABLE 5.13 ANALYSIS OF DAILY PLATANUS POLLEN COUNTS

MODEL: T4253H YEARS:1987-1989

PEARSON PRODUCT MOMENT CORRELATION COEFFICIENTS:

	Rainfall	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	.1033	.1942	-.2035	.0196	.0966	.0634
N.	71	71	71	71	71	71
P.	.162	.029	.018	.343	.162	.302

FIFTH ORDER PARTIAL CORRELATION COEFFICIENTS:

	Rainfall	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	-.0080	.1431	-.0916	.0101	-.0371	.0613
DF.	65	65	65	65	65	65
P.	.492	.102	.222	.402	.376	.289

STEPWISE MULTIPLE REGRESSION:
Variables entered in the order:-
1. Max. Temperature.

Multiple R = .54869
R^2 = .301069
Durbin Watson Test Statistic= 1.54178 (positive autocorrelation).
Residuals normally distributed, but positively correlated with the transformed pollen counts.

Variation of residuals with predominent daily wind direction:

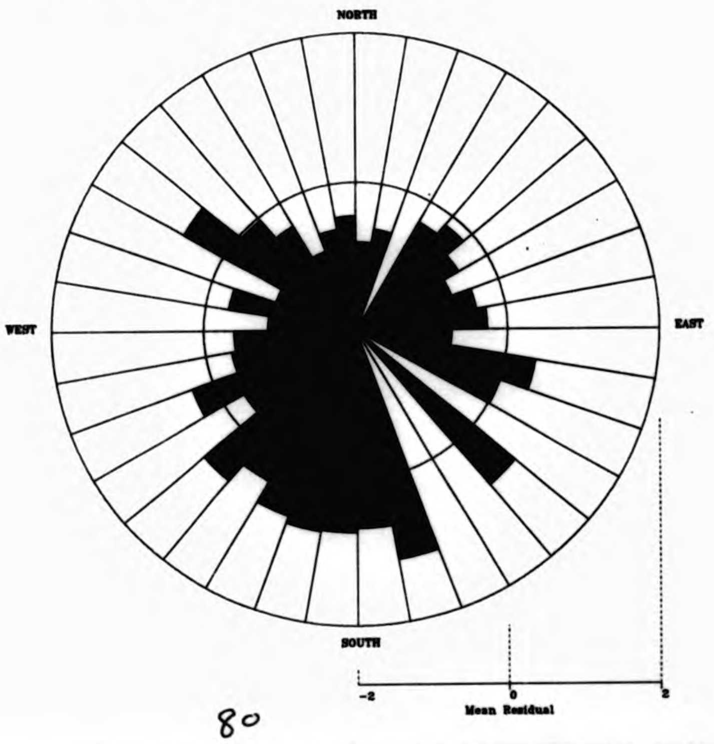


TABLE 5.14 ANALYSIS OF DAILY PLATANUS POLLEN COUNTS

MODEL: CUBIC MODEL (SPSS/PC) YEARS:1987-1989

PEARSON PRODUCT MOMENT CORRELATION COEFFICIENTS:

	Rainfall	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	.1033	.1942	-.2035	.0196	.0966	.0634
N.	71	71	71	71	71	71
P.	.162	.029	.018	.343	.162	.302

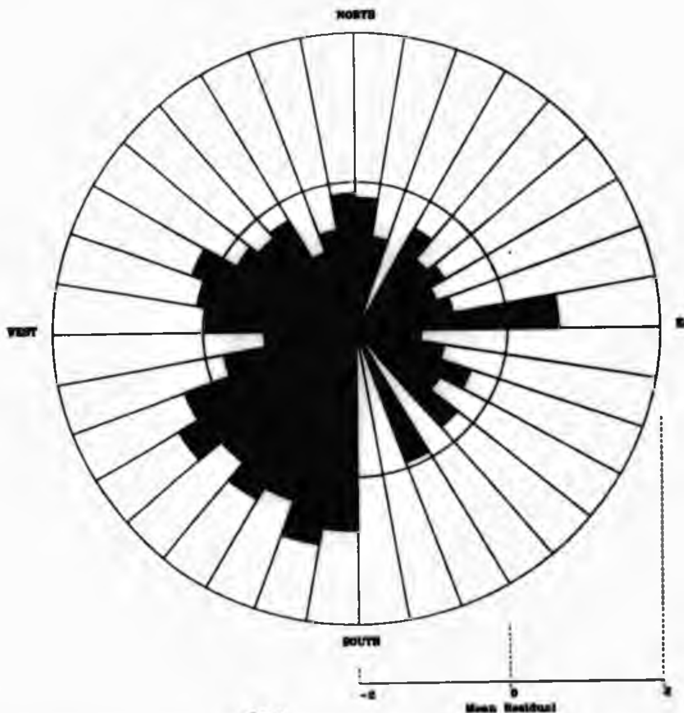
FIFTH ORDER PARTIAL CORRELATION COEFFICIENTS:

	Rainfall	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	-.0080	.1431	-.0916	.0101	-.0371	.0613
DF.	65	65	65	65	65	65
P.	.492	.102	.222	.402	.376	.289

STEPWISE MULTIPLE REGRESSION:
Variables entered in the order:-
1. Max. Temperature.

Multiple R = .60651
R^2 = .367859
Durbin Watson Test Statistic= 1.71245 (positive autocorrelation).
Residuals normally distributed, but positively correlated with the transformed pollen counts.

Variation of residuals with predominant daily wind direction:



<u>TABLE 5.15</u> ANALYSIS OF DAILY PLATANUS POLLEN COUNTS

MODEL: T4253H (SPSS/PC) YEARS:1987-1989

PEARSON PRODUCT MOMENT CORRELATION COEFFICIENTS:

	Rainfall	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	.1033	.1942	-.2035	.0196	.0966	.0634
N.	71	71	71	71	71	71
P.	.162	.029	.018	.343	.162	.302

FIFTH ORDER PARTIAL CORRELATION COEFFICIENTS:

	Rainfall	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	-.0080	.1431	-.0916	.0101	-.0371	.0613
DF.	65	65	65	65	65	65
P.	.492	.102	.222	.402	.376	.289

STEPWISE MULTIPLE REGRESSION:

Variables entered in the order:-

1. Max. Temperature.

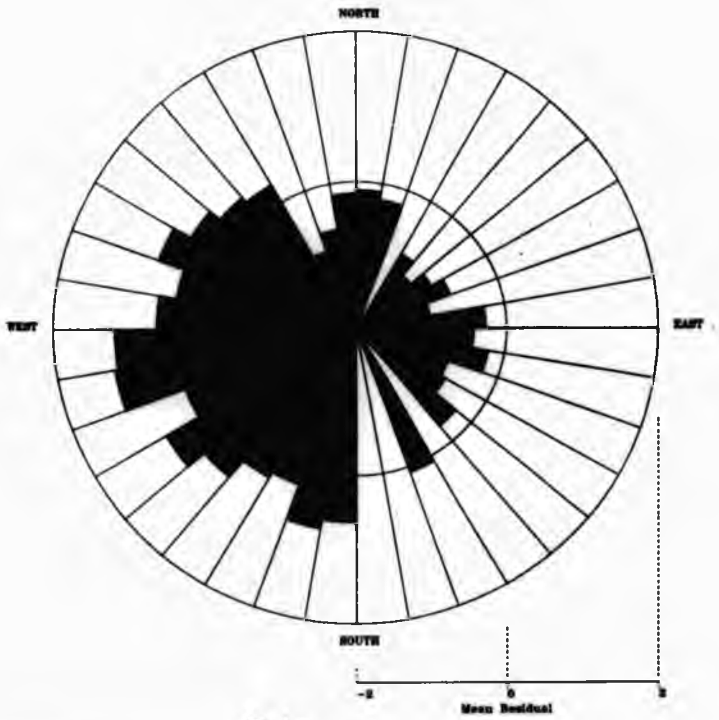
Multiple R = .54869

R^2 = .301069

Durbin Watson Test Statistic= 1.54178 (positive autocorrelation).

Residuals normally distributed, but positively correlated with the transformed pollen counts.

Variation of residuals with predominent daily wind direction:



5.3 DISCUSSION.

Following this analysis of the daily variations of three pollen taxa, the role of the meteorological variables may be considered individually.

5.3.1 MAXIMUM DAILY TEMPERATURE.

Strong positive correlations exist between daily pollen concentrations and the maximum daily temperature, even when the influence of other meteorological variables have been eliminated. Maximum temperature is the variable entered into the stepwise regression analyses more frequently than any other parameter.

The influence of temperature on the daily pollen count may be divided into two components. It will firstly effect the production and release of pollen from the anther, and secondly influence the dispersal of pollen from the source area to the sampling site. Davies and Smith (1973) and Liem and Groot (1973) reported on the role of temperature in increasing the pollen production of Gramineae and in aiding the process of anthesis by which pollen is released. Once pollen grains are exposed within the anther, a high temperature will aid in drying the grains so that they may become airborne.

Temperature will also influence the long distance dispersal of pollen by convection currents. This circulation develops when air at ground level becomes sufficiently heated and starts to rise. Pollen grains released into convection currents are raised to the upper air where they remain airborne and will be dispersed over a considerable area by the upper air flows. When the temperature at ground level starts to fall, and convection ceases, the pollen grains will begin to settle back towards the ground at their terminal velocity, but whilst still being dispersed by the wind. By this mechanism, pollen grains may disperse over much wider areas than they would if they remained close to ground level. Davies and Smith (1973) believe that most of the Gramineae pollen, and possibly also much Betula pollen, is transported into London from source areas outside the City by convection currents. The daily maximum temperature in therefore vital in determining the daily pollen concentration of these taxa. Even for Platanus pollen, which originated within London, convection currents are important in uplifting pollen from street level to roof level where it may become dispersed over a wide area.

However, if the results of the analysis of variance tests are examined (Tables 5.1, 5.6 & 5.11) it may be noted that for Gramineae and Platanus pollen extremely high temperatures (above 27°C for Gramineae and 21°C for Platanus) do not result in the highest pollen counts. This phenomena may arise for several reasons. Liem (1980), in examining the effect of temperature on the anthesis of several species of Gramineae noted that temperatures of around 20°C proved the most favourable for pollen production, although she offered no explanation for this. Hence, the actual pollen production on days of extreme temperatures may be limited despite the good potential for pollen dispersal. Another possible reason for this phenomena is that pollen counts close to ground level will become diluted when convection is occurring. Although the importance of this cannot be quantified with the data available, it would seem unlikely to be an important factor in Gramineae pollen dispersal at a site distant from many pollen sources such as London, but it may be of considerable importance to Platanus pollen dispersal where sources are locally concentrated.

5.3.2 RELATIVE HUMIDITY.

Despite the initial high negative correlation between the average relative humidity and the daily pollen counts, once the inter-relation between this and other meteorological parameters had been removed through partial correlation analysis, only very low coefficients are observed. The fact that many previous authors, for example Galan *et al* (1989), had reported strong correlations between humidity and pollen counts may have arisen if the influence of humidity was not isolated from that of temperature and cloud cover. Over the pollen seasons 1987-1989 the correlations between these two variables and the relative humidity ranged from +0.881 to -0.481 respectively suggesting strong inter-relation, ie. as temperature increases and cloud cover decreases, relative humidity will also decrease. These results are in agreement with those of Bringfelt *et al* (1982) who, having applied a multiple regression analysis to pollen counts and meteorological data from Stockholm, Sweden, concluded that relative humidity was not a significant influence on pollen concentration.

The direct influence of relative humidity on the pollen count is therefore slight and occurs mainly in the drying process of pollen in the anthers of the parent plant before dispersal can take place.

5.3.3 HOURS OF SUNSHINE.

The total hours of sunshine during a day appears to have little influence on the daily pollen counts of Gramineae, Betula or Platanus pollen. Once the inter-correlation between this and the other meteorological variables had been eliminated, the correlation is never significant at the 95% confidence level. This lack of importance, and indeed the slight negative correlation frequently recorded are in contradiction to other studies where sunshine was believed to play an important role in determining the daily pollen count. Kozlowski (1973) states that the duration of sunshine is of fundamental importance for the release of pollen while Liem (1980) recorded an increase in the daily anther production of a Gramineae species with increased light exposure. Both these studies, however, were conducted close to the pollen source where the hours of sunshine may indeed be important to the production of pollen. At sites distant from the pollen source, as for example for Gramineae pollen in London, the meteorological parameters influencing the transport of pollen to the sampling site will be of equal or greater importance than those determining pollen production and hence these may play only a minor role in determining the actual pollen count.

5.3.4 AVERAGE DAILY WIND SPEED.

Despite the lack of interrelation between the average daily wind speed and other meteorological parameters (the correlation coefficients decrease only slightly between the Pearson product moment and partial correlations), it never proves to be a very significant factor in determining the daily pollen count. Only low F ratios are observed between the pollen counts recorded under different wind speeds (Tables 5.1, 5.6 & 5.11) and low correlation coefficients are recorded for all pollen taxa (Tables 5.2 - 5.13).

Many previous authors have examined the role that wind speed plays in the dispersal of pollen and, in particular, Gramineae pollen, (for example, McDonald 1980, Spieksma and den Tonkelaar 1986). Bringfelt (1980) outlines the various effects of wind speed on pollen concentration; strong winds may 'dilute' the pollen content of the air, but may also cause the release of more pollen due to the mechanical shaking of the anther, and he also stated that previously deposited pollen may become resuspended in high wind speeds.

However, later work by Bringfelt *et al* (1982) found that wind speed did not significantly influence the daily Betula and Pinus pollen counts, but was important for the Gramineae count. McDonald (1980), working in Ireland, also found wind speed to account for much variation in the daily Gramineae pollen count as did Cadman (1991) working in South Africa..

However, in London it is possible that the local disturbance of airflow by buildings plays a more important role in pollen dispersal than the predominant wind direction of the area. Although the pollen sampler is located at roof level, this level will still experience turbulent air flows which may increase the wind speed to above the terminal velocity of a pollen grain. For example, pollen grains with a fall rate of 2 - 6 centimetres per second (Andersen, 1970) will be airborne at velocities of more than 1 - 2 metres per second (Andersen, 1974a), a wind speed usually exceeded during the pollen seasons in London.

However, the role of wind velocity in pollen dispersal is further complicated by its influence on the sampling efficiency of the Burkard sampler. At wind speeds of more than one metre per second, the sampling efficiency is reduced to below 100% and so it is possible that a slight positive correlation between the pollen count and the wind speed is being hidden by this effect.

5.3.5 WIND DIRECTION.

To isolate the influence of other meteorological parameters, the standardized residuals of each multiple regression equation are plotted on a rose diagram against the predominant daily wind direction (Tables 5.2 - 5.13). The influence of wind direction will then relate to the location of, and distance of the pollen sampler from, the major pollen source areas.

The most marked spatial variation of the residual statistics derive from the analysis of Platanus pollen concentrations whereby the highest residuals are recorded in winds of a southerly origin. This may be accounted for by the large number of Platanus spp. trees planted in central London only 4-5km from the pollen sampling site. Another minor peak in the spatial variation of the residuals fall between 80° and 90° to the east, where similarly a large number of the trees are located, (Figure 1.2).

For Gramineae and Betula pollen no clear pattern of variation of the residuals emerges (Tables 5.2 - 5.13). This suggests that wind direction has little influence on the daily pollen counts of these taxa, despite the initial high F ratios of the analysis of variance tests between counts recorded under different predominant wind directions. The differences that do occur may then relate more to the different meteorological situations experienced under different wind directions than to the origin of the airflow alone. For example, the lower concentrations of Gramineae pollen recorded under winds from the south-west are a result of the higher rainfall, lower temperatures and higher humidities associated with these winds rather than a reduction in the source strength of Gramineae pollen in this direction.

5.3.6 SYNOPTIC SITUATION.

The analysis of variance tests for Gramineae, Betula and Platanus pollen (Tables 5.1, 5.6 & 5.11) reveal high and frequently significant F ratios between the pollen counts recorded under different synoptic situations. Gramineae pollen counts recorded under anticyclonic situations are significantly higher than those recorded under low pressure formations situated to the north of London (Table 5.1). In contrast however, Platanus pollen counts recorded under anticyclonic situations are significantly lower than those recorded under a cyclonic situation (Table 5.11). However, although the synoptic data could not be entered into partial and multiple regressions equations, it would seem likely that much of this variation would already have been accounted for by the variation of the other meteorological parameters. For example, summertime anticyclonic situations are generally characterized by high temperatures and levels of sunshine and by low relative humidities, rainfall, cloud covers and wind speeds, all variables which have previously been taken into account by the multiple regression analyses.

Previous works which have investigated the influence of synoptic situation on pollen concentrations have also concluded that its influence is of significance (for example, Skre, 1981 in Norway) but have not attempted to isolate the influence of other meteorological parameters.

The remaining direct influence of synoptic situation, not previously accounted for, is its impact on the predominant wind direction, a variable that cannot be entered into any multiple regression analysis. The influence of wind direction on the residuals of the multiple regression equations for Gramineae, Betula and Platanus pollen concentrations has however been considered separately in Section 5.3.5.

5.3.7 RAINFALL.

In the analyses of variance tests, only that for Gramineae pollen reveals a significant F ratio between the pollen counts recorded on wet and dry days (Table 5.1) and this relationship is negative and approximately linear. For Betula and Betula pollen no clear pattern between daily pollen abundance and rainfall is evident. These results disagree with the proposals of previous authors, for example Hyde (1952) who suggests that the relationship between pollen abundance and rainfall intensity is simple and linear, as on some occasions the highest rainfall amounts do not result in the lowest pollen concentrations. This complex relationship between rainfall and pollen concentration is examined in detail in Chapter 7.

5.4 APPLICATIONS TO OTHER POLLEN TAXA

The analysis of daily variations in the pollen count, and the influence of the meteorological parameters on these, has so far been limited to three pollen taxa. However, much of this analysis could also be applied to other pollen taxa not yet considered.

The direct controls on the anthesis of species apart from Gramineae have been little considered. Richards (1985) examined the flowering controls on Ulmus and Taxus and concluded that flower initiation is triggered both by the timing declines in the previous year as well as by the accumulation of temperature prior to the pollen season. He did not examine the controls on the day to day variation in the release of pollen. However, once pollen has ripened in the anther, its release and dispersal are likely to be governed by the same mechanical processes as determine the release of grass pollen; namely the temperature, humidity, wind speed and turbulence, processes which operate independently of the flowering phenology of the plant. Once pollen release has taken place, the dispersal is controlled by the size and settling velocity of the grain relative to the wind regime and source area. These controls operate in the same way as for pollen taxa already considered, the main differences between taxa resulting from either differences in the pattern of pollen release of different source areas.

5.5 SUMMARY.

This chapter has identified the main controls on the day to day pattern of pollen abundance for three common pollen taxa, and has considered the relevance of these for other taxa. Overall, the meteorological variable exhibiting the greatest influence on pollen abundance, regardless of pollen taxa, the model of abundance used or the influence of other weather parameters, is the maximum daily temperature. This variable however has no direct physical influence on the diffusion of pollen, but instead influences the release of pollen from the plant and the dispersal of pollen from the source area through its interrelation with other meteorological parameters such as sunshine, rainfall, relative humidity and turbulence. Other meteorological parameters of importance in determining daily pollen concentrations are the relative humidity, wind speed, wind direction and, for Gramineae pollen, rainfall.

The inclusion of these variables in a multiple regression equation to explain the day to day variations in pollen abundance results in a multiple R coefficient of 0.68939 for Gramineae pollen ('Quadratic' model, Table 5.3), 0.54110 for Betula pollen ('Cubic' model, Table 5.8) and 0.54869 for Platanus pollen ('T4253H' model, Table 5.15). In these models of pollen abundance the maximum daily temperature is frequently the only meteorological predictor included. Other parameters such as the relative humidity and wind speed may also be included but contribute less to the level of explanation attained than does the maximum temperature.

CHAPTER 6

DIURNAL VARIATION OF POLLEN CONCENTRATION IN THE AIR OF NORTH CENTRAL LONDON.

6.1 INTRODUCTION.

Pollen concentrations recorded during three years sampling in north-central London have shown distinctive diurnal variations. This chapter will therefore identify these variations and consider them in relation to the meteorological parameters influencing the production and dispersal of pollen, and to the flowering phenology of the source plants. The meteorological variables combining to cause high pollen counts will be considered as the times of highest pollen counts will be of most relevance to allergy sufferers.

The diurnal variation of pollen concentration has previously been investigated in selected locations, for example Steel (1983), Spieksma and den Tonkelaar (1986), Mullins, White and Davies (1986), Galan *et al* (1989a). However, these works have tended to concentrate on the diurnal variation of Gramineae pollen, while other pollen taxa have scarcely been considered. Galan *et al* (1989b) examined the daily variations of Amaranthaceae and Chenopodiaceae in Spain, while Kapyla (1981 and 1984) has examined both arboreal and herbaceous pollen types. An exception to this preoccupation with Gramineae pollen comes from Galan *et al*, (1991), a more detailed paper which examines the diurnal variation of 24 different pollen taxa over three years in Spain.

Little previous work has considered the diurnal variations of pollen at sites distant from the pollen source but has concentrated on patterns of pollen release close to the source plant, Jones (1952), Ogden *et al* (1969), Liem and Groot (1973) and Liem (1980). Mullins *et al* (1986) and Steel (1983) have compared the diurnal variations of Gramineae pollen recorded in rural and urban areas. Both authors found that maximum pollen concentration was recorded up to four hours later in the urban situation when compared to that in a rural area. Kapyla (1984), working in the Finnish cities of Turku and Jyvaskyla, recorded regular diurnal patterns of Picea, Populus, Quercus, Salix and Ulmus pollen with daytime maxima and night-time minima concentrations. No regular patterns of Alnus, Betula, Juniperus or Pinus pollen concentration are observed.

This study is novel in the investigation of the diurnal variation of pollen abundance at a site within a densely built urban area with few local pollen sources.

Patterns of diurnal variation recorded in London may differ from those in other cities due to the size of the urban area. The work of Kapyla in Finland considered only towns of moderate size (estimated populations 60 000 and 40 000) compared to those in the UK and the rest of Europe, while Mullins *et al* (1986) and Galan *et al* both considered regional centres with populations in the order of 200 000. The lack of some pollen sources within London suggests that most pollen grains trapped at the sampling site will have been transported some distance and may therefore display markedly different diurnal variations to those at the pollen source.

Any consideration of the diurnal variations of pollen concentration must therefore take account of the three processes of pollen dispersal, namely anthesis, pollen release and pollen transport. For the special circumstances of London, where sampling takes place at a site remote from some pollen sources, consideration must also be given to the location of these.

Several pollen types have been selected for further investigation of diurnal patterns. The pollen taxa of Gramineae, Betula, and Platanus have been chosen on the basis of their abundance, allergenic potential and source areas as outlined in Chapter 5.

The analysis of the diurnal variations of each pollen type is performed only during a closely defined pollen season following the methodology of Nilsson and Persson (1981) where 95% of the total yearly pollen count is included. This method avoids including in the analysis resuspended pollen outside of the main pollen season. Also, only days during which no precipitation fell are considered for the analysis of diurnal variations due to the marked effect of rainfall on the pollen count (Chapters 5 and 7).

Diurnal variations in pollen concentration will be considered in relation to the meteorological variables of maximum temperature, humidity, wind speed and wind direction, sunshine intensity, cloud cover, and rainfall. Other meteorological parameters that show little change through a twenty four hour period, such as synoptic situation, are not considered here, as are the parameters of turbulence or mixing height for which two hourly data records are not available. Turbulence will however be considered indirectly through the analysis of two hourly temperature and wind velocity measurements.

An initial statistical analysis has been performed to investigate the relevance of the meteorological variables. Because the pollen data are log-normally distributed, a log-transformation is applied to fill the requirements of normally-distributed data for the analysis of variance statistic. Because some of the meteorological variables also exhibit a regular diurnal variation (for example, temperature, humidity and sunshine) a curve of their average variation has been calculated for each of the relevant pollen seasons and the deviation of each two-hourly value from this curve used instead of the actual value in the analysis. Analysis of variance is then calculated between the pollen counts recorded under different categories of the weather variables. Where linear relationships have been observed partial and multiple correlation coefficients are calculated to isolate the influence of inter-related variables.

The diurnal variation of each pollen type is then investigated by averaging the two-hourly pollen counts to produce one 'model' pollen day showing the change of the average pollen concentration through a 24 hour period.

6.2 GRAMINEAE POLLEN.

An initial examination of the analysis of variance statistics shows that the diurnal variation of Gramineae pollen is closely related to both temperature and relative humidity (Table 6.1). The relationship between humidity and the pollen count is log-linear with a partial correlation coefficient of -0.4324 when all other variables in the equation are held constant (Table 6.2). This coefficient is significant at the 99.9% confidence level (Table 6.2). The relationship between the variation from the two-hourly temperature average and the pollen count is not, however, linear as the average count recorded under temperatures more than 5°C above the normal diurnal variation is lower than that recorded under temperatures within 5°C of the normal variation (Table 6.1). A stepwise multiple regression analysis designated humidity and temperature as the meteorological variables most influential to the two-hourly pollen count (Table 6.2).

TABLE 6.1 ANALYSIS OF VARIANCE BETWEEN TWO-HOURLY GRAMINEAE POLLEN COUNTS (LOGGED/STANDARDIZED) AND METEOROLOGICAL PARAMETERS WITH WET DAYS EXCLUDED.
(*denotes groups significantly different at the 95% confidence level)

CLOUDCOVER:
F. Ratio: 33.7360
F. Prob.: 0.0000

Group		Mean Pollen	Group	6	5	4	2	3	1
6	7.2 - max octaves	1.1686							
5	6.6 - 7.1	1.4881		*					
4	5.8 - 6.5	1.6442		*	*				
2	3.1 - 5.0	1.6880		*	*				
3	5.1 - 5.8	1.7049		*					
1	0.0 - 3.0	1.7675		*	*				

WINDSPEED:
F. Ratio: 1.3978
F. Prob.: 0.2220

NO TWO GROUPS SIGNIFICANTLY DIFFERENT AT THE 95% CONFIDENCE LEVEL

SUNSHINE:
F. Ratio: 14.0414
F. Prob.: 0.0047

Group		Mean Pollen	Group	1	2	3	4	5	6
2	0.06 - 0.1 hour below	1.4116							
1	>0.11 below	1.4626							
3	0.0 - 0.05 below	1.5654							
5	0.06 - 0.1 above	1.6044							
4	0.0 - 0.05 above	1.6288			*				
6	> 0.11 above	1.8288		*	*	*	*	*	

RELATIVE HUMIDITY:

F. Ratio: 122.1483
F. Prob.: 0.0000

Group		Mean Pollen	Group	6	5	3	4	1	2
6	> 10.1% above norm	1.0260							
5	5.1 - 10% above	1.4444		*					
3	0 - 5% below	1.5587		*					
4	0 - 5% above	1.5964		*	*				
2	5.1 - 10% below	1.7512		*	*	*	*		
1	> 10.1% below	1.9987		*	*	*	*	*	

TABLE 6.1 (continued)

TEMPERATURE:

F. Ratio: 98.7748
F. Prob.: 0.0000

Group		Mean Pollen	Group	1	2	5	6	4	3
1	>5°C below norm	1.2300							
2	2.1 - 5.0 below	1.4868		*					
3	0.0 - 2.0 below	1.8440		*	*				
6	>5°C above	1.9583		*	*				
4	0.0 - 2.0 above	2.1563		*	*	*			
5	2.1 - 5.0 above	2.2412		*	*	*			

WIND DIRECTION

F. Ratio: 30.0848
F. Prob.: 0.0000

Group		Mean Pollen	Group	3	2	4	1
3	181 - 270°	1.3700					
4	271 - 360	1.5625		*			
2	91 - 180	1.7272		*	*		
1	00 - 90	1.7485		*	*		

TABLE 6.2

ANALYSIS OF TWO-HOURLY GRAMINEAE POLLEN COUNTS (LOGGED / STANDARDIZED) 1987 - 1989, WITH WET DAYS EXCLUDED.

PEARSON PRODUCT MOMENT CORRELATION COEFFICIENTS:

	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	.4248	-.4324	-.1883	.1447	.0107
N.	1929	1929	1929	1929	1929
P.	.000	.000	.003	.049	.320

FOURTH ORDER PARTIAL CORRELATION COEFFICIENTS:

	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	.2288	-.2298	-.1328	-.1275	-.0014
DF.	1923	1923	1923	1923	1923
P.	.000	.000	.000	.000	.476

STEPWISE MULTIPLE REGRESSION:

Variables entered in the order:-
1. Humidity.
2. Temperature
3. Cloud cover
4. Sunshine

Multiple R = .49499
R^2 = .24502

When the influence of wind direction is examined an F ratio is calculated, significant at the 95% probability level, where pollen counts recorded in winds of a south-westerly origin are significantly lower than those in winds from any other direction (Table 6.1). This variation may result from the significantly higher humidities and lower temperatures recorded under the wind direction. Unfortunately, this relationship cannot be examined through multiple regression analysis due to the nature of the wind data.

Days within the pollen seasons have then been divided into categories based on the meteorological variables designated by the statistical analysis as most influential to the two-hourly pollen concentration. For Gramineae, these variables are temperature and humidity but because of the high intercorrelation between them only one, temperature, is used as a basis for sub-dividing the data. For Gramineae, which flowers during June and July, cool days are those with a maximum temperature below 21°C and warm days above 21°C. The data have also been divided into days of different predominant wind directions. Although wind direction could not be included in the multiple regression equations, the analysis of variance between pollen counts in different wind sectors displayed significant F ratios (Table 6.1) and may therefore be important with respect to the diurnal variation. Wind direction will also be of importance in examining the influence of different pollen source areas.

Examination of the diurnal variation of Gramineae pollen in north-central London (Figure 6.1) shows how the average pollen concentration, regardless of differences in temperature and wind direction, achieves a maximum concentration between 1800 and 2200 hours. Concentration is at a minimum at 0800 hours and then rises gradually through the day. There are however variations in the size of peak concentration and small differences in their timing with temperature and wind direction. The highest pollen concentrations are recorded under north-easterly wind directions with daily maximum temperatures above 21°C, and the lowest with south-westerly winds below 21°C (Figure 6.1). Under both such conditions a maximum concentration is recorded at 2000 hours, as it is for all other winds from a westerly direction. For winds from the north-east on cool days and from the south-east on cool days, peak concentration is not achieved until 2200 hours.

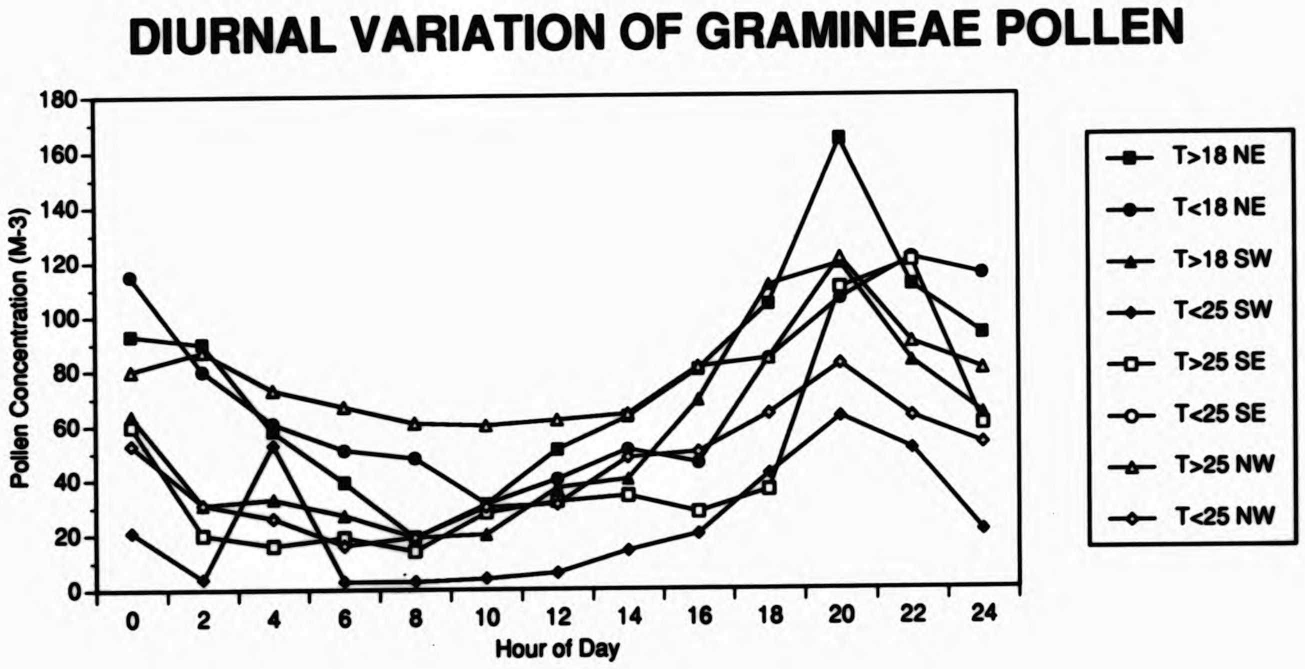


Figure 6.1 Diurnal Variation of Gramineae Pollen. Days are divided into those with a maximum temperature above or below 21oC (T>21 or T<21) and by the predominant daily wind direction (eg. NE).

A similar analysis has been performed to examine the diurnal variations on days with high pollen counts. For Gramineae, days with an average daily pollen count above 50 grains M^{-3} are considered 'high' following the guidelines of Davies and Smith (1974) who state that on such days, all people prone to hayfever will experience symptoms. 'Model days' are then calculated by averaging the two hourly pollen counts from high count days, without further subdivisions into meteorological categories.

The diurnal variation of peak Gramineae pollen counts (above 50 grains M^{-3}) exhibits a similar pattern to that of all count days, with minimum concentrations recorded at 0600 and maximum concentration at 1800 hours (Figure 6.2).

Anthers of different species of Gramineae dehisce (split to expose their pollen) at particular times of day, so that the concentration of pollen in the air might be expected to increase around this time of emission. Several authors have examined the timing of anthesis in grasses. Hyde (1952) suggests that most grasses have regular daily periods of anthesis, mostly at about 0900 hours, however the bents (Agrostis tenuis and A. stolonifera) and fescues (Festuca spp.) dehisce around midday while sweet vernal (Anthoxanthum odoratum) and Yorkshire fog (Holcus lanatus) flower in the morning and in the late afternoon (Hyde and Williams 1945). Liem and Groot (1973) related anthesis in Festuca rubra and Holcus lanatus to changes in temperature, humidity and light intensity, such as occur in the early afternoon.

So, if the anthers of Gramineae mostly dehisce during the morning and early afternoon, why should the maximum pollen concentration not be reached until the evening?

Pollen is not necessarily released into the air following anthesis. Indeed, Subba Reddi & Reddi (1985) could find little correlation between anther dehiscence and air borne pollen concentrations. Anther dehiscence is a mechanical process, dependent on both the plant and meteorological factors. Pollen dispersal from the open anther is a mechanical process governed by wind speed and turbulence. Pollen emission may therefore continue long after anthesis as the available pollen exposed in the open anther is dispersed.

Rempe (1937) suggests that the timing of a peak is related to the time at which fluctuations in the temperature trace cease. It is supposed that convection ended

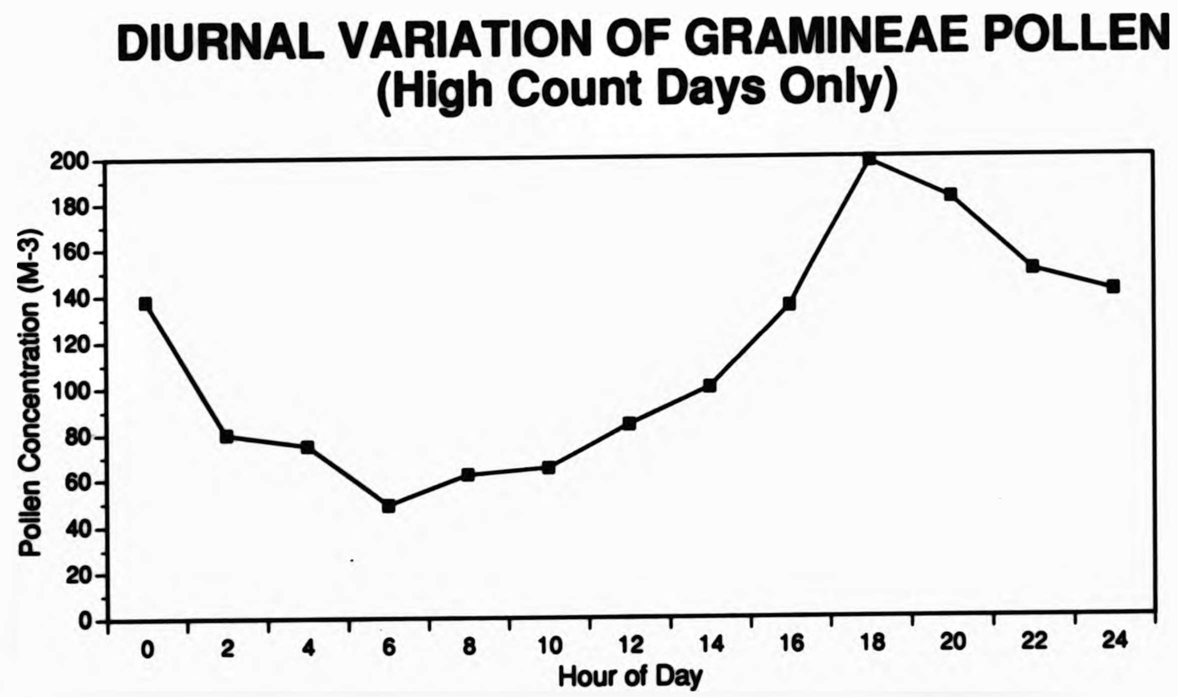


Figure 6.2 Diurnal variation of Gramineae pollen on days with an average concentration of more than 50 grains M-3.

at this time, allowing particles previously suspended in the air at height to settle down into a shallow, stable layer, thus increasing concentration at ground level. Gramineae pollen released through the day will be lifted up into the upper air by convection currents. The lack of a peak or a dramatic rise in pollen concentration following the supposed time of anthesis suggests that little Gramineae pollen derives from close to the sampling site. When convection ceases, pollen previously held aloft will settle down into a shallow, stable layer close to ground level. However, as most Gramineae pollen originates from outside London there will be a delay between the timing of the peak in and outside of the city. The time of peak Gramineae pollen concentration in London will therefore relate to the time of anthesis, the amount of convection occurring, the wind direction and the wind speed.

The lack of any major differences between the timing and abundance of the pollen counts under different wind directions suggests a relative evenness of Gramineae pollen sources both around the sampling site and outside of London. The differences in abundance that do occur with wind direction are likely to be associated with different meteorological conditions rather than differences in pollen source strength. For example, in the north-eastern sector of London, there is no greater abundance of Gramineae source areas, so the higher counts recorded from that wind direction may be accounted for by the greater frequency of hot, dry weather conditions experienced with north-easterly winds and a pressure cell centred to the south-east of London. The two-hour delay in the time of maximum concentration under winds from the south-eastern sector might also be accounted for by the hot, dry weather associated with these winds, whereby if insolation continues for longer during the day, convection will also continue not allowing pollen held aloft to settle back towards ground level until later in the day. However, why this influence is not also apparent for pollen counts recorded under winds from the north-east needs further investigation. Similarly, the lower pollen counts recorded under winds of a westerly origin will be influenced by the increased frequency of mild, humid weather associated with it.

The results from the London sampling record conflict with those reported by Galan *et al* (1989a, 1991) where the maximum Gramineae concentrations were observed in the morning, between 9am and 12 noon although this is not surprising given the different dispersal environments of the study areas. The London work is however in agreement with that of Steel (1983).

6.3 BETULA POLLEN.

As has been observed for Gramineae pollen, the meteorological variables with most influence on the two-hourly Betula pollen count are temperature and relative humidity (Table 6.4). Both variables exhibit a linear relationship with the pollen concentration and when fourth-order partial correlation coefficients are calculated (holding all other meteorological variables constant), the R values are 0.4640 for temperature and 0.2058 for humidity (Degrees of Freedom = 787), both significant at the 99.9% confidence level (Table 6.4). The influence of wind direction on the Betula pollen count is also significant with a F ratio of 12.2032 (Table 6.3).

Dry days within the pollen season are also divided into two categories - warm and cool days, based on the maximum daytime temperature. For Betula, a spring flowering tree, this division is at 18°C. A further sub-division based on the predominant daily wind direction is made in order to examine the influence of the different pollen source areas on the diurnal variation of Betula pollen.

The diurnal variation of Betula pollen concentration reaches a maximum concentration at around 1800 hours (Figure 6.3). For all cases, higher counts are recorded on days with a maximum temperature above 18°C. On days with south-westerly winds, a peak concentration is recorded at 1600 hours.

No previous research has investigated the diurnal variation of Betula pollen emission. If, as several authors have suggested (Kapyla 1984, for example), there is no regular pattern of dehiscence, then the same meteorological parameters that control Gramineae pollen emission may operate to influence the release of Betula pollen. These parameters, namely increasing temperature and decreasing humidity, may trigger dehiscence in the early afternoon and pollen emission would then continue through the day. The early rise in the Betula pollen count may be attributable to pollen released from local sources. Although the majority of this may be uplifted by convection currents in the same way as Gramineae pollen, small amounts may also be brought back to ground level by turbulent airflows triggered by the differential heating of the urban environment. Pollen counts under temperatures above 18°C rise more quickly than those below 18°C (Figure 6.3). When convection ceases, pollen descends slowly towards ground level. The earlier peak in the Betula pollen count

TABLE 6.3 ANALYSIS OF VARIANCE BETWEEN TWO-HOURLY BETULA POLLEN COUNTS (LOGGED/STANDARDIZED) AND METEOROLOGICAL PARAMETERS WITH WET DAYS EXCLUDED.
(*denotes groups significantly different at the 95% confidence level)

CLOUDCOVER:
F. Ratio: 4.1259
F. Prob.: 0.0011

Group		Mean Pollen	Group	1	6	3	5	4	2
6	7.1 - 8.0octaves	1.4709							
5	6.5 - 7.1	1.7616		*					
1	0.0 - 3.0	1.7709		*					
4	5.8 - 6.5	1.7881		*					
3	5.0 - 5.8	1.8670							
2	3.1 - 5.0	1.8853		*					

WINDSPEED:
F. Ratio: 1.2539
F. Prob.: 0.2821

NO TWO GROUPS SIGNIFICANTLY DIFFERENT AT THE 95% CONFIDENCE LEVEL

SUNSHINE:
F. Ratio: 2.4241
F. Prob.: 0.0341

Group		Mean Pollen	Group	1	2	3	4	5	6
2	0.06 - 0.1 hour below	1.6225							
1	>0.11 below	1.6477							
5	0.06 - 0.1 above	1.7164							
4	0.0 - 0.05 above	1.7587							
3	0.0 - 0.05 below	1.8746							
6	>0.11 above	1.9167		*					

RELATIVE HUMIDITY:

F. Ratio: 18.9579
F. Prob.: 0.0000

Group		Mean Pollen	Group	6	5	4	3	2	1
6	>10.1% above norm	.3647							
5	5.1 - 10% above	.6393		*					
4	0 - 5% above	.6752		*					
3	0.0 - 5% below	.7113		*					
2	5.1 - 10% above	.7432		*					
1	>10.1% above	.9697		*	*	*	*	*	

TABLE 6.3 (continued)

TEMPERATURE:

F. Ratio: 31.0285
F. Prob.: 0.0000

Group		Mean Pollen	Group	1	2	5	6	4	3
1	>5°C below norm	1.3331							
2	2.1 - 5.0 below	1.6424		*					
3	0.0 - 2.0 below	1.8968		*	*				
4	0.0 - 2.0 above	2.2352		*	*	*			
6	>5°C above	2.3969		*	*				
5	2.1 - 5.0 above	2.4919		*	*	*			

WIND DIRECTION

F. Ratio: 12.2032
F. Prob.: 0.0000

Group		Mean Pollen	Group	3	2	4	1
1	00 - 90°	1.4837					
2	91 - 180	1.7127		*			
4	271 - 360	1.7938		*			
3	181 - 270	1.9347		*	*		

TABLE 6.4

ANALYSIS OF TWO-HOURLY BETULA POLLEN COUNTS (LOGGED / STANDARDIZED) 1987 - 1989 WITH WET DAYS EXCLUDED.

PEARSON PRODUCT MOMENT CORRELATION COEFFICIENTS:

	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	.5398	-.3858	-.0364	.1238	.0903
N.	793	793	793	793	793
P.	.000	.000	.153	.000	.005

FOURTH ORDER PARTIAL CORRELATION COEFFICIENTS:

	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	.4640	-.2058	-.0636	-.1367	.0869
DF.	787	787	787	787	787
P.	.000	.000	.037	.000	.007

STEPWISE MULTIPLE REGRESSION:

Variables entered in the order:-
1. Temperature.
2. Humidity.
3. Sunshine.
4. Winspeed.

Multiple R = .57862
R^2 = .33480

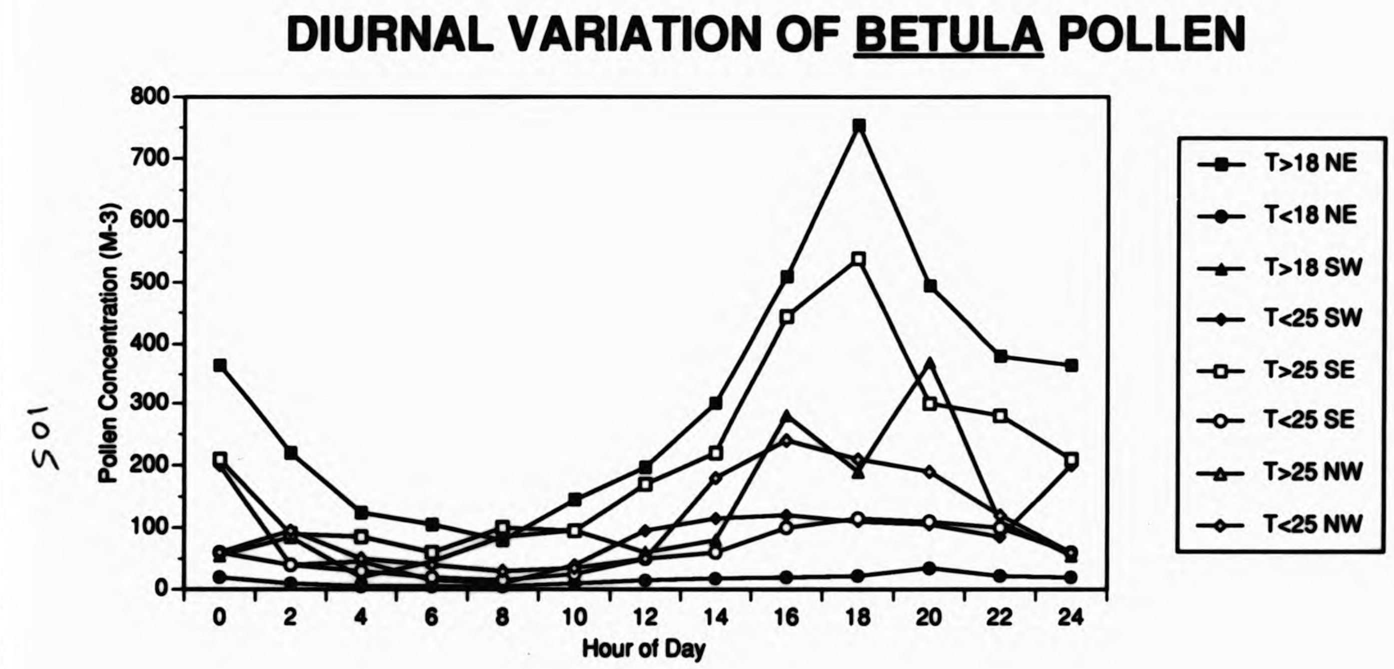


Figure 6.3 Diurnal Variation of Betula Pollen. Days are divided into those with a maximum temperature above or below 21oC (T>21 or T<21) and by the predominant daily wind direction (eg. NE).

compared to that for Gramineae may be explained by the shorter daylength during April, the Betula pollen season, so that convection finishes earlier.

Few differences exist in the timing of the maximum Betula pollen concentration with regard to wind direction or temperature (Figure 6.3). However, differences in abundance may be attributed to the influence of the pollen source areas which, unlike those for Gramineae, vary around the sampling site. The highest Betula pollen counts occur under winds from an easterly origin, the direction of an important pollen source 2km from the sampling site. High counts may also be promoted by the presence of a high pressure cell situated to the south-east of London which generally bring weather conducive to high pollen production combined with easterly winds. However, the reasons why winds from the east at temperatures below 18^{o}C should contain such low Betula pollen counts remain unclear.

A similar analysis is performed to examine the diurnal variation of Betula pollen on days of high pollen counts. No threshold at which Betula pollen invokes an allergic reaction has been calculated in Britain. However, Viandder and Koivikko (1986), working in Finland, have suggested a sliding threshold of 80 grains M-3 at the start of the pollen season, and 30 grains m-3 at its close. For the purpose of this study, a compromise threshold of 50 grains m-3 has been used to delimit high daily Betula pollen counts.

The diurnal variation of Betula pollen on high count days (Figure 6.4) shows a marked pattern with minimum concentrations at 0400 hours and a maximum value at 1600 hours, two hours earlier than for high and low counts combined. As with Gramineae pollen, days of peak Betula pollen concentrations exhibit a different diurnal variation to the other days with a maximum concentration two hours earlier at 1600 hours. These peak concentrations occur most commonly with winds from an easterly direction and may be attributed to the major pollen source located in this direction. This would also explain why the peak concentrations occur earlier in the day as the pollen has a shorter distance to travel to the sampling site.

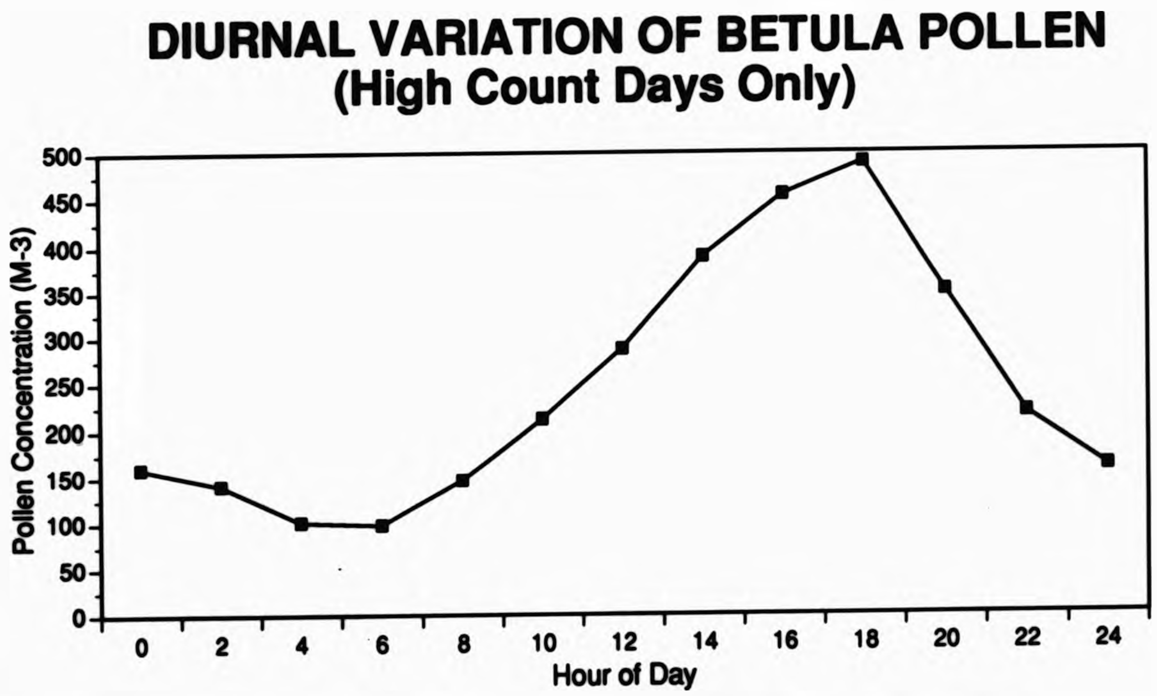


Figure 6.4 Diurnal variation of <u>Betula</u> pollen on days with an average concentration of more than 50 grains M-3.

6.4 PLATANUS POLLEN.

The meteorological variables temperature and relative humidity again prove the most influential to the Platanus pollen concentration through multiple regression analysis, both having linear relationships significant at the 99% level. The variable wind speed is also significant at the 99% confidence level in both the Pearson product moment and partial correlation analysis (Table 6.6). Once again, wind direction is an important variable with differences between pollen counts under different wind directions significant at the 95% confidence level (Table 6.5). The highest Platanus pollen counts are recorded under winds of a southerly origin, 90° to 270°.

As for the Betula pollen season, dry days within the Platanus pollen season are separated into warm and cool days (above and below 18°C) and different predominant wind directions. The two hourly pollen counts are then averaged for each category to produce a 'model' pollen day.

The diurnal variation of Platanus pollen (Figure 6.5) exhibits marked differences in abundance. Maximum concentrations of almost 200 grains M^{-3} are recorded under south-easterly winds on days with a maximum temperature below 18°C. (No days with a maximum daily temperature above 18°C and a south-easterly wind fell within the Platanus pollen season.) Minimum concentrations are recorded under north-westerly winds regardless of temperature.

No research has been conducted to determine what concentration of Platanus pollen is likely to invoke an allergic reaction. For this study an arbitrary threshold has been set at 18 grains M^{-3} as this resulted in approximately the same proportion of the pollen season being classified 'high' as for Gramineae and Betula. The diurnal variation of Platanus pollen on days of high concentration is markedly different to the other pattern with a maximum level at 1200 hours (Figure 6.6).

The time of or processes that invoke anthesis of Platanus are unknown. Platanus pollen derives almost totally from local sources within 5km of the sampling site, and as the maximum pollen concentration occurs from 1600 hours onwards (depending upon the wind direction), the release of the pollen must occur shortly before that time. Anthesis would then occur during the

TABLE 6.5 ANALYSIS OF VARIANCE BETWEEN TWO-HOURLY PLATANUS POLLEN COUNTS (LOGGED/STANDARDIZED) AND METEOROLOGICAL PARAMETERS WITH WET DAYS EXCLUDED.
(*denotes groups significantly different at the 95% confidence level)

CLOUDCOVER:
F. Ratio: 6.2475
F. Prob.: 0.0000

Group		Mean Pollen	Group	1	6	3	5	4	2
1	0.0 - 3.0octaves	.5046							
6	7.1 - 8.0	.6166							
3	5.1 - 5.8	.7887							
5	6.5 - 7.1	.8050		*					
4	5.8 - 6.5	.8339		*					
2	3.1 - 5.0	.9376		*	*				

WINDSPEED:
F. Ratio: 11.5647
F. Prob.: 0.0000

Group		Mean Pollen	Group	1	3	4	2	5	6
1	0.0 - 6.0 knots	.6749							
3	7.11 - 8.4	.8634							
4	8.41 - 10.0	.9472							
2	6.01 - 7.1	.9624							
5	10.01 - 12.0	1.0072		*	*	*			
6	12.01 - max	1.1120		*	*	*	*	*	

SUNSHINE:
F. Ratio: 3.4114
F. Prob.: 0.0047

Group		Mean Pollen	Group	1	2	3	4	5	6
1	>0.11 hour below	.6166							
4	0.0 - 0.05 above	.6679							
6	>0.11 above	.6746							
2	0.06 - 0.1 below	.7336							
5	0.06 - 0.1 above	.9702		*		*			
3	0.0 - 0.05 below	1.0244							

RELATIVE HUMIDITY:

F. Ratio: 13.1060
F. Prob.: 0.0000

Group		Mean Pollen	Group	6	5	3	4	1	2
6	>10.1% above norm	.3647							
5	5.1 - 10% above	.6393		*					
2	5.1 - 10% below	.6752		*					
4	0.0 - 5.0% above	.7113		*					
3	0.0 - 5.0% below	.7432		*					
1	>10.1% below	.9697		*	*	*	*	*	

TABLE 6.5 (continued)

TEMPERATURE:

F. Ratio: 14.7932
F. Prob.: 0.0000

Group		Mean Pollen	Group	1	2	5	6	4	3
1	>5°C below norm	.5759							
2	2.1 - 5.0 below	.7267		*					
5	2.1 - 5.0 above	.8039		*					
6	>5°C above	1.0432							
4	0.0 - 21.0 above	1.1752		*					
3	0.0 - 2.0 below	1.3682		*	*				

WIND DIRECTION

F. Ratio: 33.0388
F. Prob.: 0.0000

Group		Mean Pollen	Group	3	2	4	1
4	271 - 360°	.4876					
1	00 - 90	.5144					
3	181 - 270	.9326		*	*		
2	91 - 180	1.1838		*	*	*	

TABLE 6.6

ANALYSIS OF TWO-HOURLY PLATANUS POLLEN COUNTS (LOGGED / STANDARDIZED) 1987 - 1989 WITH WET DAYS EXCLUDED.

PEARSON PRODUCT MOMENT CORRELATION COEFFICIENTS:

	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	.2264	-.2827	.1026	.0606	.2454
N.	746	746	746	746	746
P.	.000	.000	.003	.049	.000

FOURTH ORDER PARTIAL CORRELATION COEFFICIENTS:

	Max.Temp.	Humidity	Cloud	Sunshine	Wind
Coeff.	.0993	-.1937	.0891	-.0331	.1959
DF.	740	740	740	740	740
P.	.003	.000	.008	.184	.000

STEPWISE MULTIPLE REGRESSION:

Variables entered in the order:-
1. Humidity.
2. Wind speed
3. Cloud cover
4. Temperature

Multiple R = .38206
R^2 = .14597

DIURNAL VARIATION OF PLATANUS POLLEN

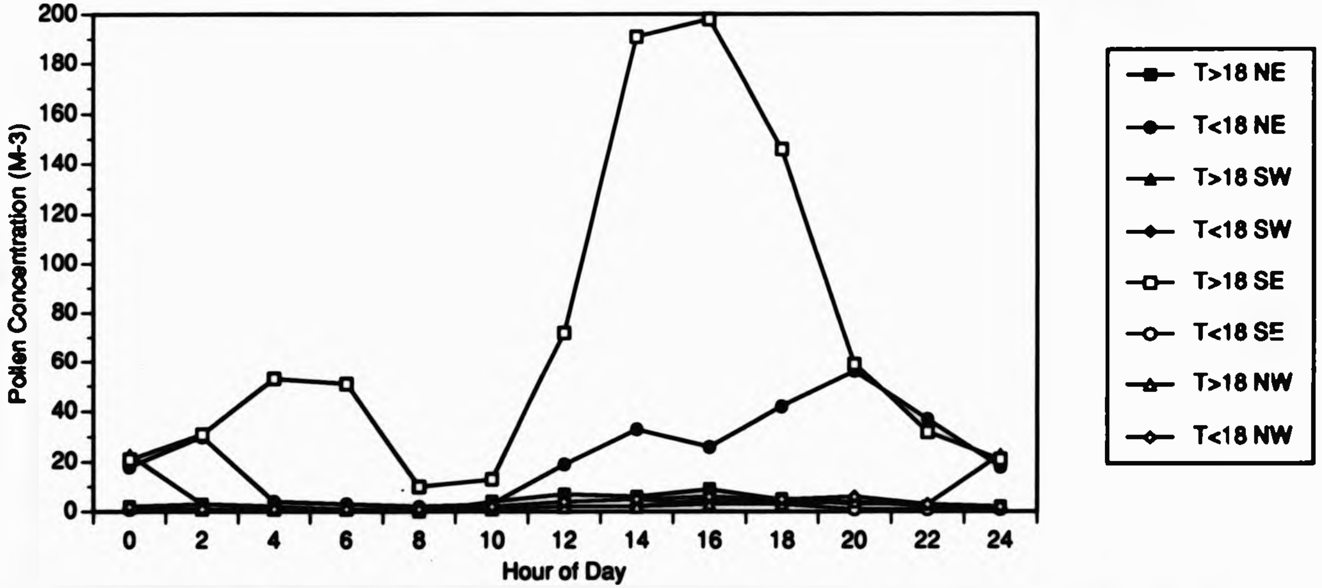


Figure 6.5 Diurnal Variation of Platanus Pollen. Days are divided into those with a maximum temperature above or below 18oC (T>18 or T<18) and by the predominent daily wind direction (eg. NE).

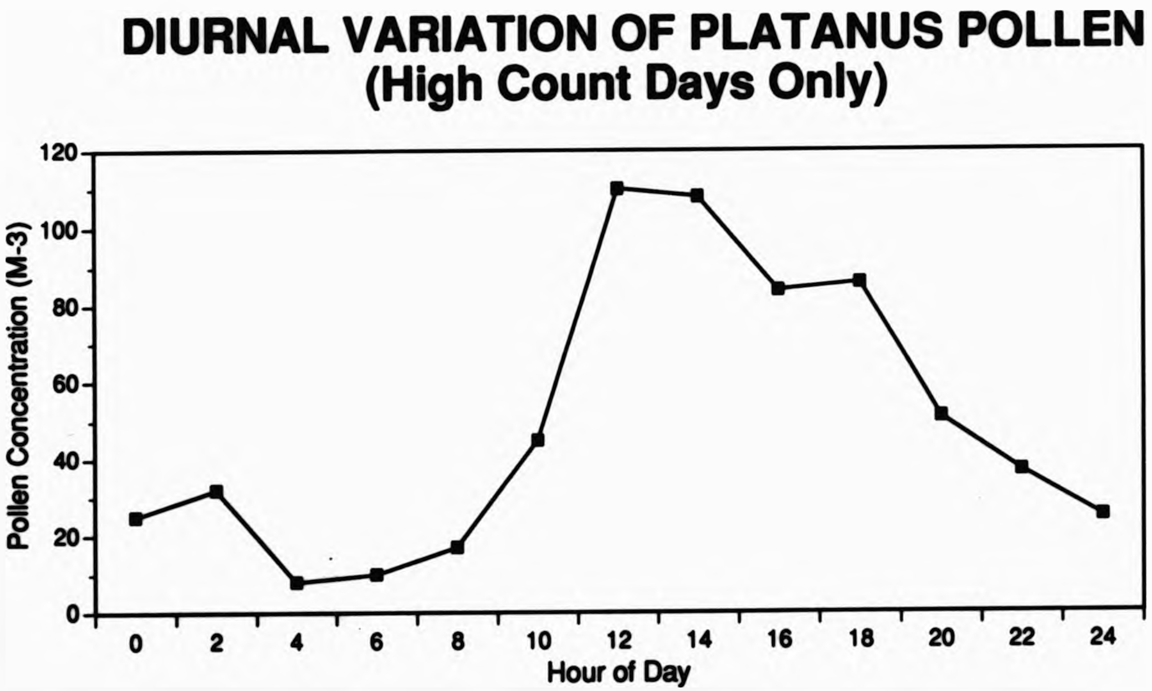


Figure 6.6 Diurnal variation of <u>Platanus</u> pollen on days with an average concentration of more than 18 grains M-3.

morning when the increasing temperature and decreasing humidity cause the drying and opening of the Platanus anthers. Galan *et al* (1991), working in Cordoba, Spain, recorded maximum concentrations of Platanus pollen in the morning, between 10am and 12 noon, several hours earlier than in the London study, and suggests that the highest concentration coincides with the maximum values of temperature and sunlight. This is not however the case in London where the enhanced heat island effect of the larger town may cause pollen to be airborne at least until the rising convective air currents diminish.

However, as can be observed from the diagram of diurnal variation, Figure 6.5, the highest Platanus pollen counts do not occur on the warmest days, but on days with a maximum temperature below 18^{o}C, although the analysis of variance statistic and partial correlation coefficients (Tables 6.5 and 6.6) indicate a significant positive relationship between temperature and the pollen count. Pollen released from local sources on warm days might be quickly uplifted by convection currents, dispersed away from the sampling site and so the concentration recorded there is diluted . On days with temperatures below 18^{o}C more pollen remains near ground level, unable to disperse far from its source and so is recorded in abundance by the pollen sampler.

With regard to wind direction, the highest pollen counts are recorded under winds from the south where the major Platanus sources are located. Significantly lower counts are recorded in northerly airflows, (Table 6.5).

6.5 SUMMARY.

Marked variations in pollen abundance occur through the day and these relate both to the phenological patterns of pollen release inherent in plants and to the role of meteorology in dispersing pollen from the source plant to the sampling site. All three pollen taxa examined in detail exhibit a regular diurnal maxima between 1800 and 2200 hours. This results when pollen is released through the day in response to sunlight, increasing temperatures and decreasing humidity, and becomes uplifted in the rising currents of warm convectional air. When these convection currents cease at the end of the day, then the pollen previously held aloft is able to fall back down towards ground level where it is recorded at a maximum by the pollen sampler in the evening.

That all three pollen taxa exhibited similar diurnal patterns of abundance demonstrates how at sites such as London, distant from the main source areas, the time of day of pollen release is of lesser importance in determining the diurnal concentrations than are the processes of pollen dispersal by which the pollen is transported to the sampling site. It is the transport processes of wind speed and direction and air turbulence that are of importance in determining the diurnal pattern of pollen concentration in London.

CHAPTER 7

SOME FURTHER PROBLEMS OF THE ANALYSIS EXPLAINED.

7.1 THE INFLUENCE OF PRECIPITATION ON POLLEN CONCENTRATIONS WITH SPECIAL REFERENCE TO EPISODES OF INCREASED CONCENTRATION ASSOCIATED WITH RAINFALL.

The influence on rainfall events on the daily and hourly pollen counts has proven difficult to evaluate using the same statistical techniques as applied to the other meteorological parameters. An initial examination of the relationship between the daily pollen counts and daily precipitation total over the three years of sampling (Tables 5.1, 5.6 & 5.11) reveals that the relationship is not simply negative and linear as suggested by previous authors, for example Hyde (1952) and McDonald (1962). A close inspection of the data reveals how on some days high pollen counts are recorded on days with high rainfall totals. However, before proceeding to examine this phenomena, the influence of precipitation on pollen counts on more typical days when a decrease in pollen concentration has been recorded is considered.

For this analysis, individual pollen taxa have been grouped together to form a total pollen sum so that rainfall events from any time of year might be considered and to eliminate some of the variation caused by diurnal patterns of pollen abundance (Chapter 6).

During most rainfall events pollen concentrations decrease rapidly and, even from the highest concentrations, will be reduced to a count of less than 10 grains M^{-3} by the following two-hour period. Figure 7.1 demonstrates how pollen counts during June are reduced from almost 200 grains M^{-3} to below 8 grains M^{-3} following the onset of 1.5mm of precipitation during a two-hour period. Figure 7.2 also demonstrates this decline but shows how large pollen grains are removed from the air at a more rapid rate than are small grains. The smallest pollen grain in the pollen spectrum, Urtica (16 microns, Moore & Webb, 1978), is recorded at a higher concentration during precipitation than are the larger grains of Gramineae (25 to 35 microns) and Tilia (16x33 to 21x41 microns), a pattern of washout that is observable in most rainfall events.

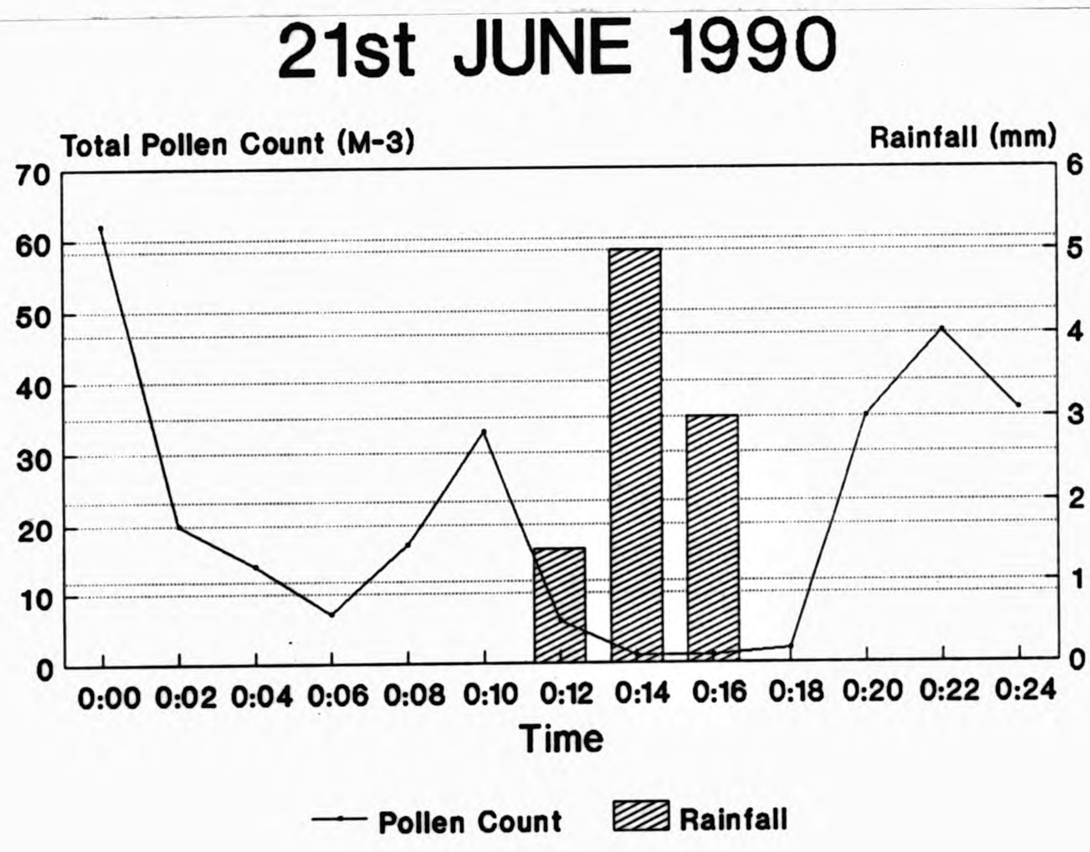


Figure 7.1 Influence of rainfall on pollen concentration showing a typical decline in concentration.

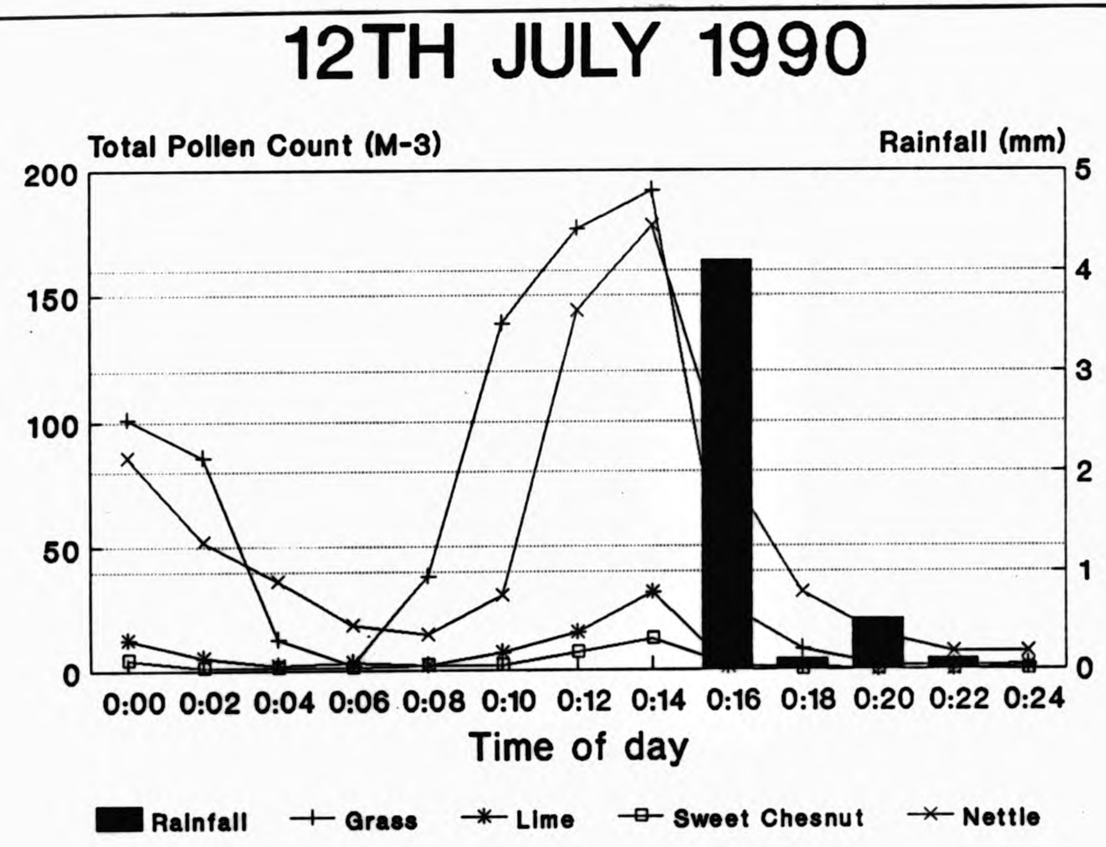


Figure 7.2 The influence of rainfall on pollen concentration with regard to pollen grain size.

The washout of pollen from the atmosphere is influenced by the rainfall intensity and size of raindrops as well as the size of the pollen grains. The removal of pollen from the atmosphere may be by one of three processes. Pollen grains may act as condensation nuclei around which raindrops form, and Sumner (1988) states that the development of precipitation in some storms is dependent on the number and size of aerosols in the atmosphere. Alternatively, pollen grains may become encapsulated in a raindrop if it strikes a grain when falling. The third mechanism of removal occurs if an airborne pollen grain is deposited on a wet surface at ground level and becomes incorporated into the water.

Puhls & von Wahl (1990, 1991) have attempted to determine the relative importance of these processes of pollen removal by examining the airborne pollen concentration and pollen collected in raindrops during a single rainfall event. They concluded that very little pollen was removed from the air by raindrops, and that the main process of air cleansing was by the deposition of pollen on wet surfaces. However, Dingle & Gatz (1966) working in the United States, recorded large quantities of pollen in rainwater and found that this water-borne concentration declined progressively through a storm. They did not, however, examine changes in airborne pollen concentrations.

However on several occasions during the three year sampling period, high daily pollen counts have been recorded on days with high rainfall totals. Two reasons are apparent for this phenomena. First, rain may either fall very early or late in the day, away from the time of maximum pollen concentration (Chapter 6), so that the precipitation does not disrupt the normal diurnal peak. For example, if rain falls early in the day, before approximately 12 noon, a high daily count may still be recorded as there is sufficient time for the anthers of a plant to dry and to release more pollen, or for a small part of the pollen washed out of the atmosphere to become resuspended on evaporation of the rainwater.

Second, high daily pollen counts may coincide with high rainfall amounts when a marked increase in pollen concentration occurs during or immediately preceding a rainstorm. This is an unusual occurrence in London and during the sampling period 1987 to 1989 it occurred on only eleven occasions. These occurrences do, however, deserve special consideration as they reveal a little known mechanism of pollen dispersal.

Unfortunately, insufficient occurrences of increased pollen concentrations with rainfall have been recorded to allow a robust statistical analysis of the different meteorological conditions of these compared to other rainfall events. For example, an interesting study would be to compare the different rainfall intensities and durations, the wind regimes and the back trajectories of these rainfall events to determine their role in pollen dispersal. Instead, the total pollen concentration was plotted against rainfall for the eleven events and the patterns compared to selected days showing a typical decrease in concentration with rainfall.

A examination of the changes in total pollen concentration that occur within these rain events shows how concentration is increased during the first two-hourly period of rainfall. This increase is always short-lived for concentrations usually decrease to less than 10 grains M^{-3} by the second time period. For example, on the 5th June 1988 the pollen count, which at this time of year comprises mainly Gramineae and Pinus, follows a typical diurnal variation with a peak count of 87 grains M^{-3} at 1400 (Figure 7.3). However, the decline from this peak is interrupted by a small rain shower at 2000 hours which is accompanied by a pollen count of 54 grains M^{-3}. A similar pattern may be observed on the 7th May 1988 when a pollen count of 127 grains M^{-3} was recorded during 3.3mm of precipitation (Figure 7.4).

On rare occasions increases in the pollen count have been recorded some time after the onset of precipitation as, for example, on the night of the 29/30th May 1990 (Figure 7.5). After two hours of rainfall and pollen counts of less than 30 grain M^{-3}, at midnight the total pollen count rose to 49 grains M^{-3} during a two hour period. This increase, non-coincident with the time of a normal Gramineae or Urtica peak count, was short lived and by 2am was reduced to 15 grains M^{-3}. This increase in concentration might possibly be explained by the resuspension of pollen in brief breaks in the rainfall. However, precipitation was continuous during this two-hour period and, thus indicating that the increase was concurrent with the rainfall.

O'Rourke (1990) examined the condition of pollen grains as evidence of resuspension during rain events. Recognizing the reentrainment of pollen as a

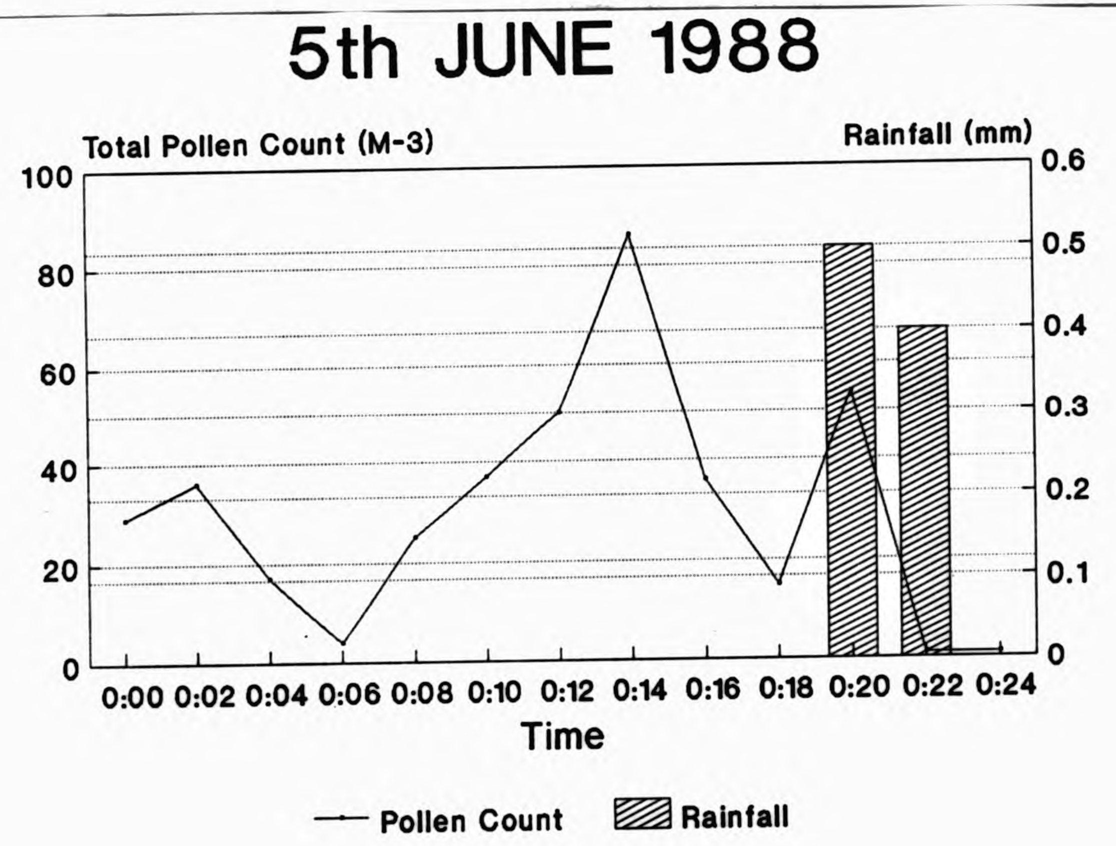


Figure 7.3 **The influence of rainfall on pollen concentration, 5th June, 1988.**

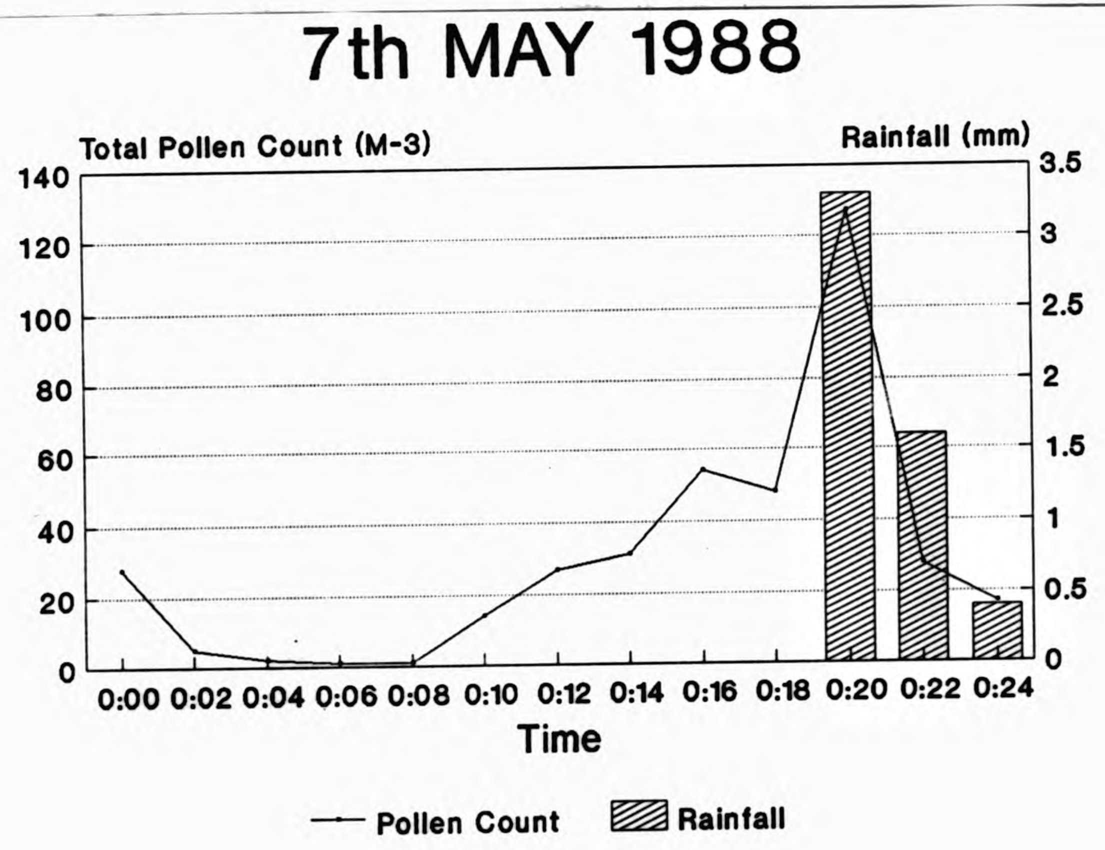


Figure 7.4 The influence of rainfall on pollen concentration, 7th May, 1988.

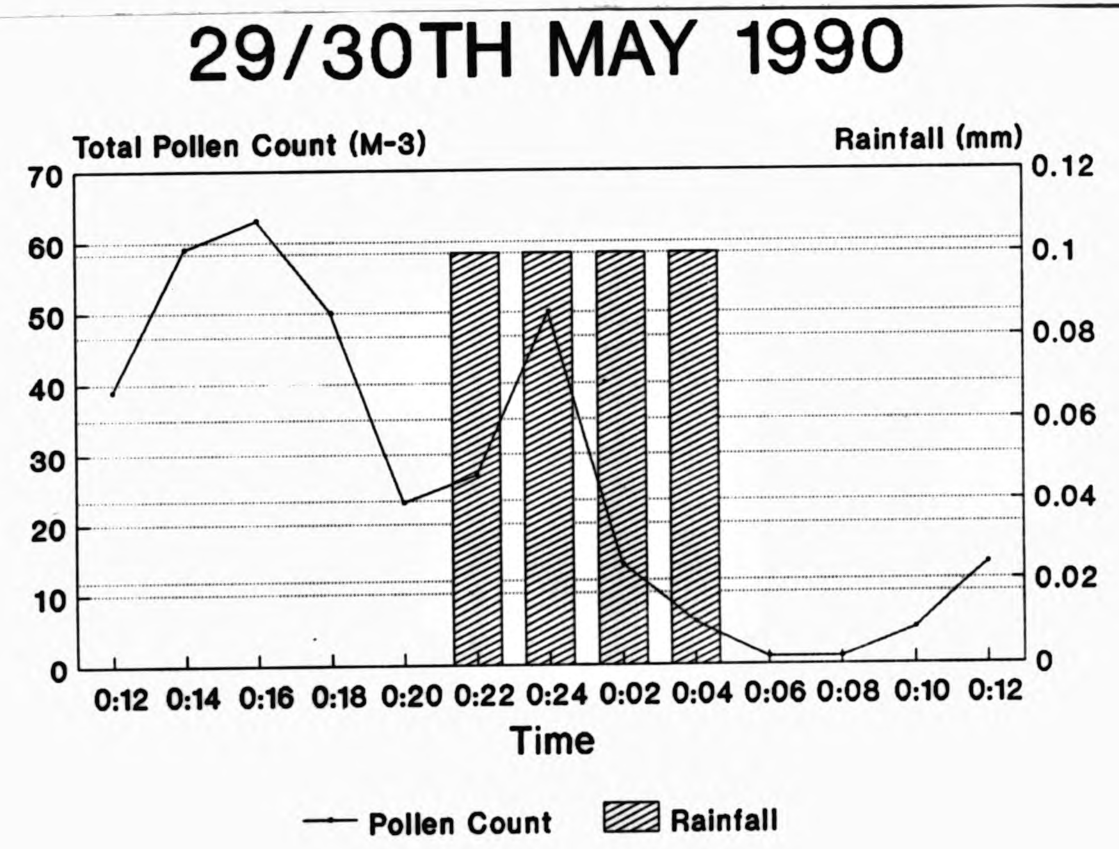


Figure 7.5 **The influence of rainfall on pollen concentration, 29/30th May, 1990.**

possible source of error in fossil sediments (Birks & Birks, 1980) she was able to identify two categories of pollen grain damage. The first includes pollen grains possessing an intine and an uncrumpled exine; such grains are presumed to be freshly released. The second category comprises grains which lack an intine or which exhibit a severely crumpled exine and these are presumed to have been reentrained by the airflow. O'Rourke observed that 11% of the total pollen catch in Arizona comprised of damaged grains and that the concentration of these was highest (accounting for almost 90% of the total at times) during convective rainstorms, rainfall events similar to those producing increased pollen counts in London. The question must then be asked, are reentrained pollen grains accounting for the increases in pollen concentration associated with rainfall? An examination of the damage or alteration of pollen grains from the London record revealed that fewer than 4% of the total pollen catch during these times of increased counts comprised of grains that could be classified as damaged according to O'Rourkes second category. There is therefore little evidence to suggest that the high pollen concentrations recorded during certain rainfall events in London might be accounted for by the reentrainment of previously deposited pollen grains. However, the process of the reentrainment of pollen grains may make a small contribution to the increased pollen concentrations recorded during rain events, although it is not of major importance.

The large difference in the proportion of damaged pollen grains recorded between Arizona and London might be accounted for by the different dispersal environments. In London there will more moisture present in the air and hence more damp surfaces capable of removing pollen from the airflow, as well as possibly a more thorough washout of pollen to the water courses. As a result less pollen will be remaining for resuspension by the wind. Indeed, O'Rourke does suggest that the reentrainment values from Arizona approach a maximum.

Other authors have used different techniques to identify the resuspension of pollen grains. Phillips (1972) suggests that fluorescence microscopy might be used to identify pollen grains of different ages within a fossil pollen sample. This method might then be used also to assess the age of modern pollen grains and hence establish whether or not they have become reentrained. It was not however used in this study due to the difficulties involved in using it with pollen samples from the Burkard sampler.

When examining the influence of rainfall on pollen concentration, other meteorological variables associated with rainfall must be considered, and in particular the wind regime. Showery or stormy weather is frequently characterized by strong winds which will independently influence pollen dispersal. The increased wind velocities experienced at ground level associated with rainfall may enable more pollen to become airborne, which might partly account for the increased pollen concentrations recorded at such times. Another indirect influence of an increase in wind speed may be to increase the airflow through the orifice of the Burkard sampler, thereby increasing its sampling efficiency. This may also account for some of the increase in pollen concentration.

However, both of these effects are likely to occur during all rainfall occurrences, and not just those recording increased pollen concentrations. To investigate this, an analysis of variance test was performed between the wind velocities recorded immediately before and during normal rainfall events and those recording increased pollen concentrations. Table 7.1 shows that there was no significant difference in the wind velocities under these two types of weather condition and increased wind velocities are therefore unlikely to be the cause of the increased pollen concentrations.

TABLE 7.1 ANALYSIS OF VARIANCE BETWEEN WIND VELOCITIES RECORDED UNDER NORMAL RAINFALL EVENTS AND THOSE SHOWING MARKED INCREASES IN POLLEN CONCENTRATION, 1987 - 1989.

F Ratio 0.8761 Probability 0.6547

Several characteristics distinguish the rainstorms under consideration from other rain events. All the events were of a short duration (all lasted less than 6 hours), with a high intensity (up to 5mm of precipitation in a two hour period) and all occurred under an anticyclonic synoptic situation with a high maximum daily temperature of above 25°C. These characteristics combine to suggest that the rainstorms are convectional in origin, rather than longer lasting and less intense cyclonic storms (Sumner, 1988). Convectional storms develop as a result of a rapid uplift in the atmosphere and frequently result in periods of intense but short lived rainfall. Urban areas, such as London, are considerably warmer than the surrounding areas (Oke, 1973) and generally have reduced wind speeds (Chandler, 1965), effects which combine to increase convectional airflows. This in turn promotes the development of convectional storms; Changnon (1978), working in St. Louis, Missouri, estimated an increase in convectional rainfall over an urban area of between 10 and 115%.

As a convectional storm develops any particulate matter present will be uplifted in the airflow and may be transported horizontally within the storm if it moves. If precipitation forms this frequently produces a strong, cold downwards draught of air which transports the uplifted pollen back to ground level and hence may result in a marked increase in pollen concentration there. The same process has been observed for sulphur dioxide and particulate pollution concentrations (Emberlin, 1980). An examination of the increased pollen concentrations shows that they are all shortlived; within the second two hour period the total pollen count is usually reduced to less than 10 grains M^{-3} and to almost zero by the next time period (Figures 7.3 to 7.5).

Puhls and von Wahl (1990, 1991) reported similar increases in both Gramineae and Betula pollen concentrations during rainfall events in Essen, Germany, particularly for pollen traps located close to ground level. They attributed these increases to the action of air current which force airborne pollen carried between the raindrops down to ground level, in a similar way to convective airflows. However, they also suggest that raindrops can increase pollen emission from the anthers of plants by shaking and impacting on these, hence loosening pollen that is ready for dispersal, and that this may account for some of the increase in concentration at the lower sampling site. This process may also occur at the London site for pollen taxa which derive from close to the sampler as well as at other pollen source areas where it may contribute to the occasional increased pollen abundance in convective airflows. However, with only one sampling height, it has not been possible to determine any vertical differentiation in pollen concentration as was recorded at Essen. The vertical variation of pollen concentration in London is considered by Bryant *et al*, 1989.

Cadman (1991) also hints at an unexpected relationship between rainfall and pollen concentration, similar to that observed in London, when she reports a slight positive correlation between these two variables.

From the data available in this study it is not possible to determine whether pollen has been transported far from its origin during the convective storms. The pollen spectra recorded during these peak concentrations do not greatly differ from those present before the rise in concentration, and so this provides no evidence of long distance transport. However, this does not imply that no transport has occurred as much of south east England has a pollen spectrum similar to that of London.

The fact that these periods of increased pollen concentration are shortlived indicates that the airborne pollen is quickly removed from the atmosphere by the same processes as operate during a normal rainfall event, or that the pollen becomes diluted in the atmosphere. Pollen concentrations at ground level will be diluted if the mixing height of the atmosphere is raised during or following from a rainstorm.

SUMMARY

The influence of rainfall on pollen concentrations has been shown to comprise of several complex processes which act according to factors such as the origin of a rainstorm as well as the size of pollen grains. To summarize, rainfall will usually lead to a rapid decline in the pollen count due to both the washout of pollen by raindrops and to the deposition of pollen to wet surfaces. Large and heavy pollen taxa are more easily removed from the air than are lighter grains. However on rare occasions, a rapid rise in pollen concentration may immediately precede a rainstorm. This unusual phenomena which occurred only 11 times during three pollen seasons, results when pollen is uplifted at the leading edge of a convective storm and is brought back down to in the same air current as the rain, increasing the concentration at ground level until this pollen is in turn washed out of the atmosphere. There is little evidence to suggest that the pollen grains have become resuspended.

7.2 THE OCCURRENCE OF HIGH NIGHT-TIME POLLEN CONCENTRATIONS.

An further rare and unusual feature of the diurnal pollen data is the occasional occurrence of high concentrations of pollen at night. These may be seen to occur for several pollen taxa from approximately 2200 hours, at times non-coincident with the normal peak diurnal concentration (Chapter 6). For the purpose of this investigation, high night-time concentrations have been defined as occasions when the total pollen count rises for at least two consecutive sampling periods after 2200 hours. No individual pollen taxa exhibited a regular maximum diurnal concentration at this time, but occasional rises in the count have been observed throughout the growing season. The nights exhibiting increased counts for the 14 most common pollen taxa are given in Table 7.2. Two examples of this pattern of diurnal variation overnight are illustrated by Figures 7.6 and 7.7 which show the variation of Gramineae pollen concentration on the nights of the 24/25th June 1987 and Platanus pollen concentrations on the 22/23rd April 1989.

Several previous authors have also observed high night-time pollen concentrations. Steel (1983) recorded over-night peaks in the Gramineae pollen count in London, frequently at concentrations higher than those of the daytime maxima. Having examined the temperature profile at a site outside of the City, she concluded that the development of a ground level temperature inversion is the chief cause of nocturnal peaks in pollen concentration. A temperature inversion will provide a capping effect in the atmosphere and will concentrate pollen at ground level by reducing the upwards movement of air.

However Spieksma (1983), working in the Netherlands, also recorded night-time peaks of Gramineae pollen, but concluded that the presence of temperature inversions had no influence on their formation. In a later paper (Spieksma and den Tonkelaar, 1986) night-time peak concentrations were related to high pollen production processes which occur during the day and to the development of temperature inversions and the fall-out of pollen during the night. Other authors have examined the influence of night-time temperature inversions on pollution concentrations and dispersal. For example, Lawrence (1967) recorded increased levels of sulphur dioxide with spells of low level temperature inversion but this study was carried out in winter, a time when inversions are

TABLE 7.2

NIGHTS EXHIBITING NOCTURNAL PEAKS IN POLLEN CONCENTRATION (1987 to 1989).

	Max. temp. of previous day	Max. wind speed	Min. cloud cover	Stability category
20/21nd April 1987	12.55°C	7knots	2oct.	E
26/27th April 1987	22.75	7	6	D
26/27th May 1987	21.40	10	4	D
16/17th July 1987	18.03	6	3	F
17/18th July 1987	16.60	9	7	D
23/24th July 1987	15.05	6	1	F
26/27th April 1988	14.95	7	8	D
7/8th May 1988	18.15	5	7	E
22/23rd April 1989	12.75	8	2	E
23/24th April 1989	12.60	11	8	D
31st May/1st June 1989	14.75	6	2	F
5/6th June 1989	17.10	7	6	D
7/8th July 1989	21.50	4	3	F
8/9th July 1989	22.05	11	7	D
9/10th July 1989	17.60	5	7	E
6/7th August 1989	27.10	6	3	F
9/10th August 1989	24.05	11	7	D

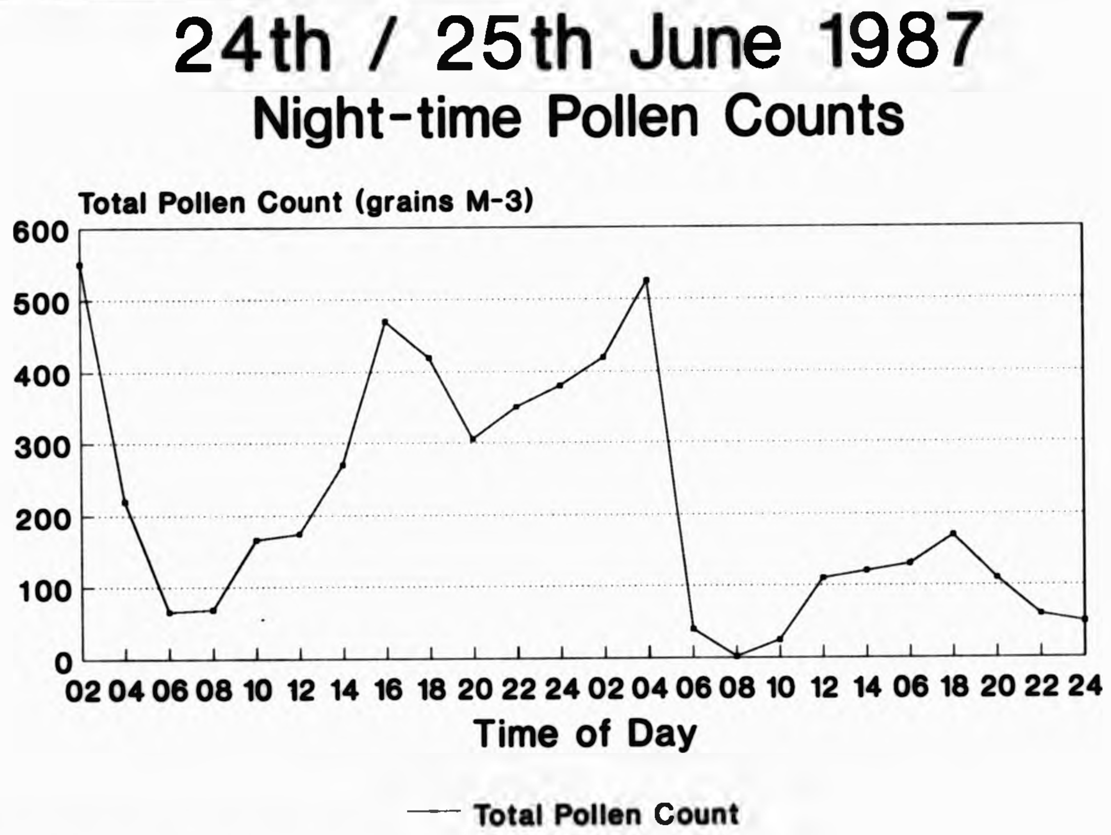


Figure 7.6 High night-time pollen counts

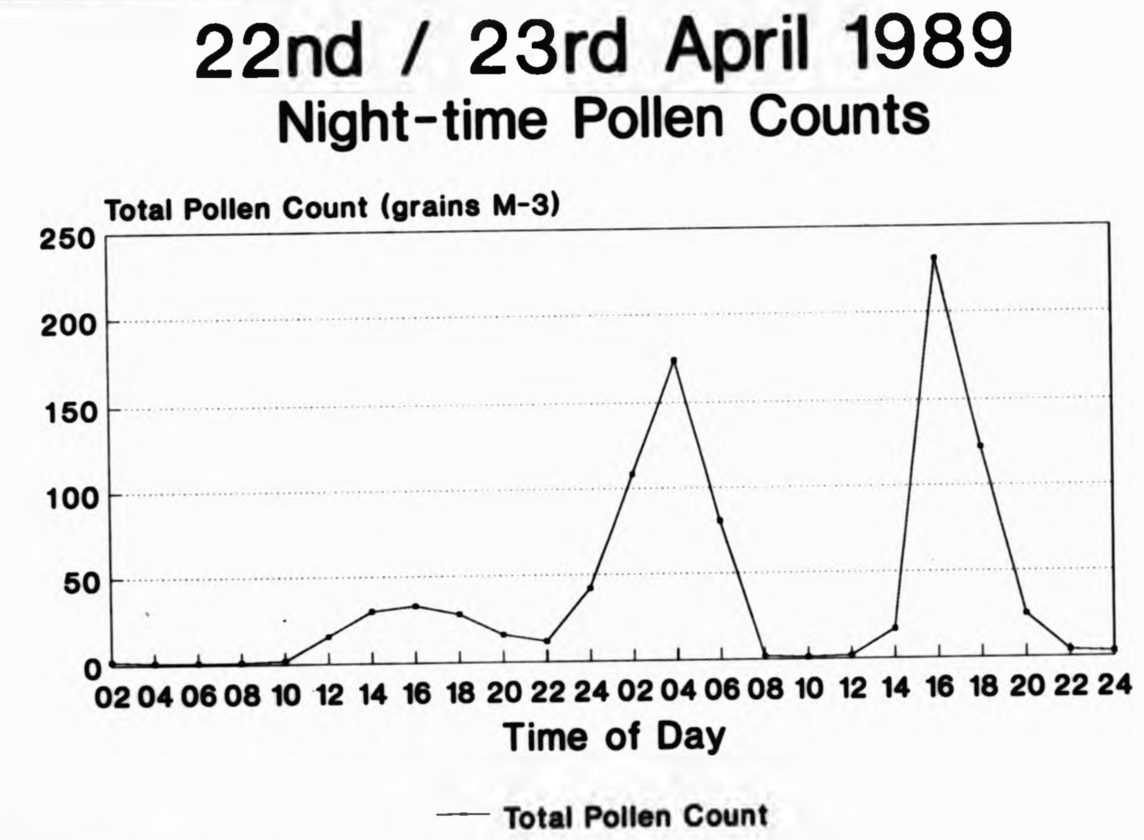


Figure 7.7 High night-time pollen counts

frequently much more pronounced and more common than during the spring and summer, the times of pollen release.

The meteorological conditions recorded during nights experiencing high pollen concentrations therefore need to be examined to determine the factors contributing to their formation. Because detailed the temperature profiles necessary to identify temperature inversions are not available in London, the atmospheric stability has been estimated using the system devised by Pasquil (1962). This estimates night-time stability as a function of wind speed and cloud cover (Table 7.3) and derives six stability categories ranging from 'very unstable' (A) through 'neutral' (D) to 'moderatly stable' (F).

An analysis of variance test is then performed to test for significant differences between both the pollen counts recorded under each of the stability categories that may occur overnight, ie. categories 'D', 'E', and 'F' over the entire pollen seasons for the three years of sampling, irrespective of whether or not a peak in concentration was recorded. For ease of calculation, the individual pollen taxa have been grouped together to form a total pollen sum and this sum used in the analysis. The results of these tests are presented in Table 7.4. The highest pollen counts are recorded under conditions of stability (Pasquil's categories 'E' and 'F'), a difference from the other stability categories significant at the 95% confidence level. However, a significant number of the instances of high night-time pollen concentrations were recorded during nights experiencing neutral stability conditions (Pasquil's category 'D').

These results are in general agreement with the idea proposed by Steel (1983) and Spieksma and den Tonkelaar (1986); that high nocturnal pollen concentrations result from ground level temperature inversions. Although the presence of inversion layers cannot be proven in this study in London, they form under conditions of extreme stability such as frequently occur overnight (Sumner, 1988). Extreme stability and temperature inversions result when, contrary to the norm, temperatures increase with height due to the radiative cooling of the earths surface. Because of the different radiation balances between night- and daytime conditions stable lower atmospheres tend to dominate at night and unstable ones by day. At night continued cooling of the ground surface also chills the air in immediate contact with it and this, combined with the downslope movement of colder and denser air into the valleys and street canyons, result in a comparatively deep inversion layer in the lowest few

TABLE 7.3

STABILITY CATEGORIES (AFTER PASQUIL, 1962).

Wind speed at 10m (m/sec)	INSOLATION Strong	Moderate	Slight	NIGHT TIME >4/8 cloud	<3/8 cloud
<2	A	A/B	B	-	-
2 - 3	A/B	B	C	E	F
3 - 5	B	B/C	C	D	E
5 - 6	C	C/D	D	D	D
>6	C	D	D	D	D

KEY

A Very Unstable **B** Unstable **C** Neutral

D Slightly stable **E** Stable **F** Very stable

TABLE 7.4

ANALYSIS OF VARIANCE BETWEEN THE TOTAL POLLEN COUNTS (LOGGED AND STANDARDIZED) RECORDED UNDER PASQUILS STABILITY CATEGORIES D - F.

CATEGORY	MEAN COUNT
D	1.0026
E	1.2819
F	1.2655

F Ratio 24.5622
F Prob. 0.0008

hundred metres of the atmosphere (Sumner, 1988). Stability is therefore usually characterized by a lack of vertical movement in the atmosphere and frequently low wind velocities (Pasquil, 1962). Many authors have suggested that the top of an inversion layer can trap pollution (for example Oke, 1987, Sumner, 1988) and therefore at the same time this will also limit pollen dispersal. It is hypothesized that any pollen remaining in the air overnight is unable to be dispersed upwards but is concentrated close to ground level where it is recorded in abundance by the Burkard sampler. The height of the pollen sampler relative to the top of the inversion layer will therefore be of significance in determining the frequency and abundance of high night-time pollen concentrations. If, for example, a temperature inversion does form overnight bit is so shallow that the top is below the height of the pollen sampler then its effects would not be monitored by the sampling record inspite of the possibility of high pollen concentrations at ground level. However, most authors suggest that temperature inversions usually form to several hundred meters, a height well above the position of the sampler and so this scenario is believed to occur only very infrequently. The rarity of high night-time pollen concentrations is instead thought likely to reflect the infrequency of temperature inversions in an urban area (where increased turbulence may be sufficient to breakdown any layers of stable air) and the need for these to be combined with times of pollen release, for unless pollen is becoming suspended at ground level then the effects of capping or concentration will be minimal. Most temperature inversions tend to occur at night but yet, as Chapter 6 has demonstrated, most pollen is released during daylight hours and so this coincidence of pollen release and temperature inversion are likely to be rare.

If pollen dispersal does become limited by the capping effect of stable layers of air, then a reduction in the pollen count will gradually occur as the grains begin to sediment out of the air at values approaching their settling velocities. However further dilution of pollen may occur as the stable conditions forming overnight generally disintegrate in the morning when insolation on the urban surface results in convection and turbulence (instability). Most authors generally agree that overnight stability, and an inversion if formed, usually disappear by 1000 hours (for example, Schmidt, 1973). However, the nocturnal peaks in the pollen count in London start to decline as early as 0400 hours, and a diurnal minima is frequently recorded at 0600 to 0800 hours (Figures 7.6 and 7.7) suggesting that the fall-out of pollen from the atmosphere may well be of importance in reducing the count. However, this early collapse of night-time temperature stability may come about because stability layers forming at ground level in an urban area are frequently weakly developed (Oke, 1973) and so will be rapidly broken down by solar induced convection. Night-time peaks in pollen concentration recorded in the early spring do tend to remain later in the morning although this difference is difficult to evaluate given the sampling resolution of two-hours.

Inspite of the difficulty in accurately identifying whether or not temperature inversions have occurred during the nights experiencing high pollen concentrations, there do appear to be conditions of extreme stability which are limiting pollen dispersal. These ideas tend to agree with the proposals of previous authors (for example Steel 1983, Spieksma and den Tonkelaar 1986, and Lawrence, 1967). However, the night-time peaks in pollen concentration do not occur exclusively under conditions of extreme stability; they are also recorded under windier conditions (typified by Pasquil's category 'D') when the average wind speed during the night is greater than 9 or 10 knots. The causes of peak counts during these nights remain unclear. However a possible explanation rests with the increased efficiency of the Burkard pollen sampler in high wind speeds, so that the increased concentrations are not in fact 'real' but instead reflect an increased sampling efficiency.

SUMMARY.

The occurrence of night-time peaks in pollen concentration have been examined in relation to contemporaneous meteorological conditions in an attempt to elucidate the possible causes of this phenomenon. Although the exact role of temperature inversions in determining night-time pollen concentrations could not be evaluated, they are associated with conditions in which inversions are likely to form, and hence the dispersal of pollen away from ground level is limited. However, as with the determination of the exact role of wind speed, the causes of night time peak pollen concentrations is also further complicated by the increased sampling efficiency of the Burkard sampler in high wind speeds.

CHAPTER EIGHT

MODELLING DAILY POLLEN CONCENTRATIONS WITH A VIEW TO FORECASTING THE DAILY POLLEN COUNT.

8.1 INTRODUCTION.

Daily pollen concentrations have been shown to vary markedly from day to day in response to the influence of meteorology, (Chapter 5). An accurate forecast of these variations would permit hayfever sufferers to avoid high pollen counts in order to reduce their suffering. The aim of this chapter is therefore to develop models that forecast pollen concentrations and will enable a prediction of the daily pollen count to be made two or three days in advance. Few previous authors have developed systematic methods of forecasting daily pollen concentrations in advance (Bringfelt 1980, Bringfelt *et al* 1982) especially for pollen taxa besides Gramineae. This research is novel in attempting a systematic forecast of both Gramineae and arboreal pollen types and also in the forecast of daily pollen counts based on an estimate of the potential severity of the season. This is especially important for tree pollen types which exhibit marked seasonal variations in abundance (Chapter 4) and may also be the reason why previous authors have not attempted such predictions. Models are developed here for the pollen taxa analysed in depth within Chapters 5 and 6, namely Gramineae and the two arboreal types of Betula and Platanus using a variety of methods.

A further novel approach of this study is the alternative methods used for the modelling of pollen concentration, for example the use of different mathematical functions to produce smoothed curves of potential pollen abundance (as outlined in Chapter 5) and the use of accumulated meteorological variables which indirectly take account of weather conditions during the pollen formative period as well as conditions immediately prior to the time of the pollen forecast. The performance of the models in forecasting pollen counts during the 1990 pollen season is then assessed in Chapter 9 and the models compared to one another to test their efficiency.

8.2 POSSIBLE APPROACHES TO THE MODELLING OF POLLEN CONCENTRATION.

Two approaches to modelling the day to day variations in the pollen count are possible: source orientated and receptor orientated models. Source orientated models use mathematical formulae of diffusion to calculate concentrations at various distances from the source or release site. Examples of this type of model are the Gaussian plume, the step-function, curvilinear and area/box models. All source orientated models make certain assumptions about the dispersal environment which need to be fulfilled before they can be applied. They are all are based on known or estimated emission rates, assume that the airflow passes over flat terrain and all, except the area/box model, estimate dispersal from point or localized source areas. However, none of these conditions can be met for forecasting pollen dispersal in London; emission rates of pollen are seldom known and prove difficult to estimate as they relate to two processes, the influence of meteorology and biological rhythms (Ogden *et al*, 1974). Pollen emission can only be measured accurately by monitoring immediately above the source area which, for most pollen types in London, comprises large areas both inside and outside the city. The final stipulation for source orientated models, that the topography is smooth, is also invalidated in London as the urban structure generates considerable turbulence (Oke, 1973) which will influence particle dispersal.

Source orientated models have frequently been used to estimate air pollution dispersal from well-defined area or point sources, but have rarely been employed in the prediction of the dispersal of natural particles from ill-defined sources. However, such models have been used to model the dispersal of pollen and spores from small, definitive areas such as fields of crops. McCartney and Lacey (1991), for example, employed a steady state advection model to predict pollen concentration downwind of an oil-seed rape plot, estimating the emission rate by sampling the airborne concentration of the pollen immediately above the crop.

An alternative to the modelling of pollen dispersal is the use of receptor orientated techniques. Receptor orientated models predict concentrations without knowledge of source conditions or calculations of diffusion, by relating recorded concentrations, in a systematic way, to another variable or variables that can be measured or predicted. This approach has previously been used to forecast pollen concentrations abroad by Bringfelt *et al* (1982) in Sweden and by Raynor & Hayes (1970) in the U.S.A. but has never been developed for use in Britain.

Two techniques of receptor orientated modelling are possible. Regression modelling involves the use of independent variables operating as predictors of the pollen count through a multiple regression equation. For the purpose of this present study, the independent predictors would be the meteorological variables. For illustration, Bringfelt *et al* (1982) used the variables of maximum daily temperature and relative humidity to forecast Betula pollen concentrations in Stockholm, achieving a level of explanation of 64%. However, where daily pollen counts are autocorrelated (where a value is close to the value that precedes it) time-series techniques may also be used. These explain the variation in a series by its past behaviour, and expand upon this to forecast future values of the series. Moseholm *et al* (1987) used time-series techniques to forecast Gramineae pollen counts in Denmark.

The use of source orientated models to forecast pollen concentrations in London is clearly inapplicable, and therefore the receptor orientated approach will be taken for the purpose of this study. In the receptor orientated modelling, the development of regression modelling will be emphasized, as opposed to time-series techniques, as the statistical analyses of Chapter 5 indicated only low levels of autocorrelation in the pollen counts. Because of the different meteorological influences on, and patterns of abundance of the pollen taxa already considered, separate models will be developed for each of the three pollen taxa.

8.3 THE MODELLING OF GRAMINEAE POLLEN CONCENTRATION.

The results of the examination of day to day variations in the Gramineae pollen count (Chapter 5) reveal that the analyses accounting for the greatest variation in the daily pollen counts are those using either a third-order polynomial smoothed curve (the 'cubic model'), accumulated meteorological variables or a seasonally standardized and log-transformed pollen count. Alternative methods of analyzing variations in the daily Gramineae pollen count did not significantly improve the level of explanation achieved. However, the use of these models to forecast future concentrations is not straight forward for both are dependent on the total seasonal potential of pollen abundance; the cubic model in order to determine the size of the estimated smooth curve, and the logged-standardized model to standardize the daily pollen count according to the total pollen count for the season.

For the three years that sampling took place for this study, it is possible to obtain an estimate of the total pollen catch during June and July by adapting the methods of Davies & Smith (1973). An estimate of the total pollen catch with a standard error of just 19 grains ($R^2 = 99.8\%$) is obtained by regressing the total pollen catch against the sum of average daily temperature in the preceding May. The inclusion of temperature data for April (part of the pollen formative period suggested by Davies & Smith) does not significantly improve the efficiency of the prediction. Therefore, by using this regression equation, the total pollen catch for June and July may be forecast at the end of May and this can be used as a basis on which to forecast the daily pollen count.

8.3.1 Method 1 The seasonally standardized and log-transformed model.

In this model, the transformed daily pollen count is directly related to one or more of the meteorological variables. Table 5.2 (Chapter 5) shows that the stepwise multiple regression analysis of logged and standardized pollen counts entered the variables of average humidity, maximum daily temperature, daily rainfall total and average wind speed into the regression equation as all these variables significantly contributed to the explanation of the variance in the pollen counts. The use of these variables to forecast the logged-standardized pollen count results in the equation,

$$S(p) = 3.29 - 0.03368\, Rh + 0.6559\, T(max) - 0.04657\, R - 0.0001\, W$$

where S(p) = the standardized and log-transformed daily pollen count,
Rh = the average daily relative humidity (%),
T(max) = the maximum daily temperature (^{o}C),
R = the total daily rainfall (mm),
W = the average daily wind speed (knots).

Once an estimate of the total pollen catch for June and July has been obtained, it is then simple to obtain a forecast of the untransformed daily count (P) by reversing the equation of transformation (Section 3.4.4),

$$P = \frac{P\,(\mathrm{Antilog}\ S(p) - 1)}{1000}$$

where P = the untransformed daily pollen count,
S(p) = the standardized and logged pollen count,
P = the estimated total pollen catch for June and July.

The use of this method should provide a quick and easily calculated estimate of the daily pollen count with a standard error of 1.10457 grains M^{-3} and a level of explanation (R^2) of 43%. However, it is dependent on a reliable forecast of four independent meteorological variables which may not always be possible to obtain. A prediction of the maximum daily temperature is readily available in the media and it generally assumed to be reliable. Likewise, estimates of daily rainfall totals are also available, although they are liable to be less accurate than those for temperature due to the frequently irregular patterns of rainfall intensity and amount. However, forecasts of average relative humidity and wind speed are more difficult to obtain, although due to the high intercorrelation between meteorological variables, an attempt to forecast relative humidity may be based upon the estimate maximum temperature.

An alternative method to the rather suspect prediction of the meteorological parameters of humidity and wind speed may be to drop these from the multiple regression equation, use only those variables that may be accurately forecast, and assume that due to the intercorrelation between the variables, the reduction in the level of explanation achieved will not be too great. The multiple regression analysis may then be rerun with the forced entry of only maximum daily temperature and daily rainfall as predictors. This analysis results in an R^2 value of 39% and a standard error of 1.20837 grains M^{-3}, not a significant reduction compared to the inclusion of all previous variables. This relatively small decrease in the level of explanation may be explained by the role that temperature and rainfall play in determining the relative humidity and although the variation in wind speed is not sufficiently explained by either variable, its contribution to the original multiple regression equation is only 0.92%. The resulting equation is thus,

$$S(p) = 0.05519 + 0.04732\ T(max) - 0.03492\ R$$

where S(p) = the standardized and log-transformed daily pollen count,
T(max) = the maximum daily temperature (°C),
Rh = the average daily relative humidity (%),

8.3.2 Method 2 The 'Cubic' Model.

In this method, the meteorological variable of maximum daily temperature is used to predict the variation of the daily pollen count from the potential pollen abundance, a third-order polynomial curve. Table 5.3 (Chapter 5) shows how by using the maximum daily temperature alone as a predictor, the Gramineae pollen count may be forecast with a standard error of 25.6 and an efficiency of 47.5%. The analysis results in the equation:-

$$S(p) = 1.0165 + 0.02561\ T(max)$$

where S(p) = the standardized and logged daily pollen count,
T(max) = the maximum daily temperature.

The standardized pollen count may then be converted to an actual count per cubic meter of air by reversing the normalizing process:-

$$P = \frac{P\,(\text{Antilog } S(p) - 1)}{1000}$$

where P = the untransformed daily pollen count,
S(p) = the standardized and logged pollen count,
P = the estimated total pollen catch for June and July.

As previously mentioned, forecasts of the maximum daily temperature are readily available making it feasible to predict daily pollen concentrations with this model.

8.3.3 Method 3 The Use of Accumulated Meteorological Variables.

For this method, the last to forecast daily Gramineae concentrations, no smooth curve to estimate the potential pollen abundance is computed in advance. Instead, the seasonal variation in abundance is described by a second power expression of meteorological variables such as temperature and sunshine. This approach to the modelling of daily pollen concentrations has not previously been attempted in Britain. The combination of accumulated and daily values of meteorological parameters accounting for the greatest variance and having the lowest standard error for the daily Gramineae pollen count results in the following equation:-

$$\begin{aligned} S(p) = -0.54155 - 0.0278\,Rh - 0.00000303\,Acctemp^2 \\ + 0.00666\,Acctemp + 0.0727\,T(max) - 0.0552\,R \end{aligned}$$

where S(p) = the standardized and logged daily pollen count,
Rh = the average daily relative humidity (%),
Acctemp = the accumulated daily average temperature since 1st March (°C),
T(max) = the maximum daily temperature (°C),
R = the daily rainfall (in mm).

This method of forecasting Gramineae pollen concentrations results in a standard error of 0.78663 and may account for 52% of the variance in the daily pollen counts over the three years of sampling. An advantage of, and possible reason for the greater variance explained by this model, is that the use of accumulated meteorological variables takes account of the weather conditions during the pollen formative period, a factor not considered by the other forecasting methods. Therefore, if the weather since 1st March is conducive to a high pollen production with high temperatures, the value of Acctemp. will be large, and high forecasts of the daily Gramineae pollen count will result.

8.4 THE FORECASTING OF DAILY BETULA POLLEN CONCENTRATIONS.

8.4.1 Method 1 The 'Cubic' Model.

The analysis of daily patterns of Betula pollen concentration that best explains the variations in the count is the 'cubic' model (Table 5.8, Chapter 5) thus,

$$S(p) = 1.124 + 0.06751\ T(max) - 0.03613\ Rh$$

where S(p) = the standardized and logged daily pollen count,
T(max) = the maximum daily temperature (^{o}C),
Rh = the average daily relative humidity (%).

The use of this model results in a standard error of 2.1753 and a multiple R value of 0.54869. Because this method of forecasting Betula pollen concentration is based upon pollen counts normalized according to the seasonal pollen sum, an estimate of this figure would need to be calculated in advance. This, however, is not as straight forward as for Gramineae pollen. Potential Betula pollen abundance is dependent nor only on the weather conditions during the pollen formative period and preceding the season, but also on the seasonal cycles of pollen abundance identified in Chapter 4. For this reason, a forecast of the daily Betula pollen counts based on the cubic model is not feasible and other methods of forecasting the counts are considered.

8.4.2 Method 2 The Use of Accumulated Meteorological Variables.

An alternative method of forecasting daily Betula pollen counts, and one which negates the necessity of forecasting the potential pollen abundance in advance, is the use of accumulated meteorological variables. If the variables of accumulated hours of sunshine and daily average temperature after 1st March each year are considered, then a stepwise multiple regression analysis results in the equations:-

$$\mathbf{Ln(P) = -1.188 + 0.2149\ T(max) - 0.0000213\ Acctemp^2 + 0.03544\ Accsun + 0.25174\ W}$$

(R^2 = 0.70216, standard error = 0.96019)

where P = the untransformed pollen count,
T(max) = the maximum daily temperature (°C),
Acctemp = the accumulated average daily temperature since 1st March °C),
Accsun = the accumulated hours of sunshine since 1st March,
Wind = the average daily wind speed (knots).

The use of this forecasting method should provide a reliable prediction of the daily Betula pollen count with the need for information on only three meteorological variables, and without an estimate of the seasonal pollen production in advance. If, as discussed in Section 8.3.1 for Gramineae pollen, a reliable forecast of the average daily wind speed is not available, then this variable may be dropped from the equation with the following reductions in the explained variance:-

$$\mathbf{Ln(P) = -1.2997 + 0.24296\ T(max) + 1.71^{-07}\ Acctemp^2 - 0.0000528\ Accsun}$$

(R^2 = 0.67417, standard error = 0.99710)

where P = the untransformed pollen count,
T(max) = the maximum daily temperature (°C),
Acctemp = the accumulated average daily temperature since 1st March (°C),
Accsun = the accumulated hours of sunshine since 1st March.

8.5 THE MODELLING OF PLATANUS POLLEN CONCENTRATIONS.

8.5.1 Method 1 The 'Quadratic' Model.

Of the models previously considered in Chapter 5 in the examination of daily variations in the Platanus pollen count, the one which explains the greatest variance in the counts is the 'T4253H' model (Table 5.15). This model considers the residual of the Platanus pollen count from a smoothed curve derived by the use of a compound data smoother which estimates the potential abundance of pollen through the season, and results in a R^2 value of 0.21060 with a standard error of 1.06566. However, because the method by which the 'T4253H' model forecasts uses running averages of the Platanus pollen counts (Chapter 3), the day to day prediction of the pollen count is not feasible using this method. An analysis using a prior moving average of the pollen counts from the previous three and five days instead of the T4253H function has been attempted but the level of explanation achieved is below 20%. After the T4253H function, the next best model considered in Chapter 8 is the 'Cubic' model (Table 5.15). This considers the residual of the Platanus pollen count from a third order polynomial curve based on the position of a particular day within the pollen season. However, if the 'Quadratic' model of Platanus pollen abundance is also examined (Table 5.13) then this has a lower standard error than the cubic model, despite the slightly lower level of explained variance, (by its nature a quadratic curve cannot account for a greater variance than a cubic curve.) Therefore the second model, with a lower standard error is considered for testing against the 1990 Platanus pollen counts.

$$S(p) = 0.96245 + 0.01467\,T(max) + 0.02613\,W$$
$$(R^2 = 0.31271, \text{ standard error } = 1.11426)$$

where S(p) = the standardized and logged daily pollen count,
T(max) = the maximum daily temperature (°C),
W = the average daily wind speed (knots).

However, once again, this method of forecasting daily Platanus pollen concentrations is based upon the seasonal total count which is not known in advance. A forecast of potential pollen abundance would be extremely difficult to generate given the marked seasonal variations in Platanus pollen abundance identified in Chapter 4 and the influence of meteorological conditions in promoting the formation of pollen. Data from only three Platanus pollen seasons have not been sufficient to formulate any reliable estimates of the seasonal variation in the count.

8.5.2 Method 2 The Use of Accumulated Meteorological Variables.

In an attempt to overcome the problem of a lack of a reliable estimate of the potential Platanus pollen abundance, the variation of the untransformed Platanus pollen count may also be examined in relation to the accumulated meteorological variables as well as to the variation in the daily weather parameters. Thus, considering accumulated values of sunshine, average daily temperature and rainfall since 1st March results in the equation,

$$Ln(P) = -0.28049 + 0.00379\ Acctemp + 0.12232\ W$$

$$(R^2 = 0.29315,\ \text{standard error} = 1.13451)$$

where P = the untransformed daily pollen count,
Acctemp = the accumulated average daily temperature since 1st March,
W = the average daily wind speed (knots),

This method, instead of being based on an estimate of potential pollen abundance, relies on the weather conditions immediately prior to the Platanus pollen season as a predictor of the overall pollen abundance.

8.6 SUMMARY.

Models to forecast daily pollen counts of Gramineae, Betula and Platanus in advance have attained levels of explained variance of from 30% to 70% over the years 1987 to 1989. Each of the models developed in Chapter 8 will now be tested against data from a fourth years sampling (1990) to assess their accuracy in forecasting daily pollen concentrations.

One possible reason for these comparatively low levels of explanation is that the meteorological data used in the analysis have been obtained from within London and these do not necessarily reflect the conditions experienced by some pollen producing areas outside of the city. For pollen taxa mostly deriving from within the urban area then the use of this data is appropriate. However, its use may not be so appropriate for those taxa which originate exclusively from outside London.

However, the relevance of using this meteorological data is validated if the proportion of the day to day variance in different pollen counts which can be accounted for by the meteorological variables is examined. The pollen type deriving its greatest component from within London and close to the sampling site where the meteorological data should reflect the conditions experienced is Platanus and yet this has the lowest level of explained variance (Tables 5.12 - 5.15). Conversely, the taxon with the highest level of explained variance is Gramineae (Tables 5.2 - 5.6) which is presumed to derive from areas predominantly distant from the study site. The lack of meteorological information from the specific pollen source areas is therefore not perceived as a factor contributing to the unexplained variance, rather that other meteorological phenomena and fluctuations of pollen production are more important. Indeed, the fluctuations in weather conditions are more important in determining pollen counts than are the absolute values and these probably vary little throughout the London region.

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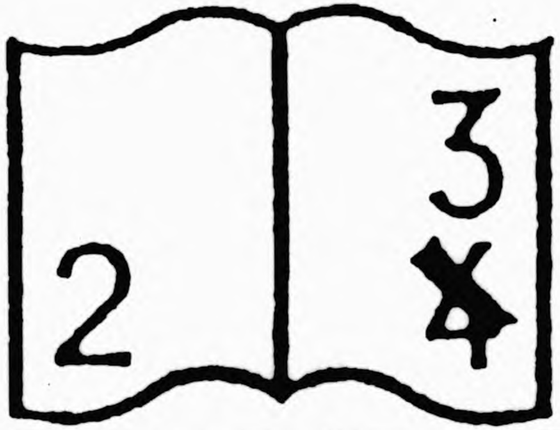

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CHAPTER NINE

THE TESTING AND APPRAISAL OF THE MODELS FORECASTING DAILY POLLEN CONCENTRATIONS.

9.1 GRAMINEAE POLLEN CONCENTRATIONS.

To test the efficiency of the models developed in Chapter 8 to predict daily pollen concentrations, their accuracy in forecasting pollen counts from an independent data set, the 1990 pollen season, is assessed. For the purpose of this study, a indicator of the reliability of each model needed to be devised. Following the guideline of Raynor & Hayes (1970), forecasts are considered to be accurate if they predicted the count to within 20%, or 10 pollen grains M^{-3}, of the recorded concentration. The lower limit of 10 grains M^{-3} is needed for the situation of very low pollen concentrations when a difference of 20% would require a model to forecast the pollen concentration with an accuracy of one or two pollen grains M^{-3} to be considered correct. The percentage of pollen counts accurately forecast by each model is then compared.

9.1.1 FORECASTING THE SEASONAL POLLEN SUM.

All the models previously developed to forecast Gramineae pollen counts in advance are dependent on a reliable estimate of the seasonal pollen sum. Following the methodology of Davies & Smith (1973), outlined in Chapter 8, an estimate of the seasonal pollen sum for June and July 1990 may be obtained using the accumulated daily average temperature and rainfall total for the month preceding the start of the pollen season, May 1990. Hence,

$$Cs = 2081.27 + 37.48\ Rm - 0.39\ Tm$$

where Cs = the estimated cumulative pollen sum for June and July,
Rm = the rainfall total for May (in mm.),
Tm = the cumulative average daily temperature for May (^{o}C).

This equation results in a forecast of 2266 Gramineae pollen grains for June and July 1990. The recorded pollen sum for these months was 2230 and hence the above equation provides a satisfactory estimate of pollen abundance to within

2% of the actual amount. This forecast may then be used in the following models of Gramineae pollen concentrations.

9.1.2 THE LOG-TRANSFORMED AND SEASONALLY STANDARDIZED MODEL.

The final version of this model used the meteorological variables of maximum daily temperature and daily rainfall total as predictors to forecast daily Gramineae pollen counts (Section 8.3.1). The equation is thus,

$$S(p) = 0.05519 + 0.04732\ T(max) - 0.03492\ R$$

where S(p) = the estimated standardized and log-transformed daily pollen count,

T(max) = the maximum daily temperature (^{o}C),

R = the daily rainfall total.

The estimated pollen count for each day is obtained by reversing the process of standardization (Section 8.3.1) using the figure 2266 as an estimate of the total pollen sum for June and July (Section 9.1.1), and by anti-logging the result. The estimated pollen counts for June and July 1990 are then displayed as Figure 9.1, along with the actual pollen counts recorded.

A visual examination of Figure 9.1 reveals that the log-transformed and seasonally standardized model of Gramineae pollen counts quite accurately estimates the day to day trends of the recorded pollen counts. For example, during the period from the 7th to 24th June 1990 the direction of movement of the pollen count from day to day is accurately predicted. However,the magnitude of the pollen counts is clearly not being correctly estimated. During the same period the estimated pollen counts reach a maximum at over 200 grains M^{-3} while the actual counts reach 128 grains M^{-3}. To evaluate the efficiency of the forecasting model, pollen count estimates that are within 10 grains M^{-3} or 25% different from the actual recorded daily count are considered correct and the frequency of correct forecasts is examined as a measure of efficiency. For the logged and standardized model of Gramineae pollen abundance, Figure 9.1, none of the counts have been accurately forecast using the criteria outlined in

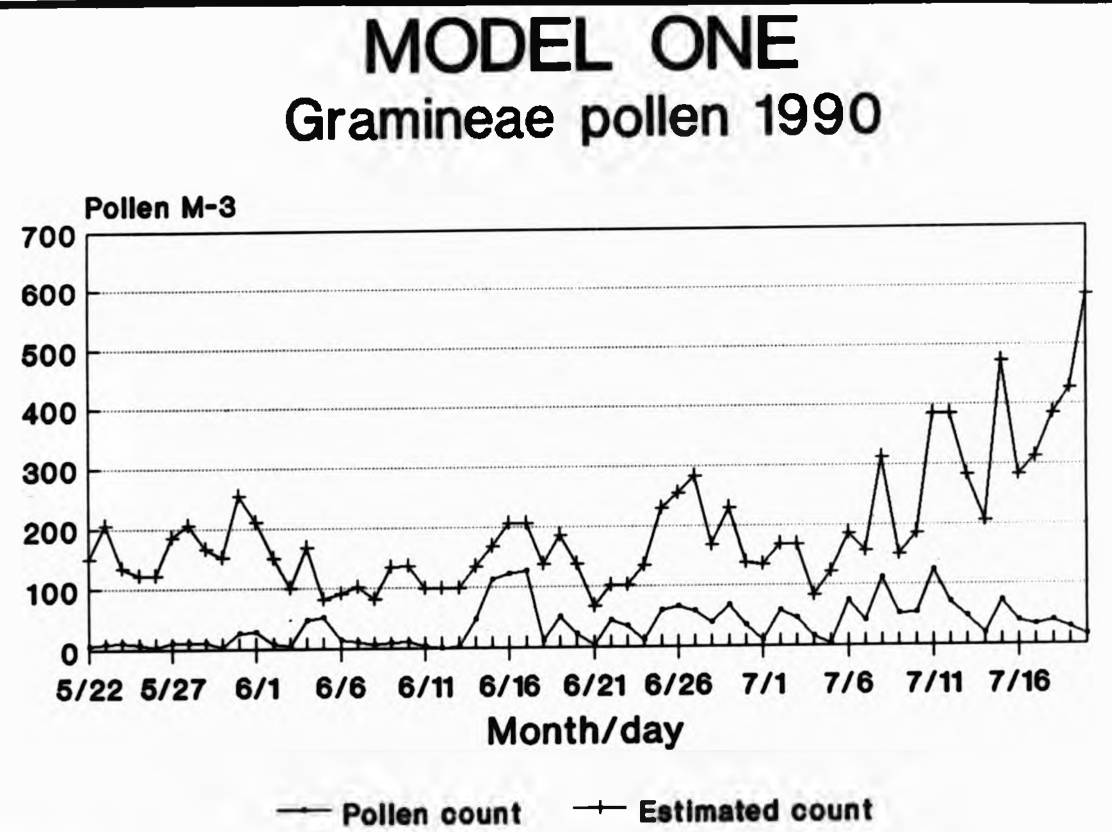

FIGURE 9.1 THE LOGGED/STANDARDIZED MODEL

Section 9.1. The largest errors in the forecasting model can be seen to occur in two distinct phases as at the beginning and end of the Gramineae pollen season, the log-transformed and seasonally standardized model frequently over-estimates the recorded pollen counts. These discrepancies result from the failure of the model to account for the variations in potential pollen production that occur through the season. This is best illustrated at the end of the pollen season, from the 5th July, where with rising temperatures, the forecasted pollen counts rise to their highest level, 571 grains M^{-3}, but as the potential reserves of pollen within the grasses are exhausted the actual pollen count falls.

Therefore, although the meteorological variables of maximum daily temperature and rainfall provide an indication of the day to day trend of pollen abundance, accounts must also be taken of the seasonal curve of potential pollen abundance.

9.1.3 THE CUBIC MODEL.

The cubic model of Gramineae pollen counts (developed in Section 8.3.2) uses a third-order polynomial curve to estimate the potential pollen production through a season, and the maximum daily temperature to estimate deviations from this. The estimated potential pollen production, as it varies through the Gramineae pollen season, can be derived from the curve,

$$Epp = 70.7109 - 1.2698\,D + 0.0163\,D^2 - 0.00006\,D^3$$

where Epp = the estimated pollen production,

D = the number of days from the start of the pollen season (as outlined in Section 3.3.2)

The deviation of the recorded pollen count from this curve is again influenced by the meteorological parameters, such that

$$V = 76.98 - 0.82302\ Rh - 2.196\ W$$

where V = the difference of the pollen count from the estimated pollen production,
Rh = Average daily relative humidity,
W = Average daily wind speed.

The estimated pollen count may then be derived by combining the difference from the estimated pollen production, thus

$$P = Epp - V$$

where P = the daily pollen count,
Epp = the estimated pollen production,
V = the difference of the pollen count from the estimated pollen production.

Using these formulae, estimated daily Gramineae pollen counts may be derived for the 1990 season and compared to the recorded pollen counts (Figure 9.2).

MODEL TWO

Gramineae pollen 1990

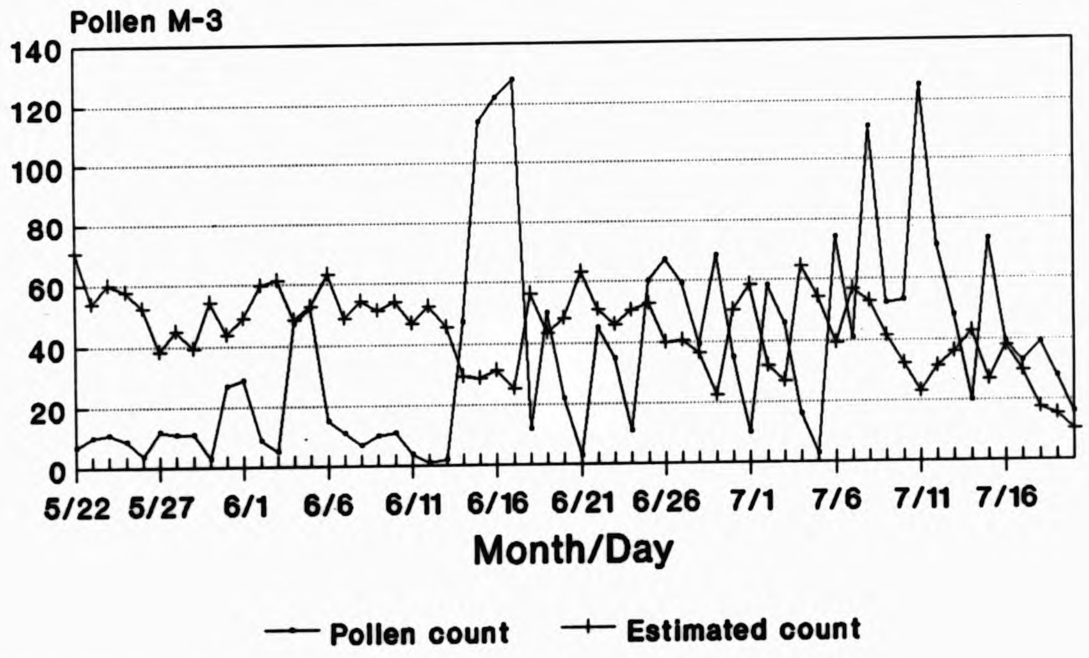

FIGURE 9.2 THE CUBIC MODEL

Unlike the previously considered model of logged and standardized Gramineae pollen counts, the cubic model has generally estimated the correct magnitude of the pollen counts for the 1990 season. It does not however correctly estimate the day to day changes in the count, particularly for the period between the 19th June and 16th July when the estimated count and the recorded count frequently appear to diverge. The efficiency of this model is only 23%.

In an attempt to overcome this failure, the cubic model of Gramineae pollen counts is rerun with the forced entry of the variables maximum daily temperature and daily rainfall into the multiple regressions equation as these variables accurately forecast the daily variations in the previous model. The resulting equation to estimate the variation of the pollen count from the estimated pollen production potential is therefore,

$$V = -23.10387 - 1.24018\,R + 1.27910\,T(max)$$

where V = the difference of the pollen count from the estimated pollen production,
T(max) = the maximum daily temperature,
R = the daily rainfall total.

The results from this model of Gramineae pollen counts for the 1990 season are displayed as Figure 9.3. This model is not however an improvement on the previous cubic model and does not provide a good forecast of the daily pollen counts over the 1990 season. Once again, the magnitude of the counts is correctly estimated but the forecast counts show little day to day variation from each other and the efficiency of the model increases only slightly to 28%.

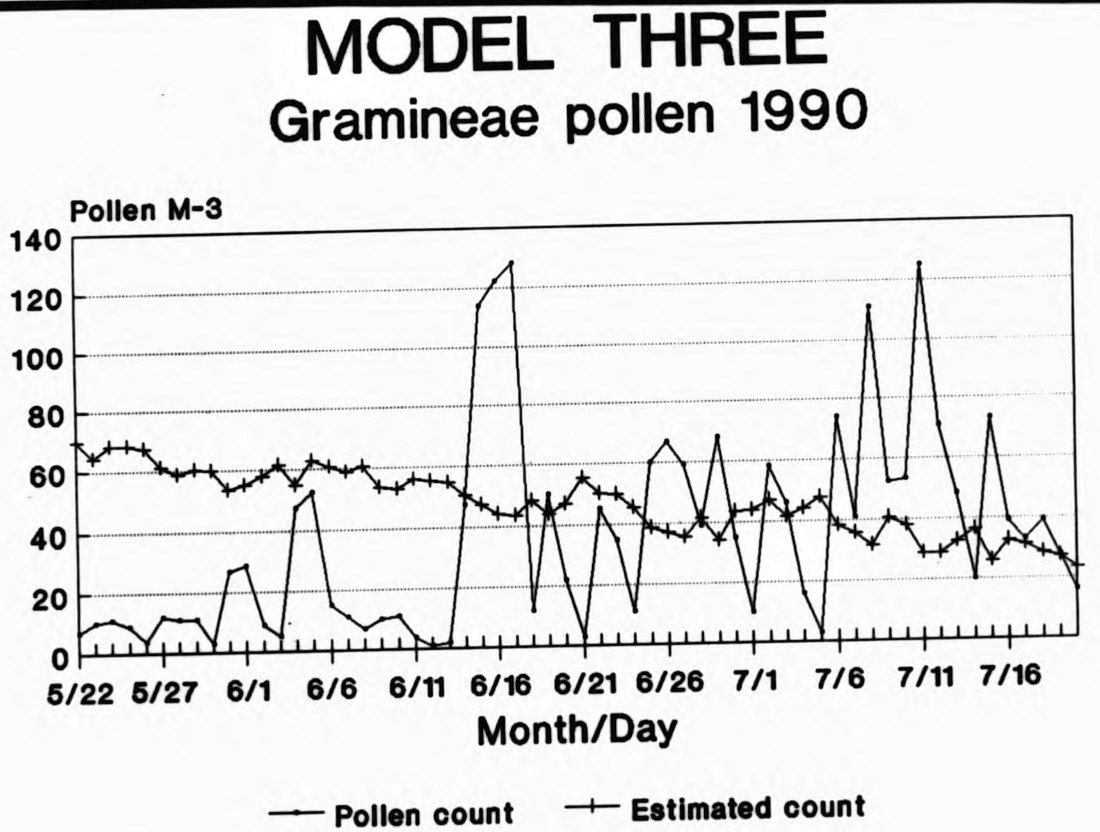

FIGURE 9.3 THE CUBIC MODEL (TEMP/RAIN)

9.1.4 THE USE OF ACCUMULATED METEOROLOGICAL VARIABLES.

This third method of forecasting daily Gramineae pollen counts again uses the meteorological variables of maximum daily temperature and daily rainfall along with the average daily relative humidity and accumulated average daily temperature. Hence, from Section 8.2.3,

$$Ln(Sp) = -0.29174 - 0.03194\ Rh - 0.00000358\ Acctemp^2 + 0.00812\ Acctemp + 0.0754\ T(max) - 0.0756\ R.$$

where Sp = the estimated pollen count,
Rh = the daily average relative humidity (%),
Acctemp = the accumulated average daily temperature since 1st March,
T(max) = maximum daily temperature (^{o}C),
R = daily rainfall (mm).

The results obtained from this equation for the 1990 Gramineae pollen season are displayed in Figure 9.4 along side the actual recorded pollen counts.

The model of daily Gramineae pollen abundance using accumulated meteorological variables accurately forecasts the day to day changes in the pollen count through the season (Figure 9.4). The magnitude of the pollen counts is approximated, but not accurately forecast. The overall efficiency of the model is 30%. As with all previous model considered here, the pollen counts at the beginning of the season are overestimated until the 4th June 1990, but following from that the counts are then correctly predicted through the rest of the season. However, this model does not correctly forecast the very highest pollen concentrations recorded through the 1990 season. The counts of the

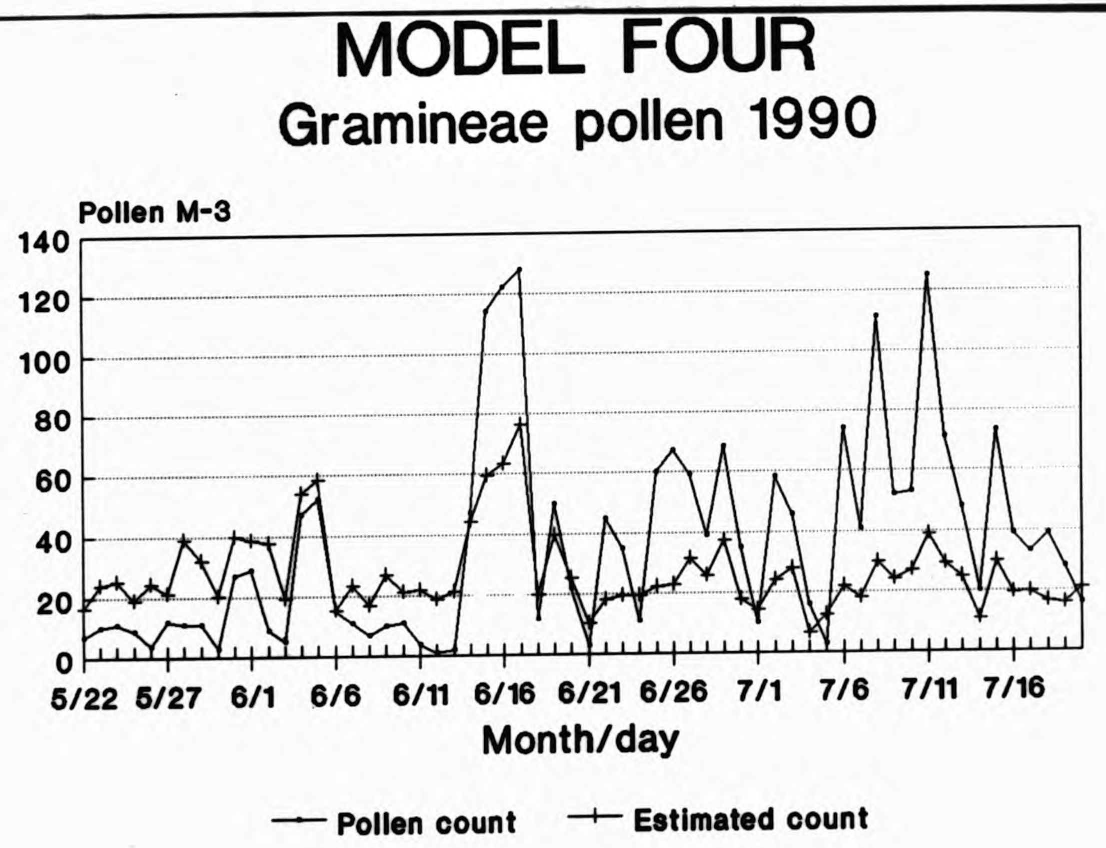

FIGURE 9.4 THE ACCUMULATED MET VAR MODEL

15th, 16th and 17th June (maximum 128 grains M^{-3}) are only forecast to reach 77 grains M^{-3} whereas the counts in mid-July of between 70 and 125 grains M^{-3} are only forecast to attain 40 grains M^{-3}. Low pollen counts are correctly estimated, for example on the 21st June, 1st July and 5th July, but low count days are less important to hayfever sufferers than are days of high counts.

9.1.5 AN APPRAISAL OF THE METHODS OF MODELLING DAILY GRAMINEAE POLLEN CONCENTRATIONS.

The highest level of explained variance for Gramineae pollen counts is attained with the use of the accumulated meteorological variable of average temperature combined with the daily variables of maximum temperature, relative humidity and rainfall. This model (Section 9.1.4) explains 56% of the variance in the daily Gramineae pollen counts over the years 1987 - 1990 and achieved a standard error of 0.86673. However, it only forecast 30% of the 1990 Gramineae pollen counts to within the criteria specified in Section 9.1. The second cubic model (using maximum daily temperature and rainfall as predictors) came a close second best to this model with an R^2 value of 52% and standard error of 1.09316 over the four years of sampling.

An error common to all the forecasting models is the overestimate of daily pollen concentrations at the start of the Gramineae season, until the 12th June 1990. In contrast to this, the models mostly predict counts at the end of the season efficiently indicating that the models do give some consideration to the variation in potential pollen abundance through the season. An exception to this is the model of logged and seasonally standardized pollen counts (Section 9.1.2) where the forecast pollen concentration rises towards the end of the season in response to rising temperatures, when pollen reserves in plants had become depleted and hence the airborne pollen concentrations were reduced to less than 40 grains M^{-3}. That all models of pollen concentration over-estimate counts at the start of the season may be attributed to the extremely hot and dry weather conditions experienced at that time. The rapid accumulation of temperature and lack of rainfall prior to the start of the Gramineae pollen season may have limited the amount of moisture available to the plants and hence may have inhibited the production of pollen in the grass flowerheads. During the following season, when hot and dry conditions provided conditions ideal for pollen dispersal, the flowerheads were not able to respond by producing high pollen concentrations.

The hot and dry weather conditions which prevailed through the whole of the 1990 Gramineae pollen season (Table 9.1) may also have caused the logged and seasonally standardized model of pollen abundance to over-estimate the pollen count through the whole season. The reliance of the model on the maximum daily temperature and daily rainfall as predictors meant that in a season with rainfall only 76% and 14% of the seasonal average in June and July respectively, and the average maximum temperature 1.0^{o}C in June and 2.7^{o}C in July above average (Table 9.1), high pollen concentrations will be forecast.

This lack of rainfall and predominance of high maximum daily temperatures during the 1990 Gramineae pollen season is in contrast to the meteorological conditions of the previous seasons when temperatures were moderate and rainfall adequate (Table 4.3). The models of pollen concentration have hence been developed to take account of these conditions and not the extreme weather conditions recorded during 1990.

A further possible reason for the low levels of explanation attained by the models of pollen concentration is that the Gramineae pollen season has a tendency towards a bimodal distribution, a phenomenon not recognized by previous authors. This pattern is most apparent in the 1990 Gramineae pollen season when the influence of rainfall in reducing pollen counts was at a minimum: high counts were recorded between the 14th and 17th June after which they declined in spite of the continuing dry and hot weather. A second period of high counts is evident between the 6th and 16th July, which was followed by a reduction in pollen concentration towards the end of the season. This bimodal pattern of pollen abundance may occur as different species of Gramineae have different flowering periods which overlap to constitute the total Gramineae pollen season. The flowering time of several common Gramineae species may then coincide during these two periods of high counts to produce the bimodal pattern of pollen abundance.

The use of meteorological data from a location close to the sampling site may also limit the degree of explanation achieved as weather conditions affecting the Gramineae pollen sources outside of London are likely to differ from those recorded in London. A future examination of conditions at the source area may then lead to an increase in the accuracy of the forecasts of daily Gramineae pollen concentrations.

In conclusion, Gramineae pollen counts during the 1990 season have been forecast with an accuracy of 30% by the accumulated meteorological variable model, although it is able to account for 52% of the variance in the counts between 1987 and 1989. Other models of daily pollen concentrations developed here have forecast counts from the 1990 season with a lower efficiency.

9.2 BETULA POLLEN CONCENTRATIONS.

9.2.1 THE CUBIC MODEL.

In Chapter 8, the model which explains the greatest variance in the Betula pollen counts is the cubic model (Section 8.4.1). However, as no reliable estimate of the total seasonal pollen catch is available, the model will be tested using the actual seasonal Betula pollen sum. For 1990, this sum was 1787 pollen grains and the potential daily Betula pollen abundance may be estimated by the curve,

$$Epp = 23.9873 - 0.1745\ D + 0.0181\ D^2 - 0.00005\ D^3$$

where Epp = the estimated pollen production,
D = the number of days from the start of the pollen season (as outlined in Section 3.3.2)

The deviation of the recorded pollen count from this curve is again influenced by the meteorological parameters, such that

$$V = 22.17 - 1.24782\ T(max) - 1.012\ W$$

where V = the difference of the pollen count from the estimated pollen production,
T(max) = Average daily relative humidity (%),
W = Average daily wind speed (knots).

The estimated pollen count may then be derived by combining the difference from the estimated pollen production, thus

$$P = Epp - V$$

where P = the daily pollen count,
Epp = the estimated pollen production,
V = the difference of the pollen count from the estimated pollen production.

Using these formulae, estimated daily Betula pollen counts may be derived for the 1990 season and compared to the recorded pollen counts (Figure 9.5).

Figure 9.5 illustrates how the 'cubic' model of daily Betula pollen concentration quite accurately estimates both the magnitude and day to day variations of the 1990 pollen season. The model does, however, fail to estimate the high pollen count of 451 grains M^{-3} on 1st April 1990, instead predicting a count of only 171 grains M^{-3}, although this day is correctly forecast as having the highest count of the year. The efficiency of this model is 53%.

9.2.2 THE LOGGED/STANDARDIZED COUNTS MODEL.

The first model considered in Section 8.4.1 to forecast Betula pollen concentrations is the model using the log-transformed and seasonally transformed pollen counts. Thus,

$$Ln(Sp) = 1.124 + 0.06751\ T(max) - 0.0361\ Rh$$

where Sp = the seasonally standardized pollen count,
$T(max)$ = the maximum daily temperature (°C),
Rh = the average daily relative humidity (%).

Estimated pollen counts may then be derived for the 1990 Betula pollen season by including the relevant meteorological data. These estimated counts are displayed alongside the recorded pollen counts as Figure 9.6.

The estimated pollen count may then be derived by combining the difference from the estimated pollen production, thus

$$P = Epp - V$$

where P = the daily pollen count,
Epp = the estimated pollen production,
V = the difference of the pollen count from the estimated pollen production.

Using these formulae, estimated daily Betula pollen counts may be derived for the 1990 season and compared to the recorded pollen counts (Figure 9.5).

Figure 9.5 illustrates how the 'cubic' model of daily Betula pollen concentration quite accurately estimates both the magnitude and day to day variations of the 1990 pollen season. The model does, however, fail to estimate the high pollen count of 451 grains M^{-3} on 1st April 1990, instead predicting a count of only 171 grains M^{-3}, although this day is correctly forecast as having the highest count of the year. The efficiency of this model is 53%.

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where Sp = the seasonally standardized pollen count,
T(max) = the maximum daily temperature (°C),
Rh = the average daily relative humidity (%).

Estimated pollen counts may then be derived for the 1990 Betula pollen season by including the relevant meteorological data. These estimated counts are displayed alongside the recorded pollen counts as Figure 9.6.

MODEL FIVE
Betula pollen 1990

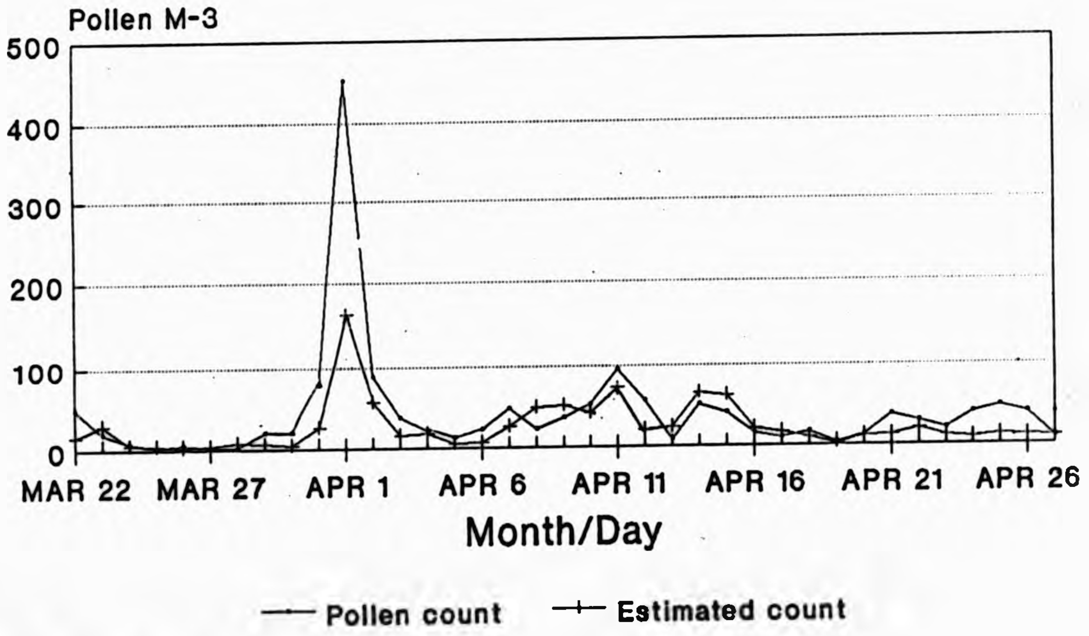


FIGURE 9.5 THE CUBIC MODEL

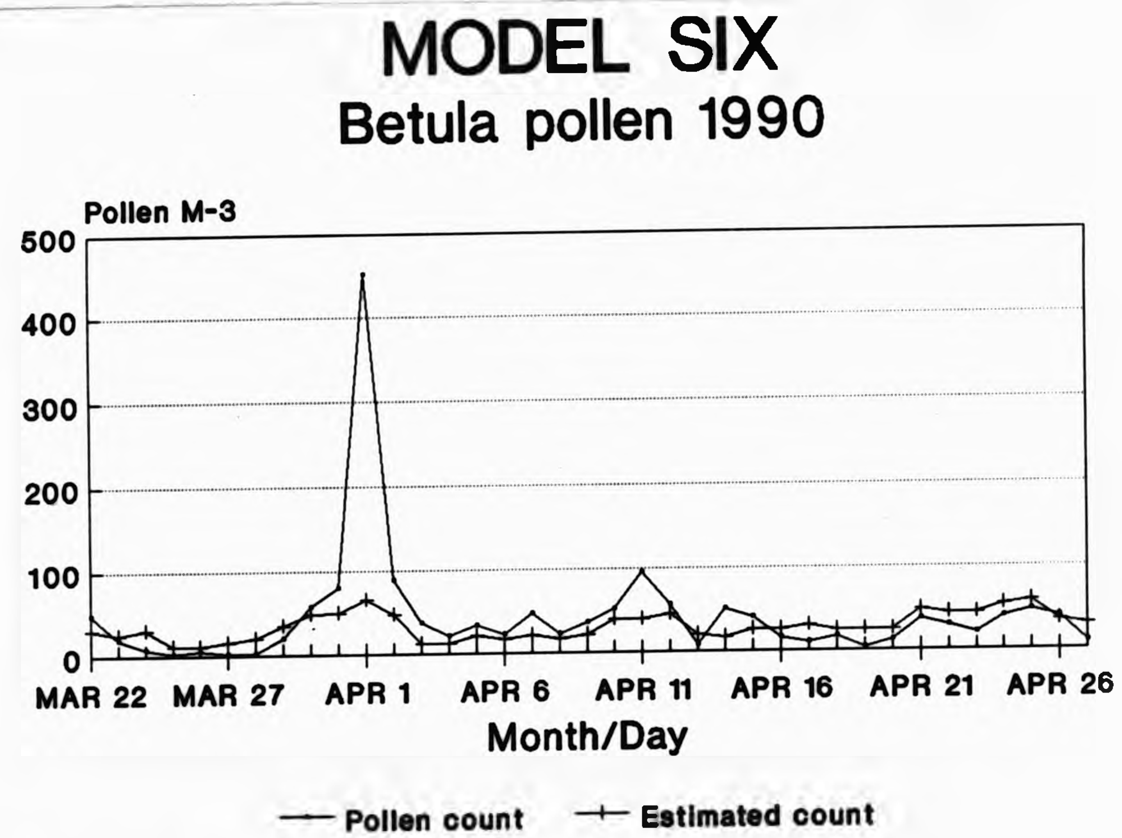


FIGURE 9.6 THE LOGGED/STANDARDIZED MODEL

The accumulated meteorological variable model forecasts the 1990 Betula pollen counts with an accuracy of 53%. The days with the highest pollen concentrations, 31st March to 2nd April, are not correctly forecast, although the model did predict these three days as having the maximum counts through the season. Counts during the rest of the season are however fairly accurately forecast with day to day changes in concentration predicted and with estimated counts rarely more than 25 grains M^{-3} different from the recorded count.

9.2.3 THE USE OF ACCUMULATED METEOROLOGICAL VARIABLES.

Of the two methods using accumulated meteorological variables considered in Section 8.4.2 to forecast the daily Betula pollen concentrations, Method 2 accounted for the highest variance and has the lowest standard error for the daily pollen counts. Hence,

$$\mathbf{P = -11.98 + 16.52\ T(max) + 0.00276\ Acctemp^2}$$
$$\mathbf{+10.15\ Accsun - 0.0181\ Accsun^2 - 4.16\ Acctemp + 5.13\ W}$$

where P = the untransformed pollen count,
T(max) = the maximum daily temperature,
Acctemp = the accumulated average daily temperature since 1st March,
Accsun = the accumulated daily sunshine hours since 1st March,
Wind = the average daily wind speed (in knots).

When the relevant 1990 meteorological data is substituted into this equation, the estimated daily pollen displayed as Figure 9.7 result. Also displayed are the actual recorded counts for the 1990 Betula pollen season. A visual examination of the difference between the actual and the estimated pollen counts reveals that the model correctly forecasts the lower concentrations of the 1990 season, but fails to estimate the magnitude of the highest counts, a scenario similar to that for the cubic model of Betula pollen concentration. Once again, the counts of more than 80 grains M^{-3} between the 31st March and 2nd April, as well as on the 11th April, are not anticipated, although the 1st April is correctly forecast as having the highest Betula pollen count of the season. The overall efficiency of the model according the criteria specified in Section 9.1 is 47%.

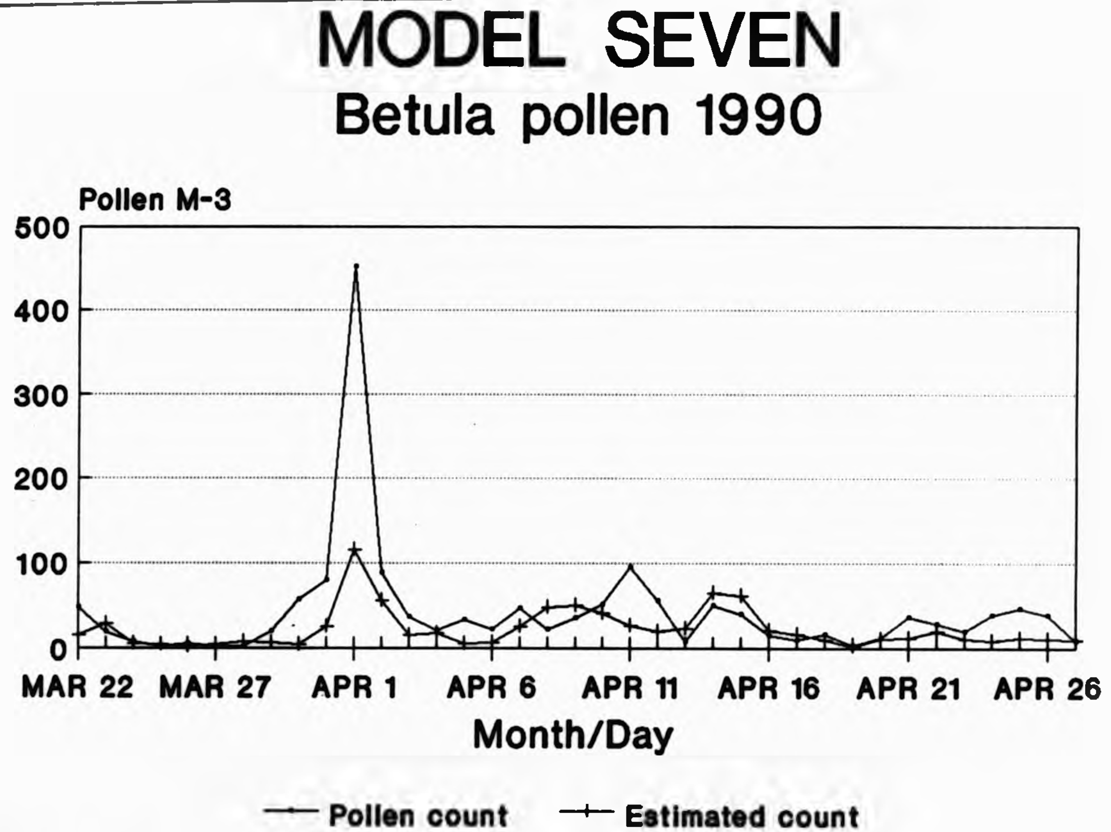


FIGURE 9.7 THE ACCUMULATED MET VAR MODEL

9.2.3 AN APPRAISAL OF THE METHODS OF MODELLING DAILY BETULA POLLEN CONCENTRATIONS.

The methods developed to model daily Betula pollen concentrations have similar levels of accuracy in forecasting the 1990 daily pollen counts. All also forecast counts below 30 grains M^{-3} with efficiency but under-estimate high concentrations. The count of 451 grains M^{-3} on the 1st April 1990 has not been anticipated by any model. This was however an exceptionally high count, the maximum daily concentration recorded during the sampling period 1987 to 1990, and is forecast by all the models as being the highest count of the season with estimated concentrations ranging from 77 to 171 grains M^{-3}.

The seasonal variation in Betula pollen abundance complicates the forecasting of daily Betula pollen counts, especially when no method of forecasting the potential sum is available. Following the biennial variation in abundance identified in Chapter 4, the total Betula pollen sum was the second lowest sum recorded over four years, with a total pollen sum of 1787 grains. However, during this season, the highest ever Betula pollen count was recorded (451 grains M^{-3}) making the 1990 season rather atypical. Weather conditions during this season were extremely dry and warm (Table 9.1) and this combined with the favourable conditions during the time of pollen formation the previous year (Table 4.3) ensured that pollen concentrations approached their maximum potential for a year of 'low' abundance. The reliance of all models of daily Betula pollen abundance on the maximum daily temperature as a predictor ensures that the day to day variation in the counts is accurately forecast although the magnitude of the counts is frequently under-estimated.

Given the similar levels of accuracy attained by the models of Betula pollen abundance, the least complicated model to use in practice is that using accumulated meteorological variables as predictors as this is not reliant on a forecast of the potential pollen abundance for the season.

9.3 PLATANUS POLLEN CONCENTRATIONS.

9.3.1 THE USE OF ACCUMULATED METEOROLOGICAL VARIABLES.

As no reliable estimate of the seasonal Platanus pollen sum is available, the model using accumulated meteorological variables developed in Section 8.5.2 that is independent of this figure is considered for testing against data from the 1990 pollen season. Hence:-

$$Ln(P) = -0.28049 + 0.00379Acctemp + 0.12232W$$

where P = estimated daily pollen count,
Acctemp = the accumulated daily temperature since 1st March,
W = the average daily wind speed (in knots).

The resulting estimated Platanus pollen counts are displayed alongside the recorded counts for 1990 as Figure 9.8. This model forecast daily pollen counts from the 1990 season with an accuracy of 58%. However, an examination of the estimated counts reveals that only the lower Platanus pollen concentrations are reliably estimated, and that this model fails to forecast any of the counts above 30 grains M^{-3}. The highest count forecast by this model is 29 grains M^{-3} and this does not coincide with the highest recorded count of 258 grains M^{-3} on 1st April when a count of only 27 grains M^{-3} is anticipated.

A possible reason for the under-estimate of these high Platanus pollen counts is the seasonal variation of this pollen type. No clear seasonal pattern of abundance has been identified for Platanus pollen (Chapter 4), however the total pollen sum recorded in 1990 was the highest over the four years of sampling (1110 grains compared to 947 in 1987, 576 in 1988 and 186 in 1989). Whether or not these data suggest a triennial pattern of pollen abundance will need evidence from a longer sampling period to confirm, but the model developed over three years of lower counts is not able to anticipate the concentrations recorded in this year of high abundance.

Chapter 5 concluded that wind direction exerts a strong influence on Platanus pollen concentrations. As this parameter could not be included in this model of

MODEL EIGHT
Platanus pollen 1990

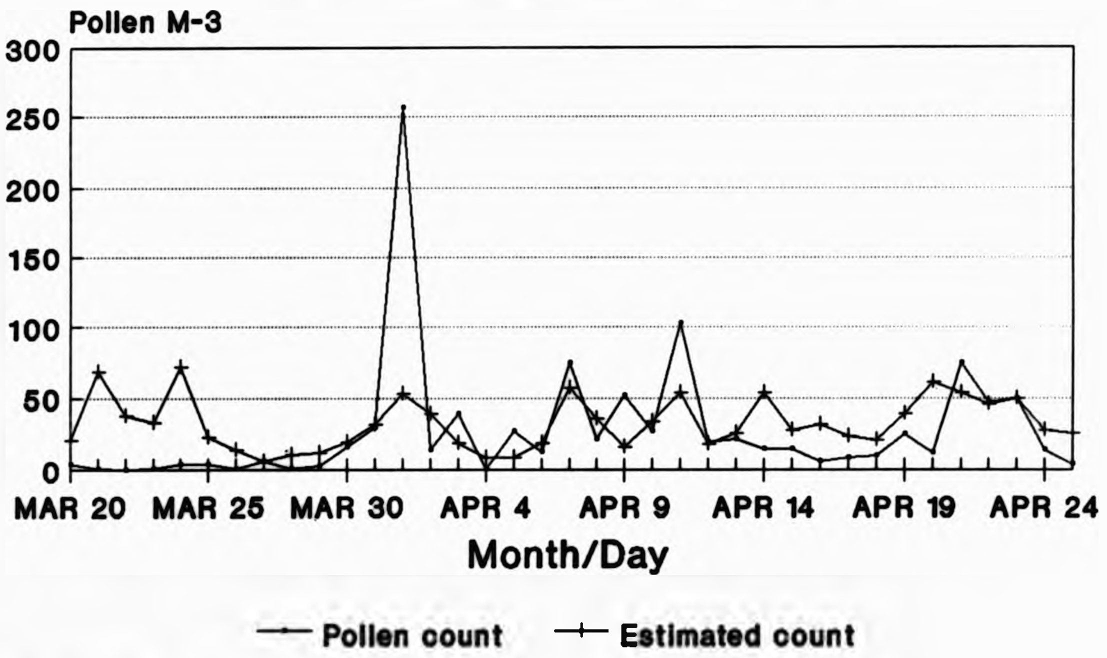


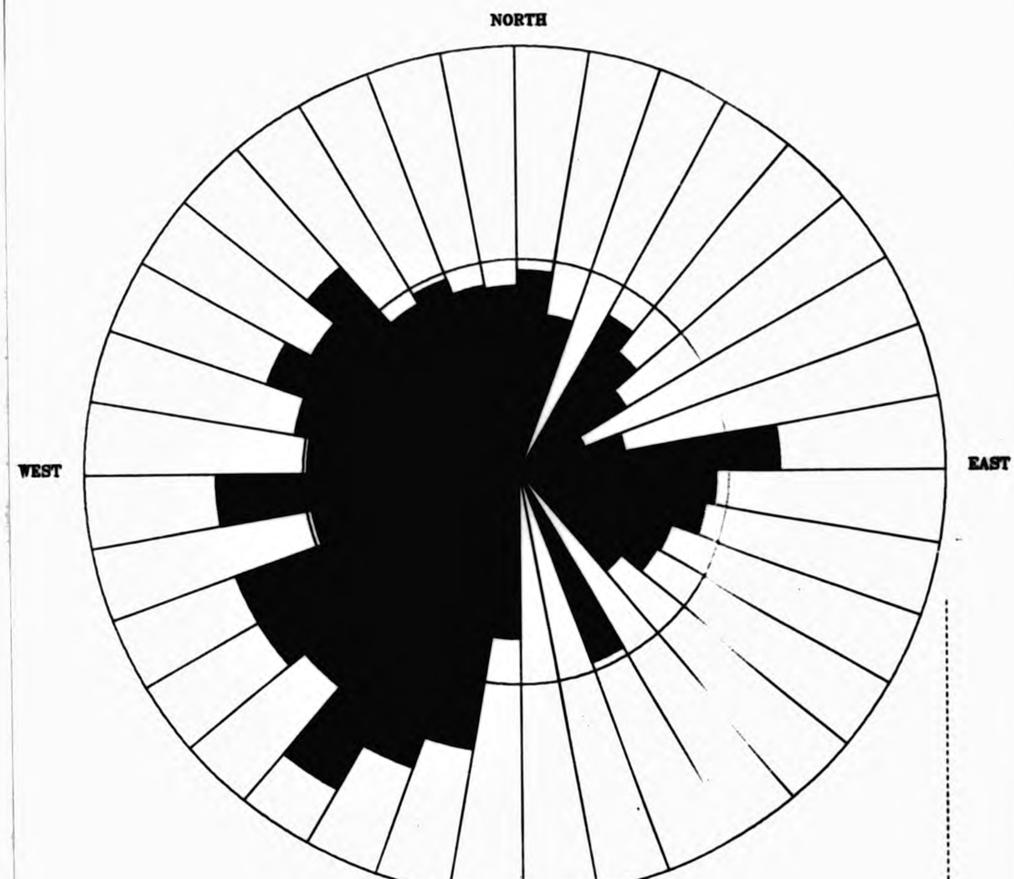
FIGURE 9.8 T4253 (SPSS/Pc) MODEL

Platanus pollen concentrations the residuals of the model may then be plotted against the predominant daily wind direction to establish whether any bias does occur, (Figure 9.9). This wind and pollen rose reveals how the greatest under-estimates of Platanus pollen concentration occur associated with winds of a southerly origin, from the areas of Platanus dominated streets and parks (Figure 1.2). Concentrations recorded under northerly wind regimes are more accurately forecast.

The influence of local pollen source areas, which for Gramineae and Betula pollen concentrations is not significant, must therefore be taken into account when forecasting Platanus pollen concentrations.

The low levels of explanation achieved in the forecasting of Platanus pollen concentrations also might be attributed to the nature of the pollen source. Because of their appeal to town planners, Platanus trees are frequently planted along streets which are hemmed in by tall buildings ('urban street canyons'). The dispersion of this pollen type upwards and out of the canyon will then be limited by the movement of airflows across the roof level of the urban environment, which in effect form a cap to the airflow within the canyon and isolate it from the upper air movement. Using sulphur hexafluoride gas, SF_6, as a tracer of airflow, DePaul & Sheih (1986) observed how urban street canyons can partially trap pollutant emissions for extended periods of time, and this presumably may also effect the dispersion of particulate pollutants and pollen. The dispersion of pollen from such sites is therefore more sporadic than from other, more exposed areas and hence the prediction of Platanus pollen concentrations more difficult. The other major sources of Platanus pollen are the parks and gardens of London which are again small and discrete and so the dispersal of pollen from these would also be sporadic and influenced by wind direction, a parameter which could not be included in the multiple regression analyses.

FIGURE 9.9 RESIDUALS OF THE PLATANUS (ACCUMULATED METEOROLOGICAL VARIABLES) MODELS WITH RESPECT TO WIND DIRECTION.



9.4 A REVIEW OF THE MODELS FORECASTING DAILY POLLEN CONCENTRATIONS.

Of the various methods devised to model daily pollen concentrations, the method which frequently proves the most efficient is that using accumulated meteorological variables. These models usually prove more accurate than others as they directly describe not only the day to day variations but also the overall seasonal variations in pollen counts. However, where extremes in seasonal pollen abundance occur due to phenological rhythms of pollen production, as in Betula and possibly Platanus pollen, these models are not always able to forecast the magnitude of the counts. In the 1990 season, the highest pollen concentrations are frequently under-estimated by models using accumulated meteorological variables, especially for the arboreal taxa with identifiable variations in pollen production, Betula and Platanus. In other methods of forecasting concentrations, the potential seasonal variation is determined in advance, based on the start date of the season, and so cannot be influenced by weather conditions during the season. As was anticipated, the log-transformed and seasonally standardized models do not accurately forecast pollen counts as they contain no estimate of potential pollen abundance as it varies through the season.

Previous authors such as Bringfelt (1982) and Moseholm *et al* (1987) have achieved levels of accuracy approaching 70% in forecasting daily pollen concentrations, an accuracy far higher than achieved in this study. However, these are all retrospective models, being based on a known seasonal pollen sum which in practice can not be known in advance, and thus making the models unsuited to forecasting concentrations on a day to day basis through the season. In contrast, the models of pollen concentration developed during this research have been designed specifically for forecasting in advance and so suffer from a lack of accuracy in the calculation of the potential seasonal pollen sum as well as in forecast of the day to day variation in pollen concentration.

In addition, these studies have also had much longer time periods on which to perform basic analyses of the interrelationships of pollen counts and meteorological data, frequently periods of 10 - 12 years which would obviously allow more accurate forecasts than might be achieved with three years worth of information. A further important point in comparing the efficiency of the pollen forecasting methods is the exceptional characteristics of the 1990 season. The meteorological conditions experienced during the 1990 season are displayed as Table 9.1. during the Betula pollen season (late March to late April) rainfall was significantly lower than the 30 year average, whilst the hours of sunshine and mean monthly temperature were significantly higher. Similar hot and dry conditions continued through the Platanus and Gramineae pollen seasons (mid April to mid May and late May to late July respectively). These weather conditions are markedly different to those experienced in the previous three years when temperatures and rainfall were less extreme (Table 4.3). The relevance and value of using 1990 as a year for testing models of pollen abundance developed during years of very different weather conditions must therefore be questioned and the results obtained viewed in light of this.

Therefore, in conclusion, where an estimate of the seasonal pollen potential is available in advance, then a model using accumulated meteorological variables and a log-transformed and seasonally standardized pollen count will most accurately estimate daily pollen concentrations. Where no such estimate is available, the same model may be used with an untransformed pollen count, although counts will be forecast with less accuracy and errors in the magnitude of pollen concentrations.

TABLE 9.1 MONTHLY METEOROLOGICAL FIGURES FOR LONDON COMPARED TO THE AVERAGE FOR THE PREVIOUS 30 YEARS.

TEMPERATURE Difference from mean monthly temperature (oC)
SUNSHINE Percentage of average monthly sunshine hours
RAINFALL Percentage of average monthly rainfall

1990

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temp.	+1.1	+4.4	+3.4	+1.4	+3.4	+1.0	+2.7	+4.4	+0.5	+1.7	+0.5	+0.3
Sun.	118	149	132	167	146	125	144	141	119	118	109	109
Rain	92	242	16	73	8	76	14	47	45	89	35	93

CHAPTER 10

THE RELEVANCE AND CONTEXT OF THE RESEARCH.

10.1 THE RELEVANCE TO MODELS OF FOSSIL POLLEN DISPERSAL AND THE INTERPRETATION OF FOSSIL POLLEN DIAGRAMS.

A prerequisite to the interpretation of the fossil pollen record is the understanding of the processes that have led to the formation of the record. The transformation of the living vegetation to a fossil assemblage is extremely complex and pollen analysts carry out studies of the modern pollen rain in order to understand how these assemblages are formed, what factors act to bias the record and what the vegetation assemblage represents in terms of former vegetation, (David, 1989). Large numbers of palynological studies have therefore been undertaken to investigate the taxonomy of pollen grains, the production and dispersal of different pollen types, and the deposition and preservation of pollen from different vegetation communities. The research on pollen abundance and dispersal in London contributes knowledge of the production and dispersal patterns of pollen and so will aid in the interpretation of fossil pollen assemblages. As with this work on the modelling of pollen concentrations in London, most previous research in this field has been by necessity receptor orientated, studying pollen transport to one point of entrapment. Examples of such works include Prentice (1985), Lamb (1984), Webb & Bryson (1972) and Webb *et al* (1981).

One of the most important factors to consider in interpreting fossil pollen records is the source of pollen, and this has been identified as one of the most acute problems in palynological interpretation (Oldfield, 1970) and is especially important in archaeological studies based on anthropogenic activity (Edwards, 1979). An important contribution of this thesis is therefore to allow an examination of the distances travelled by pollen grains. The advantage of undertaking this research in a heavily built-up urban area is that the collection site is isolated from local pollen sources that, in a rural area, would contribute too much background "noise" (Jacobson & Bradshaw, 1981) to enable the identification of long range pollen transport.

An example of this type of transport is the contribution to the London pollen spectrum that sources outside of the urban area make. The source areas for Gramineae pollen are remote from the sampling network, yet in London this pollen type is recorded in quantities 50% lower than immediately outside of the urban area[1]. There are no source areas immediately adjacent to the sampling site that produce Gramineae pollen as there are no parks or open spaces in the vicinity and gardens are well managed. This suggests that large quantities of pollen are transported over distances of 5 - 20 km, a factor not previously encountered by authors working in rural environments who recognized either predominantly curvilinear declines in pollen abundance with distance (for example Tinsley & Smith, 1974, Soloman & Harrington, 1979, Bradshaw, 1981b and Prentice, 1985) or a step-function decline (Soloman & Silkworth, 1986).

In contrast to this supposed wide spread dispersion of Gramineae pollen, other pollen types do not appear to disperse far from their source areas. Tilia for example, which as well as producing only small amounts of pollen, is not recorded in abundance at the sampling site despite the proximity of the tree both along roadsides and in parks in north London. Platanus pollen does not appear to disperse far from its source areas either, possibly due to the location of Platanus trees in urban canyons which limit the upwards dispersion of pollen as has been observed for pollutants by De Paul & Sheih, 1985.

Other pollen taxa that are recorded only very occasionally by the pollen sampler may also provide evidence of long distance transport of pollen into London. Heathland species, such as Ericaceae, Cyperaceae and Pteridium aquilinum, have been recorded in north-central London under southerly wind conditions making it unlikely that they originate from the vestiges of heathland at Hampstead Heath. Instead, the closest heathlands to the south of London are the open lands of Wimbledon Common and Richmond Park, some 10km distant from the sampler, or the scrublands of Surrey.

A single grain of pollen identified as Narthecium ossifragum (bog asphodel) has been recorded during airflow of a southerly origin. Bog asphodel is a plant of bogs and wet heaths and this pollen grain is believed to have originated from the

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1 A comparison of the total yearly Gramineae pollen counts from London, Maidstone and Windsor revealed that the totals from outside of London were approximately twice those from within the urban area.

wet heathlands of surrey, some 30 - 35km distant and again providing evidence of long distance transport of pollen into London.

However, the appearance of other unusual pollen taxa in the sampling record cannot always be interpreted as evidence of long distance transport for a wide variety of plants are now commonly grown in London gardens. An example of this is the occasional presence of Endymion non-scriptus (Bluebell) pollen in the pollen spectrum but it cannot be assumed to originate from outside of London as it is now a common garden plant and could derive from one of the many gardens surrounding the sampling site.

Several other authors have observed the long-distance dispersal of pollen. Cour *et al* (1981) recorded several incidences of long-distance pollen transfer, frequently over much larger distances than that observed in London, as for example the recording of Saharan pollen types in France and Switzerland. Other examples of such transport are quoted by Hjelmroos (1991), van der Knapp (1987, 1988), Wynn-Williams (1991) and Wallin *et al* (1991). The quantification of the contribution that long distance dispersal makes to the pollen spectrum of London is however extremely difficult and has not been attempted.

The evidence of the long distance transport of some pollen types is frequently over-looked by those interpreting fossil pollen diagrams. The occasional occurrence of a particular pollen type in a pollen spectrum does not necessarily imply the growth of that plant in the immediate vicinity (Peteet, 1986); it may have been transported many tens of kilometres before being incorporated into the pollen bearing sediment. This phenomenon is more likely to have occurred if a large sampling area is under consideration as this will reflect pollen spectra of a wider source area (Jacobson & Bradshaw, 1981).

In the identification of the pollen sources contributing to lake sediments, Jacobson & Bradshaw (1981) identify three components to the pollen catch: local pollen deriving from plants within 20m of the sampling site, the extra-local component from between 20m and several hundred meters, and regional pollen which derives from vegetation at greater distances. Pollen samples taken from non-pollen producing areas of different sizes will then be expected to contain varying proportions of pollen from the different source areas. Small sampling areas will contain pollen derived mostly from the local vegetation, but with small quantities from the extra-local and regional spectrum whereas larger sample areas comprise a predominantly regional pollen spectrum with only minor contributions from the local and extra-local vegetation (Jacobson & Bradshaw, Figure 1). An analogy may then be drawn between the lakes of Jacobson & Bradshaw's work and the urban area of London as, for selected pollen taxa, both represent non-pollen producing areas. However, these authors considered lakes of up to only 1000m diameter or 75ha in area, whilst for some taxa at least the non-pollen producing area surrounding the sampling site exceeds this in size. If the model is extrapolated to include a larger site then the ratio between the various components does not change significantly and the regional airflow still contributes the majority of the pollen catch. The pollen record from the London sampler is therefore representative of the regional airflow, at least for pollen taxa deriving some distance from the sampling area. This confirms the assumptions made earlier concerning the origin of much of the grass pollen caught at the London site.

However, the importance of evidence of long-range transport of pollen into present day London for the interpretation of fossil pollen assemblages is limited by the different dispersal environments of the two situations. Urban environments are well known to modify the meteorological conditions experienced (Oke, 1973, 1987). Some of the most important modifications include the increase in temperature and subsequent decrease in humidity, a change in the ground level wind speeds and direction due to the alteration of airflows by buildings, and the increase in turbulence due to the differential heating of the urban environment. These modifications therefore combine in increasing the potential dispersal of pollen from its source area when compared to the rural situation of the deposition of pollen in palynological studies. Nevertheless, pollen originating from outside of the London urban area must still have to travel through a little-modified rural environment to the urban edge of London before being influenced by the improved conditions for dispersal.

This adaptation of the dispersal environment limits the contribution of modern day pollen dispersal studies in urban environments to the models of pollen transport designed to aid in the interpretation of fossil pollen assemblages as they have mostly been based on pollen dispersal beneath closed canopy woodlands (for example, Tauber, 1965, 1967a, 1967b, Di-Giovanni 1986 and Di-Giovanni *et al*, 1989).

Other studies, however, have examined pollen dispersal in mountainous regions, from which analogies may be made to the urban environment. Both montane and urban environments comprise marked changes in elevation over short distances, have steep gradients of temperature and humidity, increased precipitation and modified wind regimes. However given these similarities in situation, several features in contrast to the findings in London emerge from the studies of pollen dispersal in mountainous areas.

Markgraf (1980) investigated pollen deposition along a 4km transect spanning 1230m in elevation in Switzerland and recorded very rapid declines in deposition away from the pollen source. Quercus and Ulmus pollen, for example, demonstrated a fivefold or more decline in deposition between samplers located 1.2km apart. Soloman & Harrington (1979) however recorded a more gradual curvilinear decline in pollen deposition across the Owens Valley in California while Soloman and Silkworth (1986), working at the same site, observed a more marked step-function decline in pollen deposition. Salgado-Labouriau (1979) concluded that the dispersal power of pollen types from the Venzuelan Andes varied according to the pollen type and their source area.

The results of Soloman and Harrington (1979) and Soloman and Silkworth (1986) contrast in the patterns of pollen dispersal observed. From the data available it is not possible to determine which of these patterns is occluding within the London region, although the conclusion reached that large quantities of pollen are being transported over distances of at least several kilometres leads to the conclusion that a step-function decline is more likely. However the role of topography and meteorological conditions in determining pollen concentration will be of importance in all such studies. Similarities exist between the dispersal of pollen from montane regions, particularly from valley sites, and the dispersal of pollen from urban street canyons in London. The dispersal of Platanus pollen from its London source is observed to be restricted by the movement of airflows across the tops of the canyons, which in effect separates the pollen from the regional airflow. A similar situation may exist in a mountainous region where pollen dispersal from the valley floor is restricted and this may account for the relatively rapid rates of fall-off in pollen deposition recorded by Soloman & Silkworth (1986).

This restriction of pollen movement out of the valleys will be greatest under hot and dry weather conditions, especially when associated with a daytime temperature inversion, and it is these times when pollen concentrations will be greatest, thus enhancing the importance of this process. In contrast, times of mild and damp weather with low wind velocities and a minimum vertical structuring of the atmosphere are also those of lowest pollen concentrations and so will prove of less importance to the pollen record.

The consideration, in this study, of the role of meteorology in influencing pollen abundance is also pertinent to many other researches on pollen dispersal which do not or cannot include this in their considerations. Price & Moore (1984) examine pollen dispersion in the uplands of Wales and conclude that local scale, anabatic winds are important in determining the spatial variation of pollen deposition across a plateau. This theory is provided with further justification by the study of pollen abundance in London. Anabatic winds which form due to the warming of the landscape by solar radiation will probably be at their strongest during the late afternoon, the time at which the concentration of many pollen types is at a maximum. There is therefore an increased likelihood of anabatic winds transporting large quantities of pollen upslope to the plateau in question and, as the authors suggest, this process might well be occurring at many other sites. For example, it might well account for the significant quantities of pollen from lowland areas being carried to higher elevations that Markgraf (1980) and Andrews *et al* (1975) observed.

In contrast, katabatic winds which flow overnight would have less opportunity to transport pollen as ambient concentrations would be lower at the time of their strongest flow. Few authors have reported large amounts of pollen being transported from upland to lowland regions.

The examination of the role of rainfall in influencing pollen concentration also has relevance for the interpretation of fossil pollen diagrams. Previous authors have recognized the possible sources of error in fossil sediments caused by the reentrainment of previously deposited pollen grains (Erdtman, 1969, Birks & Birks, 1980 and Lowe, 1982). However, in London less than 2% of the total pollen catch can be defined as "altered" according to O'Rourke's (1990) criteria, hence demonstrating that the problem of resuspension contributes only a minor source of error in sediments from similar environments. Other studies (Tauber, 1967, Jennings, 1985 and O'Rourke, 1990) have demonstrated how resuspended pollen can attain much higher proportions of the total pollen catch and hence may be more important sources of error. An assessment of the relative contribution of reentrained pollen is therefore vital before the interpretation of pollen diagrams in which the resuspension of pollen grains is possible.

10.2 THE RELEVANCE OF THE RESEARCH TO MODELS OF PARTICULATE POLLUTION DISPERSAL.

The relevance of the modelling of pollen concentration to models of pollution dispersal may also be considered. In some situations the receptor orientated approach taken to the study of pollen dispersal in London may provide several advantages over the source orientated models commonly applied when forecasting pollution dispersal. The dispersal of many pollutants will be influenced by meteorological conditions in the same way as will pollen grains and so knowledge of the factors controlling pollen dispersal will further increase our understanding of pollutant dispersal.

A receptor orientated technique was used successfully by Bringfelt (1971) to forecast sulphur dioxide concentrations in Sweden since the release of this pollutant is diffuse and is indirectly controlled by meteorological conditions. Many of the meteorological factors designated by Bringfelt as being of most importance in determining the concentration of sulphur dioxide were also found to important in regulating the pollen concentration in London as the most influential parameter in both studies proves to be the maximum daily temperature. However, the influence of temperature is two-fold in both studies. It governs both the production and the release of pollen, as well as its dispersal from the source area, and in Bringfelts study, he observed that temperature was important in determining the amount of sulphur dioxide released (When the ambient temperature dropped more sulphur dioxide was produced due to the greater demand for heating) and also its dispersal and diffusion.

The times of high pollen concentrations are also those frequently associated with high concentrations of other air pollutants. The hypothesized temperature inversions which result in high pollen concentrations overnight (Chapter 7) will also restrict the dispersal of other urban pollutants such as particulate matter (dusts containing toxic elements such as silica, arsenic, lead, copper, nickel, etc. and organic aerosols emitted as smoke from combustion), sulphur dioxide, nitrogen oxides and carbon monoxide. This may possibly result in high concentrations at ground level with important health consequences for those people exposed to the pollutants. Indeed, Walker (1985) has observed high concentrations of some air pollutants at the top of an atmospheric inversion layer that frequently developed on sunny days in the USA. Such pollutant episodes will not be restricted just to times of high pollen concentration but may also occur outside of the main pollen season.

High pollen concentrations may also be associated with high levels of other pollutants which are characteristic of urban areas, including those of photochemical origin such as ozone , peroxy acetyl nitrate (PAN), hydrogen peroxide, and aldehydes. Of these ozone is by far the most damaging to both human and animal health and to plant life. These pollutants area all of secondary origin, that is they are not emitted but are formed in the atmosphere by photochemical reactions involving emitted gases such as derive from vehicle exhaust emissions, particularly nitrogen oxides and hydrocarbons. Concentrations of these pollutants are greatest with high intensities of solar radiation and marked atmospheric stability (Stern, 1976, 1986), conditions identical to those producing high pollen counts.

These photochemical pollutants exhibit pronounced diurnal patterns in concentration, just as pollen does, with concentration dependent on the time and rate of emission, on the atmospheric stability and on the intensity of solar radiation. Haagen-Smit & Wayne (1976) examined these diurnal variations in Los Angeles and the patterns of variation identified for both aldehydes and ozone are very similar to those identified for some pollen types in the London study (Chapter 6) with maximum concentrations occurring in the afternoon, between 1200 and 1600 hours. Williams *et al* (1977), again working in California, identified maximum concentrations of ozone between 1200 and 2200 hours. Pollutant concentrations decrease after this time as they become diluted by fresh air masses or are consumed by further photochemical reactions (Urone, 1976).

The consequences of high ozone concentrations on human, animal and plant health have only recently been realised. The concentration at which human health is jeopardized is difficult to ascertain (Goldsmith, 1986) but Holman (1989) reports long term effects of asthma and bronchitis and short term effects including eye, nose and throat irritations. More research has investigated the levels at which damage to plant life occurs. Roberts (1984) reports that a yield decrease results in crops exposed to 100 ppb of ozone, whilst the World Health Organization recommend a maximum one hour average concentration below 60 ppb in order to prevent significant damage to vegetation (Grennfelt & Schjoldager, 1984). The maximum one hour peak concentration in London is

90 - 180 ppb (Roberts, 1984) although levels during the hot and dry summer of 1976 rose above 200 ppb in southern England (Skarby & Sellden, 1984) and similar levels were reported by the media in the summers of 1989 and 1990.

The association between high concentrations of photochemical pollutants and pollen would therefore enable the possibility of using pollen concentration as a biological indicator of pollutant levels, although allowance would have to be made to account for the seasonal variation in pollen abundance. A receptor orientated approach to modelling the concentrations of these pollutants, in a way similar to that developed for pollen in this study, would be both appropriate and useful. The emission rates of photochemical pollutants are extremely difficult or measure or estimate which would make the use of source orientated methods of modelling difficult and unreliable. Instead, if their formation could be related in a systematic way to meteorological conditions then a receptor orientated approach would be more appropriate.

A similar receptor orientated approach to forecasting concentrations may also be applied to other forms of pollution such as aerosol pesticides and fungal spores, pollutants released over wide areas at ground level, in a similar way to pollen. Once released, the same meteorological factors that control the dispersion of pollen also control the dispersion of these particles so that a regression or time-series analysis of their concentrations may allow forecasting models to be developed. Other types of particulate pollution that are released in a similar fashion and may be studied in the same way include low level incinerator wastes which may include particulate matter and dioxins, the health effects of which are considered by Gatrell (1991), Gatrell *et al* (1992) and Gustavson (1989).

The prediction of high concentrations of both pollen and air pollutants is particularly important because of the hypothesized synergistic effect between them (Lebowitz, 1991). Recent investigations have studied the role that air pollution has in allergic reactions and have concluded that pollutants may modify the pollen grain wall and hence its allergic potential. Weeke (1989) states that airborne particulate pollution from heavily industrialized areas has been shown to induce cytotoxic and mutagenic effects in mammals, and also that irritant gases and vehicle exhaust emissions affect the mucosal barrier, thus enhancing sensitization to common allergens. She also quotes epidemiological investigations which have shown increased prevalence of asthma attacks during episodes with high concentrations of sulphur dioxide in the air and suggests that this pollutant may even provoke both asthma and rhinitis alone. Petre *et al* (1991) and Santra *et al* (1991) have investigated the mechanisms which cause such effects, although the results that emerge are somewhat contradictory. While Petre *et al* observed significant modifications of the pollen grain exine following exposure to common air pollutants, they observed no marked changes in the allergen content of the grain. In contrast, Santra *et al* (1991) did observe a significant change in pollen protein content following exposure of the grain to sulphur dioxide and nitrogen oxides, and believed that that naturally occurring aeroallergens alter their allergenic potential with exposure to these pollutants. The identification and accurate prediction of the times and places of high pollution levels and high pollen counts is therefore of vital importance in reducing the suffering of people with hayfever and asthma.

10.3 THE RELEVANCE OF THE RESEARCH TO HAYFEVER SUFFERERS.

A primary aim of this thesis has been to aid in the alleviation of the symptoms of hayfever. Hayfever and other allergic diseases have increased dramatically in prevalence in industrialized and developing countries in the past two decades (Emanuel, 1988 and Morley, 1989). Although treatment of the symptoms of these allergic diseases has greatly improved since the introduction of non-soporific anti-histamines, they still prove to be debilitating to approximately 10 to 15% of the population (Davies, 1989). The ideal treatment of all diseases is to prevent them, rather than to cure the symptoms, and so this thesis may aid allergic individuals in reducing the contact with their allergen by forecasting high pollen concentrations in advance. The benefits of this avoidance therapy are two-fold. Not only should the immediate symptoms of allergic rhinitis be reduced but further sensitization to the allergen (usually created through exposure to it, Viandder & Koivikko, 1978) will also be limited.

The specific ways in which this thesis may help sufferers of pollen allergies to identify and avoid exposure to pollen are as follows.

The first step in the avoidance of sensitization to pollen is the identification of the specific pollen allergen. The pollen calendars presented in Chapter 4 may be examined and compared to the times of year at which symptoms are normally experienced. The identification of an allergic reaction to Gramineae pollen is usually straightforward as the pollen season is fairly consistent in both its timing and abundance. The identification of an allergy to any of the tree pollen types is more difficult due to the seasonal variations in timing and abundance that occur between the pollen seasons. Seasonal rhinitis that perhaps occurs only every two or three years may not even be diagnosed as hayfever and an inappropriate treatment taken to cure the symptoms. As many trees flowers are inconspicuous, and pollen release periods frequently vary in timing between years, the main allergen can only be identified by a close comparison of symptoms and pollen calendars. Clinicians might also use pollen calendars to identify allergens and save the time-consuming and frequently misleading procedure of skin-prick testing.

Once a pollen allergen has been identified, then action may be taken to reduce an individuals exposure which will not only reduce the immediate symptoms but should also limit further sensitization to the antigen.

The analyses of pollen abundance carried out in London also has relevance to models forecasting pollen concentrations in other places, for example Bringfelt *et al* (1982) and Raynor & Hayes (1970).

Another model forecasting pollen counts was developed by Moseholm *et al* (1987) who used a time-series (Box-Jenkins) model building strategy to forecast daily grass pollen concentrations in the air of Copenhagen and Viborg in Denmark. These authors concluded that a time-series technique was the most appropriate in predicting pollen concentrations and this is in contrast to the findings in London where regression analyses of pollen and meteorological data provided a more accurate forecast. Bringfelt used regression analyses alone. The residuals of the models of daily pollen counts developed in this study are indeed autocorrelated which suggests that a time-series approach might be helpful. However, this apparently high autocorrelation my be caused by a similar autocorrelation between the meteorological conditions which determine pollen concentrations in the air and so would already have been taken into account by the regression analysis. This is assumed to be the reason why time-series techniques contribute only slightly higher levels of explained variance compared to regression analyses in this study.

10.4 THE USE IN PRACTICE OF PREDICTIVE MODELS OF POLLEN CONCENTRATION.

A major factor governing the use in practice of predictive models of pollen concentration is that they are, by necessity, dependent on forecasts of meteorological parameters. Although the choice of variables to be included in the prediction models (Chapter 8) was, in part, influenced by their ease of prediction, the testing of the models used accurate, retrospective weather data. The day to day accuracy of a pollen forecast will also therefore be influenced by the accuracy of the meteorological data.

The reliability of the prediction of different meteorological variables varies. Some parameters, the best example being the maximum daily temperature, may be forecast reliably up to five days in advance. For this reason, the variable has been used in many of the prediction models outlined in Chapter 8, even if it was not entered into the regression analysis using the stepwise procedure. Forecasts of other meteorological parameters are, however, less accurate. The prediction of rainfall in particular is unreliable, both for rainfall amount, duration and timing and is especially difficult in urban areas where rising air currents may promote convectional rainfall. Relative humidity is another parameter for which forecasts are not readily available. However, the reliance of the models forecasting pollen concentrations on these parameters was deliberately limited.

Where a prognosis of pollen concentration is dependent on an unreliably forecast meteorological variable, then a qualifying statement may need to be added to the prediction to avoid erroneous statements. The best example of this in practice would be on days when weather forecasters were uncertain whether rain would fall. If a prediction of a high pollen count was made assuming no precipitation , then this could be accompanied by a statement that if rain did fall during the day, then the pollen count would decline. In this way the final prediction of the pollen count could be based on weather conditions local to the situation.

CHAPTER ELEVEN

CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH.

11.1 THE MAIN CONCLUSIONS OF THE RESEARCH.

This research has established the main seasonal, daily and diurnal temporal patterns of pollen abundance in an urban area, and has attempted to use these patterns in the development of models which forecast daily pollen concentrations in advance for three taxa.

The main conclusions resulting from the study are as follows.

For several pollen taxa, distinctive seasonal variations in abundance occur which, it is suggested, relate both to meteorological conditions and to the flowering phenology of these plants. A biennial pattern of abundance is proposed for Betula, Fagus and Platanus pollen, patterns which had not previously been identified in Great Britain. Longer term patterns may also occur in the abundance of other pollen types, for example Pinus and Fraxinus pollen but these cannot be confirmed with data from just three years of sampling.

These seasonal variations in pollen concentrations form the underlying basis of pollen abundance onto which further fluctuations relating to meteorological conditions are superimposed. Further variations in pollen abundance have been related to weather conditions at the time that pollen is being formed in a plant. Warm or mild weather with adequate rainfall during this period will promote the formation of large quantities of pollen in the anther which are then stored for release later. In contrast, cool weather or drought conditions inhibit pollen production so that only low or moderate pollen concentrations will result during the season. The periods of pollen formation have been identified as the late summer and autumn of the year preceding the pollen season for the spring flowering trees, and as the late spring (May) for Gramineae, herbaceous plants and the summer flowering trees.

For one pollen taxon, Gramineae, an attempt has been made to forecast the seasonal pollen sum by the use of the meteorological data from the month preceding the pollen season. No seasonal variation in Gramineae pollen abundance has been observed. The model accurately forecast the 1990 pollen sum (to within 2% of the recorded figure) but sampling over a longer period is needed to determine whether or not this model is sufficient to take account of more extreme weather conditions than those observed over the four years of measurement.

Further variations in pollen abundance result from the meteorological conditions experienced during the pollen season. Although day to day variations in pollen counts are marked, prolonged periods of either good or bad weather during the season are frequently sufficient to influence the seasonal total of pollen abundance. The best example of this to be observed during the study is the significantly lower quantities of Platanus pollen recorded during the 1989 pollen season when, despite the potential for high pollen concentrations resulting from the conditions conducive to pollen formation in the previous year, a spell of cold and wet weather coincided with the pollen season and limited the release and dispersal of the pollen from the trees.

This research has also identified the meteorological parameters of most importance in determining the day to day variations in pollen concentration for three common pollen types. Of the eleven weather parameters under consideration, the daily maximum temperature proved to be the most influential to the daily pollen count, irrespective of the pollen taxa or the model of pollen abundance used. However, temperature has no direct control on pollen concentration although its influence operates in two separate manners. Temperature may influence the production of pollen within the anther of a plant prior to and during the pollen season and may also determine the release of pollen in association with decreased humidity and turbulence. Once pollen has been released into the airflow, then the main influence of temperature on the dispersal of pollen from the source area towards the point of entrapment operates through its association with other weather parameters. The highest pollen counts are generally recorded on days with high temperatures, and these tend to be characterised by low rainfall, sunny and cloudless skies, low humidities and light winds, conditions which combine to ameliorate the dispersal potential of pollen. In contrast, in summer low temperatures are frequently characterised by cloudy skies, an increased likelihood of precipitation and by strong winds, conditions not conducive to either the production, release or dispersal of pollen. However, on rare occasions, thundery and showery conditions may also give rise to high pollen counts due to the long-distance transport or resuspension of pollen within storms. This phenomenon was recorded eleven times during the three years of sampling, 1987 to 1989.

Other meteorological variables of importance in determining pollen concentrations are rainfall and wind speed and direction. Pollen concentrations will generally show a rapid decline following the onset of precipitation and are frequently reduced to less than 10 grains M^{-3} by the following two-hour sampling period. It is theorized that rainfall may reduce pollen concentrations by a combination of several processes. Raindrops may either form around pollen grains or incorporate pollen within themselves through impaction when falling. Rainfall, through its association with decreased temperatures and increased humidities, will also inhibit the release of pollen from the source plant and prevent the resuspension of pollen grains previously washed out of the atmosphere.

Whilst the variables of wind speed and wind direction did not prove of importance to Gramineae and Betula pollen concentrations, they were both of importance in determining Platanus pollen counts. The highest Platanus pollen concentrations were recorded under winds from a southerly origin due to the discrete nature of the Platanus pollen source areas.

The remaining meteorological parameters, cloud cover, synoptic situation, and hours of sunshine, frequently showed significant correlations with pollen concentrations but did not independently appear to influence the pollen count, instead being associated with other parameters which did exert an independent control on pollen dispersal.

The diurnal patterns of pollen abundance for three common pollen taxa have been established with all types exhibiting regular diurnal maxima between 1600 and 2000 hours. Meteorological conditions, such as temperature and wind direction, were not observed to influence the timing of these peaks concentrations but did appear to alter the abundance of pollen with maximum values recorded under south-easterly winds for Platanus pollen, and under north-easterly winds for Gramineae pollen and Betula pollen. The diurnal variation on days of peak pollen concentrations displayed similar patterns to those through the rest of the season.

Models of daily pollen abundance have been developed from the analyses of pollen concentrations and meteorological data and these have been tested for efficiency against data from a year independent of those used to devise the models. For Gramineae pollen, the model that most accurately predicts the 1990 daily pollen counts was the use of accumulated meteorological variables, a novel approach to the forecasting of pollen concentrations. This model is able to account for 52% of the variance in the pollen concentration from 1987 to 1989 and correctly predicts 30% of the 1990 counts.

Models of Betula pollen abundance achieve a slightly higher level of explanation than those for Gramineae pollen despite the difficulty in forecasting a seasonal pollen sum for this species. While the 'cubic' model of Betula pollen abundance using the actual seasonal pollen sum for 1990, correctly forecast 53% of the 1990 season pollen counts, this was reduced to 47% with the next best model (the use of accumulated meteorological variables) which contains no direct estimate of the potential pollen abundance through the season.

Due to the seasonal nature of abundance, no direct estimate of Platanus pollen abundance is available or may be reliably forecast. Both methods of predicting Platanus pollen concentrations achieved levels of explanation close to 45% over the years 1987 to 1989, but the first model more accurately forecast the pollen counts from 1990 (with an accuracy of 48%).

The relevance of this work in determining meteorological influences on pollen dispersal is considered with respect to a number of other theories of pollen dispersal developed by authors wishing to aid in the understanding of vegetation history. Analogies are made between the dispersal environments of montane regions and of urban settings so that this research illuminates the influence of meteorology on pollen dispersal under these conditions. A further contribution is to the knowledge of how far pollen grains may disperse from their source areas and this should be considered when interpreting fossil pollen diagrams. However, the relevance of this research to fossil pollen diagrams is limited by the different dispersal environments of the two situations.

11.2 AN APPRAISAL OF THE RESEARCH.

Whilst undertaking this study on pollen abundance in London several key difficulties have been evident running through many aspects of the work.

A fundamental problem arising from this study is the representivity of data on pollen concentration derived from sampling a very small quantity of air from a single sampling point. The efficiency of the Burkard volumetric sampler has been considered in Chapter 3 and it is acknowledged that the sampling efficiency is not always 100% as under wind speeds greater than one metre per second the efficiency is reduced. Pollen concentrations recorded under high wind velocities will thus be under-estimated and this has complicated the analysis of the influence of wind speed on pollen concentration.

The representivity of data obtained from a single sampling point is also of importance when making inferences about pollen dispersal across London. In an ideal situation pollen could be monitored at several locations, both within London and in the surrounding rural areas, in order to clearly establish patterns of pollen movement. This was not however possible in this study due to constraints of both time and money. A brief pilot study (Emberlin and Norris-Hill, 1991) however shows that the chosen sampling site provides a good representation of pollen abundance across London. With just one sampling site, and a wide range of pollen source areas, the use of source orientated models of pollen dispersal was clearly inapplicable, hence the development of the technique of receptor orientated modelling to forecast pollen concentrations.

Within the analysis of patterns of pollen abundance preceding the development of receptor orientated models, difficulties arose in isolating the influences of intercorrelated meteorological variables. For most parameters, for example temperature, humidity, sunshine and cloud cover, this was achieved with the use of partial and multiple correlation analyses. However some variables, namely wind direction and synoptic situation, could not be analyzed in this manner as they are recorded as categorical data.

A further key problem encountered whilst undertaking this research was the incorporation of these categorical variables, wind direction in particular and synoptic situation to a lesser extent, into the multiple regression analyses of pollen abundance. An attempt was made to consider the influence of wind direction, whilst taking the other meteorological variables into account, by the examination of the residuals of multiple regression equations with respect to the predominant daily wind direction. For two of the three pollen taxa considered in detail, when the influence of wind direction was isolated from the other meteorological parameters, it did not prove to influence the daily pollen count. For Platanus pollen, however, marked differences in abundance were observable and these occurred irrespective of the other parameters due to the local and well-defined nature of the pollen sources.

Difficulties also arose in obtaining some meteorological data pertinent to the dispersal of pollen. Much of the unexplained variance in the modelling of pollen concentration may be attributed to variations in other meteorological parameters not considered in this analysis, but which may exert some control on the dispersion of pollen. Although previous authors, Bringfelt (1980) for example, concluded that weather parameters such as mixing height were not of direct relevance to pollen concentrations in Stockholm, this hypotheses has not been tested for the case of London where data on mixing height are not available for the central urban area. More detailed information on the turbulence of the lower atmosphere and patterns of wind shear may also add to the levels of explanation attained, although part of the influence of such variables will already have been included in the analysis through their intercorrelation with other parameters already considered.

A further possible reason for the low levels of explanation attained in this study might be the use of meteorological data from within central London when much of the pollen derives from outside of the urban area. Whilst weather data from the London Weather Centre will provide a good representation of the conditions experienced by some pollen sources located entirely within London, Platanus for example, taxa deriving partly or wholly from outside the city will be subjected to different meteorological conditions and hence the pollen abundance derived from such places may show little association with the weather data examined during this study.

11.3 SUGGESTIONS FOR FUTURE RESEARCH.

The most obvious need for future research to arise from this study is for the sampling scheme to continue over a longer time period. This would allow the identification of further seasonal patterns of pollen abundance and may enable a reliable forecast of the potential abundance of pollen types such as Betula and Platanus to be made in advance. This information could then be incorporated into the model developed to forecast daily variations in the abundance of these pollen types to enable a more accurate assessment of the magnitude of each pollen season. A major difficulty in the development of these models was the lack of a basis on which to compute the potential pollen abundance.

Sampling over a longer time period may also allow the development of a forecast of the start of a pollen season which would be of utmost importance to hayfever sufferers if adequate warning of the start could be given. Davies & Smith (1973) attempted to forecast the start of the Gramineae pollen season with nine years of pollen and meteorological data, as did Driessen *et al* 1990, 1991) in the Netherlands. An accurate forecast would then need information collected over a time span of approximately ten years, although some progress could be made with just five or six years of sampling.

A further need for future research to arise from this study is for an extensive spatial survey of pollen abundance across London to be undertaken. The pilot study examining variations in weekly pollen deposition revealed significant differences in pollen abundance between sampling sites within one kilometre of each other and such marked changes need to be examined in more detail and with a volumetric pollen sampler.

An expansion of this spatial survey might also include a detailed investigation of the source areas of particular pollen taxa. Whilst source areas of the three taxa considered in detail in this thesis have been established, they remain unclear for other common pollen taxa such as Quercus, Taxus and Pinus. The relative contribution of local and regional sources to the total pollen sum would aid in a more detailed investigation of their diurnal, daily and seasonal abundance. Detailed research into the origins of Gramineae, Betula and Platanus pollen would also be of use and might clarify some unanswered questions with respect to their diurnal variation.

The source of pollen might be successfully investigated through the use of trajectory analysis. This technique would also be useful in clarifying the cause of some unexplained high pollen counts that occurred during the sampling period, including those occurring during rainfall (Chapter 7).

A more detailed knowledge of the spatial variation of pollen dispersal across London might enable also the use of source orientated models to forecast pollen counts. Pollen concentrations measured in the pollen source areas could be used as an indication of source strength and hence substituted in an area/box model of particulate dispersion. This method of forecasting pollen concentration may further explain day to day variations in pollen counts and hence supplement information derived through the receptor orientated models developed in this study.

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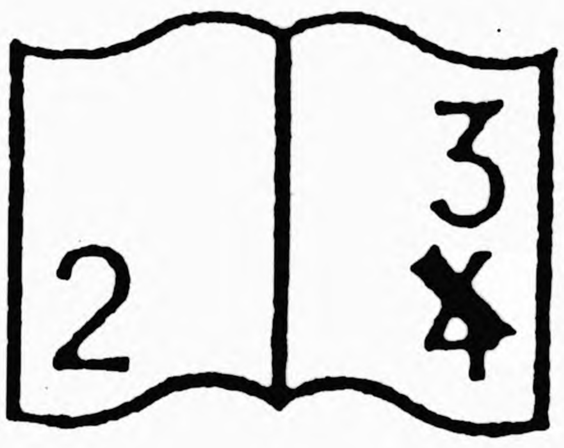

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