TITLE ALLERGENIC POLLEN CONCENTRATIONS IN THE UNITED KINGDOM

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ABSTRACT

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This study investigates the variations in the start and severity of the grass and birch pollen seasons at a network of sites in the United Kingdom. Daily grass and birch pollen concentrations have been monitored during the course of the study (1992-1994) at the University of North London site. Retrospective pollen data of up to 30 years in length at London, Cardiff and Derby has been incorporated into the database, along with between 2 and 7 years of retrospective data from 7 other European Aeroallergen Network(UK) sites. Annual grass and birch pollen concentrations, start of season dates and seasonal severities have been identified and analysed in relation to meteorological conditions and local pollen source areas. Variations have been found at the individual sites from year to year, and between the different sites in the same year. Multiple regression analysis has been used on the long term data sets at London, Cardiff and Derby to produce forecast models to enable the prediction of the start of the season and total seasonal grass and birch pollen concentrations at the 3 sites. Data from the other EAN(UK) sites has been incorporated into these models to assess their use on a regional basis.

This research has relevance within many subject areas. The long term data sets on which a large part of the thesis is based are of great interest to Aerobiologists in the identification of long term trends in pollen data. The research has relevance to Quaternary palynologists interested in the influence of the source area on the pollen catch. The influence of climate on the seasonal variation of grass species will be of interest to Agriculturalists, Ecologists and Biogeographers. Finally, through the accurate forecasting of the start and severity of the grass and birch pollen seasons, hayfever sufferers are able to have increased knowledge, and therefore may be able to avoid the amount of medical consultation required by means of prophylactic treatment.

The research is unique in that it is the first study to be conducted on the UK pollen databank. It is also unique research in that data sets of this length do not exist anywhere else in Europe and probably the world, and therefore this study poses an important piece of research both on a national and an international level.

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CHAPTER 1 - INTRODUCTION

1.1 BACKGROUND AND OBJECTIVES OF THE RESEARCH

This thesis presents a study of the variation in the start and severity of the grass and birch pollen seasons at a network of sites in the United Kingdom, with the overall aim of creating models to forecast the main characteristics of the seasons. The work represents a major advance in the field as this is the first research which has been conducted on the national databank. Previously, very specific information was known about regional variations in the start and severity of pollen seasons in the United Kingdom.

There are four main aims to the research. First to investigate trends in the start and severity of the pollen seasons for the two main allergenic pollen types (grass and birch) at the long term data sites, London (1961-1993), Cardiff (1962-1993) and Derby (1969-1993). Secondly to investigate the variations in the start and severity of the seasons at the European Aeroallergen Network (UK) (EAN(UK)) sites for the eight years 1987-1994 and to analyse these variations in relation to geographical situation, local trends in weather patterns and local pollen sources. The EAN(UK) network will be described in detail in chapter 3, however it consists of eleven sites distributed around the country (ranging in location from the Isle of Wight in the south, to Invergowrie in the north, Belfast in the west and London in the east). The third aim is to build predictive models to forecast the start and severity of the pollen seasons at the 3 long term data sites, London, Cardiff and Derby. The final aim is to apply the long term data models to the EAN(UK) data to assess their use in the regional prediction of the start of the grass pollen season.

Pollen concentrations have been monitored, during the course of this study, over a three year period (1992-1994) at the University of North London site. Retrospective pollen data has also been incorporated into the database for this site in London, and also the long term site at St Mary's Hospital, Paddington. Pollen data has also been collected from the other ten sites in the EAN(UK) network (Fig 1, chapter 3). The database consists of daily average concentrations of grass pollen, birch pollen and meteorological data. For the long term data sets, records date from 1961 for London, 1962 for Cardiff and 1969 for Derby. The short term data sets used are from Edinburgh (1988), Isle of Wight (1988), Leicester (1990), Preston (1992), Invergowrie (1992), Belfast (1992), Chester (1993) and Taunton (1993). The long term data pollen data sets were analysed statistically to establish trends in the data, and both long and short term data sets were then analysed with the meteorological data to determine the influence of meteorological variables on the start and severity of the grass and birch pollen seasons. On the basis of these relationships, predictive models were built for the long term data sites, and their application at the short term data sites assessed by testing the models on the 1993 and 1994 data.

The need for a study of this kind is discussed in more detail in the literature review (chapter 2), but will also be discussed briefly in this chapter. Apart from the early work of Hyde in 1950, no detailed study of regional variations in start dates and seasonal totals has taken place using a number of different sites throughout one country over a number of years, and no work has taken place on this topic in Britain since Mullins *et al* (1977). Papers that did report regional variations tended to be very descriptive due to the limited use of statistical techniques and the availability of computers during the period, merely reporting on the presence or absence of the various pollen types between the sites.

Little appears to be known of seasonal variations in pollen production by trees which have both different source areas and differing flowering rhythms to those of grass pollen. The existence of cycles of high and low pollen production has been acknowledged since the work of Hyde (1950), Andersen (1967) in Denmark looking at birch pollen, and Fairely and Batchelder (1986) in San Francisco studying the flowering and phenology of oak. The seasonal variations in tree pollen production has not been investigated fully in any part of Britain until recently when Emberlin *et al* (1993a) considered seasonal variations in birch pollen in London based on a thirty year record.

Since the mid 1970s, workers have started to define pollen seasons (Davies and Smith 1973b, Mullenders *et al* 1974, Nilsson and Persson 1981, Lejoly-Gabriel and Leuschner 1983). More recent works have been concerned with the building of predictive models mainly for grass pollen, for example Anderson (1980) in Denmark, Bringfelt (1980) in Stockholm and Driessen *et al* (1989,1990) in the Netherlands. The only study that has been concerned with long term data sets and the development of predictive models in the United Kingdom was by Davies and Smith (1973b). Although this paper was important in that it was amongst the first research to consider the factors which govern the start of the grass pollen season, it considered only grass pollen in London and was based on only 10 years of data. More recently Emberlin *et al* (1993b) have studied the trends in grass pollen seasons over a 30 year period in London, and built models to predict the various characteristics of the season. This thesis develops these models further and also makes comparisons with long term data sets at two other sites, Cardiff and Derby.

It is now possible to build models for other parts of the United Kingdom due to the advances in computing and aerobiology and the existence of large data sets from some regions, some of more than thirty years in length. These long term data sets also make possible detailed analysis of the trends in grass and birch pollen, particularly in the identification of the alternating flowering rhythms in the *Betula* species, although an analysis of this sort has not yet been done on such a long range of data. The analysis is further complicated as there have been considerable changes in land use patterns in the regions during the period covered by the data sets. The analysis presented here is unique research in the respect that datasets of this length do not exist anywhere else in Europe and probably the world. Thus the research will not only be important for the United Kingdom, but also internationally.

1.2 ORGANISATION OF THE THESIS

This thesis has been divided into three main sections; the first is the introductory section, the second presents and analyses the data, and the third develops the analysis towards the predictive modelling of the pollen data.

The second chapter presents a study of the past and more recent literature, thus providing a historical review and presenting studies more relevant to this analysis that have taken place both in the United Kingdom and abroad. Chapter 3 provides details about the EAN(UK) network, the sampling procedures, the nature of the data and the analysis undertaken.

In the second section of this thesis, chapters 4 and 5 present the pollen data and identify long term trends in the grass and birch pollen seasons at the 3 long term data sites. Relationships are established between the start and severity of the seasons and meteorological data at the long term data sites and other EAN(UK) sites.

The final section of the thesis is concerned with the predictive modelling of the start and severity of the grass and birch pollen seasons at the long term data sites. Chapter 8 tests the long term models on the 1993 and 1994 data. Due to lack of data at the short term EAN(UK) data sites, it was not possible to develop models for each individual site. The long term models for grass pollen are applied to the short term data sites in order to assess their use in modelling the start of the grass pollen season on a regional basis.

1.3 RELEVANCE OF THE RESEARCH

In the United Kingdom the results of this study will be of relevance to a great number of people and organisations.

First it is an important area of research of interest to aerobiologists. The long term data sets on which a large part of the thesis is based are the longest data sets that exist in Europe and probably the world, and therefore this poses great opportunities not only for predictive modelling but also the statistical analysis and identification of long term trends in start dates with seasonal severity. As there are 3 sites in the United Kingdom with long term data sets, this also allows for comparison between sites in regions with varying topographies, climates, situation etc.

The research will be of relevance to Quaternary palynologists in the understanding of the variation and timing of pollen production between years and also over a number of different years. It will also provide insight into the influence of the source area on the pollen catch of an area and develop the knowledge of the influence of the 'regional' or 'local' component of a particular pollen assemblage.

The study will be of use to Agriculturalists interested in the influence of climate on the seasonal variation of particularly the grass pollen species, along with the different influence of climate at the individual sites. The analysis will identify the significant climatic variables at the individual sites, and therefore provide background information on crop development.

According to Benninghoff (1991), this type of study will also be of use to Biogeographers and Ecologists in providing information on the changes in pollen concentrations in relation to environmental change. This would also aid the revision of biogeographical analysis and ecological histories.

Grass pollen allergy is fairly common causing seasonal allergic rhinitis (hayfever) and also contributing to the aggravation of asthma (Davies 1973b). Over the last thirty years the incidence of summer hayfever in the London area has increased from 3.3% in 1961 (Davies 1986) to an estimated 15% in 1989 (Davies 1989), and it is assumed that this increasing trend has occurred throughout the whole of the United Kingdom. If this rising trend continues, more than a quarter of the population could suffer allergic reactions to pollen at some time in their life.

Although the majority of hayfever sufferers are allergic to grass pollen, the proportion of the population allergic to tree pollen may be underestimated as the allergenic potential of these pollen types are not well known, even amongst doctors. Also, as hayfever is a condition often associated with the summer, seasonal allergic symptoms experienced in the spring may not be diagnosed as being hayfever.

Analysis of the long term trends in birch pollen at London, Cardiff and Derby will provide insight into the alternating flowering pattern of the birch, and this will be of relevance to rhinitis sufferers allergic to tree pollen types. If biennial alternating flowering rhythms are identified in this study, and their existence is synchronised at all three sites, then years of potentially high pollen counts can be identified and sufferers warned. The lack of knowledge and awareness concerning tree pollen allergy could be a result of these alternating rhythms, leading to a situation whereby the allergic patient will experience symptoms one year and then not experience them the following year, and therefore not attribute the symptoms to being those of seasonal allergic rhinitis.

Geller-Bernstein *et al* (1991) looked at the possibility of using aerobiology as a tool for preventing hayfever. Hayfever is an allergic reaction to pollen and hence the patient suffers at the time when the allergenic species flowers. For that reason they found that it is important to identify what species flowers and when. They concluded that hayfever can be controlled provided that the allergists work in close collaboration with the botanists and aerobiologists.

Although hayfever is not life threatening, the symptoms can be very distressing.

Furthermore the costs to the social sector due to pollen related diseases are high because of medication, consultation and investigation by specialists. The results of this study would enable accurate forecasts of the start and severity of the grass and birch pollen season in certain regions of the country. Through this information sufferers would have increased knowledge, and the number and intensity of consultations could be reduced by means of prophylactic measures and this would result in reduced costs.

CHAPTER 2 - LITERATURE REVIEW

2.1 INTRODUCTION

Pollen analysis is less than 100 years old. One of the first studies was on the pollen of forest trees in bogs of southern Sweden, presented in 1916 by Lennart Von Post at the XVIth Meeting of Scandinavian Naturalists in Oslo. The term 'Palynology' was later given by Hyde and Williams (1944), who defined it as being "the study of pollen and other spores, their dispersal and applications thereof". The historical development of palynology has been reviewed by Wodehouse (1935), Erdtman (1943) and Faegri and Iversen (1964, cited in Faegri and Iversen 1974). It was not until 1950 however, that palynology began to grow. This thesis is concerned primarily with aeropalynology, consisting mainly of atmospheric pollen and spores.

The interest in atmospheric pollens and spores can be found in the literature going back to the mid 1800s. Charles Blackely performed some of the earliest aerobiological studies in the United Kingdom. Between 1859 and 1871 he carried out a series of experiments on the possible causes of hayfever. Blackely collected grass pollen during the summer, stored it for several months, and inhaled some on a winter's day. The effect was immediate, confirming that pollen was a cause of hayfever. He then went on to collect other pollen from trees and weeds and found that these also caused a reaction. Other experiments that he performed included flying a kite with a sticky glass microscope slide attached, and then observing the slide under the microscope. This experiment proved that pollen was present high in the atmosphere. Blackely also invented a pollen trap and made the first pollen counts (Blackely 1873). Maddox (1870) published a paper discussing the various apparatus used for collecting atmospheric particles. One of the earliest works considering the abundance of airborne pollen grains was by Hesselman (1919, cited in Erdtman 1943) who exposed plates to trap pollen on lightships in the Gulf of Bothnia. Malmstrom (1923, cited in Erdtman 1943) performed a similar experiment in a densely wooded part of northern Sweden and concluded that the pollen had been carried from southern Sweden. Erdtman in 1937, whilst attempting to establish the absolute amount of pollen grains disseminated by the winds across the Atlantic, trapped pollen grains using vacuum cleaners during a voyage from Gothenburg to New York. Erdtman (1943) also cites other such experiments on atmospheric pollen which used deposition samplers.

Most of the works discussed so far (with the exception of the work of Blackely), representing the earliest palynological works, were performed on the basis of Quaternary palynology and were mostly seen as providing an aid to the interpretation of fossil pollen data, rather than being of siginficance in their own right.

Very little palynological work took place in Britain in the first half of this century, the major pioneers in the field worked in Germany and Scandinavia. Much literature dates from the early 1930s (for example, Rempe 1937, Pohl 1937, Tauber 1965, 1967) and was mostly concerned with pollen dispersal, particularly the role of long distance transport. This chapter will consider certain aspects of these early studies, however, will concentrate on the later studies concerning regional variations and the predictive modelling of pollen concentrations.

2.2 DISPERSAL

Since the development of pollen analysis, it was a common assumption amongst the writers such as Erdtman (1937), Rempe (1937), and Pohl (1937) that most pollen grains are first carried to high altitudes by convection currents, are then spread over a large area, and later fall back to the ground and into lakes in a more or less vertical descent as 'pollen rain'.

One of the earliest workers in the field of pollen analysis to reject this idea of uniform dispersal was Ludi (1947). He suggested that this 'pollen rain' was not evenly distributed for two reasons. Firstly because mixed plants flower at different periods, and secondly because wind and turbulence may vary and thus the pollen rain from a particular patch of vegetation may be deposited in different places in different years. The further away from the pollen-producing vegetation, the less pronounced this effect. This was a particularly important area of early research targeted towards Quaternary pollen studies.

Tauber in 1967 also criticised the concept of 'pollen rain'. His main argument was that the idea of a 'pollen rain' was too simple and did not take into account a number of factors eg. varying wind velocities, variation in atmospheric turbulence at different times of the year, different terminal velocities of pollen grains of different species, and the influence of the physical structure of the vegetation on the dispersal process. When studying the transport of pollen under a closed canopy woodland, he maintained that a major part of the pollen transport takes place not above the canopy, but within the trunk space. He saw a pollen deposit consisting of 3 different components:-

i) coming through the trunk space. Mainly local in origin, especially for large, heavy pollen grains

ii) via the lower most strata of the atmosphere above the canopy

iii) via the higher air strata

The relative importance of these three components is not well known, but it is suggested that it would vary a great deal according to the composition of the forest and with physical conditions such as wind, temperature, precipitation etc. He also introduced a fourth component which consisted of pollen brought back to ground level by rainfall ie.'rainout' or 'washout'.In contrast to the trunk space component this would have a distant origin, having been transported some way by the upper air flow. This study is particularly relevant when considering regional variation throughout the United Kingdom as in certain regions pollen clouds encounter forest and woodland areas, and it is also possible to make an analogy between the forest and an urban area where trees may be replaced by buildings in that they both restrict the upward movement of pollen grains. Tauber's idea of the trunk space being one of the major components for pollen transport was rejected by Andersen in 1967 who showed conclusively that in a forest of varying composition there is almost a perfect correlation between the composition of the pollen deposited on the forest floor and that of the canopy immediately overhead. If there was transport within the forest then this would not be so. Even in Tauber's own measurements he shows that the quantity of pollen in the trunk space is much lower than would be expected if it were the main route of pollen.

When considering regional variation in pollen concentrations it is also important to consider the distance which pollen grains can travel. Faegri and Iverson in 1975 suggested that a distance of 50-100km forms a natural limit of pollen dispersal. Many studies however give examples of even longer distance transport. Haftsen (1960) found unmistakable pollen grains of the southern beech tree, *Nothofagus* in peat on the Island of Tristran de Cunha, 4500km from the nearest sources in South America. Bassett and Terasmae (1962) found *Ambrosia* pollen grains 600km north of its northern most occurrences in Canada. Such distances are possible if the grains are incorporated into the upper air masses. Sreeramulu and Ramalingam (1961) performed an experiment in which a known volume of microbial spores were liberated from a point and 90% were deposited within 100km of the point of liberation. (It can be assumed that pollen grains, although bigger in size than the majority of microbial spores, would act in a similar manner). They explained the remaining 10% as having diffused far enough upwards to put it beyond the risk of any deposition to the ground, Gregory (1978) referred to this as the 'escape fraction', and it is within this fraction that long distance transport is possible. The possibility of particles rising into this 'escape fraction' is greater in dry areas and hence pollen from steppe/desert plants are frequently recorded at great distances from the source. Long distance travel is regarded by many as insignificant and most of the pollen is usually deposited long before this limit has been reached. Solomon and Silkworth in 1986 looked at the distance decay in pollen deposition from the source in a mountainous area, and concluded that pollen deposition within the source area was high and variable, but that at distant sites the deposition was low and uniform. This work is of great importance when considering regional variation in ambient pollen concentrations.

2.3 ENVIRONMENTAL FACTORS

The United Kingdom is characterised by a varied topography ranging from low-lying flat areas such as East Anglia, to high rugged mountainous areas such as the Scottish Highlands and the Lake District, and therefore when considering regional variation it is important to consider the effect of natural topography on dispersal patterns.

Ludlam in 1967 considered the airspora content amongst mountain ranges and said that cross-winds force the air movements upwards and create 'lee-waves'. If the vegetation on the two sides of the mountain range is different, the transport of pollen from the windward side is a factor to be taken into account. Changes in incidence of pollen from the windward side may then simply reflect the changes in wind pattern and have no relation to local vegetational changes behind the mountains.

Along with natural variations in topography, it is also important to consider changes in topography as a result of an increased urban development. The influence of the urban environment on pollen dispersal has been reported by Norris-Hill (1992). Pollen sites located in dense urban areas, such as London, are under the influence of many different phenomenom. The 'urban heat island' influences the phenology of plants within the city, usually resulting in earlier flowering compared with plants in the rural source areas. The heat island is also important indirectly in the influence it exerts on airflow patterns. Consideration must also be given to airflow systems around individual buildings and the influence of the urban structure on factors such as the transport of material from the rural areas, dispersal of particles from within the city, the heterogeneity of airflows and particle deposition. Davies (1969) working in London, found that spore concentrations at street level were very much lower than in the air streams above the city as the buildings confer shelter from the wind.

A further factor to take into consideration when studying pollen dispersal is meteorology. Perhaps the most studied aspect of this is precipitation. M^{c}Donald (1962), Dingle and Gatz (1966) and Chamberlain (1967) showed that even moderate amounts of precipitation clear the atmosphere of its suspended particles in a short time, and after extensive rains, very little remains. Scott (1970) suggested that the effect of rain on pollen concentration varies with the time of day. In the morning rain washes pollen out rapidly as pollen is still in the lower strata, as compared with the evening when rain may cause an immediate increase of pollen concentration near ground level. More recent works concerning the temporal and spatial distribution of pollen rely heavily on meteorological factors such as precipitation (total and intensity), wind (velocity, direction and duration), temperature (mean,maximum, minimum and total), sunshine hours, relative humidity, cloud cover etc. for explanation and this shall be discussed in more detail later (particularly in chapters 4, 5, 6, 7).

Land use changes also affect the pollen catch. Despite this, few studies have actually considered variations in land use when studying trends in seasonal pollen characteristics. Davies and Smith (1973a) when studying the effect of wind direction on the pollen catch incorporated percentage grassland data into the analysis, however very few other works consider land use patterns and phenology. This aspect will be considered in more detail in chapter 4.

2.4 REGIONAL VARIATIONS

Although a great deal of the early work was concerned with the study of dispersal patterns, comparatively few people have studied the variation between different sites, and the majority of the early work was done in Britain.

In 1942, the first detailed day to day survey of pollen deposition in the United Kingdom was made at Cardiff in South Wales by two workers, Hyde and Williams (1944). In 1943 this survey was extended to eight stations situated in towns or lowland situations extending from South Wales and London, north to Aberdeen (Hyde 1950). The aim of the study was to determine the constituents of the pollen "rain" in the United Kingdom, and the variation in its composition from day to day and from place to place in relation to local source areas and weather conditions. In Hyde's paper in 1950 he reported on the results and concluded that the main pollen types caught were common to all stations and that the pollen season lasted from mid January until late September and although the main incidence of each type of pollen was felt simultaneously at the southern stations, the Scottish sites lagged up to a fortnight behind. He also considered the influence of meteorological factors on the pollen catch and found that bright sunshine was correlated with the incidence of grass pollen, changes in wind direction produced marked effects on the pollen catch, temperature showed an effect, and finally rainfall sometimes reduced the pollen catch but at other times it had no effect. This was the first detailed study of spatial variations in pollen concentrations throughout the United Kingdom, and it lead to the production of a series of six papers examining a range of aspects of pollen abundance. Hydes' work is of great interest and relevance to this study, however it was limited by the use of depositional samplers whose sampling efficiency is influenced by the wind and the settling velocity of pollen grains.

Davies, Denny and Newton in 1963 studied the variation in the pollen catch between sites. Although they only compared two sites, London and Liverpool, the advantage of their work over that of Hyde was that they used the Hirst trap to monitor pollen and this proved to be more reliable and efficient. Monitoring took place for one season, May through to October, using 2 Hirst traps which were set up in similar situations in London and Liverpool in 1961, in order to compare the changing concentrations of pollen and spores in 2 densely populated areas. They were mainly concerned with grass and nettle *(Urtica)* pollen and concluded that in 1961 the grass pollen season at London reached its peak 9 days earlier than at Liverpool where the season was shorter, hence confirming Hyde's (1950) observation of the existence of a time lag between southern and northern Britain. It was not until 1969 that an attempt was made to explain this variation as being associated with a more rapid rise in the value of accumulated temperature in London than Liverpool. Davies' paper (1969) comparing the effect of climate on the airspora of London with Davos in Switzerland is an important study as although sites in 2 different countries are compared, the effect of topography as well as, and along with meteorology was included. Like Ludlam (1967), Davies considered the effect of relief on the airspora content. Although the Alps around Davos are a larger mountain range than one would find in the United Kingdom, his observations are important and comparisons can be made.

In 1973, a comparative study of atmospheric pollen concentrations began in Europe, when workers from Bologna, Brussels, London, Munich and Strasbourg made observations of variations in grass pollen concentrations. This was not only the first comparative work between a large number of different countries, but also the first in a series involving international collaboration between workers in the European Economic Community (E.E.C). It also went a step further than previous comparative studies in that it defined the start of the season as the first 100% symptom day ie. the first day that receives a count of greater than or equal to 50 grains per cubic meter of air was recorded (according to Frankland and Davies unpublished, cited in Davies and Smith 1973b). Bagni *et al* (1976) attempted to explain the variation in the start of the season, and seasonal totals according to land use and mean maximum June temperatures based on one seasons observations. This was followed by a study by Spieksma *et al* (1980) who compared weed concentrations (ie. *Rumex, Plantago, Chenopodiaceae, and Artemisia*) between 5 European sites over two seasons.

In the United Kingdom, two other comparative studies took place. In 1969 Morrow-Brown and Jackson working in Derby in the Midlands, produced a number of papers on grass and nettle pollen concentrations. Using eight identical Hirst spore traps within a 60km radius of Derby located within different land use areas, grass and nettle pollens were monitored in order to find out whether one sampling site located at Derby could provide adequate data for the surrounding area. They found a good correlation between rural sites, but not between rural and urban sites, and hence concluded that the pollen count taken at one site was not representative of the whole surrounding area (Morrow Brown and Jackson 1978). Following this they were the first to monitor pollens on the east coast of Britain. Four identical spore traps were set up in locations across Britain from Port Lynas off Anglesey to Cromer in East Anglia, and pollens were monitored from June to October over one year. Variations in the pollen catch were explained according to the SW prevailing wind resulting in lower pollen catches on the west coast due to onshore winds and an emphasis on moorland and rough grasslands, and higher counts on the east coast due to offshore winds and intensive cereal farming.

In Cardiff Mullins *et al* (1977) reported a study of the grass pollen content of the air at four sites bordering the Bristol Channel based on one seasons observations. They reported that although occasional fluctuations occured in the count between the sites, overall the results for the four sites were similar and that any changes in the atmospheric pollen concentration were a function of meteorological factors.

2.4.1 Progress in Europe

Up until the 1980s the United Kingdom lead the way in work on regional variation. Mullins *et al* (1977) were amongst the last people to perform such a study until the late 1980s when Emberlin and co-workers (1990, 1991, 1993a, 1993b) produced a number of papers. Most work during the lapse period of the late 1970s to the late 1980s took place mainly throughout Europe and other parts of the world.

Lejoly-Gabriel and Leuschner (1983) compared the pollen composition of two sites, Louvain in Belgium and Basel in Switzerland over a two year period 1979-1980. The concept of their paper was not new, after all it was very similar to Bagni *et al* (1976) and Spieksma *et al* (1980) in that it compared European sites but on a much smaller scale. However the paper put forward a number of new ideas. The season was defined as the 'principal period of pollination' which "begins on the day when the sum of the annual pollen percentage reaches 5%, provided that this day corresponds to a release of greater than or equal to 1% of the total catch. The period ends on the last day when the daily percentage is greater than or equal to 1%, and the sum of the pollen percentage for this day and the preceding days is greater than or equal to 3%". Variation in the totals of over 20 species were explained according to the surrounding vegetation patterns. They then introduced the idea of an index of the onset of flowering time, whereby the sum of the dates (expressed in days from January 1st) of the beginning of the pollen period are divided by the number of taxa considered. The resultant index can then be compared for both sites as an overall value for all pollens, or certain individual ones in the different years. This paper provides a number of useful comparative techniques that can be used when studying regional variation throughout the United Kingdom.

Larsson *et al* (1984) studied the variation of pollen incidence between 3 stations in Sweden over a 7 year period (1976-1982). They examined the variation in the daily means of the various pollens, and went on to define the season according to Nilsson and Persson (1981) ie. the period in which the sum of the concentrations reaches 5% of the total sum, until the time when the sum reaches 95%. When comparing the pollen catch between sites they firstly tested the reliability of the sampling method by measuring the pollen concentration using 2 Burkard traps at one site. It was found that often the correlation between sites at great distances apart was higher than that of two traps at the same site. Variation was explained according to randomness, vegetation, weather and site (Larsson *et al* 1984).

Halwagy (1988) compared the concentration of airborne pollen between three sites in Kuwait over six years (1977-1982). Variation in the pollen count over the years at the different stations was attributed to variation in the surrounding vegetational patterns. Explanation was hindered by the fact that apart from wind direction no other meteorological factors were considered.

Meiffren (1988) compared three sites; Toulouse, Bordeaux and Montpellier over 3 years (1981-1983). The main difference between this study and the previous ones was that the sampling method developed by Cour (1974) was used rather than the Hirst trap, as tests found that the vertical filters developed by Cour were more efficient in the collection of smaller and larger pollen grains (Seignalet 1979). The main relevance of this paper is in defining a pollen calendar for the South of France, any variation that became apparent was attributed to the surrounding vegetation patterns.

In 1989, Spieksma *et al* compared airborne pollen concentrations of alder, grass, and mugwort at 2 stations in the Netherlands with 2 stations in Central Italy over four years (1982-1985). It was found that the concentrations of the pollen types did not differ greatly between the two countries, and any differences that did occur were due to variations in vegetational composition and meteorological factors. The various seasons were defined according to Mullenders (1974) ie. the season is deemed to start when greater than 1% of the annual total according to the 5 day running mean has been achieved. From this definition lag times were discovered in that the Netherlands' grass pollen season started one month later than that of Central Italy, and 9 days later in mountainous Italy than in the coastal area. This lag was attributed to air temperatures during the period preceding the start of the season.

2.5 PREDICTIVE MODELLING

Work on regional variation has so far mainly been descriptive. However, the work that has taken place has provided a basis on which to model pollen concentrations. By using models it may be possible to predict the start, severity and length of the seasons for different pollens, and, along with local weather forecasts, forecast daily pollen counts. Aerobiologists in the United Kingdom (Davies and Smith 1973b), Italy (Frenguelli *et al* 1989), and the Netherlands (Spieksma 1980) have all produced predictive models to forecast grass pollen concentrations, grass pollen being of sufficient importance to warrant extensive research as it is the most allergenic airborne particle in those countries. Aerobiologists in Scandinavia and Denmark have been concerned with forecasting tree pollen concentrations of *Betula* species and *Pinus sylvestris* pollen (Eriksson 1978), along with grass pollen (Andersen 1980, Moseholm *et al* 1987). In the United States, concentrations of *Artemisia* and *Ambrosia* pollen (Raynor and Hayes 1970) have received more attention than those of grasses or trees.

Most of the models have been empirical, although a few also have a theoretical basis. The overiding theme throughout most of the literature is the use of preseason temperatures, some using cumulative temperatures to the start dates, but others attempting predictions several months in advance based on temperatures for one month (eg Arobba *et al* 1992).

2.5.1 Simple Predictive Models

One of the earliest studies concerning empirical predictive models was by Raynor and Hayes (1970) who compared three different methods to predict daily ragweed concentrations; climatology (predicting the average conditions which occurred on that date in past years- this does not take into account the expected weather conditions), persistence (by assuming that current conditions will continue,thus the forecast for tomorrow is the same as that for today), and a forecast based on the predicted weather conditions. It was found that the latter was the most accurate method (75% of predictions were correct), and persistence was the most inaccurate method (only 56% of predictions were correct). They concluded that the accuracy of the prediction depended entirely on the accuracy of the weather forecast.

In 1973, Davies and Smith (1973b) were the first people to forecast grass pollen concentrations in Britain. Following on from their previous regional comparative work (Davies *et al* 1963, Davies 1969), they attempted to forecast the start of the grass pollen season (defined as the first 100% symptom day, monitored when the daily average pollen count is greater than or equal to 50 grains/m^3 of air) in London, based on records of grass pollen concentrations over a 10 year period (1961-1970) along with meteorological data from four stations surrounding London. This work was the first work to consider the controls on grass growth and flowering, and concluded that the start of the season depended on the mean air temperature in April and May, ie.during the period of pollen formation. On the basis of cumulative pollen counts during the season the severity could also be predicted. The accuracy of these predictions, they reported, would be affected by weather factors during, and in the few days leading up to the start of the season, such as rainfall, lack of sunshine and wind.

Bringfelt (1980) used correlation and regression analysis on pollen counts in Stockholm and Sweden. Bringfelt *et al (1982)* extended this work and developed predictive models for the *Betula* and *Gramineae* pollen seasons using multiple regression analysis. This model proved more accurate for *Betula* pollen with an efficiency of 80%, than for *Gramineae* with an efficiency of 58%.

Spieksma (1980) developed a model to produce a daily hayfever forecast for the Netherlands based on a regression analysis similar to that of Bringfelt, but simplified by the use of fewer meteorological variables. Spieksma *et al* (1985) suggested that, based on 5 years observations, the start of the season in the Netherlands, was triggered by a rise in temperature in the last week of May or the first week in June, and although a long term prediction for the start of the season cannot be made, a short-term forecast based on weather, pollen concentrations and patient complaints records reaches an accuracy of over

80%.

Andersen (1980) working in Denmark, studied the influence of climate on the pollen season, but he was mostly concerned with its influence on severity, particularly for birch, alder, oak, beech, grasses and nettle. He found that birch and alder behaved similarly in that they both flowered biennially and pollen production was influenced by the precipitation in the preceding April. Oak and beech were best correlated with average maximum temperatures and low rainfall over the preceding summer (ie.June-Sept). For grasses, he agreed with Spieksma (1980) and Bringfelt *et al* (1982), in that he found that it was possible by performing a regression analysis with mean maximum temperatures for April and May and precipitation to produce a prediction for the start of the season by the first week of May.

Up until the early 1980s, most of the work on predictive models, apart from work by Raynor and Hayes (1970), had taken place in Europe. In 1986, Fairley and Batchelder, working in San Francisco, produced a paper on the prediction of the severity of the oak pollen season based on geographic and meteorologic factors over a nine year period. By using regression analysis they found that although the amount of precipitation leading up to the season bore no relation to the pollen catch, there was a strong correlation with the pollen catch and the amount of precipitation in the previous winter, they agreed with Andersen (1980) in that above average temperatures and low rainfall in the preceding summer stimulated pollen production. However the main difference between San Francisco and Denmark is that San Fransisco is devoid of summer precipitation and therefore pollen production is dependent on winter precipitation and this may explain why the study demonstrated substantial oak pollen release 12-14 months after a winter with heavy rainfall. The usefulness of this is that the severity of the oak pollen season can be predicted long before the season occurs.

In 1989 and 1990, much work on the prediction of the grass pollen season (Driessen *et al* 1989,1990) was taking place in the southern and western Netherlands. A new method of defining the start of the grass pollen season as the day when the accumulated sum (from January the 1st) of average daily grass pollen concentrations reaches 100 grains/m^3 of air was proposed. This method is called the 100sum method and was chosen because it was felt that it best reflected the weather conditions preceding the flowering of the grasses. The start of the grass pollen season was predicted by using the phenological method along with pollen counts to relate the start of the grass pollen season to the start of that for an 'indicator plant' that normally flowers earlier, in this case birch was used. They found that for the western part of the Netherlands a prediction with the aid of an 'indicator plant' was twice as accurate as one without. Having tested four limit-setting methods; the 50, 75, 100 and 125method, it was found that the start of the season by the 100method was most accurately predicted with the 125method for birch by applying a regression analysis which gave an overall efficiency of 65.2%. In the southern Netherlands, using a similar technique, it was found that the most accurate prediction was gained from using the 25method for birch, and the 75method for grasses and then performing a regression analysis, this gave an overall efficiency of 50%. This level of accuracy is inadequate and although using birch as an 'indicator plant' produced better results than without, there was no account taken for biennial rhythms which may alter the magnitude of the birch count, and the work ignored the fact that *Betula* and *Gramineae* have a different response to environmental factors.

Keynan *et al* (1989) working in Israel produced a simpler alternative to the previous regressional analysis methods of predicting the start of the season. They suggested two ways of forecasting; first by conducting a continuous survey of all airborne pollens, and second by following the phenology of the allergenic plants and watching the time-course of development of their flowers and pollen release. They tested these methods over nine years in various regions of Israel, and although detailed statistical analysis were not used, they did conclude that as flowering is positively correlated with airborne pollen counts (Zerboni *et al* 1986) it is possible to make a prediction on the basis of phenological observations alone. Although the accuracy of this method is questionable, and it does not yield any quantitative information, it has the advantage that it is simple, easy and inexpensive, and weekly surveys near the time of the main flowering season can give a reliable forecast. It is also a useful forecasting method for developing countries who have little money to spend on detailed monitoring and research and often have substantial climatic and botanical variability which would make monitoring more complicated.

Another method using phenology was presented by Marletto *et al* (1992) using species of lawn plant. They used 3 years phenological data on a lawn in Bologna and recorded the date of flowering of 56 species according to a 7 stage phenological key. Analysis assumed a linear relationship between air temperature and the rate of phenological development. Two methods were used, first, temperatures sums were defined and combinations of base temperatures and start dates were found, some species were however rejected from this method because of the lack of stability in the character of the phenology. The second method looked at the time intervals of flowering dates of a leading species and a following species, the temperature sum relative to every pair was computed starting from the flowering time of the leading species. The main problem with this work was that only 24 of more than 700 possible pairs of species passed the test, only observations for three years were used, the results were only tested out on data for one year, and photoperiod and rainfall were not included in the analysis. The study did however present an interesting line of work.

2.5.2 Complex Predictive Models

Moseholm *et al (1987)* proposed an alternative to the regression analysis method of developing predictive models. He suggested that if the pollen counts were autocorrelated then a time-series technique could be used against the meteorological data whereby variation in a series is explained by its past behaviour and from this future values in a series can be predicted. It was found that mean daily temperatures and humidity were the best correlated parameters to the variation in daily pollen counts.

Frenguelli *et al* (1989) based their work on the grass and olive pollen concentration at two sites in Italy and attempted to predict the start of the season (defined according to Lejoly-Gabriel and Leuschner 1983). By using correlations they agreed with earlier work in that the start date was determined by the preseason air temperature. They also included the use of 'heat units' which were calculated by determining the mean temperature for each day, subtracting a base temperature (5°C) as suggested by Dennis (1984) and accumulating the remainders for each day from March 1st to the beginning of flowering.

Although they said that it was possible to use heat units to predict the start of the season for grass pollen, the main problem was that results vary from region to region and this produces difficulties.

Andersen (1991) working on 14 years of data from Denmark, developed a model combining Utah phenoclimatology chill units and growing degree hours to predict the first blooms in *Alnus, Ulmus* and *Betula*. This model was adequate but rather complex, and did not take into account biennial rhythms, photoperiods and relied on an accurate long term weather forecast.

Frenguelli *et al* (1992) considered the role of air temperature and chill units in determing the flowering of *Corylus avellana*. This consisted of seven years pollen monitoring in Perugia. They found that the start of the pollen season varied by up to three weeks, and there was a significant correlation between the onset of pollen production and temperature conditions in the period once the chilling requirement had been fullfilled. From this it was then possible to estimate the start of pollination by measuring the temperature from the start of dormancy. The main problem however was that the model was only based on seven years of data, and it was not made clear exactly how the chill units were used in the prediction.

One of the most recent studies on forecasting used the cumulated activity method (Larsson 1993). This paper attempted to predict the start, peak and end of the pollen season for a wide range of species including *Corylus, Alnus, Ulmus, Betula, Quercus, Pinus, Gramineae* and *Artemisia*. The objective was to calculate activity corresponding to the efficiency of processes in the plant that are relevant for the development and release of pollen. Data from sixteen pollen seasons were used (1973-1988) and the start of the season was defined at the 5% level, the peak was on the day of highest pollen concentrations, and the end of the season was when 95% of the total catch had been reached. The model used an activity formula, and was based on the idea that activity doubles with every 10°C increase in temperature, and that the activity gains a value of one as the temperature exceeds a defined temperature threshold. This model gave good results for some species and poor results for others. However the model could only be used retrospectively becauses of the method used to define the season.

2.6 SUMMARY

Very little, if any work on regional variations in pollen concentrations and the development of predictive models, has taken place in the United Kingdom since 1977, and the United Kingdom holds one of the longest databases for grass and birch pollen in the world. In the papers reviewed, one of the main drawbacks in the prediction of any characteristic of a pollen season is that for empirical predictive modelling, a long time series of data is required, and the longer the time series, the more significant the result. This literature review thus highlights the need for more detailed work on regional variations of pollen concentrations and the prediction of pollen seasons.

CHAPTER 3 - RESEARCH METHODOLOGY

3.1 INTRODUCTION

It is generally agreed that allergic sensitivity to any particular kind of pollen or spore is usually aquired by inhaling it from the atmosphere. Both the diagnosis of allergic disease due to such inhalents and the assessment of the efficiacy of treatment demand a reasonably exact estimate of exposure. In early aerobiological studies (eg. Hirst 1953, Gregory and Hirst 1957, Davies 1965, 1969), the Hirst Automatic Volumetric Spore Trap was used. This trap was further developed and resulted in the Burkard seven day recording volumetric spore trap and it is this trap that is used to monitor pollen by all the EAN(UK) sites used in this study.

3.2 POLLEN DATA

3.2.1 Development of the Pollen Database

3.2.1.a The British Initiative

Over the past five years the number of airborne pollen and spore monitoring stations has increased considerably due to a growing awareness of the importance of atmospheric concentrations of pollen and spores in the study of pollinosis.

The UK network was first developed in 1990 however much work had taken place before this. There were a few independent long established sites eg. Cardiff which dates from 1954, St Mary's Hospital in London which dates from 1961, and Midlands Asthma and Allergy Research Association (MAARA) dating from 1969. In 1983, the National Pollen and Hayfever Bureau (NPHB) was set up, and was co-ordinated at Rotherham. This initially consisted of 26 sites which decreased to 20 during the first five years. The sites within the NPHB were based mainly at Environmental Health Offices of County Councils, and counted grass pollen only for 8-10 weeks per year. The network existed as a public service set up primarily to bring sites together in an attempt to create a national framework. In 1990, a National Forum was held to discuss ways to develop the 'Science of

Aerobiology in Britain'. Groups represented included the NPHB, the National Asthma Campaign, MAARA, and the Pollen Research Unit. As a result of this the British Aerobiology Federation (BAF) was formed with the aim of promoting research, scientific exchange and communication in aerobiology. A standardised monitoring network, under the name of Pollen UK consisting of 2 main components - the NPHB and the European Aeroallergen Network (EAN(UK)) was also created. The EAN(UK) was formed at the same time and initially consisted of six sites; Edinburgh, Derby, Leicester, London, Cardiff and the Isle of Wight. The network was extended in 1992 to nine sites with the addition of Belfast, Invergowrie and Preston and then a further four sites joined in 1993 and 1994; Taunton, Chester, Plymouth and Norwich (Fig 1). These sites monitor concentrations of the main allergenic pollen types from late January through to October:

Salix, Corylus, Alnus, Betula, Ulmus, Platanus, Quercus, Gramineae, Fraxinus, Urtica, Artemisia, Plantago, Rumex, Tilia, Pinus

Results were reported weekly to the Pollen Research Unit at the University of North London (now relocated at Worcester) to be stored in the UK database and also to be forwarded to the main European database in Vienna. Some of the sites also had retrospective data dating from 1987 (with the exception of London, Cardiff and Derby who had data from 1961, 1962 and 1969 respectively) and this has also been included in the UK database.

The EAN(UK) co-operate with the NPHB resulting in a large network of approximately 31 sites located throughout Britain. Since the British Aerobiological Federation was formed site standardisation has occurred to try and avoid local bias and to standardise factors such as trap operation, exposure, height of trap above ground, slide counting proceedures etc. During the grass pollen season a 'data swap' system exists whereby the EAN data is sent daily to the NPHB and vice versa.

Data from the eleven sites in the EAN(UK) network (Table I) form the data set for the analysis presented in this thesis. Because of their late inclusion in the network data, Norwich and Plymouth were not included in the analysis, nor was data for the site at

Preston because of the unavailability of meteorological data.

Details of the EAN(UK) pollen monitoring sites are given in the table (Table I).

Table I Details of EAN(UK) Site Locations and Characteristics

Site	Position	Altitude (m)	Height of trap above ground (m)	Local pollen sources
Isle of Wight	50.42N 1.18W	25	10	Rural. Forests to N, E and SW. Mainly grassland
Taunton	51.01N 3.06W	16	11	Semi-rural. Mainly mixed deciduous woodland. Large areas of farm and grassland
London	51.3N 0.2W	37	18	Urban. Densely populated. Tree-lined roads. Highgate Hill and Hampstead Heath nearby
Cardiff	51.29N 3.1W	26.7	13	Urban. Parkland to W. Lies on coastal plain, 7km to nearest wood
Leicester	52.38W 1.05W	60	30	Urban. Streets lined with deciduous trees. Low-lying hills. Mixed farming.
Derby	52.55N 1.29W	110	10	Suburban gardens with deciduous trees, playing fields. Grass areas
Chester	53.12N 2.54W	25	10	Suburban. Areas of grassland and dairy farms in surrounding.
Preston	53.46N 2.42W	30	8	Suburban gardens, small parks. Open country, dairy farms

(Continued)

(Continued)

Belfast	54.4N 5.5W	21	24	Urban. Tree-lined road. Grassland and dairy farms surrounding.
Edinburgh	55.57N 3.13W	90	35	Urban. Few deciduous woodland species lining streets.
Invergowrie	56.28N 3.04W	35	7.5	Rural. Decidous woodland species and grass. Local arable farms.

3.2.1.b The Two Allergenic Pollens used in the Analysis

Over the season from February to October concentrations of twenty pollen types were recorded at the different sites. This thesis focuses on two types namely; *Gramineae* and *Betula*.

Gramineae pollen allergy is the most common pollen allergy in Europe overall, although it is overtaken in some places by other species eg. *Betula* in Scandinavia. Allergy to *Gramineae* pollen ranges from 20% of the allergic population in Denmark, to 80% in France and Holland (Weeke and Spieksma 1991). In the UK it is estimated that approximately 15% of the total population are allergic to pollen, and of this 15% the majority are allergic to *Gramineae* pollen. The most important species of *Gramineae* as far as allergies are concerned are *Phleum pratense* and *Dactylis glomerata*, in this analysis however the pollen was not identified to species level but merely represented within the *Gramineae* family. In the UK the *Gramineae* pollen season generally starts in late May or early June (Emberlin *et al* 1993b), however this depends greatly on the preceding spring weather conditions.

The second major cause of pollinosis in the UK is from *Betula sp.* pollen. *Betula* pollen is responsible for many cases of pollinosis in Scandinavian countries (Eriksson *et al* 1984), but more recently it has been found that *Betula* pollen can be a cause of allergic reactions elsewhere (Ott *et al* 1981) especially in years with very high airborne concentrations (Oei *et al* 1986). Koivikko *et al* (1986) working in Scandinavia, observed that 90% of patients with birch pollinosis reported mild symptoms at pollen counts of greater than 80 grains per cubic meter in the early season. The clinical importance of birch pollen can be illustrated by investigations showing that approximately 20-25% of the allergic population suffering from pollinosis develop reactions when challenged with birch pollen (Horak *et al* 1979).

Although other pollen types are also known to cause allergic reactions, eg. *Urtica, Quercus, Corylus, Artemisia, Plantago*, the number of patients who experience symptoms from these in the UK is small and hence not all of the recorded pollen types have been included in this analysis.

3.2.2 Standardisation Techniques and Sampling Strategy

3.2.2.a The Pollen Sampler

When measuring airborne pollen concentrations the choice of sampler is of utmost importance. In 1972, Hyde summarised the desirable characteristics of a sampler as it having the ability to;

(i) trap efficiently
(ii) be independent of wind velocity
(iii) catch all particles within 3-50 μm range
(iv) be capable of yielding a continuous volumetric record of atmospheric content
(v) be simply constructed
(vi) be easily maintained
(vii) be capable of continuous long-term operation
(viii) be independent of power supply.

Twenty years on these demands are still valid.

One of the first pollen samplers used was the Cascade Impactor designed by May in 1945. This used a technique whereby air was sucked in through four progressively finer jets, and particles were impacted according to size on a series of sticky glass slides. The main problem with this sampler was that as the slides were fixed, the deposit became very dense after an hour or two, so although it proved ideal for short sampling periods an alternative method was required for sampling over a longer period of time. Although as an air sampler itself it had many problems, it represents a milestone in air sampling techniques and it is the reference instrument by which efficiencies of other air sampling devices are compared. The size grading slit sampler (Lidwell 1959), portable spore trap (Gregory 1954) and Hirst trap (Hirst 1952) are all based on it.

In 1952, Hirst, whilst experimenting with the Cascade sampler, found that most of the pollen grains in an air sample were trapped on the slide beneath the second jet, and it is on this observation that he based the automatic volumetric spore trap. The original version of the Hirst trap has been developed into the Burkard seven day recording volumetric spore trap, and it is this trap that is used by all NPHB and EAN(UK) sites to monitor pollen. According to Davies (1971) this trap is often taken as being the international standard sampler. The Burkard, or a trap with a similar design, the Lanzoni, is now being used to sample pollen concentrations and provide volumetric pollen counts throughout most of Europe (Fig 2).

3.2.2.b Operation of the Burkard Sampler

The Burkard sampler operates by sucking in air at 10 litres per minute through a 14x2mm orifice which is pointed into the wind by a vane. The particles in the air stream are directed on to a tape made sticky using petroleum jelly and 10% paraffin wax which is drawn upwards past the orifice at a rate of 2mm per hour by a clockwork mechanism. Pollen grains and other particles are impacted on the sticky surface. After 24 hour exposure a deposit measuring 14x48mm is obtained. This can then be removed or the trap can be left to run unattended for seven days. When operated continuously this apparatus provides a record of the diurnal and seasonal changes in the airspora.

One disadvantage of the Burkard trap is that as it is heavy, relatively costly, and requires power to operate, it is not easily portable and hence cannot be used to monitor pollen concentrations in the immediate environment that a pollinosis patient encounters during the day. It does however give some reflection of the airspora content over a large area, although the larger the area over which the pollen data is taken to represent the less accurate the information is likely to be (Morrow Brown and Jackson 1978). In the

EAN(UK) network this is overcome by using more traps spatially located throughout the country.

When sampling pollen and comparing concentrations between sites, it is not only important that all sites use the same instrument but that other standardisation methods must also be employed, concerning firstly the location of the sampler and secondly the counting methods used.

3.2.2.c Importance of Sampler Location

Gregory (1978) reported the existence of a vertical concentration gradient, whereby, due to a combination of upward forces, mechanical turbulence and convection acting against sedimentation under gravity, the pollen concentration decreases with increasing height. When sampling pollen and spores at Rothamsted for 5 months in the summer he found that a trap 2 meters above ground level had an airspora content 18% more than a neighbouring trap placed at 24m above ground level. Many papers have also reported examples of this. Raynor *et al* (1973) working in the United States found that ragweed pollen concentrations decreased with height in a rural area. Davies (1965) working in London found that pollen concentrations also decreased with height in an urban area, however exceptions occur according to the pollen season, individual species, pollen source, and weather conditions. For this reason it is important that the pollen sampler is placed at a level where it is exposed to pollen from a wide area. Therefore it is recommended that the sampler is placed at all sites on a roof of a building, out of the wind shadow, at a standard height above the ground. It is also recommended that the trap should be raised above the general roof level in order to avoid interference from the building itself, contamination from any roof floor level particles, and to try and expose it to an undisturbed wind flow from all directions.

3.2.2.d Pollen Counting Technique

Once the vaseline coated mellinex tape is removed from the sampler, whether it be once a week or once a day, the tape is divided into 24 hour sections each 48mm in length. It is then mounted onto microscope slides in a medium of fuschin stained glycerine jelly.

For observation, a series of single narrow traverses across the tape is taken as recommended by Kapyla and Penttinen (1981) who suggested that 12 two hourly sections should be counted at 4mm intervals. This method is used by most aerobiologists in the United States, Sweden, France and all of the Pollen UK sites as it provides a fairly accurate estimate of the daily mean concentrations and the general pattern of diurnal variation (Emberlin unpublished). Pollen is then identified under a magnification of 400 using the keys of Moore *et al* (1991) or Hyde and Adams (1958), to either generic or family level. Following this the concentration of each pollen type per cubic meter of air can be calculated for each two hour period, and this can then be averaged to give a daily pollen count for each individual taxa (British Aerobiology Federation 1994 in press).

3.2.2.e Sampling Efficiency and Sources of Error

The Hirst Automatic Volumetric Spore Trap was designed to give a high efficiency of collection. Hirst (1953) however reported that the trapping efficiency varies with wind speed and particle size because the suction rate is not altered with the wind speed to maintain isokinetic sampling. Thus because the trap is never 100% efficient the catch is always an underestimate of the actual number present. In 1952, Hirst reported that under normal conditions sampling efficiency is 100% at wind speeds of 1m/sec, but this efficiency level declines with increasing wind speed. Wind speeds in London during the pollen season generally range from 1-10m/sec with a mean of 2.1m/sec (Norris-Hill) and assuming other urban sites throughout Britain have similar wind velocities, errrors due to anisokinetic sampling are likely to be small as the wind fluctuates above and below the mean. Gregory and Hirst (1957) suggested an overall efficiency level of about 80%.

3.3 METEOROLOGICAL DATA

3.3.1 Source of Meteorological Data

Meteorological data was obtained for each individual site for all the years corresponding to the pollen data available, from either the Met Office (direct or through Rothamsted Experimental Station), or local meteorological stations (Table II).

Table II. The Distance and Direction of the Meteorological Stations from the Pollen Monitoring Site

SITE	POSITION	ALTITUDE (m)	DISTANCE FROM POLLEN SITE (km)	DIRECTION FROM POLLEN SITE
Isle of Wight	50.42N 1.18W	23	2.75	S
Taunton	51N 2.63W	18	27	SE
London (Heathrow)	51.48N 0.48W	25	21	SW
London (Rothamsted)	51.8N 0.35W	128	39	N
Cardiff	51.42N 3.2W	67	14.5	SW
Leicester	52.33N 1.11W	76	9	SW
Derby	52.93N 1.5W	95	3.3 (1969-82) 0.5 (1983-88) 0.5 (1989-94)	SW SW SW
Chester	53.05N 3.23W	210	37	SE
Preston	No Data	No Data	No Data	No Data
Belfast	54.6N 6.22W	68	17.6	NW
Edinburgh	55.85N 3.2W	184	8	S

(Continued)

Invergowrie	56.38N 2.87W	10	16	NW

The data consisted of daily records of rainfall, temperature (minimum, maximum and average and cumulated above 5.5°C), sunshine hours, wind speed, wind direction and relative humuidity. In this thesis, analysis has concentrated on rainfall and temperature as previous work has demonstrated that these variables are most important (Davies and Smith 1973b, Emberlin and Norris Hill 1991, Emberlin *et al* 1993a and 1993b).

Ideally, it would be best to have a meteorological station on the same roof as the pollen trap, however this is not always possible for economic and practical reasons, thus data from the nearest meteorological station to that particular pollen site has been used. Table II details the distance and direction of the meteorological station from each individual pollen monitoring site.

3.4 VEGETATION DATA AND POLLEN SOURCE AREA

3.4.1 Source of Land-use Information

As the analysis involves examining trends in pollen concentrations over a period of time it is particularly important to take into consideration vegetation and land-use changes over the period. Information concerning the changes in the area of grassland for the period 1960s to the 1990s has been obtained from the Agricultural Statistics for England and Wales, June Returns. More detailed information on land-use at the present time has been obtained from the Institute of Terrestrial Ecology digital Land Cover Map. This is based on a 25x25m grid in which satellite imagery over the period 1989-1992 has classified the land into 25 land cover types including built up areas, arable farm land, pastures and forestry, together with a variety of semi-natural vegetation. The Land Cover Maps for 40km and 80km radius around each site were used.

3.4.1.a The Effect of Long Distance Transport on the Pollen Catch and the Importance of Monitoring the Vegetation in the Source Areas

It is well known that pollen grains can be transported over great distances (Erdtman 1937, Bourgeois *et al* 1985) from regions where the plants are flowering to regions where flowering has not yet begun. However this long distance transport component is regarded by many as being insignificant. Faegri and Iversen (1975) suggested that 50-100km forms a natural limit for pollen dispersal and that the greatest quantities are deposited long before this limit is reached.

The long distance transport of pollen is related to the dispersal efficiency of the grain. The size and weight of a pollen grain relative to the wind speed, and the height at which it is released will determine the distance it can travel before being deposited, and also the way it is affected by the weather. Large pollen grains such as *Gramineae*, may be washed out of the air more easily by rain than smaller grains such as *Urtica* thus leading to a reduction in the daily average pollen catch. Hyde (1950) studied the influence of situation on pollen deposition at six sites throughout Britain. The sites that he considered varied according to location, being urban, rural, coastal, lowland and upland. As one would expect he found that at each site the annual pollen catch differed widely according to the surrounding vegetation. He stated that generally a catch of ≥ 50 grains/m^3 of air may be related to a source within 0.4km. If a count of ≥ 50 grains/m^3 cannot be so accounted for then its occurrence can be related to the presence of considerable stands of the source plant within 8-16km. He thus concluded that the pollen catch was largely local in origin.

Within the EAN(UK) network the sites are located at distances greater than 16km from each other. Therefore when building a model to predict the start and severity of the main pollen seasons it is important to find out over what area the model would be applicable. According to Hyde (1950) any count greater than or equal to 50 grains/m^3 of air should represent the area within a 16km radius of the trap, but what about the area extending on from this?

Lacey (1962) compared the airspora in a valley with that of an exposed site 0.6km away. She found two and a half times more grass and weed pollens (ie. *Gramineae*, *Urtica, Rumex*) in the valley site than in the exposed site, thus suggesting that the local ecology of an area was important in determining the air spora.

A similar survey was done in 1978 by Morrow Brown and Jackson. They performed a study to see whether a sampling site at Derby provided adequate data for the surrounding area. Eight identical traps were operated in 1969 at various sites up to 56km from Derby. The traps were spatially distributed around rural, urban, upland, moorland, and surburban locations. As a result of this they found that grass pollen concentrations were higher in the rural sites where grassland was close by, however there was little correlation with these concentrations and those obtained in the station at Derby. Thus Derby counts, despite providing an accurate count for Derby itself, cannot be taken as being representative of the surrounding area.

It is on the basis of the works of Hyde and future works mentioned (ie.Lacey 1962, Morrow Brown and Jackson 1978), that a detailed vegetation survey of the surrounding area for each site is essential for explaining the presence or absence and the varying trends in the pollen and spore spectra at the individual sites.

3.5 ANALYSIS OF THE POLLEN DATA

3.5.1 Nature of the Data

The pollen counts obtained from the Burkard sampler are in the form of daily average counts per cubic meter of air for each of the two taxa. This allows for analysis of both day to day and seasonal variations in the pollen count, although this thesis concentrates mostly on the latter. For the majority of the data the daily averages were from 0900 hours to 0900 hours, except at Derby for the long term data analysis when the averages were from midnight to midnight. Meteorological data in most cases was averaged from 0600 hours to 0600 hours and therefore although it does not exactly fit with the pollen data it is regarded as adequate for analysis of seasonal variations. Future, more detailed, work analysing daily variations between the sites would require a different averaging of the pollen data.

3.5.2 Definition of the Pollen Season

Annual records of daily pollen concentrations in the UK typically exhibit long periods at the beginning and end of the season when values are low. In order to overcome the bias that this may introduce to an analysis, it is necessary to eliminate these tails by defining the period when most of the pollen is released. There have been many approaches in the literature towards the statistical definition of the pollen season.

One of the earliest approaches was by Frankland and Davies (unpublished, cited in Davies and Smith 1973b) who observed that when the mean daily concentration of grass pollen grains in the air over Central London is 50 grains/m^3 of air or more, all of the patients diagnosed as being sensitive to grass pollen who visited their clinics, experienced symptoms. They described such days as 100% symptom days, and defined the start of the season as the first days when the 50 grains/m^3 threshold is reached. Although this threshold has been used by Emberlin *et al* (1993b) in London, it cannot be extrapolated throught the whole country as a means of defining the start. Many other factors need to be considered along with this definition; perhaps the most important being the synergistic effects with atmospheric pollution (Ruffin *et al* 1986, Berciano *et al* 1989, Takafuji *et al* 1989, Weeke 1989). It is well known that the pollution levels in urban areas are greater than those in rural areas, and that there are now increasing levels of certain pollutants to which large numbers of people are exposed eg. carbon monoxide, nitrogen dioxide and particulate matter. Aberg (1989) examined 55,393 men in 1971, and 57,150 men in 1981, with an average age of 18 years. He found that of this sample, 6.9% of rural dwellers showed symptoms of allergic rhinitis, as compared with 10.1% of city dwellers living in Stockholm. He concluded that continued urbanisation, leading to increased exposure to pollutants such as sulphur dioxide and particulate matter, was an adjuvant factor to allergic rhinitis. This was also suggested by Ishizaki *et al* (1987). Popp *et al* (1988) working in Austria, also found that city dwellers had a higher IgE presence than rural dwellers, and that there was an increased tendency for town dwellers to develop allergic rhinitis.

According to Frankland and Davies, a pollen count of 50 grains/m^3 of air in Central London produces symptoms in 100% of sensitive patients. This can therefore be expected to also act as a threshold value for similar urban areas however, no research has taken place into the pollen threshold value required to induce symptoms in 100% of sufferers within a rural population who are not exposed to high air pollution levels. Therefore, as the monitoring sites that are being analysed vary between rural and urban locations, it is not possible to extrapolate the 50 grains/m^3 of air threshold as being an indication of the start of the season for this study until further work has taken place.

Mullenders *et al* (1974) reported "la periode principale", which begins the day when the 5 days' running mean concentration reached at least 1% of the total annual sum on 3 consecutive days, and ended when the concentration was less than 0.9% of the total annual sum for more than 10 days. They therefore introduced the concept of the initial, the optimal and the terminal phase in pollen calendars for a given season. This method was adopted by Spieksma *et al* (1989) for their comparative study of *Alnus, Gramineae* and *Artemisia* between Central Italy and the Netherlands.

In 1981, Nilsson and Persson defined the "main pollen season" as the period between the day when the cumulation of the daily means reaches 5% of the total annual sum, until the day when it reaches 95%. This has since been adopted by Larsson *et al* (1984) who studied the incidence of *Betula, Pinus, Gramineae* and *Juniperus* pollen in Sweden, and El-Ghazaly *et al* (1993) in the comparison of airborne pollen grains in Huddinge and Stockholm.

Lejoly-Gabriel and Leuschner (1983) defined the "principal period of pollination" when comparing airborne pollen between Belgium and Switzerland, as being a period which began on the day when the cumulative count of pollen reaches 5%, provided that this day corresponds to a release of greater than or equal to 1%, and ends on the last day when the daily percentage is greater than 1%, and the sum of the percentage of this day and the preceding days is greater than or equal to 3%. This method was adopted by Frenguelli *et al* (1989) for their work on the prediction of the start of the grass and olive pollen season in Italy.

Driessen *et al* (1989,1990) were interested only in the start of the season and not the duration, and therefore they defined the season as the day on which the cumulative total pollen catch was 50, 75, 100 and 125 grains per individual species. In this way four dates were obtained and the start of the season was taken as being the mean of the four dates.

For this research, various methods of defining the start of the season were compared. These were; the sum100 and sum75 methods, that is when the cumulated sum for the daily average concentrations reaches 100 and 75 respectively (Driessen *et al* 1990), the method used by Davies and Smith (1973) as described above, and the 98% method whereby the season is deemed to have started when 1% of the total season's catch has been recorded and deemed to have finished when the 99% level has been reached. Although all of these definitions have been tested on the data all of the results are not described in the analysis. The method that proved best in describing the start of the season was the sum75 method as no retrospective data is required and therefore it is a method that can be used to predict the start of the season. However it does have disadvantages in that it is influenced by differences in the local source strengths of pollen production and therefore this must be taken into account in the analysis. Ideally, when describing the total seasonal catch, the 98% method is most suitable, however, as the analysis is mainly a comparison between sites, and that during the early stages of the development of the network sites did not necessarily start monitoring pollen at the same time, it was decided to define the total seasonal grass pollen catch as the cumulative total during the months May, June, July and August and that for birch being the cumulative total during March, April, May and June. Very little grass or birch pollen is found outside the respective periods at any of the sites and therefore this seemed to be an adequate method of defining the total seasonal pollen catch for the individual species for comparative studies.

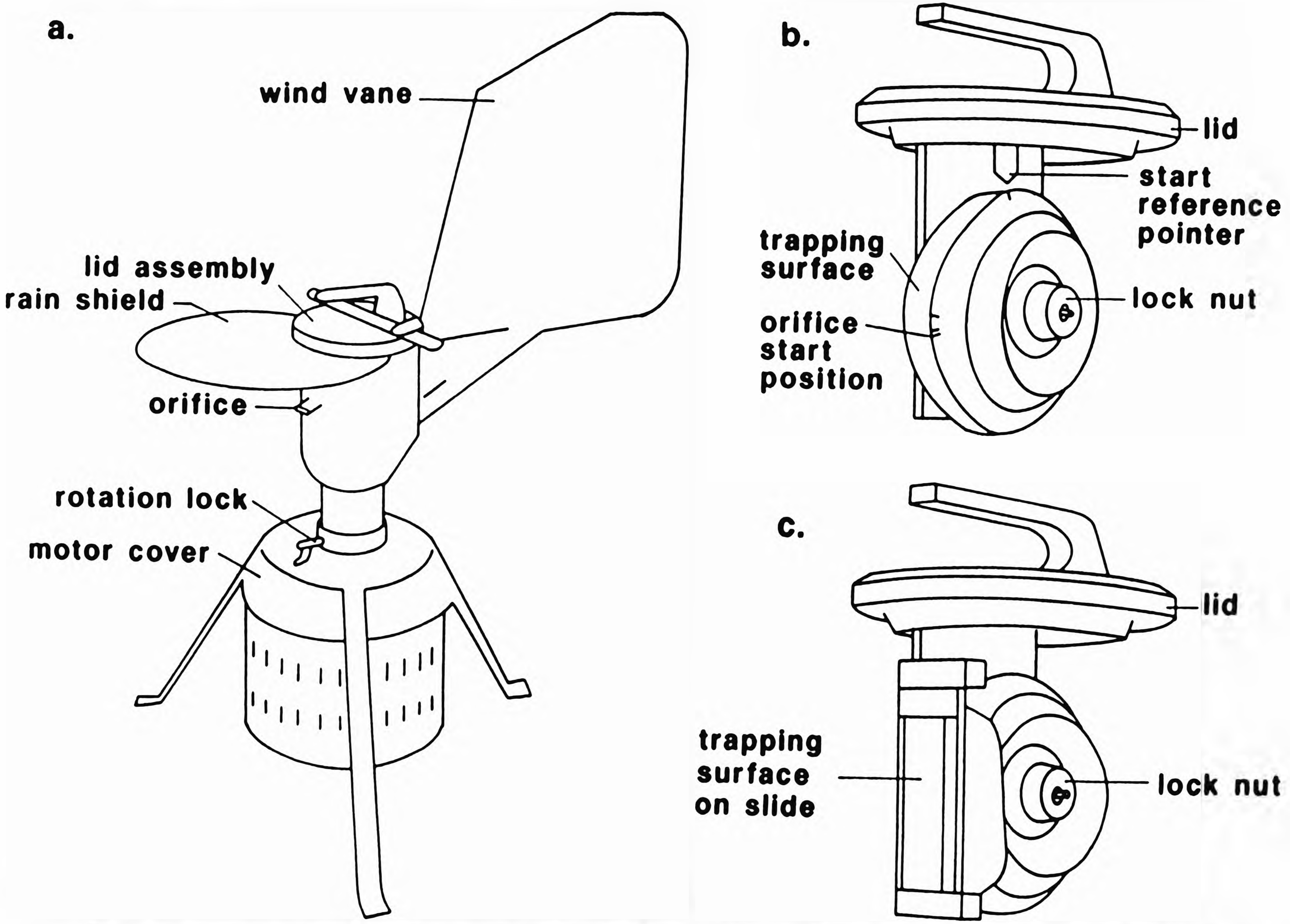
3.6 DATA ANALYSIS

The pollen data were initially displayed graphically in their raw form or as 5 year running means to determine the nature of the data and any obvious trends. Normality tests were performed on the data in order to assess the statistical method to be used. In the case of the long term data sets, where the data was not normal it was square rooted and then stepwise multiple regression analysis was used. Correlations between the start dates or total seasonal catches and the meteorological variables were calculated to identify any linear relationships. Where these linear relationships existed, the variables were incorporated into a stepwise multiple regression analysis to determine which variables provided the highest level of explanation for the observed variance. A more detailed explanation of the statistical methods used in the analysis will be found in chapter 6.

The pollen and meteorological data was stored in the University VAX mainframe computer. Analysis was performed using SPSSX, SPSSG, SPSS/PC+, MINITAB and BIOSTATS computer packages.

FIG 1

European Aeroallergen Network Sites.



The Burkard Seven Day volumetric spore trap showing (a) principal exterior parts; (b) 7-day lid assembly with drum; (c) 24-h lid assembly with slide.

FIG 2

CHAPTER 4 - COMPARATIVE ANALYSIS OF GRASS POLLEN SEASONS

4.1 INTRODUCTION

Long term trends in grass pollen concentrations have not been examined in the UK apart from at London in 1973 (Davies and Smith 1973b) and more recently in 1993 (Emberlin *et al* 1993b). These studies were based on data of 10 years and 30 years in length respectively, and their aim was to establish trends in grass pollen seasons over the period and to develop models to predict the start, length and duration of the grass pollen season in London. In the UK the grass pollen season typically lasts from the end of May through to mid August but there is considerable variation in its start date and severity.

This study is unique in that it presents an analysis of the variations and trends in the grass pollen seasons at three sites, London since 1961, Cardiff since 1962 and Derby since 1969, in relation to land use changes and the main meteorological variables. Using this information predictive models were built for the start and severity of the season in an attempt to develop reliable methods of forecasting (chapter 6). The second aspect of this chapter concerns the analysis of a larger number of sites which have records of *Gramineae* pollen ranging from one to eight years in length (1987-1994). Variations in the grass pollen seasons were determined between the sites in order to ascertain a pattern in the season in relation to geographical location, vegetation and climate. London, Cardiff and Derby data from 1987 has also been included in the analysis in order to increase the geographical range of the sites.

The major sources of pollen from the *Gramineae* family are rural areas around each site but there is also a notable contribution from parks, gardens, grass verges and wasteland areas close to each site.

The total grass pollen catch for the season is defined as the total amount of grass pollen recorded during the period May to August. Grass pollen is very rarely recorded outside these months and any pollen recorded is omitted from this analysis in order to avoid distortion through localised flowering at the start of the season, and resuspension at the end.

The start of the season was defined by the sum75 method (discussed in chapter

3) whereby the start of the season is defined as the first day when the cumulative daily count reaches 75 grains. This method of definition is useful in that it allows for the forecasting of the start of the season without the need for retrospective data, however one drawback is that it is clearly influenced by the abundance of local grasses.

4.2 A COMPARATIVE ANALYSIS OF LONG TERM RECORDS OF GRASS POLLEN CONCENTRATIONS AT THREE SITES IN THE UNITED KINGDOM

4.2.1 METHODS AND SITE DETAILS

Details for the overall pollen monitoring techniques employed and brief information concerning London, Cardiff and Derby has been provided in chapter 3, a more detailed site description follows.

4.2.1.a London

The pollen data for the period 1961 to 1990 was collected at St Mary's Hospital in Paddington. Monitoring has since stopped at this site, and although data was available from the University of North London site, it was decided that the data set was of sufficient length to be able to avoid incorporating data from another site.

Two sets of meteorological data were used in the analysis. Daily records of the climatic variables from Heathrow, 21km west of the pollen monitoring site were used to indicate urban conditions. A second meteorological site at Rothamsted Experimental Station, Harpenden, located approximately 39km north of the pollen monitoring site was used to represent climatic conditions in the rural source area.

4.2.1.b Cardiff

The pollen data for the period 1962 to 1993 has been collected continuously on the roof of the Biological Sciences Department, University College, Cathays Park, Cardiff.

Meteorological data has been obtained from Cardiff Rhoose, 14.5km south west of the pollen monitoring station.

4.2.1.c Derby

At Derby, the location of the monitoring site changed three times during the period 1969-1993. For the period;

- 1969-1982, the pollen trap was on the roof of the Derby Chest Clinic, located 3km from the nearest rural area and 3.3km from the meteorological station.
- 1983-1988, the pollen trap was moved to the roof of the Greyhound Stadium, 2km from the nearest rural area and 0.5km from the nearest meteorological station
- 1989-present, pollen monitoring has taken place at the Derby College of Higher Education, Mickleover, 1km from the nearest rural area and 0.5km from the meteorological station.

The pollen sites for the period 1969-1988 were within 1km from the city centre, and the present site is 3.9km south west of the city centre (Corden and Millington 1991).

Analysis of variance between the pollen data at the three sites showed no significant differences, therefore the data set has been treated as one population for the analysis.

4.2.1.d Vegetation Data

Information about changes in grassland area around the sites is available for the period 1961-1993 from the Agricultural Statistics for England and Wales, June Returns.

4.2.2 START OF THE SEASON

4.2.2.a London

The grass pollen season in London for the period 1961-1990 usually started at the end of May (mean start date according to sum75 method was May 31st). The range in the difference in start date for the period 1961-1990 was 39 days (Fig 3). Early start dates were characteristic of the 1960s although there was no evidence of warmer spring temperatures during this period. Later start dates were characteristic of the 1980s when springs tended to be cooler eg. 1981 and 1984 which experienced more than two spring months with below average mean temperatures along with wetter than average Mays.

The earliest start was in 1965 at 126 days from January 1st. This was after a relatively cool start to the spring with temperatures in January, February and March 0.5°C, 1.1°C and 0.2°C below the average for the period 1961-1990. Temperatures did however increase slightly, with April and May experiencing mean temperatures 0.1°C and 0.2°C above the normal. The spring of 1965 had average to below average rainfall, particularly in May with only 78% of average rainfall.

The latest start to the season was in 1984 at 165 days from January 1st. The spring of 1984 had above average mean monthly temperatures in every month except May, when temperatures were 1.7°C below the period average. In this year, the main influencing factor concerning the late start to the season is likely to be the amount of rainfall in the preseason period. January and March experienced above average rainfall. April was a dry month with only 12% of average rainfall which may have delayed grass development. This was then followed by May which experienced 183% of normal rainfall, which in combination with cool temperatures, hindered pollen release.

Examination of the 5 year running means in start dates (Fig 4) indicates a trend towards later start dates, particularly since the mid 1960s. Analysis of variance conducted on the results for individual decades shows that the data set for the 1960s is significantly different from that of the 1970s and 1980s, although these two are similar. This is particularly important when trying to build predictive models based on the data (chapter 6). By the sum75 method, the average start date in the 1960s was 145 days from January 1st, whereas it was 154 in the 1970s and 156 in the 1980s.

The cumulated temperatures above 5.5°C (this being considered the threshold temperature for the growth of grasses, Liem 1980) were calculated from January 1st through to the end of May for the two meteorological stations. The average cumulated temperatures for this part of the year were compared for each decade. There was a very slight increase in cumulated temperatures, for example at Heathrow it increased from 416 day°C in the 1960s to 433 day°C in the 1980s.

It can be surmised that the trend towards later start dates for the grass pollen season is not a function of a climatic shift. A trend towards warmer springs would encourage earlier start dates, not later ones. It is reasonable to suppose that the later starts derive from a combination of lower pollen abundance and a change in the species spectrum towards later flowering types (See section 4.2.2.d).

4.2.2.b Cardiff

The mean start date (sum75 method) for the grass pollen season at Cardiff was much earlier than that at London, being 139 days from January 1st ie. May 19th as compared with May 31st. The range in the difference in start dates for the period 1962-1993 was 37 days (Fig 5). From the raw start date data, unlike London, early starts were not characteristic of any particular decade. Early starts were in 1963, 1974, 1976, 1980, 1984, 1991 and 1993. These years all had relatively warm springs, particularly April, and were also quite dry. The earliest starts of the 32 year period were in 1980 and 1993 at 124 days from January 1st. Mean monthly temperatures in the preseason months during these two years were above average (February 2.4°C and 1.1°C, April 1.1°C and 1.6°C, May 0.3°C and 0.4°C respectively above the period average 1962-1992), and rainfall in May was 63% and 81% of normal.

Late starts appeared to dominate the 1960s and mid 1980s. These tended to be characteristic of years which experienced cool, dry springs with few months having mean temperatures above average. The latest start was in 1962 at 161 days from January 1st. March, April and May all experienced below average temperatures at 3.0°C, 0.2°C and 1.4°C respectively below the period average. Rainfall during these months was also below average at 76%, 97% and 80%.

Examination of the 5 year running means of start dates (Fig 6) shows a weak trend towards an earlier start to the season, although start dates in the 1970s were much earlier than those in the early 1980s. The average start date in the 1960s was 144 days from January 1st, whereas it was 136 in the 1970s and 140 in the 1980s, thus highlighting a fluctuating, but overall trend towards earlier start dates.

Cumulated temperatures above 5.5°C were calculated from January to the end of May. In a similar way to the London analysis, the average cumulated temperatures for each decade were compared. There was an increase in cumulated temperatures through the decades from 313 day°C in the 1960s, to 328 day°C in the 1970s, to 342 day°C in the 1980s.

Overall, the rise in cumulated temperatures and the trend towards earlier starts dates could suggest that the trend towards earlier start dates is simply a function of a climatic shift towards warmer springs. However, despite this, from the evidence provided by the 5 year running means (Fig 6), earliest starts were more characteristic of the 1970s, even though cumulative temperatures were higher in the 1980s, and therefore it is reasonable to suggest that earlier starts derive from a combination of increasing cumulative temperatures and increasing pollen abundance (Table IV).

4.2.2.c Derby

The mean start date (sum75 method) at Derby for the period 1961-1993 was 148 days from January 1st, ie. 28th May. The range in difference in start dates was 25 days (Fig 7).

Early start dates were particularly characteristic of the mid 1980s and the early 1990s. This period experienced mean monthly spring temperatures above the period average (1969-1992), and below average rainfall in May. The earliest start was in 1989 at 133 days from January 1st. This year was characterised by a warm January, February, March and May with temperatures 2.2°C, 2.1°C, 1.6°C and 2.0°C respectively above the long term average. Also, apart from April, precipitation during the spring was below average, particularly in May with only 47% rainfall, thus providing good conditions for pollen production and early release.

Late starts to the season occurred in 1972, 1979, 1984 and 1986. Apart from in 1972, all of these years had below average or average mean monthly temperatures in the period January to May. The latest starts were in 1972 and 1986 at 158 days from January 1st. In 1972 weather conditions in the spring were near normal with above average temperatures in all months apart from January and May, and average to below average rainfall. This therefore suggests that there was something other than mean temperatures and rainfall influencing the start of the season. Weather conditions in 1986 were more characteristic of a late starting year with cool temperatures (January 1.3°C, February 4.7°C, March 1.3°C, April 2.4°C and May 0.8°C below the period average) and above average precipitation in the spring, particularly in May when 209% of the normal fell, thus hindering early pollen release.

The 5 year running means of start dates show a tendency towards earlier start dates, this is most pronounced from the mid 1980s (Fig 8). Analysis of the mean cumulated temperatures above 5.5°C calculated from January to the end of May for each decade, show a trend towards a warming from 341 day°C in the 1970s to 361 day°C in the 1980s.

It can be suggested that the trend towards earlier start dates is a function of a combination of a climatic shift towards warmer springs and drier Mays, and an increasing pollen abundance (Table V).

4.2.2.d Discussion

From the above analysis it can be seen that the start of the grass pollen season at the individual sites responds to different variables. All of the sites respond in a similar way to warm and dry springs resulting in early starts to the season, however late starts at London tend to be characteristic of years with wet Mays, late starts at Cardiff are characteristic of cool and dry springs, and late starts at Derby are characteristic of cool, wet springs. There is also a difference in the trend in start dates at the sites, London showing a distinct trend towards later start dates, and Cardiff and Derby showing a weak trend towards earlier start dates, particularly since the mid 1980s and early 1990s.

The analysis of the mean cumulative temperatures above 5.5°C for the decades show those at London to be higher than those at Derby which are higher than those at Cardiff. Despite this, the season tends to start first in Cardiff (mean start date 19th May), then in Derby (mean start date 28th May) and finally in London (mean start date 31st May).

Various species of grass have different phenologies and have a varied response to environmental factors (Chapman 1990). Spikelet emergence in rye grass (*Lolium* species) is dependent on photoperiod, but the rate of elongation of the fertile shoot and the development of the inflorescence are controlled mainly by the temperature from March onwards (Beddows 1968). Other species exhibit a closer relationship to temperature during the spring, being responsive to thermal time irrespective of daylight. Therefore, as a result of the great number of species within the source area, and also their varied response to environmental factors it is difficult to determine which environmental factors have the greater influence on the start of the season (Emberlin *et al* 1993b).

From these results it can be surmised that the trend in the start of the season in London is not a function of a climatic shift, but a function of declining pollen abundance and a change in the species spectrum. The trend in start dates at Cardiff and Derby is likely to be a function of the combination of increasing spring temperatures and decreasing May rainfall and increasing pollen abundance.

4.2.3 SEVERITY OF THE SEASON

4.2.3.a London

There is a distinct overall trend of a decrease in the total cumulative daily average count over the period (1961-1990) (Fig 9). This decrease is most pronounced in the 1960s but is sustained through the 1970s and early 1980s.

Annual sums of daily average *Gramineae* pollen counts range from 8210 grains in 1964 to 940 grains in 1981 (Fig 10). In 1964 the spring was cooler than the period average, but temperatures in April, May and July were 0.1°C, 2.2°C and 0.4°C above the period average. Rainfall in July was only 44% of normal and this in combination with warmer temperatures sustained the production and dispersal of pollen. Apart from March, the spring months of 1981 experienced below average temperatures and 209% of rainfall in May, thus delaying the start to the season and hence retarding the release of pollen. Rainfall in June was low (26%) and this in combination with temperatures 1.3°C below normal lead to a low overall annual pollen sum.

In most years totals for June exceed those for July, but exceptions occurred as in 1972 and 1977, when cool, wet weather featured in June (lowest monthly mean temperatures for June in the data set).

The pollen count record shows a decline in the number of 'peak' days per season, that is the number of days on which daily average concentrations exceeded 'high' thresholds. These were set subjectively for this analysis at 50, 100 and 150 grains/m^3 of air (Fig 11). The most marked decrease in the severity of the season occurred in the 1980s which experienced only 29 days with counts over 150 grains/m^3 of air, compared with 59 days in the 1970s and 81 days in the 1960s. There is no evidence from the meteorological records of factors which would account for this trend, in fact, there is a trend towards warmer springs in the 1980s which would give rise to increased severity.

The decrease in the annual totals of grass pollen counts seems to be related directly to land use changes. Evidence from the Agricultural Statistics June returns (Table III) shows a substantial decrease in the areas of grassland in all regions around the conurbation with an overall decrease of 35.4% over the 30 year period. The greatest rates of change occurred in the 1960s, levelling off through the next two decades.

Table III. The Change in the Area of Grassland Around London 1961-1990 (Total area of grassland in acres)

REGION	1961	1970	1980	1990	% CHANGE
North West (Bucks and 1/2 Herts)	231,406	187,928	159,094	148,284	- 35.9
North East (Essex and 1/2 Herts)	202,294	137,516	117,024	101,442	- 49.9
South West (Hamps and Surrey)	324,761	223,559	216,658	227,033	- 30.1
South East (Kent)	239,732	203,160	181,278	167,758	- 30.1
TOTAL	998,193	752,163	674,054	644,517	- 35.4

Source: Agricultural Statistics for England and Wales, June Returns 1961/62, 1970, 1980, 1990

4.2.3.b Cardiff

The range in differences in annual grass pollen totals extends from 12,407 grains in 1971 to 2190 grains in 1976 (Fig 12). The spring of 1971 had average to above average mean monthly temperatures, and 230% of rainfall in June, which would lead one to expect an average to below average total pollen sum. On the other hand, the spring of 1976 experienced above average temperatures in all months except March and only 48% of average rainfall in June and 28% of average rainfall in July, perfect conditions for pollen production and dispersal. Despite this 1976 experienced the lowest total pollen sum of the study period (1962-1993). Analysis of the springs of other years with particularly high or low annual grass pollen sums did not provide evidence for the influence of temperature on the total pollen sum. This therefore suggests that other factors despite mean monthly temperatures and total monthly rainfall influenced the severity of the pollen season, and that explanations should be sought through the analysis of the variation in wind direction varying the size of the source area thus influencing the total catch. Alternatively, the monthly aggregated variables could be too crude to provide an explanation, and maybe analysis should focus on breaking the aggregated periods down further (see chapter 6).

In most years totals for June exceeded those for July except in for example, 1972 and 1985. All of the years in which totals for July exceeded those for June experienced mean June temperatures below the long term average.

There is a fluctuation in the total cumulative daily grass pollen counts over the three decades. In the 1960s there was an increase in the grass pollen catch, this declined in the 1970s and then rose again in the 1980s (Fig 13). This does not follow exactly the trend in total grassland area which fell in the period 1960-1970, almost doubled during the period 1970-1980 and since then has remained steady (Table IV).

Table IV. The Change in the Area of Grassland Around Cardiff 1961-1990 (Total area of grassland in acres)

REGION	1961	1970	1980	1990	% CHANGE
Glamorgan (Mid, South and West)	298,552	222,267	246,701	238,426	- 20.3
Gwent (Monmouth)	200,019	162,248	176,965	174,778	- 12.7
Powys (Brecon)	366,565	193,945	854,670	857,043	+ 57.3
TOTAL	865,136	578,460	1,272,040	1,270,247	+ 31.9

Source: Agricultural Statistics for England and Wales, June Returns 1961/62, 1970, 1980, 1990

(NB. Names of counties have changed over the period, but the area enclosed within them has remained the same)

The problem however with relating the area of grassland to the pollen catch is that the area of grassland is based on county boundaries, and therefore, unlike the more recently available LANDSAT maps based on 1km grid squares around a circular radius for each site, the county boundaries were selected according to their proximity to the monitoring station. At Cardiff the site is within Glamorgan and surrounded by Gwent, Powys and the Bristol Channel. Hence grassland data from counties such as Devon, Somerset and Cornwall on the other side of the Channel were not included. Assuming that the most common wind is the south westerly then grass pollen from these counties would also contribute to the annual grass pollen sum in Cardiff, and this is possibly the reason why grass pollen totals do not relate as closely to the rises and falls in grassland area as much as they do at London where all of the surrounding counties were included in the grassland figures.

The severity of the grass pollen season has followed the trend of the annual sums. The 1960s had 129 days with counts over 150 grains/m^3 of air, there were 99 days in the 1970s, and 147 days in the 1980s (Fig 14).

4.2.3.c Derby

There was a slight decline in the total cumulative daily average grass pollen counts over the period (1969-1992) (Fig 15). The decline was not as smooth as in London, as there was a trend for counts to increase from 1969 to 1975, but then decline from 1975. The grass pollen totals tends to be reflect land use changes in that, like the grass pollen totals, there has been little change, although there was a slight increase during the period 1969-1980, and then a decline 1980-1990 (Table V).

Table V. The Change in the Area of Grassland around Derby 1969-1990 (Total area of grassland in acres)

REGION	1969	1980	1990	%CHANGE
Derbyshire	358,273	365,076	350,268	- 2.0
Nottinghamshire	97,405	108,685	84,578	- 13
Staffordshire	293,289	339,008	333,205	+ 12
Leicestershire	193,009	246,190	214,165	+ 10
TOTAL	942,076	1,058,959	982,216	+ 4

Source: Agricultural Statistics for England and Wales, June Returns 1969, 1980, 1990

The range of differences in totals extended from 9515 grains in 1976 to 2818 grains in 1990 (Fig 16). Mean monthly temperatures in the spring of 1976 were above average in every month except March. May, June and July were particularly warm with temperatures 0.6°C, 3.2°C and 2.2°C above the period average. The spring was also exceptionally dry with 41%, 48%, 17%, 88%, 15% and 37% of average rainfall in February, March, April, May, June and July respectively, thus providing warm temperatures for pollen production, and exceptionally warm temperatures and dry conditions for pollen release in June and July. The lowest annual sum for the period was experienced in 1990 and this year was characterised by above average spring temperatures, except for June and July which were slightly below average, and below average to average rainfall. As a result of warm spring temperatures and low rainfall, one would have expected a higher annual grass pollen sum. In 1990, however, the low annual pollen sum may have been a result of drought conditions in the period leading up to the grass pollen season, which would have caused the grass to stop growing. The results of 1990 highlight the fact that the relationships between the meteorological variables and the pollen data are complex and this therefore can lead to problems in forecasting the characteristics of pollen seasons (see chapter 6).

Totals for July exceeded those for June in a greater number of years than for

London and Cardiff. In each of these years mean temperatures for June were below the long term average.

Following the trend in grass pollen totals, there was a decline in the severity of the season. 147 days in the 1970s decade experienced counts over 150 grains/m^3 of air, as compared with 126 days in the 1980s (Fig 17).

4.2.3.d Discussion

The years with the 5 highest total pollen counts were compared at each site in order to see if there was any synchronisation in total pollen counts. None of the 5 years for each site fell on the same year. The only year that was a high pollen producing year for London and Cardiff was 1971, however Derby did not have a particularly high pollen catch that year. This highlights the variation in the influence of meteorological and other variables between the sites from year to year and thus the need for different forecast models at the individual sites, rather than one universal model for the entire country.

From the above analysis it can be seen that concentrations of grass pollen vary from site to site, as do trends in total cumulative daily counts over the 24-32 year period. Derby and London have seen a decline in the annual total grass pollen catch over the period, and the total pollen catch at Cardiff has been more varied. The trends in the decline in grass pollen at London and Derby follow the trends in the decline in grassland area around the two sites, however the fluctuation in the total cumulative grass pollen catch at Cardiff does not follow fluctuations in the acreage of grassland in the surrounding area, possibly highlighting the importance of long distance transported pollen.

The decline in grassland area around London does not account fully for the decline in the pollen catch at London, and neither does the increase in grassland area at Derby account for decrease in the pollen catch. A number of contributing factors are important here. There has recently been a change in agricultural practice from haymaking in the 1960s to silage production in the 1970s whereby grasses are cut before they flower. At the same time there has been a change in the seed mix of sown pastures from species such as *Dactylis glomerata*, which produce abundant pollen, to species such as *Lolium perenne* which produce less (Emberlin *et al* 1993b).

In the south east the rates of decline in grassland areas may have decreased through the 1980s as a result of set aside and the prevalence of uncut verges, although it is unlikely that this would have made a notable influence on the total pollen catch as set aside was not introduced into the UK until 1988 and not made compulsory until 1991 (Mr O'Neil, personal communication, MAFF).

For the London site it is possible that there has been a greater rate of a decline in the total pollen catch due to the growth of towns in the London area. During the period since 1961, peripheral development on the urban fringe of London has largely been prevented by the green belt policy. However, building development beyond a distance of 24km from London has reduced the agricultural area (Clout and Wood 1986).

Air pollution may also have contributed to the decline in the total grass pollen catch. During the 3 decades studied (particularly in London), air pollution concentrations have changed notably. Some types, including ozone and nitrogen dioxide, have increased substantially because of the increase in vehicle exhaust emissions (Department of Transport 1991). Evidence suggests that pollution in vehicle exhaust pollutants induce growth stress on plants and that this may decrease pollen production in grasses (Mansfield 1976).

4.3. VARIATION IN THE GRASS POLLEN SEASON AT EAN(UK) SITES 1987-1994

4.3.1 METHODS AND SITE DETAILS

Five of the sites in this study have operated for many years, but six started monitoring more recently. Monitoring techniques, pollen and meteorological site details have been given in chapter 3. Since 1990 all sites have started sampling by May 1st. Prior to this sampling started at different dates during May. For this reason the start of the grass pollen season has been defined by the sum75 method calculated from the results for May 18th onwards for 1987-1989 as by this date the majority of the sites had started monitoring grass pollen, and May 1st onwards for 1990-1994. The start dates can be compared within each year, but not between years unless this is done within the subsets 1987-1989 and 1990-1994.

Land use figures for the percentage of grassland in the area surrounding each site have been obtained from the Institute of Terrestrial Ecology Land Cover Map (Table VI).

Grassland is defined as grass heath, moorland, mown grass, meadow, rough grazing, felled forest, open shrub moor, dense shrub moor and arable land. The data was collected during the period 1989-1992 and therefore is relevant to the period of this study. The amount of pollen produced by each species of grass varies, for example meadow and pasture species (eg. *Festuca rubra, Poa annua*) produce larger amounts of pollen than moorland species (eg.*Phleum alpina, Molinia caerulea*), partly as a result of the different physiology of species that grow in moorland areas, and partly as a result of increased rainfall on higher relief suppressing the release of pollen. Although, therefore, the grassland figures taken from a 40km and 80km radius around each site cannot be directly related to the total seasonal grass pollen catches at the individual sites, they do provide a good indication of the amount of grassland in the surrounding areas to be used as a comparison between the sites.

Table VI. The Percentage of Grassland in the Area Surrounding Each EAN(UK) Site

SITE	40km RADIUS (%)	80km RADIUS (%)
Isle of Wight	25	37.5
London	58.2	74.3
Taunton	50.6	67.5
Cardiff	78	62.6
Leicester	82.4	82.7
Derby	85.5	86.5
Chester	74	67.2
Preston	63.1	57.5
Edinburgh	70.7	69.2
Invergowrie	59.5	53.4

(Data supplied by the ITE Landsat Land Cover Map of Great Britain, Figs for 1989-1992) Data for Belfast unavailable.

4.3.2 START OF THE SEASON

4.3.2.a Variation at Individual Sites

Dates for the start of the grass pollen season at individual sites varied widely between different years (Table VII and Table VIII), although differences were greater at some sites than others. The results at London, for example, show more variation than those for Cardiff in both of the data sub sets.

Table VII. Start Dates for the Grass Pollen Season at Five EAN(UK) Sites 1987-1989 (Sum75 method)

SITE	1987	1988	1989
Isle of Wight	167	147	139
London	156	153	140
Cardiff	141	142	141
Derby	172	160	153
Edinburgh		159	147

Table VIII. Start Dates for the Grass Pollen Season at Eleven EAN(UK) Sites 1990-1994 (Sum75 method)

SITE	1990	1991	1992	1993	1994
Isle of Wight	138	143	138	135	130
Taunton				136	148
London	139	166	154	143	156
Cardiff	137	144	140	127	139
Leicester	139	132	145	154	136
Derby	147	153	145	142	135
Chester				144	145
Preston			138	142	145
Belfast			139	158	164
Edinburgh	156	171	149	156	159
Invergowrie			160	157	163

The monthly cumulative temperatures were compiled to spring and early summer totals using the figures from results of February through to the end of May. This period was selected as previous work by Davies and Smith (1973b) and Emberlin *et al* (1993b) had suggested the importance of spring and early summer temperatures on the start of the season. None of the sites showed a significant correlation between start dates and cumulative temperatures.

No overall trends were discernible in the relationship between start dates and preseasonal total precipitation although there was a tendency towards a positive correlation, however the only site where this proved to be significant was at Cardiff ($r=0.697$, $p<0.05$). There was a varied response to precipitation during May (ie. at the time of anthesis). The only significant correlation was found at the Isle of Wight where again there was a positive correlation (r=0.63, p=0.1).

4.3.2.b Variation between Sites

When examining the sequence of start dates, data for more than 5 years is available only for five sites, all of the other sites have data for 5 years or less. Among these, seasons start first most frequently at the Isle of Wight and Cardiff (Table VII and Table VIII). Lag times for the start of the season at the individual sites vary from 14 days to 31 days in the 1987-1989 subset, starting in either Cardiff or the Isle of Wight and the latest start being reached in Derby in all three years. In the 1990-1994 subset the lag times vary from 19 days in 1990 to 39 days in 1991. Generally, longer lag times occur in cooler years. In 1990, which had the warmest spring at all sites with mean temperatures and cumulative temperatures above average in all months, lag times were comparatively short. In comparison 1991, with cumulative and monthly temperatures below average at all sites, the lag times were much longer.

In 1992, the first year with a full geographical range of results, the season started at the south and westerly sites almost simultaneously. There was only a short lag time to start dates at sites in the Midlands, but then a further two weeks before the start in north east Scotland. These patterns show a close relationship to cumulative temperatures above 5.5°C at the different sites with those at the Isle of Wight being 501.4 day°C for the period February to the end of May, and those at Invergowrie being 287.8 day°C. The only exception is that in 1992 cumulative temperatures were higher at Derby than at Cardiff and Belfast despite the season starting earlier at these sites. A similar relationship was not found in 1993 or 1994 when the there was a more sporadic start to the season at the individual sites, and cumulative temperatures for example, in 1993 were greater at the Isle of Wight, Taunton, Derby and Chester than at Cardiff, despite it having an earlier start to the season.

Derby and Leicester sites are 37km apart, Leicester being the more southern site. In some years, for example 1992 and 1994, the seasons start very close to each other at both sites. There are, however, years when there is a great difference in start dates. Leicester tends to have earlier start dates than Derby, despite Derby having higher cumulative spring temperatures. A possible explanation for the generally earlier starts at Leicester compared with Derby is that the trap is at a higher level and therefore it may catch pollen from further afield where the season has already started rather than just monitoring the local area.

4.3.3. SEVERITY OF THE SEASON

4.3.3.a Variation at and between Individual Sites

The total pollen catch and severity of the grass pollen season varies from year to year and from site to site (Table IX).

Certain similarities can be found between the seasons, however no two seasons are identical over the eight year period. As an example of the variation, grass pollen annual sums ranged from 2495 to 4048 grains at Leicester, and 5030 to 11619 grains at Cardiff despite Leicester having a higher percentage of grassland in its surrounding area (Table VI and Table IX).

Table IX. Total Grass Pollen Counts at the EAN(UK) Sites 1987-1994

SITE	1987	1988	1989	1990	1991	1992	1993	1994
Isle of Wight	767	5753	6761	6012	1612	6682	6508	6150
Taunton							3848	3103
London	4249	2716	2025	2211	1122	1643	1997	1607
Cardiff	9071	6579	11619	5848	5030	10775	7130	5225
Leicester				3199	3168	3314	2495	4048
Derby	4033	3906	4994	2796	3259	4824	5919	5564
Chester							3287	1952
Preston						7661	5224	6004
Belfast						3159	2079	2650
Edinburgh		1812	4557	2616	1476	2325	2108	2232
Invergowrie						1820	1324	1861

NB. Results for the Isle of Wight during 1987 have been omitted from the analysis as pollen was monitored in this year using a Rotherham trap, and hence the results are not comparable.

The higher annual sums at Cardiff than at many other of the sites, despite the lower percentage grassland cover, could be a result of the type of grassland species, being a species that produces more pollen (See 4.3.1), or alternatively it could be a result of different farming practices, for example. resulting in the production of less silage. A further factor could be that the climate in the South Wales coastal area, being moist and under the influence of the warming North Atlantic Drift, may be ideal for the healthy development of grasses to their full potential, and thus producing an increase in the production of pollen within the individual flowers. Therefore it is likely to be a combination of climatological and physiological factors.

Concentrating on the five sites with the longest records, three of the sites the Isle of Wight, Cardiff and Edinburgh, experienced their highest total pollen catch in 1989. 1989 was a year with a very warm and wet spring which lead onto one of the driest Mays on record in many parts of the country (Whittakers Almanack 1991). June and July continued to be dry at all three sites with rainfall levels well below average at all three sites. The sites also experienced the greatest number of days with counts ≥ 50 grains/m^3 of air (Table X).

Table X. The Number of Days at the EAN(UK) Sites with a Grass Pollen Count of ≥ 50 grains/m^3 of air

SITE	1987	1988	1989	1990	1991	1992	1993	1994
Isle of Wight	5	28	48	41	21	32	34	37
Taunton							25	21
London	28	16	15	19	5	9	13	6
Cardiff	36	22	47	30	28	38	36	36
Leicester				21	17	20	21	26
Derby	20	21	29	23	23	26	32	30
Chester							20	9
Preston						34	30	32
Belfast						18	8	17
Edinburgh		8	31	16	7	15	11	18
Invergowrie						11	4	9

The total seasonal catch for the individual years was correlated with cumulative temperatures above 5.5°C, June rainfall and July rainfall. There was no significant relationship between the total seasonal catch and any of the variables, except at the Isle of Wight where there was a negative correlation with June rainfall ($r=-0.931$, $p>0.001$), in London where there was a negative correlation with spring cumulative temperatures ($r=-0.656$, $p>0.05$), and in Edinburgh where there was a negative correlation between the annual grass pollen sum and precipitation in July ($r=-0.628$, $p=0.1$). This highlights the varying importance of the variables at the different sites.

In 1992 the grass pollen season was relatively severe with Cardiff, the Isle of Wight and Leicester experiencing their second highest total seasonal catch. The spring of 1992 was similar to that of 1989, being warm and wet and followed by a warm and dry May and June. One of the main differences from 1989 was that in July temperatures fell and the summer was generally wet and dull. Over two thirds of the total grass pollen catch was released in June. In comparison with 1989 there were fewer days with counts ≥ 50 grains/m^3 of air thus indicating that the season was less severe than in 1989.

In 1991 all of the sites experienced their lowest or second lowest total seasonal catch of the eight year period. The spring of 1991 began in the same way as 1989 and 1992, being wet and warm, however May was a very cool and dry month. Temperatures continued to fall below average in June and it was also very wet, for example Edinburgh experienced 114% of average rainfall, Derby 153%, Leicester 137%, Cardiff 190%, the Isle of Wight 246% and London 185%. As a result of this the majority of the seasons grass pollen was released in July. Many of the sites also experienced the fewest number of days with counts ≥ 50 grains/m^3 of air, thus indicating that 1991 was one of the mildest seasons of the eight year period.

When considering the severity of the grass pollen season it is also important to analyse the cumulative curve. As mentioned previously (section 4.3.1), due to variations in the start of monitoring dates at the sites, the years 1987-1989 and 1990-1994 are considered separately. Of the period 1987-1989 the cumulative curve rose most steeply in 1988 with an average of only 44 days between the start of monitoring date and 75% of the total seasonal catch being reached. At the four most southerly sites more than 78% of the total seasonal catch was released in June, and the average time period between 25% of the total and 75% of the total being reached was 12 days, thus the majority of pollen was released over a very short time period.

Of the period 1990-1994, the cumulative curve rose most steeply in 1992 with an average of 62 days between the start of monitoring date and 75% of the total being reached. There was an average of 17 days between 25% and 75% of the total being reached, however the lag time at Belfast, Invergowrie and London was more than 20 days, and consequently at the other times the lag was much shorter. This, coupled with the fact that most sites experienced comparatively high annual totals, indicates that the 1992 season, although having lower overall totals and fewer days with counts ≥ 50 grains/m^3 of air, would have lead to allergic patients experiencing as severe symptoms as were experienced in 1989, due to the high concentration of pollen released over a short period of time.

4.3.3.b Variation in Seasonal Totals and Severity between Urban and Rural Sites

One of the earliest papers to identify variations in the seasonal catch at urban and rural sites was by Morrow Brown and Jackson in 1978 (as discussed in 2.4). They examined grass and nettle pollen concentrations using 8 identical modified Burkard traps within a 60km radius of Derby, located within different land use areas. The total catch at rural sites was well correlated with each site, but no correlation was found in the total catch between rural and urban sites.

For this study, sites were categorised into 'rural' and 'urban'. The amount of grassland in the area surrounding each site was used to clarify sites as being rural or urban. Urban sites were defined as having less than or equal to 60% grassland in a 40km radius around the site, rural sites were defined as having more than this.

The total seasonal catches were averaged over the monitoring period, and the average for each category ie. 'rural' and 'urban' was calculated (Table XI). Data for Belfast was unavailable.

When the average total seasonal catch for each site was analysed along with the area of grassland data, a positive correlation was found between sites with large grassland source areas ('rural areas') and high total seasonal catches, and a large number of days experiencing counts of ≥ 50 grains/m^3 of air, however there were exceptions. The Isle of Wight has a relatively small grassland source area but a high average total grass pollen catch over the period. Chester, although having a large pollen source area has a relatively low average total pollen catch, but this could be because only two years data were available.

The results therefore show that sites with a larger percentage of grassland in the surrounding area (ie. categorised as being 'rural') have a higher total grass pollen catch than 'urban' sites, and a greater number of days with counts ≥ 50 grains/m^3 of air.

Table XI. Categorisation of 'Urban' and 'Rural' Sites Within EAN(UK)

Category	Site	% Grassland in source area	Average Total grass pollen count 1987-1994	Average no. of days with >50 grains/m^3 of air
RURAL	Derby	85.5	4412	26
	Leicester	82.4	2648	21
	Cardiff	78	7660	34
	Chester	74	2620	15
	Edinburgh	70.7	2447	15
	Preston	63.1	6296	32
Average for Category			**4347**	**24**
URBAN	Invergowrie	59.5	1669	8
	London	58.2	2196	14
	Taunton	50.6	3476	23
	Isle of Wight	25	5640	34
Average for Category			**3245**	**20**

4.3.4. DISCUSSION

Analysis of the variation in the start and severity of the grass pollen season at the EAN(UK) sites has highlighted many problems. Firstly problems occur when trying to compare seasons at the different sites due to variations in the local vegetation, height of the traps, and local climates. Ideally the sites should be at standard altitudes and in the same type of habitat, but this is impossible for practical reasons. Contrasts in the source areas have been described in 4.3.3, however these do not always account fully for the variation in the total seasonal catch at the sites.

Other difficulties relate to the method of defining the start date. The various approaches have been described in 3.5.2, for this analysis the sum75 method has been used as, being an absolute value, it proves to be useful for hayfever sufferers, however it is clearly influenced by the abundance of local grasses.

The analysis has highlighted the variation in the start and severity of the grass pollen season both at the individual sites from year to year, and between sites. It has also highlighted the varying response to the meteorological variables at the individual sites. When looking at the sites individually, there is no clear evidence of there being a relationship between the start of the season or the total seasonal catch and cumulative temperatures in the preseason period, or with preseasonal rainfall. When the sites are analysed together in an attempt to explain lags in the start of the season there is a relationship apparent between cumulative temperatures in the preseason period, but not with rainfall.

The lack of any obvious relationships between the meteorological variables used and the start and the severity of the season at the EAN(UK) sites, and the clear relationships between the meteorological variables and the characteristics of the grass pollen season at the long term data sites makes one suggest that in order for trends and variations between sites to be explained more data is needed.

Start of Grass Pollen Season at London 1961-1990

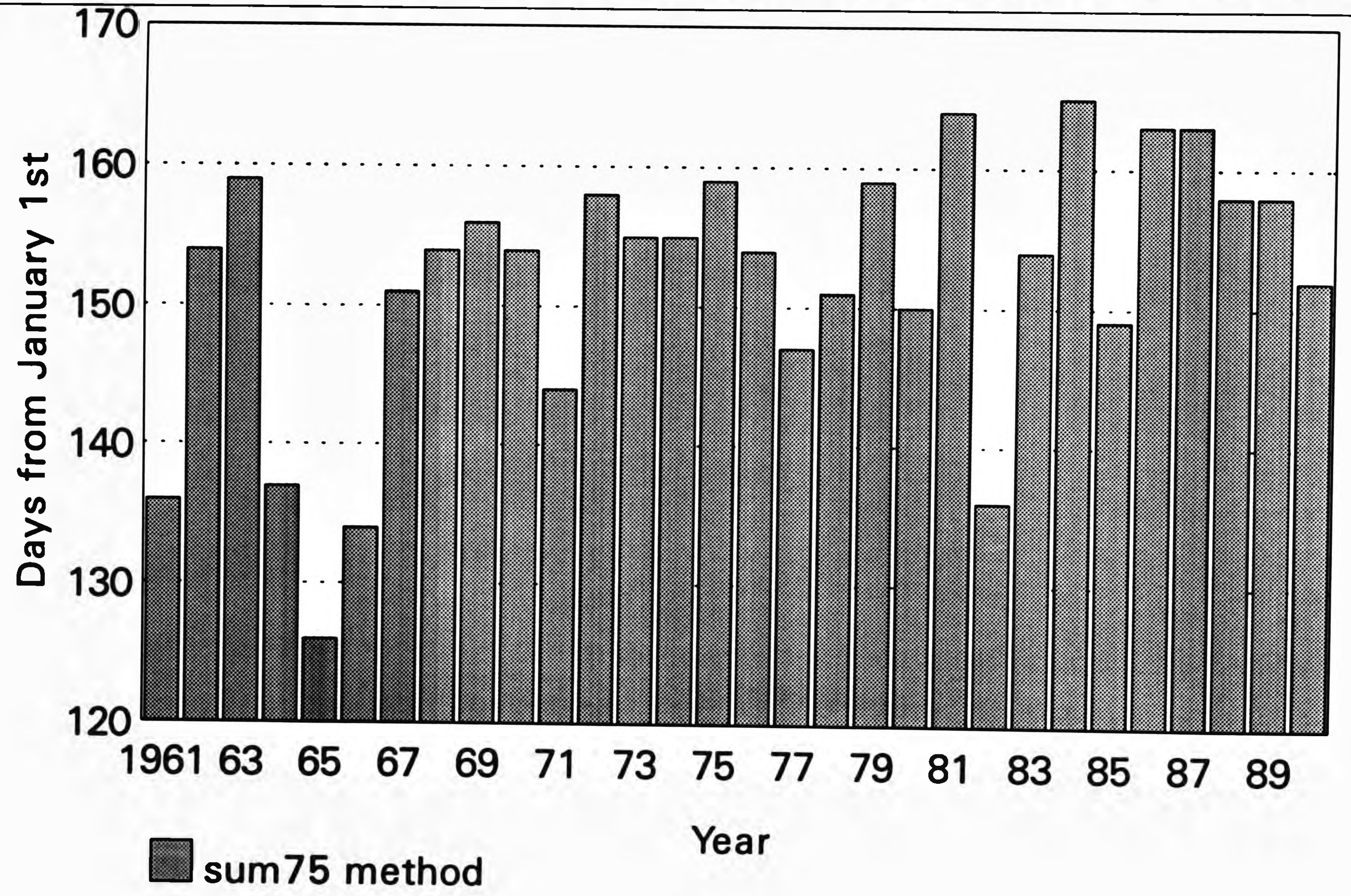


FIG 3

5-Year Running Means for the Start of the Grass Pollen Season at London 1961-1990

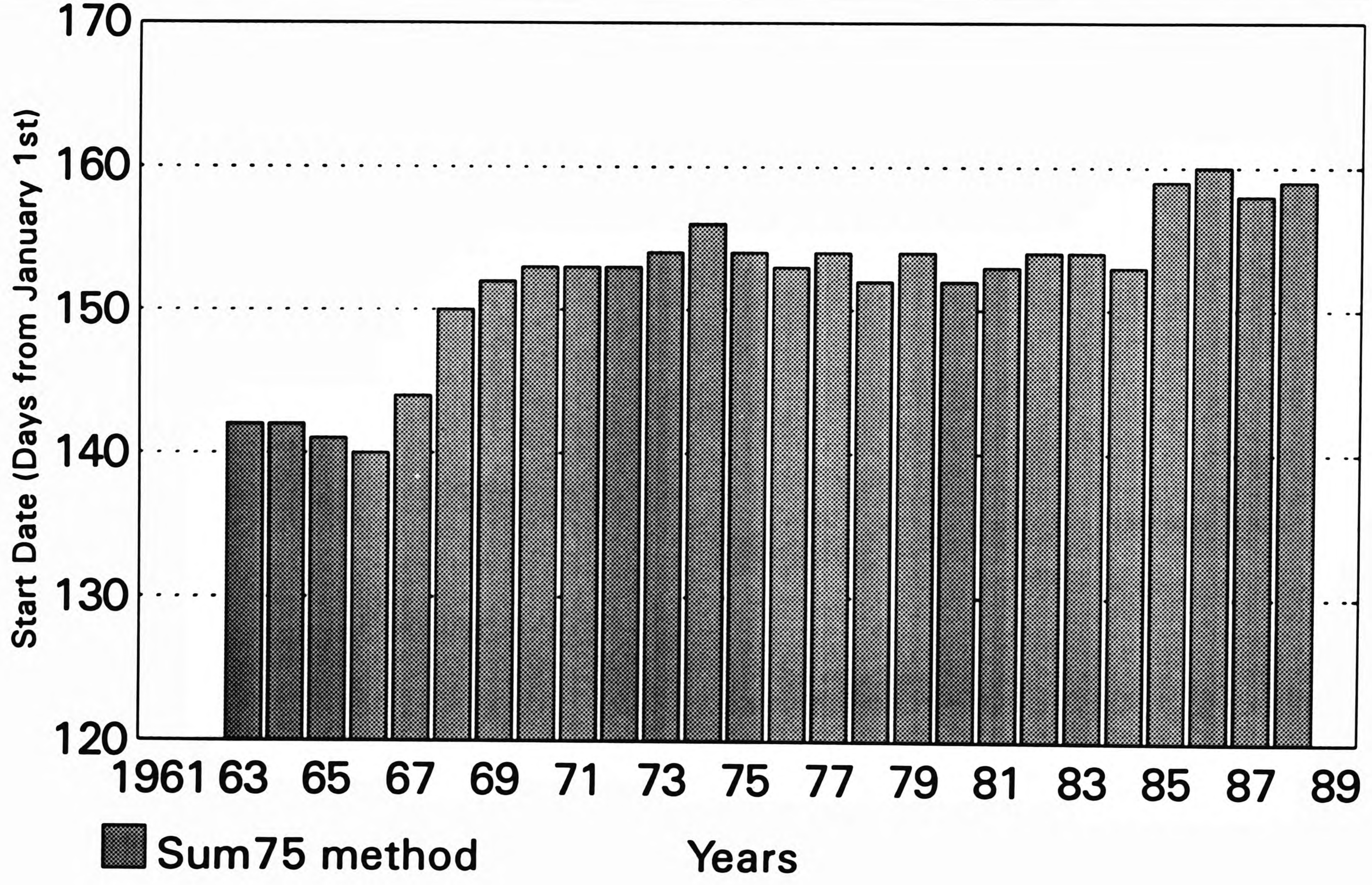


FIG 4

Start of Grass Pollen Season at Cardiff 1962-93

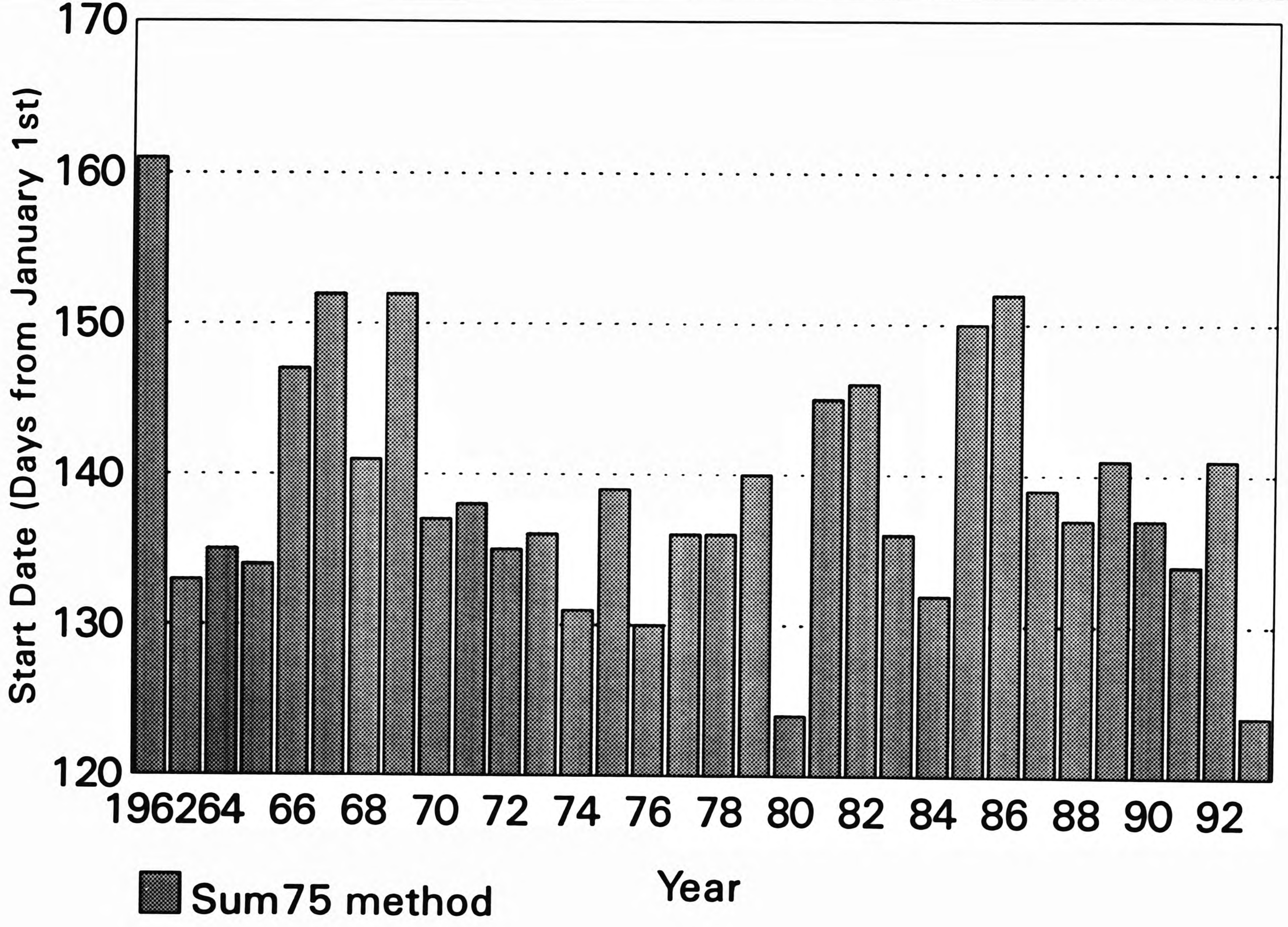


FIG 5

5-Year Running Means for the Start of the Grass Pollen Season at Cardiff 1962-1993

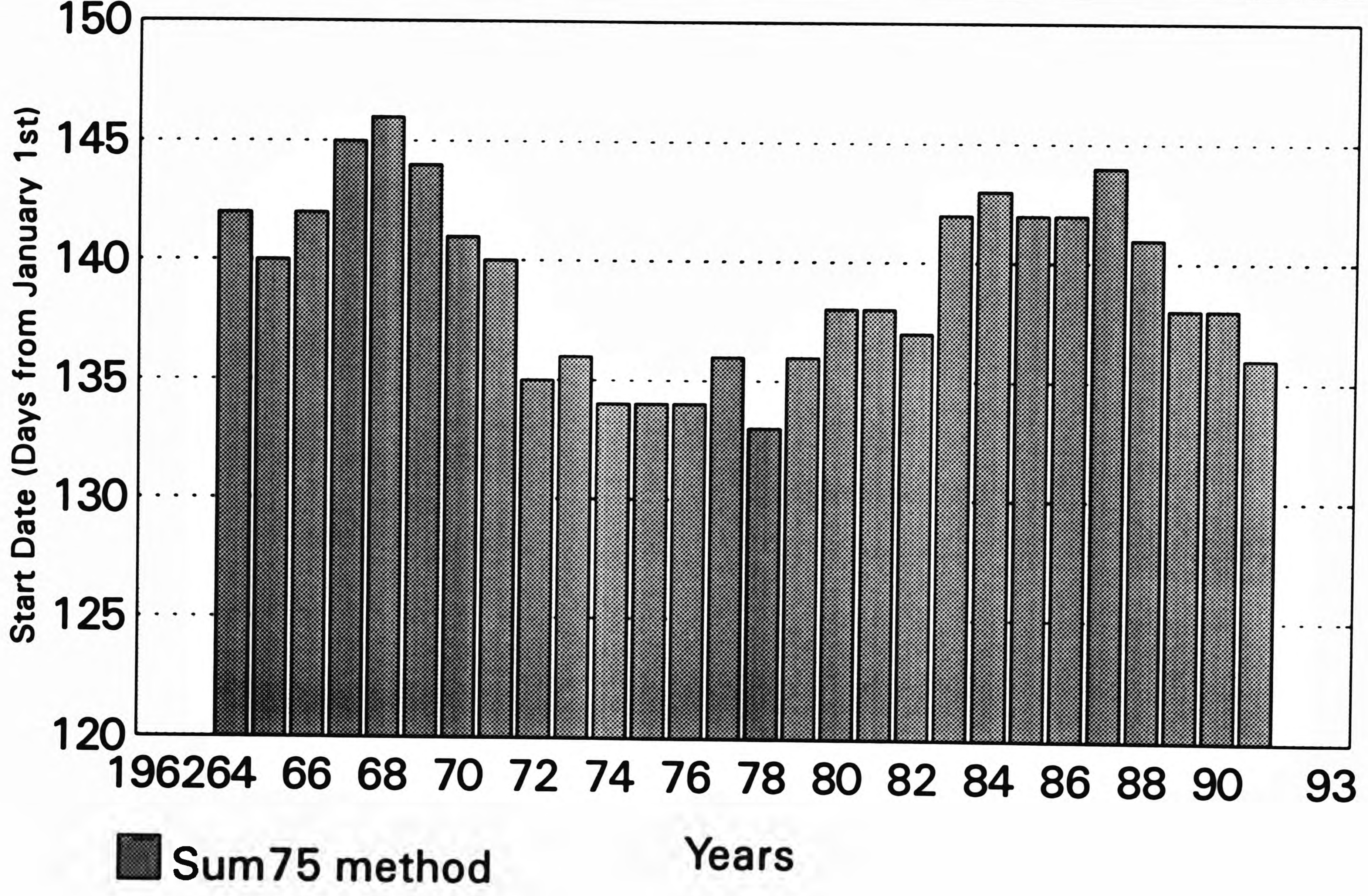
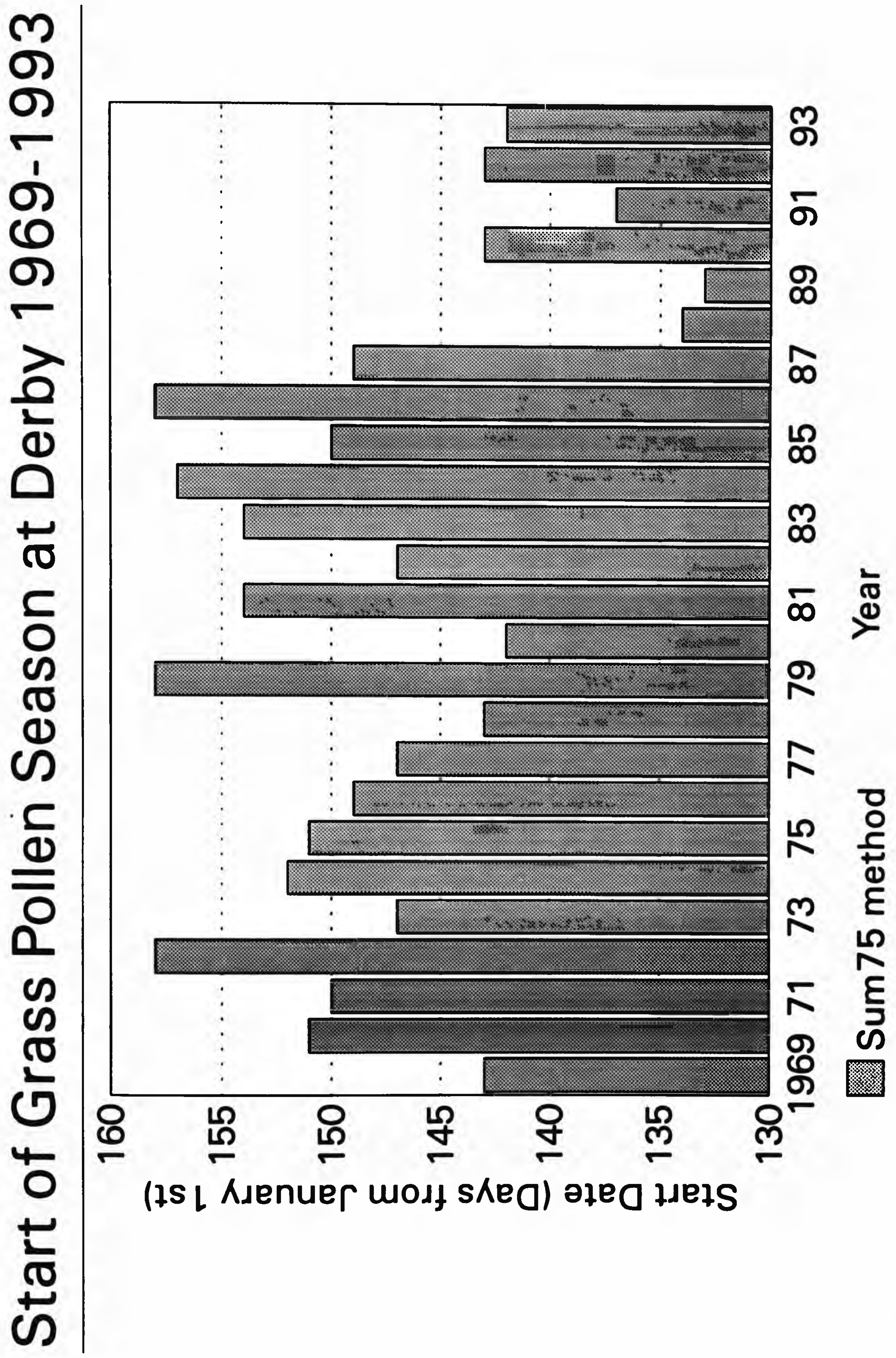


FIG 6

FIG 7


Start of Grass Pollen Season at Derby 1969-1993

5-Year Running Means for the Start of the Grass Pollen Season at Derby 1969-1993

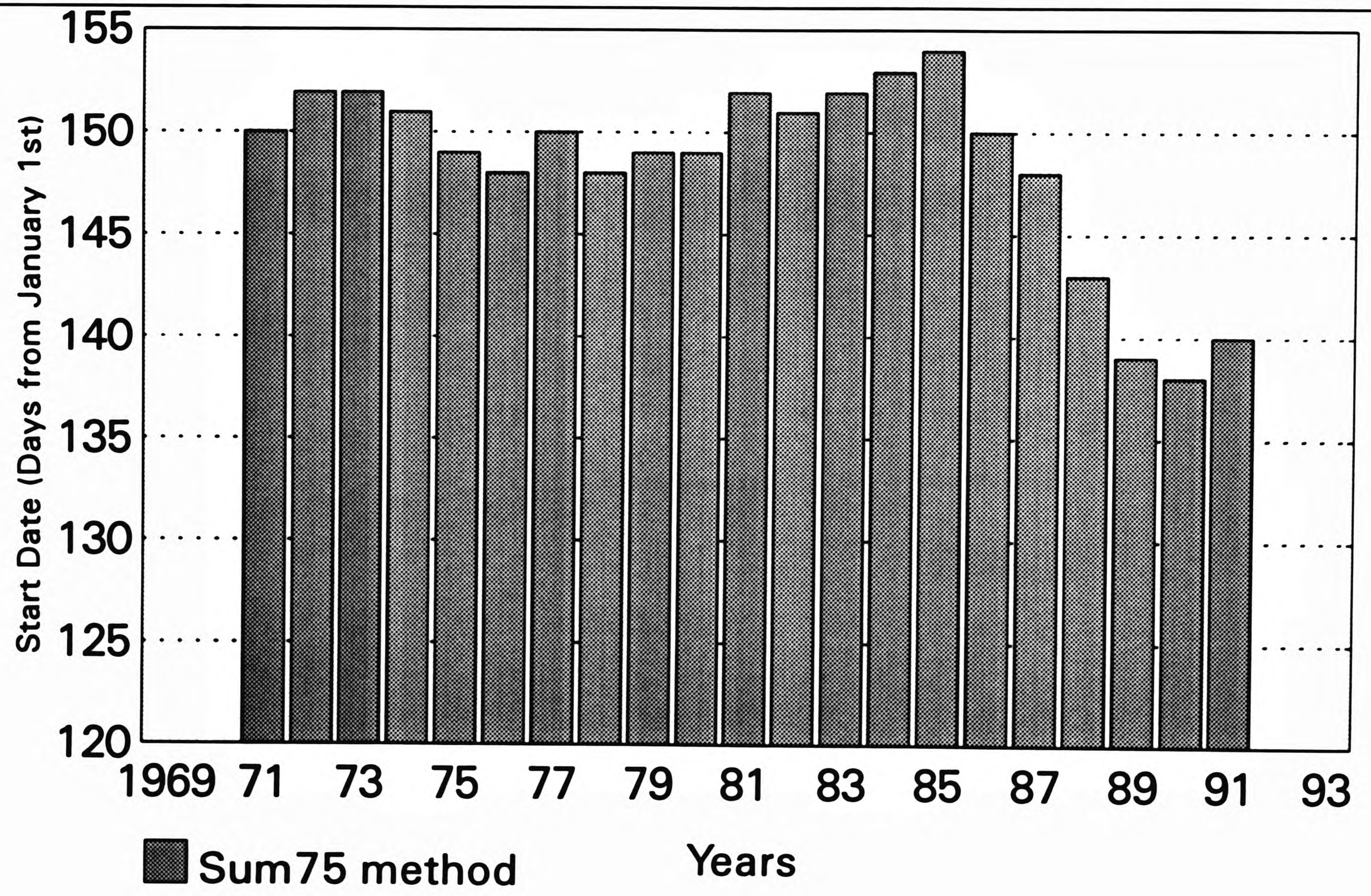
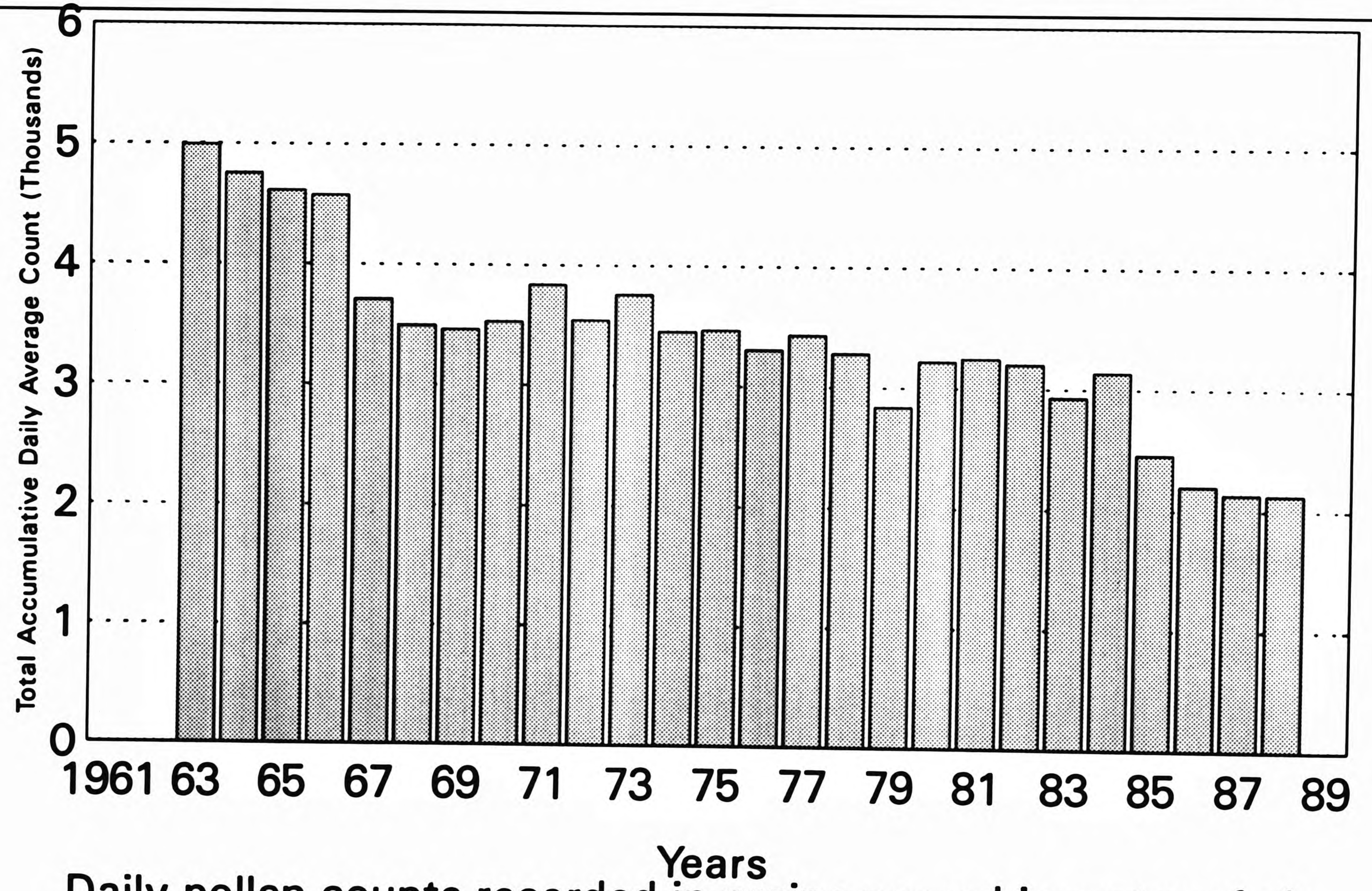


FIG 8

5-Year Running Means for Total Grass Pollen in London 1961-1990



Daily pollen counts recorded in grains per cubic meter of air

FIG 9

Total Grass Pollen Counts for London 1961-1990

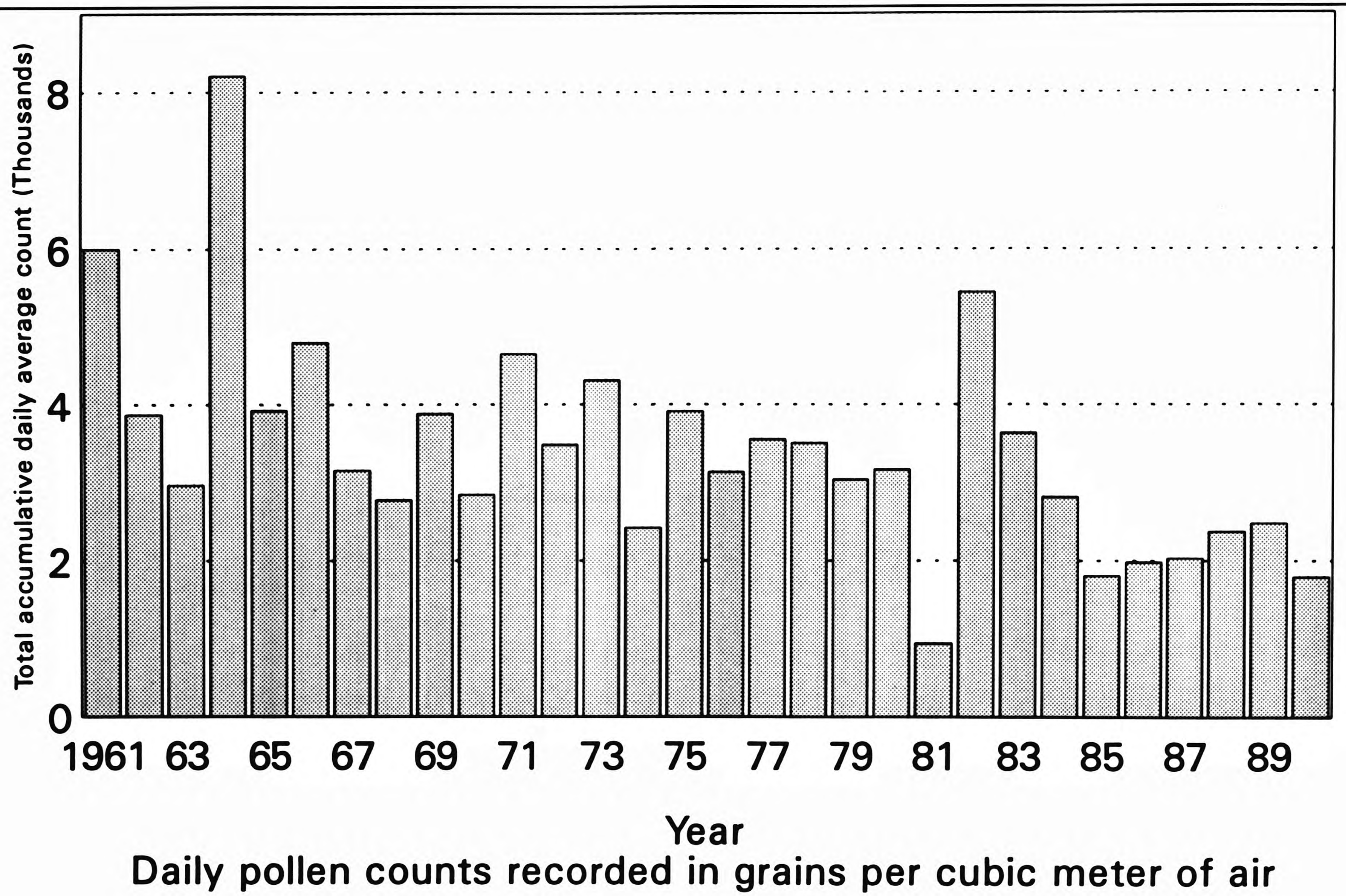


FIG 10

Severity of the Grass Pollen Season at London 1961-1990

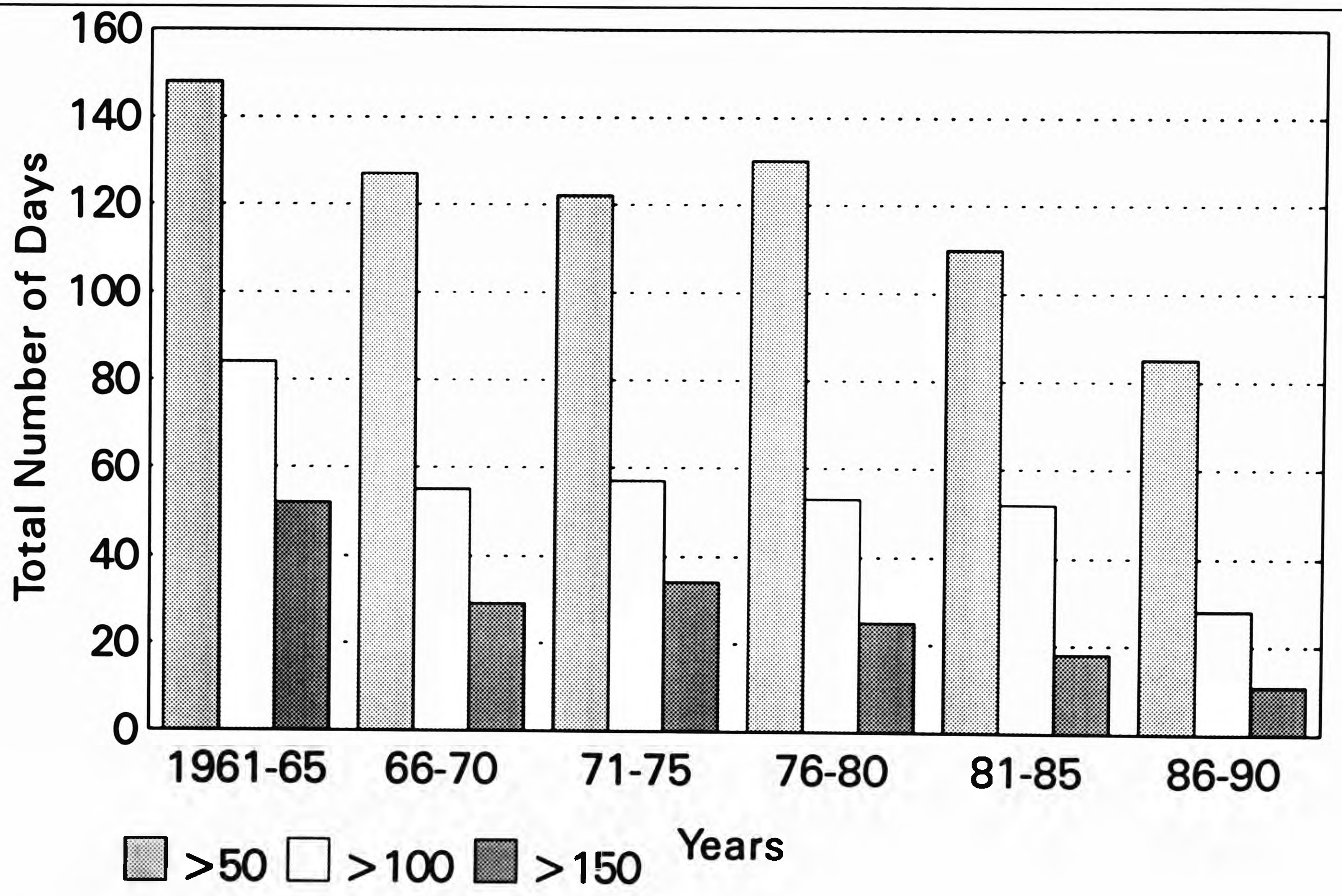
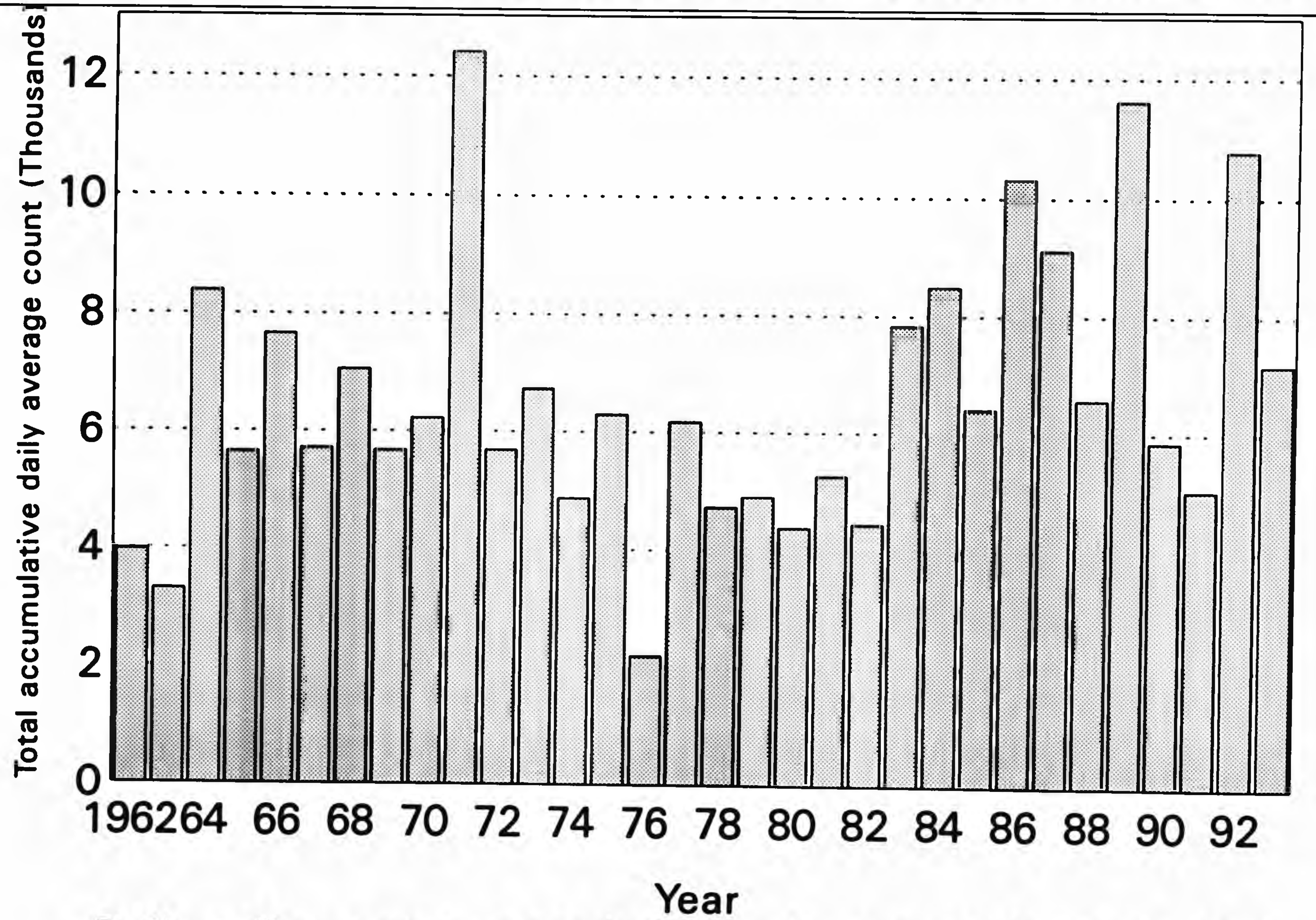


FIG 11

FIG 12

Total Grass Pollen Counts for Cardiff 1962-1993



Daily pollen counts recorded in grains per cubic meter of air

FIG 13

5-Year Running Means for Total Grass Pollen in Cardiff 1962-1993

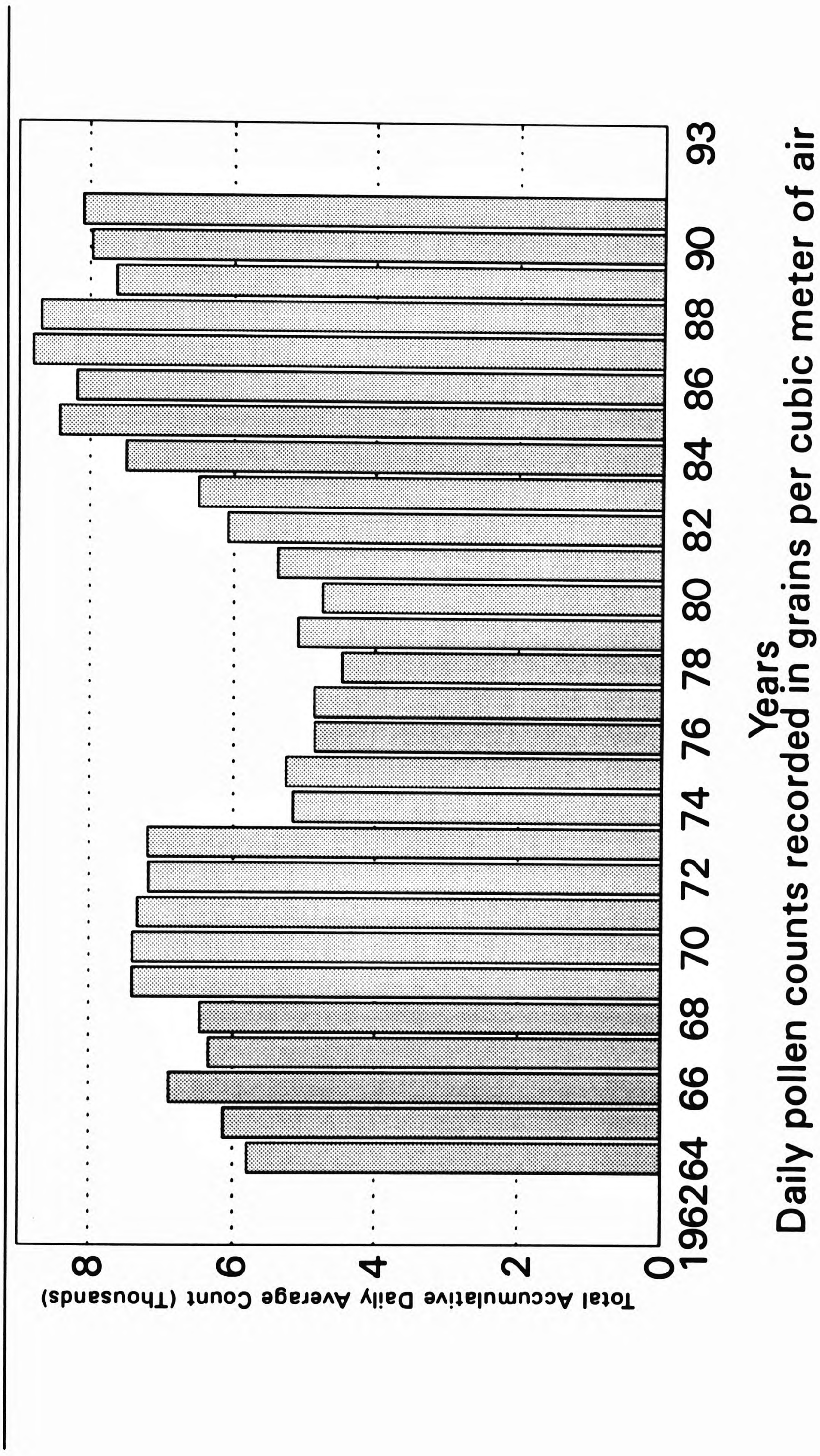
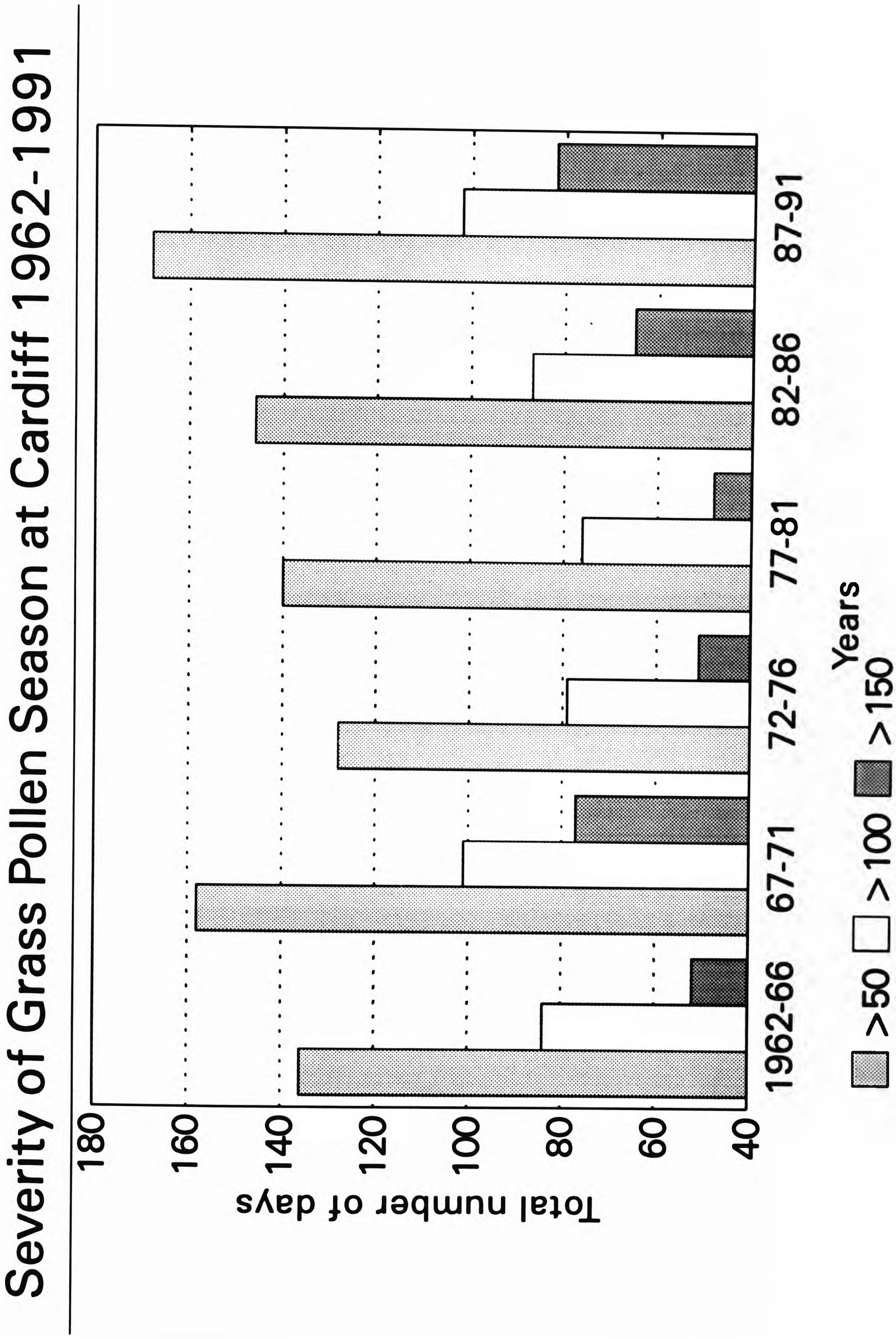
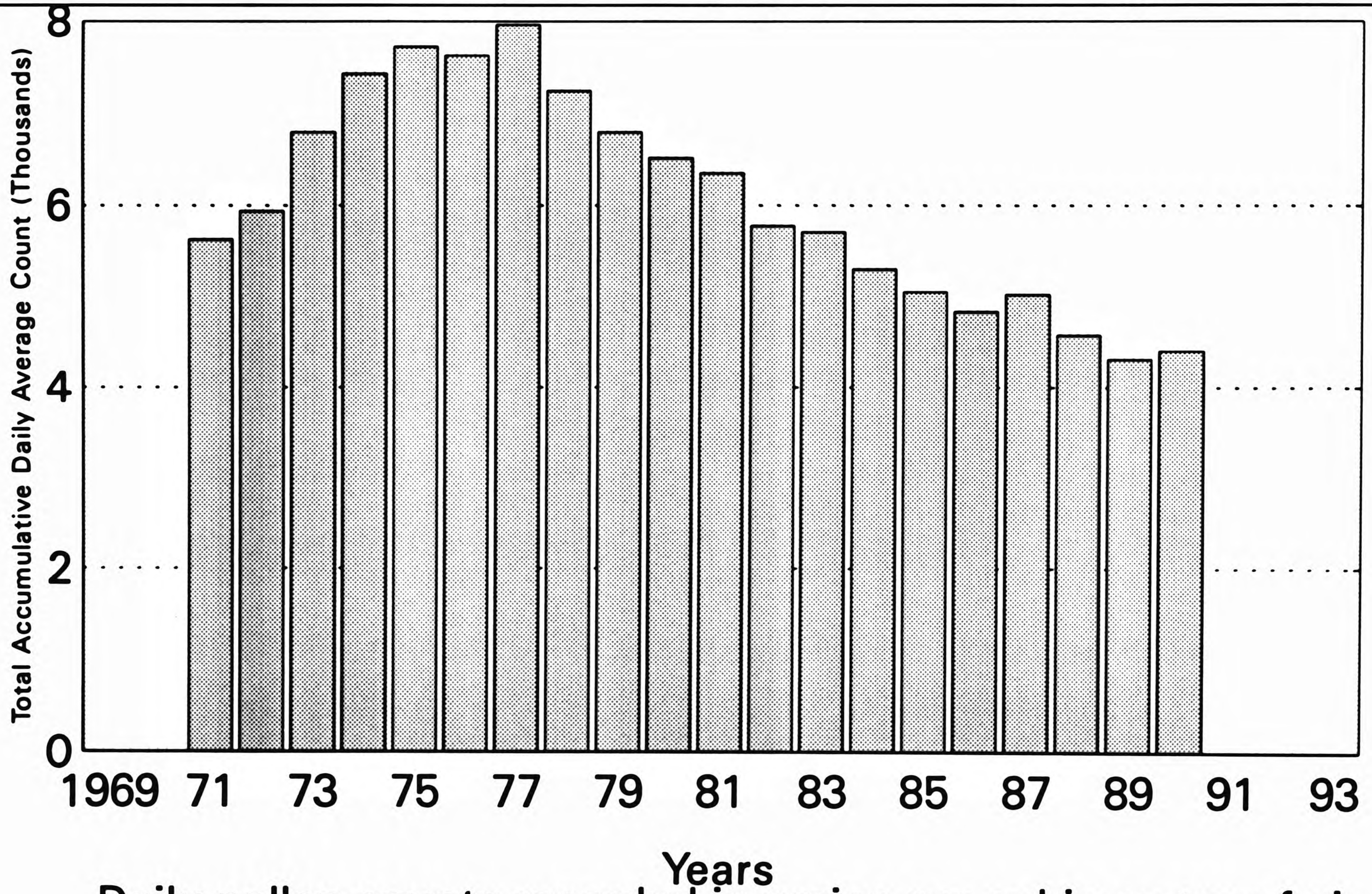


FIG 14


Severity of Grass Pollen Season at Cardiff 1962-1991
Total number of days
180
160
140
120
100
80
60
40
1962-66
67-71
72-76
77-81
82-86
87-91
Years
>50
>100
>150

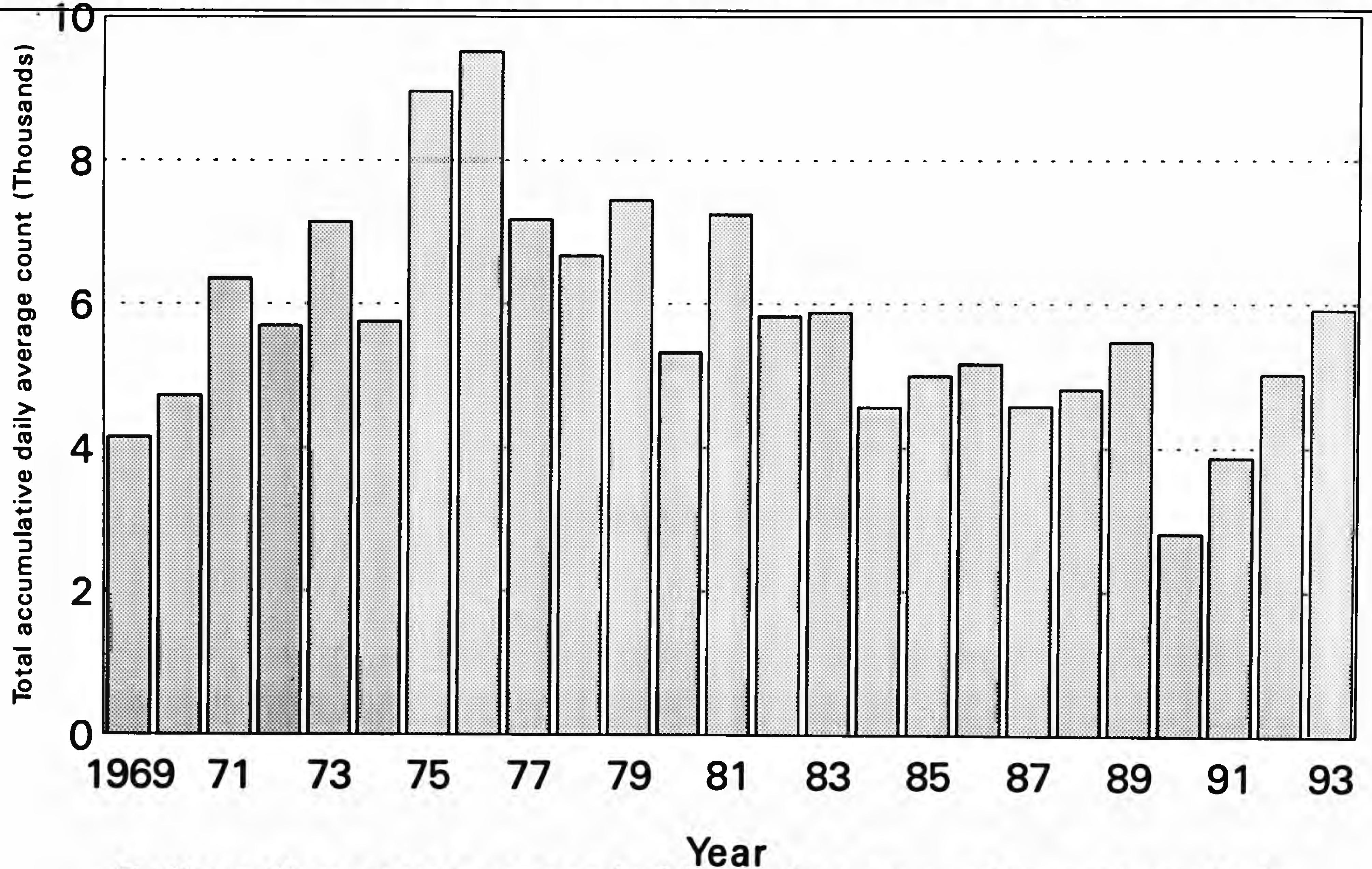
5-Year Running Means for Total Grass Pollen in Derby 1969-1993



Daily pollen counts recorded in grains per cubic meter of air

FIG 15

Total Grass Pollen Counts for Derby 1969-1993



Daily pollen counts recorded in grains per cubic meter of air

FIG 16

Severity of Grass Pollen Season at Derby 1969-1993

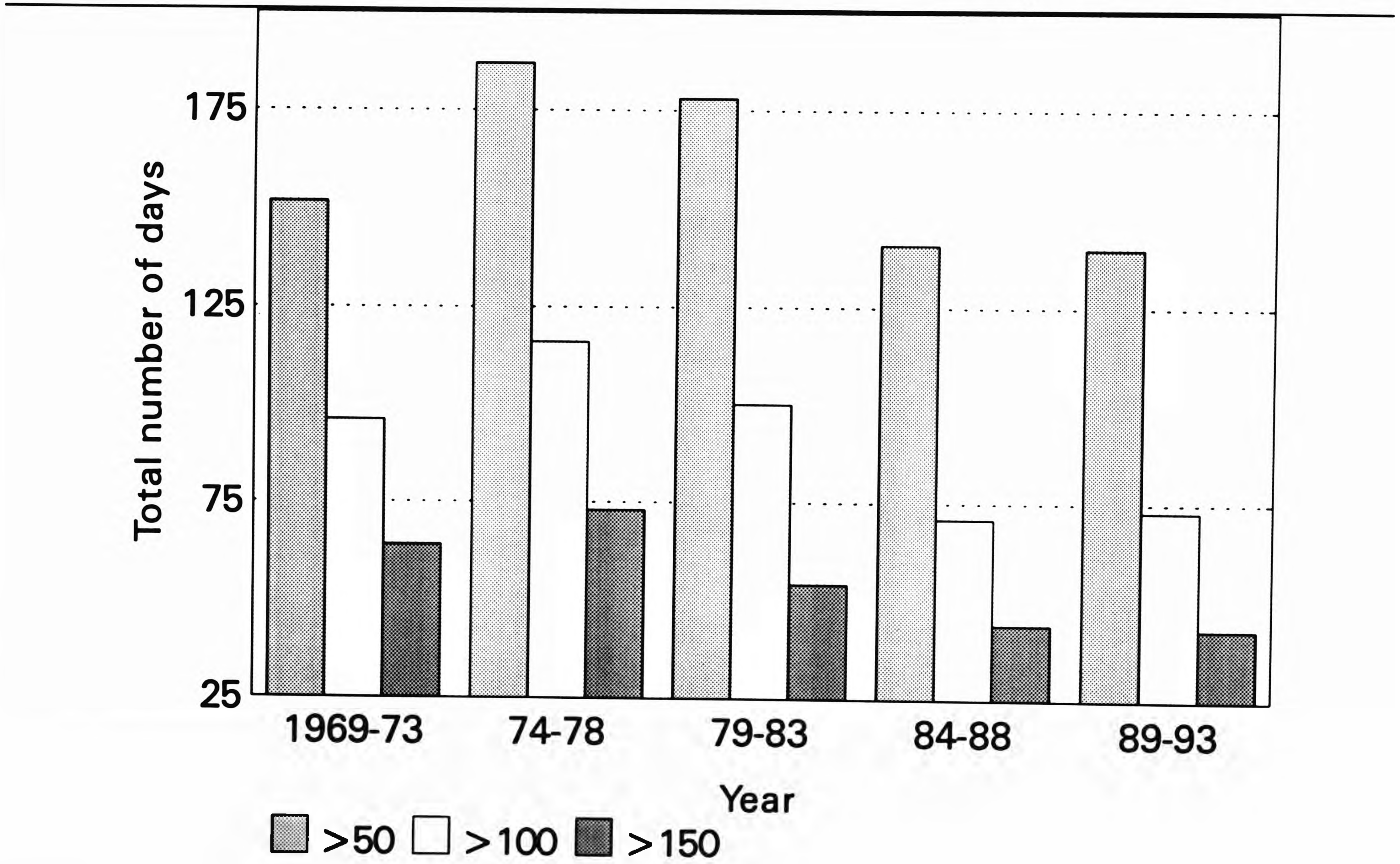


FIG 17

CHAPTER 5-COMPARATIVE ANALYSIS OF THE BIRCH POLLEN SEASON

5.1 INTRODUCTION

Betula pollen is well known as a significant aeroallergen especially in Northern European countries where it appears among the top ranked allergenic pollen types (Spieksma 1990). The cross reactivity between the Betulaceae and other tree pollen allergens has also been documented so clearly this pollen type contributes to a prolonged season of symptoms for many patients (Ott *et al* 1981, Flovaag *et al* 1982).

This chapter first analyses the *Betula* pollen seasons at three sites in the United Kingdom over a period of 24–30 years: London since 1961; Cardiff since 1963; and Derby since 1970. The overall aim was to identify trends in the start and severity of the season, and from these later (in chapter 7) to build predictive models for these aspects. Secondly, a number of other sites had records of *Betula* pollen ranging from one to eight years in length (1987–1994), and these were analysed to identify variations in the *Betula* pollen season between sites in order to ascertain whether there are general patterns in the season that exist in relation to geographical location, vegetation and climate. The London, Cardiff and Derby data from 1987 have also been included in the second analysis in order to increase the geographical range of the sites.

In Britain, the *Betula* pollen season typically lasts from mid-April to mid-May, but there is considerable annual variation in its start date and severity. The *Betula* pollen in Britain derives from *Betula pendula* and *Betula pubescens* (and some hybrids)(Frankland and Aalberse 1987). These are not distinguished in the counts. For all three sites the sources of pollen from these species are the parks, gardens, streets and other open places and also the surrounding countryside.

The total pollen catch for the season was defined as the total amount of pollen caught during the period March to June. Pollen recorded outside these months is very rare, and any pollen recorded was omitted from the analysis in order to avoid distortion through localised flowering at the start of the season and resuspension at the end.

For the long term data analysis, the start of the season has been defined according to the sum75 method (discussed in chapter 3), that is the start of the season was defined as the first day when the cumulative daily average count reached 75 grains. This method proved most useful when analysing the start of the season as it also allowed for forecasting in comparison with the 98% method where the entire pollen

pollen catch for the season is required and therefore the season can only be forecasted retrospectively. One drawback of the sum75 method however is that it is clearly influenced by the abundance of local birch trees. For the analysis of the EAN(UK) sites the 98% method was also used in order to counteract the problem of the great variation in the annual totals from year to year.

5.2 A COMPARATIVE ANALYSIS OF LONG TERM RECORDS OF BETULA POLLEN CONCENTRATIONS AT THREE SITES IN THE UNITED KINGDOM

5.2.1 METHODS AND SITE DETAILS

The details for the pollen monitoring sites and corresponding meteorological stations have been provided in chapter 3 and chapter 4, however for London, *Betula* pollen was recorded at St Mary's Hospital, Paddington for the period 1961-1983, then there was a break of 3 years until pollen monitoring began at the University of North London site in 1987. These two sites are approximately 5.4km apart in north central London and are considered to have similar local vegetation and local climate. Analysis of variance showed that there was no significant difference between the pollen data at both sites and therefore they have been analysed together.

5.2.2 START OF THE SEASON

5.2.2.a London

The range in the difference in start dates in London for the period 1961-1993 was 39 days (Fig 18). The earliest start was in 1990, 81 days from January 1st. This was after a very warm spring with January temperatures +3.1°C, February +3.8°C and March +2.9°C above the 30-year means (1961-1990); and with wet weather in winter and early spring (compared with the 30 year means December had 210% rainfall, January had 152% and February had 242%, but March had only 14%).

The latest start to the season was in 1970 at 120 days from January 1st. This was a very cool, dry spring; (February -0.6°C, March -2.2°C, April -1.4°C compared with the 30 year means; with rainfall in December 80%, March 78% and April 132% of the means for the 30 year period).

Examination of the 5 year running means of the start dates indicated a trend towards an earlier start to the season, which was most pronounced from the mid 1980s

(Fig 19). Early starts were characteristic of the late 1980s and 1990s, and late starts were characteristic of the 1960s and early 1970s. The weather profile for the period mid 1980s and early 1990s was characterised by most spring months having above average temperatures and average rainfall, and the period 1960s and early 1970s was characterised by two spring months out of three having below average temperatures and April having average to above average rainfall.

5.2.2.b Cardiff

The range in the difference in start dates between 1963-1993 in Cardiff was 55 days (Fig 20). The earliest start was, like London, in 1990, 66 days from January 1st. Again, this was after a very warm spring with January temperatures +2.9°C, February +3.8°C and March +2.3°C above the 30 year means (1963-1993); and with wet weather in winter and early spring (compared with the 30 year means December had 140% rainfall, January had 137% and February had 195%, but similar to London March had only 30%).

The latest start to the season was in 1986, 121 days from January 1st. The spring of this year was cool starting very dry but then becoming very wet; (February -4.6°C, March -0.9°C, April -2.2°C compared with the 30 year means; with rainfall in February only 2%, March 154% and April 133% of the means for the 30 year period).

The 5 year running means for start dates showed a fluctuation in the start date from the 1960s until the 1980s, however there was a pronounced trend towards earlier start dates from the mid 1980s (Fig 21). The spring period from the mid 1980s (apart from 1986 and 1991) was characterised by very warm springs, with three or four months having above average temperatures.

5.2.2.c Derby

The range in the differences in start dates 1970-1993 in Derby was 43 days (Fig 22). The earliest start, like London and Cardiff was in 1990, 83 days from January 1st. The spring had a similar temperature and rainfall profile as the other sites, experiencing a particularly warm spring with January temperatures +2.4°C, February +3.4°C and March +2.9°C above the 24 year means (1970-1993). The winter and early spring was wet (December had 200% rainfall, January had 115% and February had 187%). March was particularly dry with only 29% of average rainfall (similar to London and Cardiff in this year).

The latest start to the season was in 1971, 126 days from January 1st. Unlike the weather profiles before the latest start dates at London and Cardiff, the spring of 1971 was rather average with temperatures in January +0.5°C, February +1.0°C, March -0.4°C and April -0.2°C of the 24 year means. Apart from February being particularly dry, rainfall figures were also close to average in spring with rainfall in January 122%, February 42%, March 85% and April 124%. It is likely therefore that the later start date was a result of a lack of rainfall in February combined with a relatively cool and wet April when the pollen was being released.

There is very clear evidence from the 5 year running means of start dates of a trend towards an earlier start to the season over the 24 year period (Fig 23). Temperatures during the spring since the mid 1980s were much warmer. Since 1987, March and April have had above average temperatures, and April has had average to below average rainfall.

5.2.2.d Discussion

Overall it appears that there is a trend towards an earlier start date at all three sites, which is particularly pronounced since the mid 1980s. Detailed analysis of the variables influencing the start of the season will be discussed in chapter 7, however this study suggests that the main controls on the timing of *Betula* pollen flowering are, winter chilling/vernalisation, and spring weather (Faust 1989). Analysis of the weather profiles since the mid 1980s at all three sites, show that there has been an increase in January, February, March and April mean temperatures, and this combined with a decline in rainfall in March and April probably resulted in ideal conditions for the early dispersal of pollen.

It is sometimes suggested that the annual sums of airborne pollen are high in years with an early start date. To investigate this for birch pollen, the relationship between these two parameters was analysed by calculating the correlation coefficients. The correlation was not significant for Cardiff ($r=-0.028$), but was significant for Derby ($r=-0.599$, $p<0.01$) and London ($r=-0.418$, $p<0.02$), the two sites with the lowest annual sums. This was also found in the work of Spieksma *et al* (1995) who found that the only significant correlations between start dates and total pollen catches were at the sites with the lowest annual sums.

5.2.3 SEVERITY OF THE SEASON

5.2.3.a London

Annual sums of daily average pollen counts for *Betula* at the London sites ranged from 4310 grains in 1987 to 65 grains in 1991 (Fig 24). There was an indication of a trend towards higher annual totals in the second half of the 30 year data set, especially from 1975 onwards. Similar trends have been reported in Leiden, Netherlands (Jager *et al* 1991).

Biennial rhythms have been reported by several other workers (eg. Goldberg *et al* 1988, Lavee 1989, Jager *et al* 1991, El-Ghazaly *et al* 1993, Spieksma *et al* 1995) but there is no consistent evidence of this from the London site. Interestingly, as will be discussed later, the data from the more rural sites of Cardiff and Derby exhibit more obvious biennial rhythms. Totals were analysed in relation to spring temperatures and rainfall, particularly during the months of pollen dispersal, however this did not yield obvious patterns of biennial rhythms.

Little work has been done on dose-response relationships between ambient concentrations of *Betula* pollen and clinical symptoms in the UK. Even the acceptance that allergic rhinitis can be provoked by tree pollen is recent (Davies 1989). Viander and Koivikko (1978) reported that all clinically sensitive patients develop symptoms of hayfever when the birch pollen count exceeds 80 grains/m^3 in the early season and 30 grains/m^3 in the late season. Less pollen is needed to invoke symptoms at the end of the season as exposure to an allergen will further sensitize a sufferer. In London, over the period, the number of days with average counts $\geq$80 grains/m^3 of air ranged from zero to 17 (in 1987)(Fig 25). There were only 5 years in which there were more than 9 days with counts $\geq$ 80. There were only 6 years in which very high ($\geq$ 150) counts occurred on 5 days or more (of these 6 years 4 have been since 1980). The application of these dose response thresholds devised in Finland to sites in the UK must be questioned as *Betula* counts are much higher there and therefore arboreal pollinosis more common.

5.2.3.b Cardiff

Total *Betula* pollen counts at Cardiff ranged from 15179 grains in 1987, to 198 grains in 1977 (Fig 26). There was no obvious trend in the annual birch pollen totals, although the higher totals tended to occur from the mid 1980s.

There was evidence of biennial rhythms particularly during the years 1966 to 1973, there was then an interruption in the rhythm until 1977 to 1981, which then continued 1985 to 1989. Hence the rhythm operates for a few years, then there is a break in the rhythm of 3 years, and then the rhythm starts again. Analysis of the three 'break' years showed no significant change in the weather in the winter and spring months, and therefore it is likely that the biennial rhythmic pattern is inherent in the plant rather than being a function of climate.

The season at Cardiff was usually more severe than at the other two sites (Fig 27). The number of days with average counts ≥ 80 grains/m^3 of air ranged from zero to 20 (in 1985). There were 10 years with counts ≥ 80 on more than 9 days, and 8 years in which very high counts occurred on 5 days or more. In a similar way to London, 5 of the these years have been since 1980.

5.2.3.c Derby

The range in total annual *Betula* pollen counts at Derby was from 3709 grains in 1993, to 155 grains in 1971 (Fig 28). There was an overall trend towards an increase in the total annual birch pollen catch, this trend has become more pronounced since the 1980s.

Biennial rhythms were more obvious at Derby than at the other two sites, particularly for the period 1973 to 1982 when the 'high' years were even and the 'low' years were odd. In the late 1980s there were two small biennial sequences 1987 to 1989, and 1990 to 1992, however these sequences were of insufficient length to make any significant conclusions concerning biennial rhythms.

The birch pollen season at Derby in comparison with the other sites, and considering that Derby is a semi-rural site, is relatively mild (Fig 29). The number of days with daily average counts ≥ 80 grains/m^3 of air ranged from zero to 9. There were only 3 years with 9 days having counts ≥ 80, and only 3 years when very high counts occurred on 5 days or more, these years were all since the mid 1980s.

5.2.3.d Discussion

At all 3 sites there was a trend towards an increase in the total annual birch pollen catch over the sampling period, this however was not so obvious at Cardiff as at the other two sites. This trend has become more pronounced since the 1980s. As discussed in 5.1.2.d, all three sites showed an increase in January, February, March and April mean temperatures along with a decline in rainfall in March and April thus resulting in ideal conditions for the dispersal of pollen. Unfortunately, due to the lack of land use data on birch trees it is not possible to say whether or not this increase is also due to an increase in the number of birch trees being planted in the surrounding areas. Along with this increasing trend in the total annual sum, there has also been an increase in the severity of the season ie. the number of days with average counts ≥ 80 grains/m^3 of air.

When considering biennial rhythms of the birch flowering it can be seen both in Britain, and in the work of El Ghazaly *et al* (1993), that cyclical trends do not show a regular and reliable periodicity. The sub urban and semi-rural sites (Cardiff and Derby) show a more regular pattern than the urban site (London). Lack of a pattern in London may be a function of the prevailing dispersion patterns. It may be that sites remote from main sources do not register the full impact of variations. Alternately, a possible explanation is that the biennial rhythms are similar to those exhibited by apple trees in which the developing fruits produce hormones, mostly gibberellines and auxins, which reduce flower bud development the following year (Lavee 1989). Years with great pollination and fruit development result in high hormone production the following year giving few flowers and low pollen abundance. Research indicates that environmental factors such as severe frost or drought can induce this cycle. In this way it would be possible to have periods with no rhythms, then have patterns developing (Emberlin *et al* 1993a).

One of the first problems when studying rhythms in flowering is how the rhythms are defined. Jager *et al* (1991) and Spieksma *et al* (1995) defined 'high' years as being years with higher annual sums than the previous year, and they defined 'low' years by the same method. For this analysis the same definition was used.

There was no real evidence of any synchronisation in 'high' and 'low' years between the sites. Work by Spieksma *et al* (1995) analysing birch data over a 18 to 30 year period in Basel, Leiden, London, Stockholm and Vienna showed that alternating fluctuations coincided with high sums in even years and low sums in odd years at all stations except London, and that at all four stations rhythms were interrupted in 1986.

This is not evident in the data from the United Kingdom. In London, high sums tended to coincide with odd years, in Cardiff there was an alternating rhythm, high years tended to occur in odd years for 1966-1973 and 1985-1989, and in even years for the period 1977-1981. The high birch pollen sum years at Derby, like at the three European stations, tended to occur during even years.

5.3 VARIATION IN THE BIRCH POLLEN SEASONS AT EAN(UK) SITES 1987-1994

5.3.1.METHODS AND SITE DETAILS

Five of the sites used in this study have operated for many years, but six started monitoring more recently. Monitoring techniques and site details have been discussed in detail in chapter 3.

The sites differ in local climates, topography and vegetation. Land use figures for birch alone could not be obtained for this work, however Table XII shows the percentage of deciduous woodland in a 40km and 80km radius around each site. From the table it can be seen that there was a very small percentage of deciduous woodland in the areas surrounding each site. Within this small area of woodland there would also have been other trees, for example oak, beech, elm, hornbeam and willow. Birch trees may be planted in many of the parks, gardens and road sides in the areas close to each site, and these would not figure in the ITE survey as they would be isolated plants rather than existing within a 1km grid (on which the survey is based). Tree species vary in the amount of pollen that they produce. *Betula (Betula pubescens* in particular) is a species that produces a large amount of pollen, 6 000 000 grains per inflorescence, 5 times more than that of oak, and 34 times more than that of beech (Frenguelli 1994). Birch therefore has a very important local influence and the percentage of pollen caught in the pollen trap would not necessarily be related to the amount of birch trees in the surrounding area, but more to the proximity of the nearest birch trees to the pollen trap.

Table XII. The Percentage of Deciduous Woodland in the Area Surrounding Each EAN(UK) Site

SITE	40km RADIUS (%)	80km RADIUS (%)
Isle of Wight	11.7	6.8
London	5.7	7.1
Taunton	7.6	9.2
Cardiff	4.2	5.0
Leicester	3.2	2.4
Derby	1.3	2.2
Chester	3	4.5
Preston	0.9	1.9
Edinburgh	2.6	4.5
Invergowrie	12.7	3.5

(Data supplied by the ITE Landsat Land Cover Map of Great Britain, Figs. for 1992) Data for Belfast was unavailable.

5.3.2 START OF THE SEASON

5.3.2.a Comparison of Start Date Definitions

The start dates defined by the sum75 method tended to be later than those defined by the 98% method (Table XIII). In some years, considerable differences featured at individual sites between the start dates produced by the two definitions. In 1992 there were notable differences at most sites in the network, the largest was 35 days at Preston, possibly resulting from the cool start to the spring and wet weather in March. At the southern sites the sum75 method gave a greater range in start dates in any one year than the 98% method, however in the more northern sites, the 98% method gave a greater range.

Table XIII. Start Dates for the Birch Pollen Season at EAN(UK) Sites for 1987-1994 using Sum75 Method and 98% Method (Start dates from January 1st)

SITE	1987	1988	1989	1990	1991	1992	1993	1994
Isle of Wight								120* 62^
Taunton								120* 90^
London	103* 102^	108* 91^	91* 87^	81* 80^	X 78^	104* 81^	92* 89^	98* 79^
Cardiff	107* 107^	101* 67^	103* 94^	82* 78^	66* 66^	83* 65^	91* 88^	109* 89^
Leicester				82* 77^	100* 92^	103* 91^	103* 89^	116* 97^
Derby	108* 108^	111* 110^	102* 89^	83* 74^	100* 92^	102* 96^	91* 89^	109* 101^
Chester								112* 83^
Preston						104* 69^	93* 72^	114* 111^
Belfast						X 122^	114* 103^	121* 110^
Edinburgh		X 101^	120* 85^	98* 85^	117* 104^	117* 104^	109* 67^	122* 110^
Invergowrie						X 113^	114* 104^	X 109^

* Sum75 method definition ^ 98% method definition

A value of X indicates that the sum75 level was not reached and the start date could not be defined.

5.3.2.b Variation at Individual Sites

Dates for the start of the birch pollen season at individual sites varied widely between different years, but differences at some sites were greater than others, for example Cardiff showed more variation than Edinburgh, with a difference in start dates over the 7 to 8 year period of 43 days as compared with 24 days (according to the sum75 method)(Table XIII).

The mean monthly temperatures for December, January, February and March, were correlated with start dates defined by both methods. There was a significant negative correlation with mean temperatures in March, at all of the sites with more than 5 years of data, according to both definitions. Cardiff and Edinburgh also showed a positive correlation with temperatures in December ($r=0.716$, $p<0.05$ and $r=0.811$, $p<0.05$ respectively) but only when using the sum75 definition, and London and Edinburgh showed a negative correlation with temperatures in February ($r=-0.733$, $p<0.05$ and $r=-0.779$, $p<0.05$ respectively). This highlights the importance of the chill factor in December, and warmth in March.

No relationship was found with start dates and preseasonal (January, February and March) total rainfall, except at Derby where there was a positive correlation.

5.3.2.c Variation between Sites

The variation in start dates for more than 5 years was available for only five sites, all of the other sites had data for only five years or less. Among these sites, seasons started first most frequently at Cardiff according to the 98% method, and Cardiff and London according to the sum75 method (Table XIII). Lag times for the start of the season for all of the EAN(UK) sites varied from between 5 days and 1 day in 1987 (although only 3 sites were monitoring at this stage) to 51 days in 1991 (according to the sum75 method) and 57 days in 1992 (according to the 98% method). A full geographical range of results was not available until 1992. In 1992 and 1993 the spread of the start of the season followed a similar pattern, starting in Cardiff and moving in a north easterly direction until it reached Scotland and Northern Ireland. The time lag between the earliest and latest start of the season was 34 days in 1992, and 23 days in 1993. The season started at the southern and central sites at the same time and then there was a lag of two to three weeks before the start of the season at the more northern sites, and then a further lag of one to two weeks before the season finally started in Scotland and Northern Ireland. In 1994 there was a different pattern of movement in the start of the season throughout the country. The season started first in London, then 11 days later in Cardiff and Derby, then over the next week the season started in Chester, Preston and Leicester, followed almost a week later by the furthest south and furthest north sites ie. Isle of Wight, Taunton, Belfast and Edinburgh. The start to the season therefore does not follow a simple south to north pattern. Analysis of the mean monthly spring temperatures and total spring rainfall at the individual sites shows that of the 8 years studied, in 6 of the years the season started earliest at sites with the warmest spring mean temperatures and low rainfall for that particular site. The exceptions to this occurred in 1990 and 1992.

The sites at Derby and Leicester are only 37km apart. In most years there was a very close synchronisation of start dates between the two sites according to both methods, the start varying in most years by only 1 or 2 days. In 1994 however there was about a weeks difference in the start of the season, starting firstly at Derby. This was most likely to be a result of higher mean spring temperatures at Derby and lower rainfall.

Generally, longer lags between earliest and latest starts occur in cooler years. In 1991, which had the coolest spring, the lag was 51 days according to the sum75 method and 38 days according to the 98% method. In comparison in 1990, with above average spring temperatures, the lag was only 17 days and 11 days for the sum75 and 98% method respectively.

5.3.3 SEVERITY OF THE SEASON

5.3.3.a Variation at and between Individual Sites

Annual sums of birch pollen varied greatly from year to year at the individual sites (Table XIV). For example, total counts ranged from 20 to 922 grains at Invergowrie, and 711 to 15179 grains at Cardiff, despite Invergowrie having a higher percentage of deciduous woodland within a 40km radius (Table XII). The higher annual sums could either be a result of a variation in the composition of the deciduous woodland surrounding the sites, with that at Cardiff having a higher birch component than that at Invergowrie, or a result of lower mean temperatures at Invergowrie resulting in the production of fewer pollen grains. However, the latter explanation is unlikely as birch is also common in Scandinavia, where temperatures are much lower than those in Central Scotland, and daily average counts during the birch pollen season can exceed 3000 grains/m^3 of air (Viander and Koivikko 1978).

Table XIV. Total Birch Pollen Counts at the EAN(UK) Sites 1987-1994

SITE	1987	1988	1989	1990	1991	1992	1993	1994
Isle of Wight								100
Taunton							1170	92
London	4311	365	2296	1487	65	375	3333	308
Cardiff	15179	711	3735	3609	1610	1100	3200	650
Leicester				1501	932	656	719	146
Derby	2363	445	1123	2520	869	1196	3709	1797
Chester								186
Preston						898	1922	500
Belfast						59	306	126
Edinburgh		39	235	494	253	273	300	152
Invergowrie						20	922	65

Correlation coefficients were calculated between mean monthly temperatures for December, January, February and March and annual birch pollen sums for each site. No relationship was found between mean temperatures in February and the total count, however significant relationships were found between mean temperatures in other months and the total seasonal catch (Table XV).

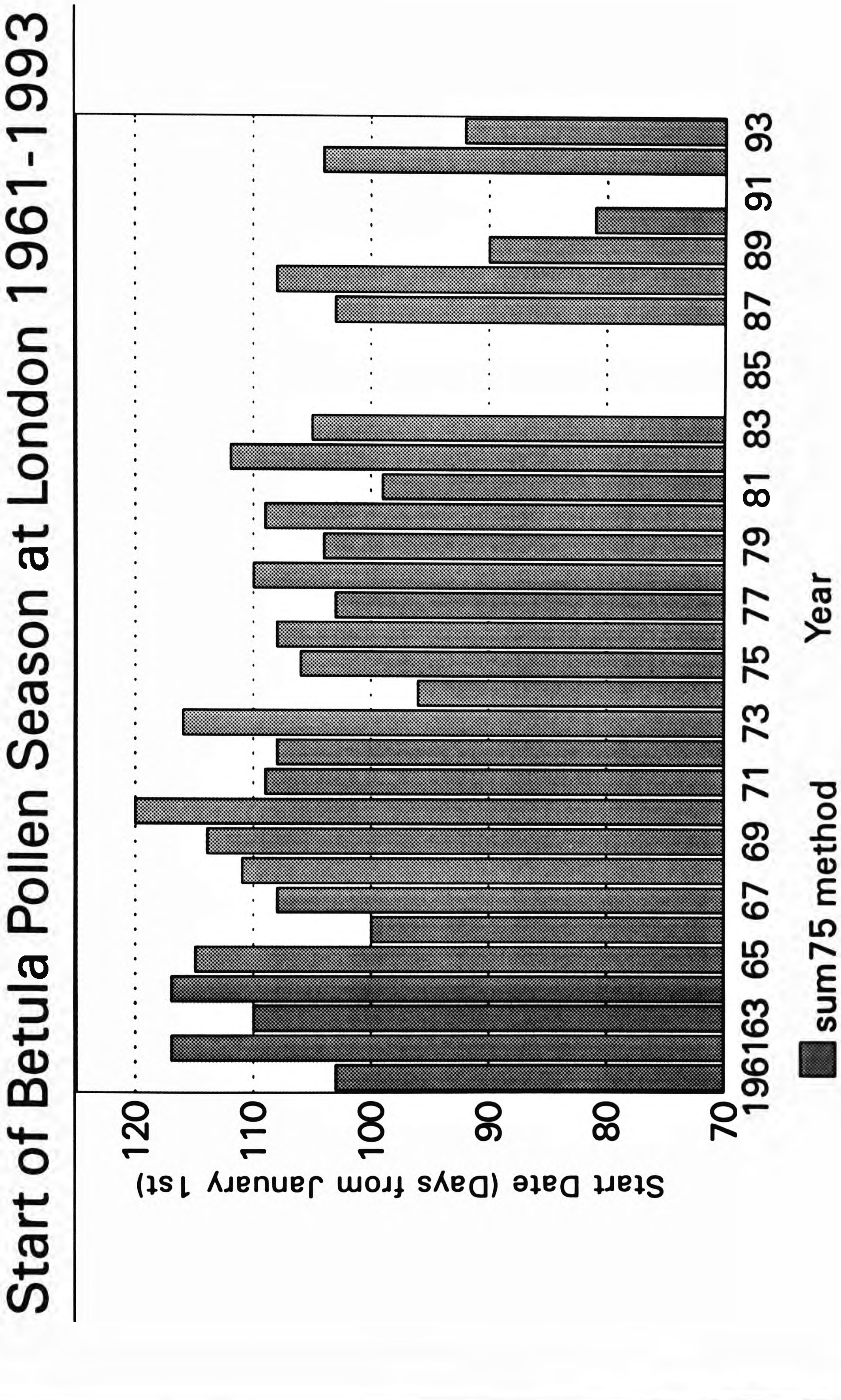
Table XV. Correlation Results to Establish the Relationship between Mean Monthly Spring Temperatures and the Total Seasonal Catch

	LONDON	CARDIFF	DERBY	EDINBURGH
Mean Dec temps	r=0.861 p<0.01	r=0.362 n/s	r=-0.677 p<0.1	r=-0.709 p<0.1
Mean Jan temps	r=-0.601 p<0.1	r=-0.622 p<0.1	r=0.147 n/s	r=0.275 n/s
Mean Feb temps	r=0.182 n/s	r=-0.133 n/s	r=0.289 n/s	r=0.348 n/s
Mean Mar temps	r=-0.643 p<0.1	r=-0.809 p<0.01	r=-0.071 n/s	r=0.945 p<0.001

No relationship was found at any of the sites with more than 5 years of data between preseasonal rainfall, or rainfall in March and April during anthesis, and the total birch pollen catch. However, a negative relationship was found at Derby with March rainfall ($r=-0.792$, $p<0.02$).

The biennial flowering pattern of birch was discussed in 5.2.3, however as the data for the EAN(UK) sites runs over such a short time span, it was not possible to make any conclusions concerning trends or biennial rhythmic patterns in the data. The only biennial rhythm that appeared in the data was during the period 1987 to 1989 at London, Cardiff and Derby where there was a 'high', 'low', 'high' pattern for the three years, and then for all of the sites during the period 1992 to 1994, there was a pattern of 'low', 'high', 'low' (Table XIV). This synchronisation in 'high' and 'low' years at all of the sites in the years 1987-1994 is probably a result of a combination of synoptic situations over the country in the preseason period resulting in warm and cool spring temperatures being experienced over the whole country in these years.

FIG 18


Start of Betula Pollen Season at London 1961-1993
Start Date (Days from January 1st)
120
110
100
90
80
70
196163 65 67 69 71 73 75 77 79 81 83 85 87 89 91 93
Year
sum75 method

5 Year Running Means for the Start of the Betula Pollen Season in London 1961-1993

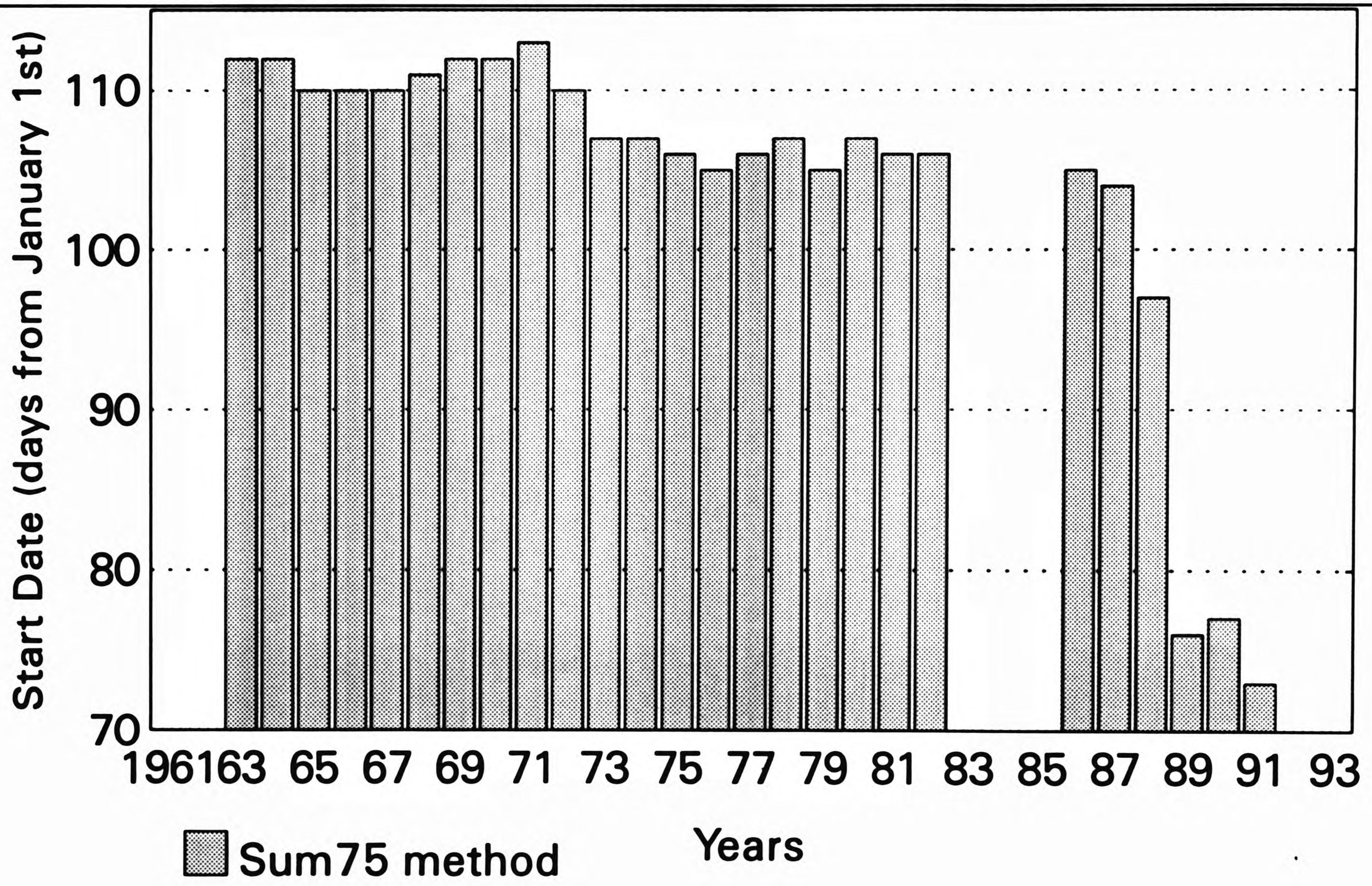


FIG 19

Start of Betula Pollen Season at Cardiff 1963-93

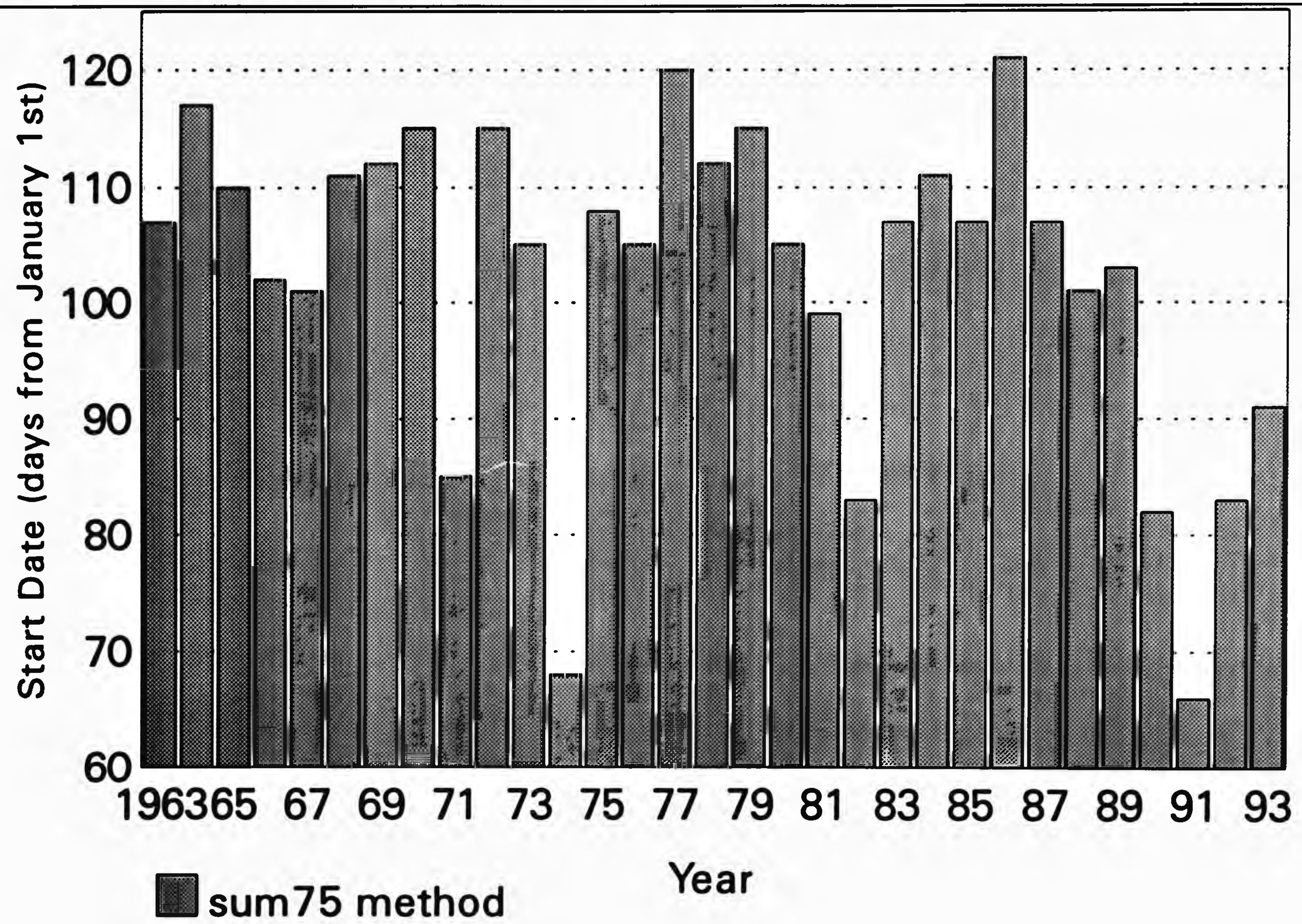


FIG 20

5 Year Running Means for the Start of the Betula Pollen Season in Cardiff 1963-1993

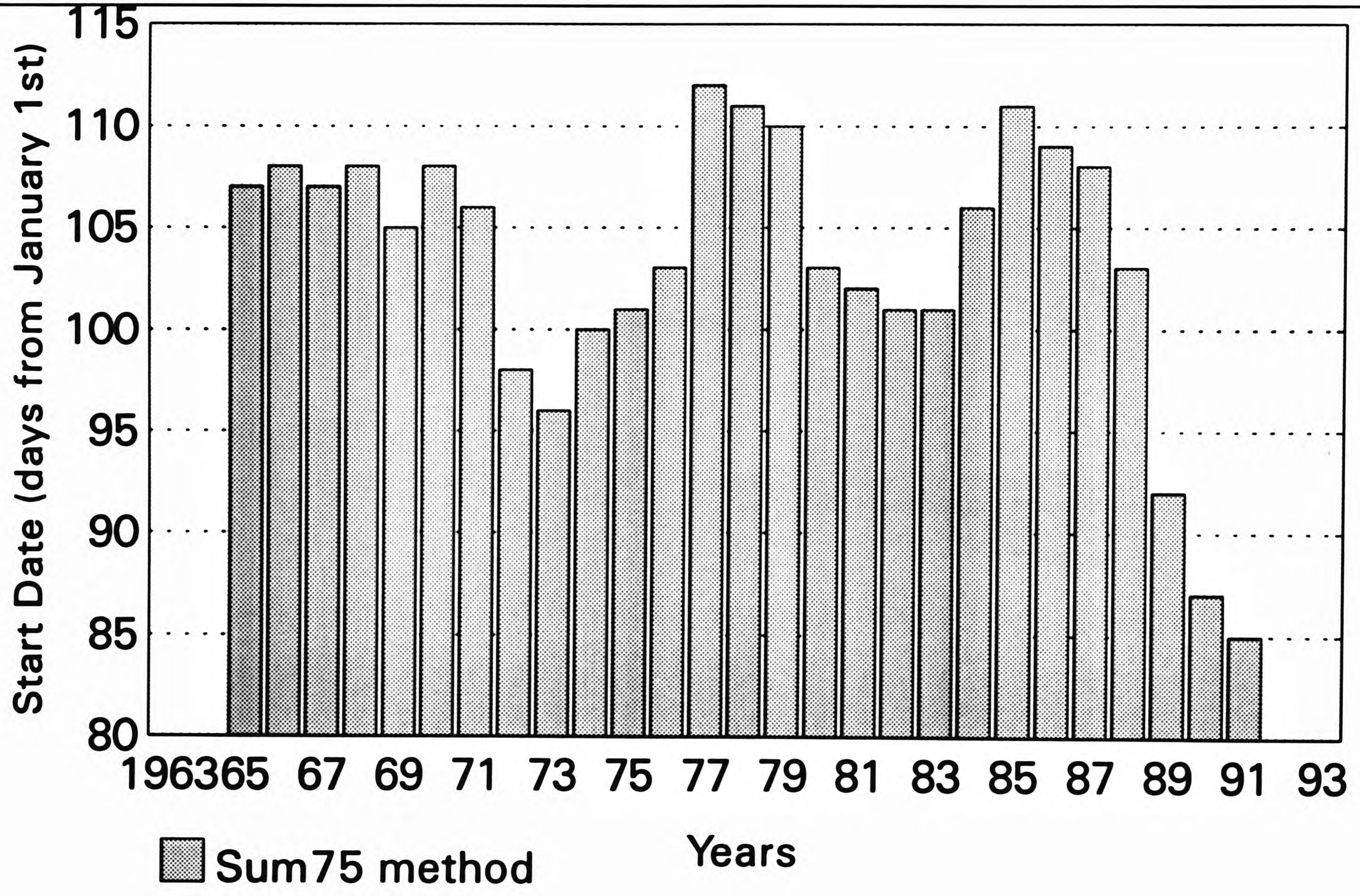
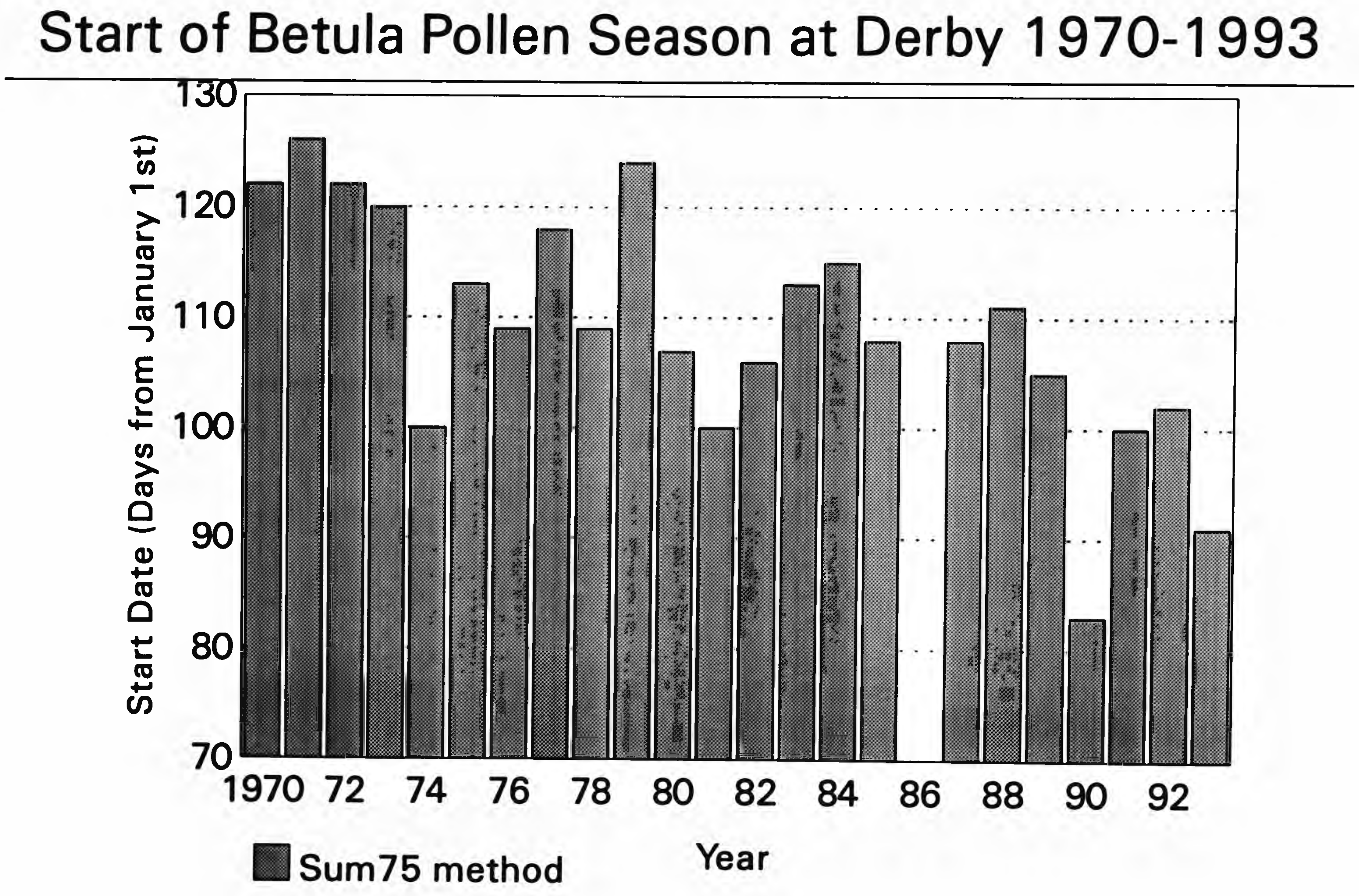


FIG 21

FIG 22



Start of Betula Pollen Season at Derby 1970-1993

5 Year Running Means for the Start of the Betula Pollen Season in Derby 1970-1993

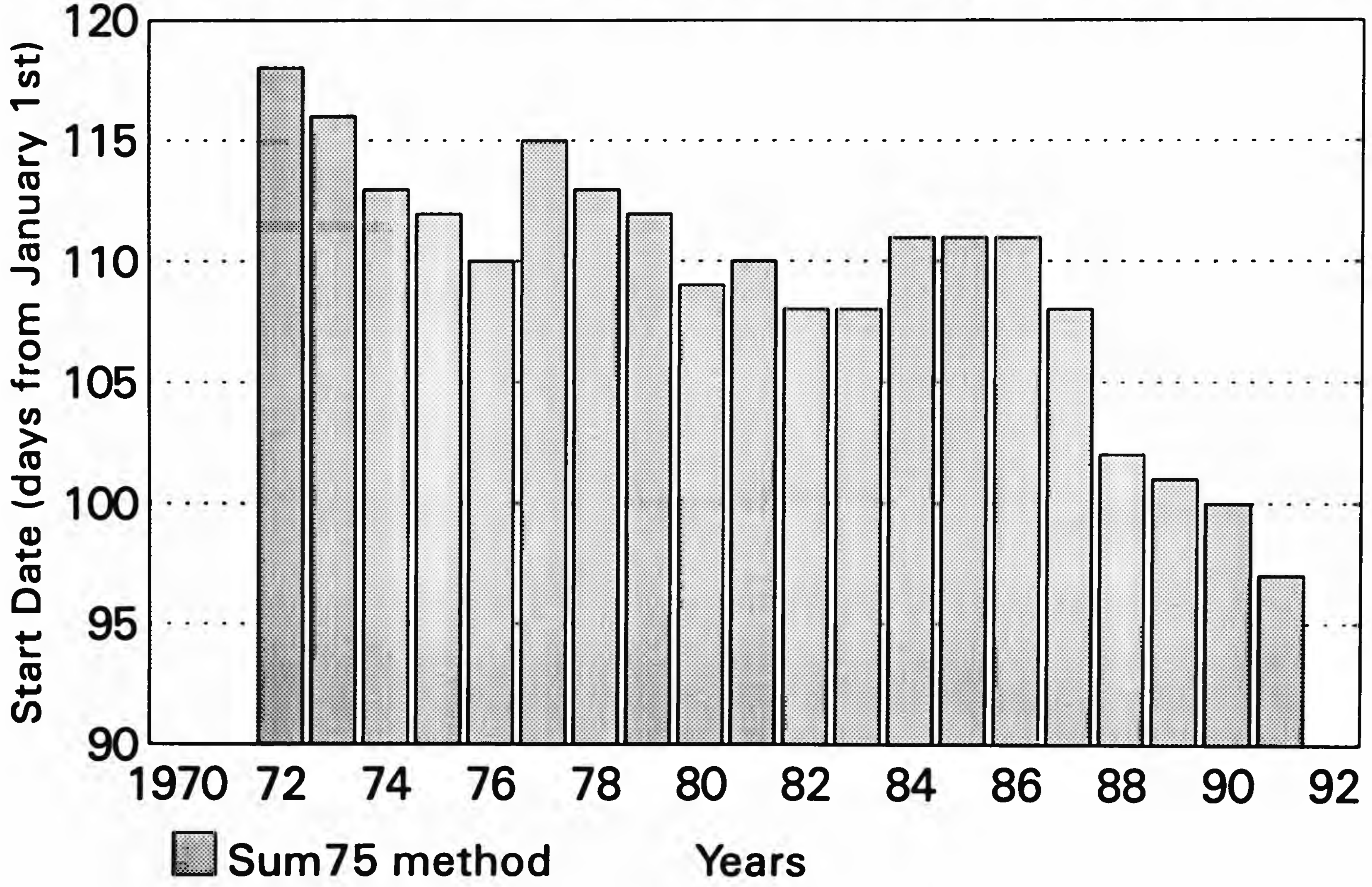
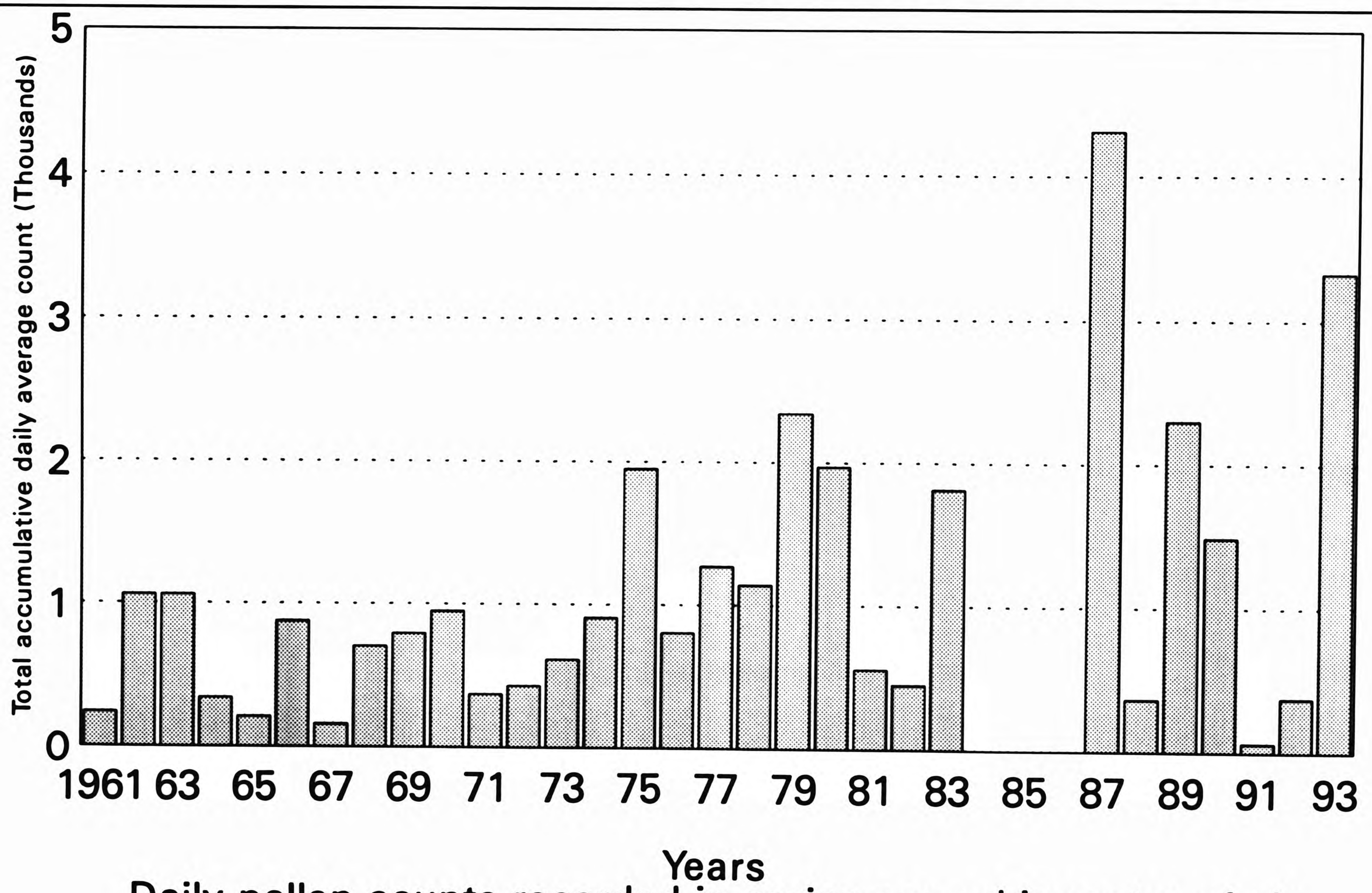


FIG 23

Total Betula Pollen Counts for London 1961-1993



Daily pollen counts recorded in grains per cubic meter of air

FIG 24

Severity of Betula Pollen Season at London 1961-1993

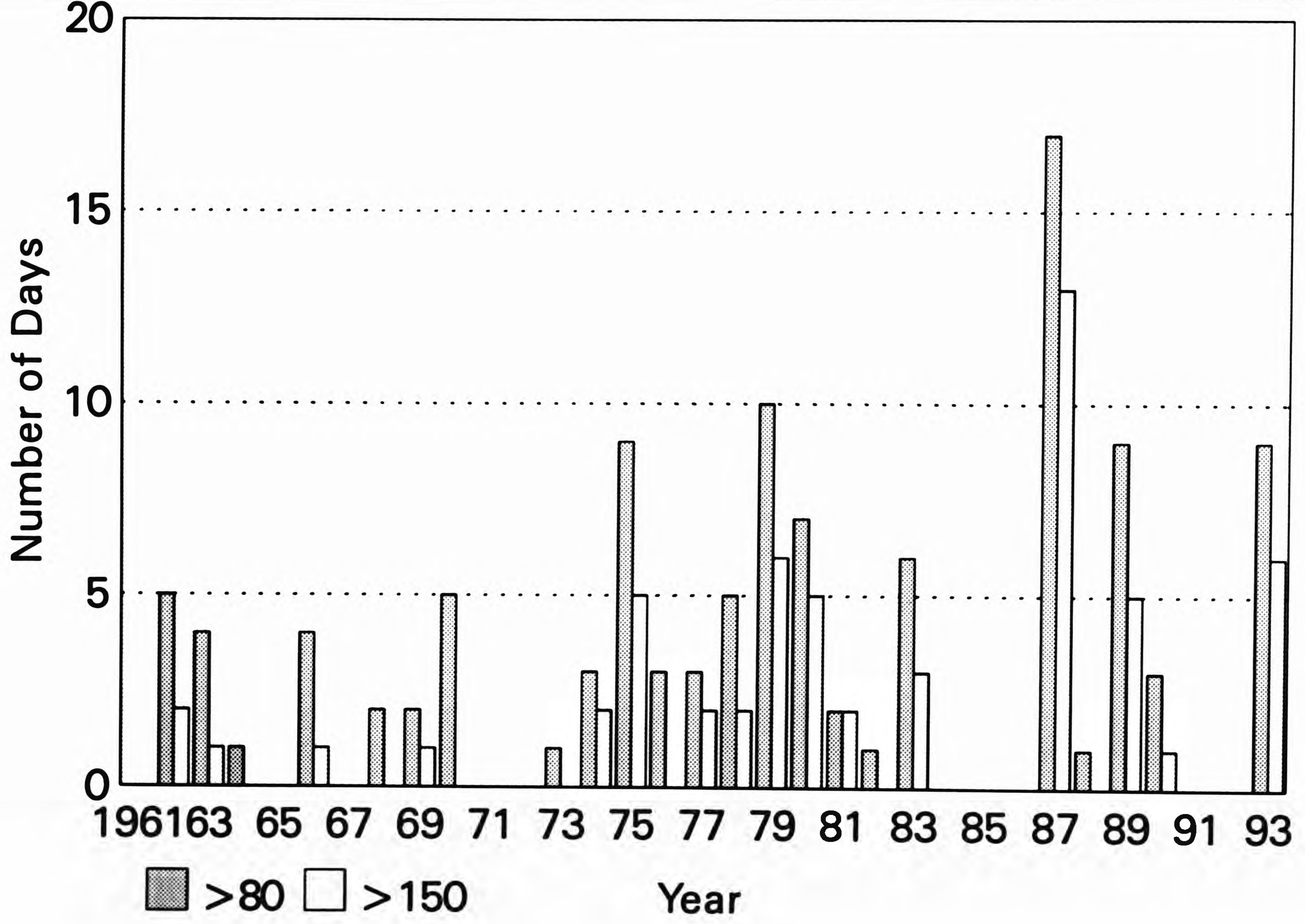


FIG 25

FIG 26

Total Betula Pollen Counts for Cardiff 1963-1993

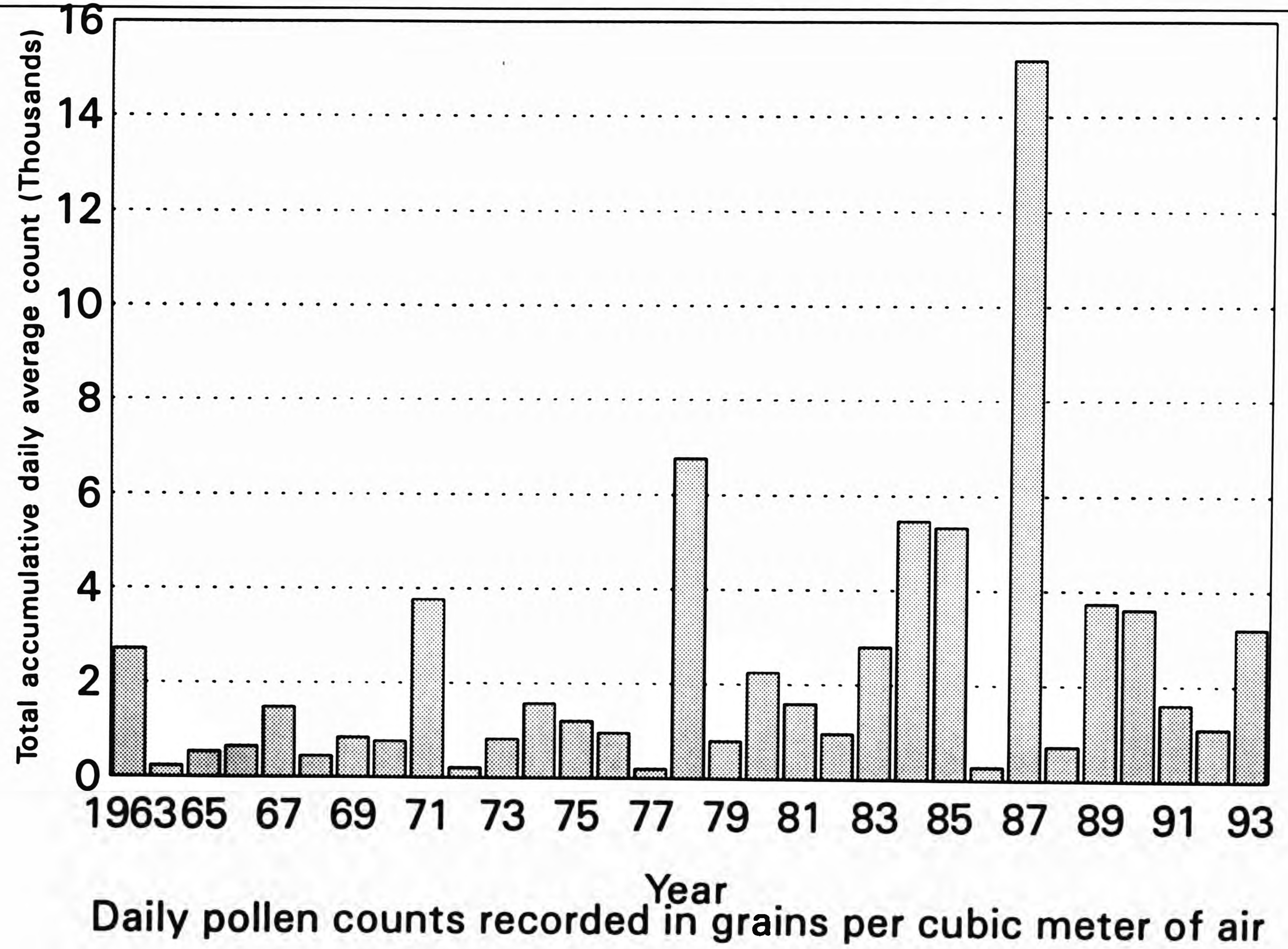
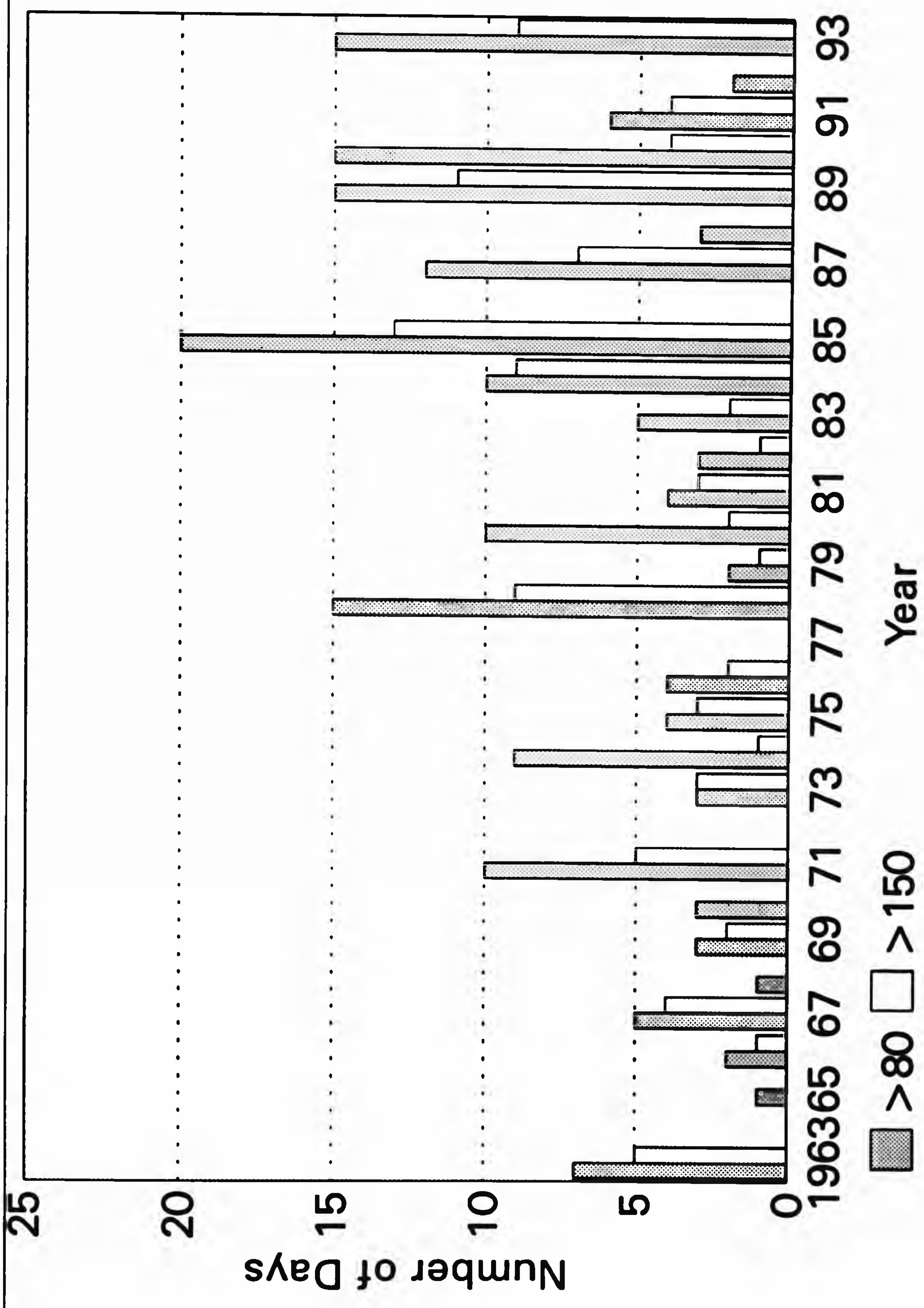


FIG 27

Severity of Betula Pollen Season at Cardiff 1963-93



Total Betula Pollen Counts for Derby 1970-1993

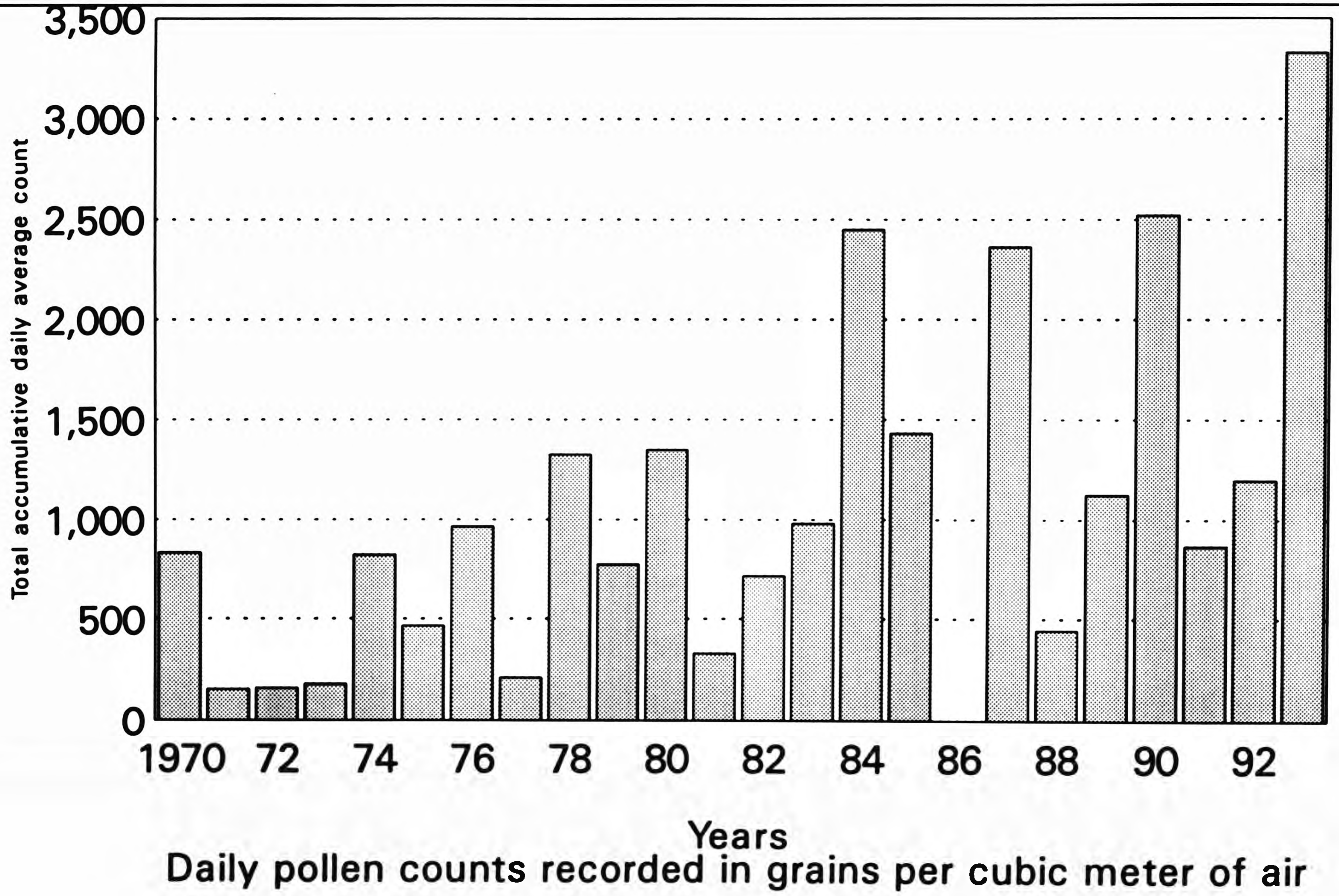


FIG 28

Severity of Betula Pollen Season at Derby 1970-1993

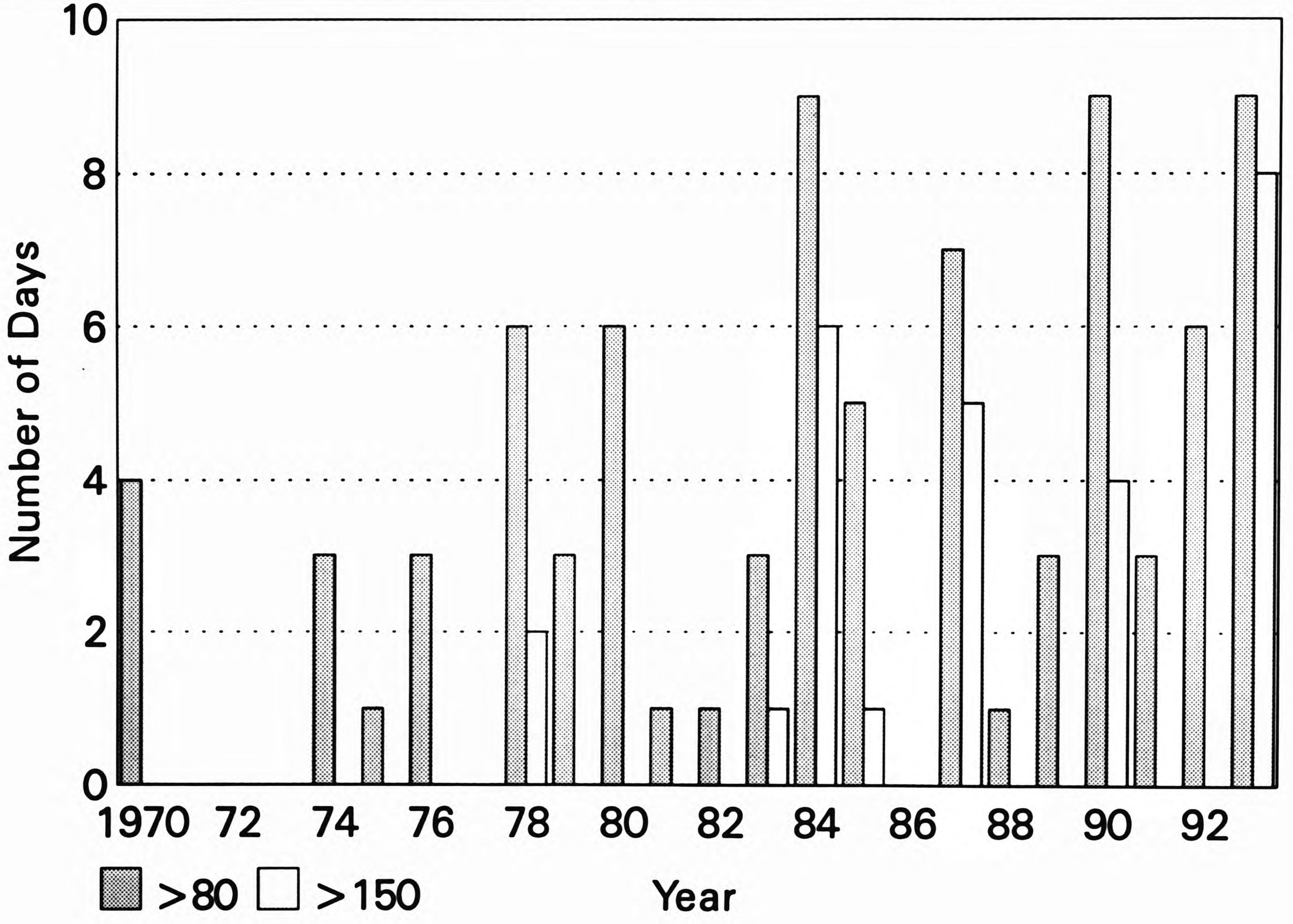


FIG 29

CHAPTER 6 - MODELLING THE START AND SEVERITY OF THE GRASS POLLEN SEASON AT THE THREE LONG TERM DATA SITES IN THE UK

6.1 INTRODUCTION

The literature review (Section 2.5) has highlighted the many and varied approaches to the modelling of concentrations of *Gramineae* pollen. One of the earliest papers concerning the modelling of the start and severity of the grass pollen season was by Davies and Smith in 1973 (1973b). Their work was based on a 10 year record of grass pollen in London, and they concluded that the start of the season was dependent on the mean air temperature in April and May, ie. during the period of pollen formation. Andersen (1980) working in Denmark reported that by performing a regression analysis with the mean maximum temperatures and precipitation for April and May it is possible to predict the start of the grass pollen season. In 1982, Bringfelt *et al* built a model to predict the start of the grass pollen season in Stockholm on the basis of a multiple regression analysis. The model proved accurate to a level of 58%. Spieksma *et al* in 1985 suggested that, based on 5 years observations, the start of the season in the Netherlands was triggered by a rise in temperature in the last week of May. He concluded that one of the main problems was that a long term prediction could not be made on the basis of this, but a short term prediction reached an accuracy of over 80%. The methods described so far have all involved the development of regression models on the basis of some form of correlation or regression analysis. Studies using slightly different forecasting methods have been published by Driessen *et al* (1989,1990) who forecast the start of the grass pollen season to an efficiency of 50% using an indicator species, in this case birch. This method proved rather inaccurate however and did not consider the biennial flowering pattern of the birch. Larsson (1993) attempted to predict the start, peak and end of the grass pollen season using an activity formula based on the fact that activity doubles every 10°C increase in temperature. The main problem with this model is that it could only be used retrospectively. Up until 1993, no work on *Gramineae* concentrations had taken place in the UK. Emberlin *et al* (1993b) built models to predict the start, severity and length of the grass pollen season in London over a period of 30 years. In this study the start of the season was predicted with an explanation of 49% of the variance using a combination of mean values of accumulated temperatures for Heathrow and Rothamsted for the months January to May inclusive and total rainfall in London in March, April and May. 66% of the variance was explained for the severity of the season using the sum75 start date at St Mary's Paddington along with mean cumulated temperatures for March, April, May and June, and total precipitation in June for London. Although similar statistical methods were used in many of the models, the results and basis on which the models were built were quite different.

Chapter 4 has determined that the main controlling variables on the start of the grass pollen season were temperature and precipitation. Barnard (1964) also suggested that photoperiod played an important role in the initiation of flowering in some species, whereas thermal response proved important in other species. Annual grass pollen sums and start of season dates vary markedly from year to year. An accurate forecast of these variations is desirable for many applications (as discussed in section 1.3). The aim of this chapter therefore is to develop models at the 3 separate sites to forecast the start of the grass pollen season and annual grass pollen sums in advance of the season.

The studies published on the modelling of the start and severity of the grass pollen season (as discussed earlier and also in section 2.5) have been based on relatively short runs of data. This research is novel in attempting to forecast the characteristics of the grass pollen season on the basis of data sets of between 24 and 30 years in length at 3 sites in one country. This data is unique in almost certainly being the longest database that exists in the world at 3 sites in the same country.

6.1.1 The Statistical Techniques used in the Development of the Forecast Models

One of the problems faced when considering developing predictive models is deciding on the statistical method that is to be used. The two main statistical methods proposed for a study of this sort were time-series analysis and regression analysis.

Time-series analysis can be used where there are variables that change with time within a data set, for example the annual variation in the start of season date of the annual pollen concentration (Chatfield 1989). The main problem with this method however is that it assumes that the season depends on the previous season, and is best used when the variation in the data is dominated by some sort of trend. When examining data subject to seasonal variation one of the main problems is knowing whether or not the variation is purely seasonal, or whether some other factors are involved. Overall, time-series is a method used best where daily pollen counts are autocorrelated (ie. where a value is related to the value that precedes it). Time-series analysis is therefore best used on the daily prediction of pollen counts as opposed to the prediction of annual concentrations. Moseholm *et al* (1978) used time-series techniques to forecast *Gramineae* pollen counts in Denmark.

Another method for the study is regression analysis. Regression analysis is a technique used for establishing a relationship between different sets of data. It is also useful in that it enables predictions on a new sample of observations based on findings of a previous sample. Because regression analysis provides a way of empirically identifying how a variable is affected by other variables, this was the method used in this study. There are various methods of regression analysis, however stepwise multiple regression analysis was used in this study. Multiple regression analysis allows the determination of whether a relationship exists between several independent variables and a dependent variable. The main problem with this however is that the result considers all of the variables together rather than their individual significance. The stepwise procedure was selected. By this method, variables were entered into the model one by one. After the entering of each new variable, the stepwise procedure examines every variable already in the model to check whether or not it should be deleted. A further reason for the use of stepwise regression analysis was that it is a relatively simple method, and new data can easily be incorporated into the analysis. The method of forecasting simply involves incorporating the significant meteorological data into the equation in order to produce a forecast, and therefore it is a method that is easily applied.

In this analysis the meteorological data (mean and accumulated temperatures above 5.5°C and precipitation) was aggregated into 10 day periods calculated from either the mean start date for the period, or July 31st (as discussed in sections 6.2.1 and 6.3.1) to a lag of between 150 and 200 days. This resulted in between 45 and 60 meteorological variables being tested against the dependent variable. In order to reduce this number, Pearson Product Moment correlations were performed on the variables with the start of the season dates and annual totals. The variables that proved to be most significant were selected and put into the regression analysis.

One of the pre-requisites for multiple regression analysis is that there must be at least 10 data points in order to obtain a accurate result. This was not available at the EAN(UK) sites, and therefore the models have been built on the basis of the long term data at the 3 sites, London, Cardiff and Derby. In chapter 8 the performance of the models in forecasting pollen counts during the 1993 and 1994 season was then assessed and the models tested on the EAN(UK) short term data sites to establish their efficiency.

6.2 MODELLING THE START OF THE SEASON

6.2.1 Methods

In the forecasting of the start of the grass pollen season at London, Cardiff and Derby based on 23-30 years of data, the parameters used were daily average temperatures compiled to monthly means, cumulated temperatures as day degrees above 5.5°C, and total monthly precipitation. Sunshine hours and relative humidity were not included because these are autocorrelated with the main variables. Wind speed was initially incorporated into the models (wind direction was not as a result of the nature of the data) however it did not improve the level of significance and therefore was removed in order to ease the use of the models. Another reason for the removal of the wind data was that the overall aim was to produce accurate models that can be used with easily acquired meteorological data. Temperature and rainfall data are readily available from the media, however detailed wind information can only be obtained through the Meteorological Office and this can be expensive, and due to the variation in wind speed throughout the day there is a problem in deciding when the best time was to take the wind direction reading.

When the start dates were correlated with the monthly aggregated variables then put into the multiple regression analysis a relatively low level of explanation was achieved in most cases. In order to increase the level of explanation, various other variables were tested, for example the meteorological data was aggregated into 5 day, 10 day and 20 day periods from 150 and 200 days before the mean season start date as this would take into account conditions both in the spring and the winter period. These aggregated variables were then correlated with the start of season dates and where significant linear relationships between start dates and these meteorological variables were identified they were processed through a stepwise multiple regression analysis to identify which parameters explained most variation in the start dates. The 10 day aggregated variables gave the highest level of explanation.

6.2.1.a London

The 1960s data was excluded from the modelling as analysis of variance tests showed that these data were different from that for 1970 onwards, largely as a result of differences in the magnitude of pollen counts. Detrending the data was not considered to be appropriate because the grass seed mix had changed (Emberlin *et al* 1993b). Predictive models for the start of the season were derived using the data for the years 1970 onwards since the pollen record for this period was considered as one population.

The meteorological data for the analysis of the London grass pollen start dates was taken from two separate meteorological stations (see 4.2.1.a). This therefore takes into account the climatic conditions in the rural source area north of the pollen site, and also conditions in the more urban central London area. Variables from the two sets of meteorological data were incorporated into the model.

Using the meteorological variables in the form of monthly aggregates, an Rsq value of 57.6% was achieved using a combination of mean and accumulated temperatures in January and April respectively, and rainfall in March. The regression equation for the model is shown below.

$$\textbf{Sum75 start} = \mathbf{149.43 + 0.09a + 0.178b - 0.132c}$$

a = total rainfall in March (Heathrow)
b = mean temperatures in April (Heathrow)
c = accumulated temperatures above 5.5°C in January (Rothamsted)

The accumulated temperatures in January at the Rothamsted meteorological site represent temperatures in the rural source areas which can influence the early growth of those grass species which have a thermal response independent of photoperiod. Temperatures and rainfall in the spring are expected to exert a great influence on growth rates and flower maturation in all grass species.

When the meteorological data was aggregated into 10 day periods calculated from the mean start date (May 31st), a much higher level of explanation was achieved. An Rsq value of 96.1% was achieved using a combination of accumulated temperatures above 5.5°C and rainfall.

Sum75 start = 190.95 - 0.55a + 0.91b - 0.26c - 0.62d + 0.79e - 0.53f - 0.1g

a = accumulated temperatures 25 May-3 June (Rothamsted)
b = total rainfall 24 February-5 March (Rothamsted)
c = total rainfall 14-23 February (Rothamsted)
d = total rainfall 24 February-5 March (Heathrow)
e = accumulated temperatures 14-23 February (Rothamsted)
f = accumulated temperatures 15-24 January (Heathrow)
g = accumulated temperatures 15-24 April (Heathrow)

In a similar way to the model based on monthly aggregated meteorological data, accumulated temperatures mid January to the end of February would have been critical in the influence of soil temperatures and the development of the grasses. Once the grasses had developed, temperatures in the last part of April and May would have determined the release of pollen. Rainfall would have been significant in providing sufficient moisture throughout February for grass development.

One of the main problems with this model is that meteorological variables up until June 3rd are required, and as the mean start date is May 31st, it implies that the start of the season in some cases cannot be predicted until after it has started. In order to overcome this a long term weather forecast 30 days in advance can be used and thus the start date can be predicted from May 4th, the accuracy of the prediction in this case would depend on the accuracy of the 30 day weather forecast.

The actual start of season dates were plotted with the predicted start of season dates and it was found that the predicted start date was within less than 2 days of the actual start date on 90% of occasions, in the other years, ie. 1984 and 1985, the predicted start date was within 3 days of the actual start (Fig 30).

6.2.1.b Cardiff

Analysis of variance tests showed that the start dates in the 1960s were significantly different to that for the 1970s onwards, and therefore predictive models have been derived using the data from 1970 onwards.

In 4.2.2.b correlations were performed to establish relationships between start dates and preseasonal accumulated temperatures, mean monthly temperatures and total monthly precipitation. Very weak trends were found, and none of these proved to be significant. When the monthly aggregated variables were incorporated into the stepwise regression analysis, none of them proved to be particularly significant and therefore a regression model on the basis of this was not established.

When the meteorological data was aggregated into 10 day periods an Rsq value of 66.5% was obtained using a combination of mean temperatures and rainfall.

$$\mathbf{Sum75\ start = 143.58 - 1.22a + 0.225b - 0.104c}$$

a = mean temperatures 19-28 February
b = total rainfall 10-19 April
c = total rainfall 30 January-8 February

The mean temperatures in mid February would have been important in a similar way to that in London, in that they influence the soil temperatures and the early development of grasses. Rainfall would also be important around this time in providing sufficient moisture for development. Unlike London, variations in spring temperatures did not appear significant in influencing the start of the season. This is most likely to be a result of spring temperatures at Cardiff being more uniform and hence resulting in only small amounts of variation from year to year. However, it could also be a result of Cardiff being a maritime site under the influence of the warming North

Atlantic Drift and therefore under the influence of warmer temperatures than at London and Derby, and therefore the presence or absence of rain during the period before anthesis would be more important.

When the actual start dates were plotted with the predicted start dates it was found that on 74% of occasions the predicted start was within 4 days of the actual start date, and on 91% of occasions the predicted start was within 7 days of the actual start. The only larger differences were found in 1982 when the actual start was 8 days later than the predicted start (Fig 31).

Using this model it was possible to predict the start of the grass pollen at Cardiff by April 20th ie. 28 days before the mean start date for the period 1970-1992 (May 17th).

6.2.1.c Derby

The pollen data for the entire period 1969-1992 was treated as one population as analysis of variance tests showed no difference in the data from the different decades.

In section 4.2.2.c a relationship was found over the period 1969-1992 between start dates and accumulated temperatures. When the monthly aggregated meteorological variables were used in the regression analysis accumulated temperatures in April proved to be most significant, but only produced an Rsq value of 22.9%.

$$\textbf{Sum75 start} = \mathbf{148.57 - 0.007a}$$

a = accumulated temperatures in April

When the 10 day aggregated variables calculated from the mean start date (May 28th) were correlated with the start dates and incorporated into the stepwise multiple regression analysis an Rsq value of 76.2% was obtained. In a similar way to London and Cardiff, accumulated temperatures in the late winter at the time of pollen development, and then temperatures and rainfall close to the start of the season appeared to be important.

$$\textbf{Sum75 start} = 147.32 + 0.43a - 0.213b + 0.574c$$

a = total rainfall 8-17 May
b = accumulated temperatures 28 April-7 May
c = accumulated temperatures 18-27 January

When the actual start dates were plotted with the predicted start dates the predicted start dates occurred within 4 days of the actual start dates on 63% of occasions. It was mainly at the beginning of the monitoring period when there were greater differences, for example in 1969 the predicted start date was 27 days later than the actual start date, this was probably as a result of there being 226% rainfall compared with the long term average for the period 8-17 May, and also accumulated temperatures during the period 28 April and 7 May being 9.7°C below the average for the period 1969-1992 (Fig 32).

Application of the model could enable the prediction of the start of the grass pollen season by 18th May, 10 days before the mean start date. Alternatively, with the aid of an accurate 30 day weather forecast, a prediction could be made by mid April.

6.2.1.d Discussion

The flowering of grasses has been studied for over 100 years (Godron 1873), and there has been great controversy over what actually initiates the various stages. Lang (1952) stated that "floral initiation is by far the most fundamental stage" of development. Gregor (1928), Kramer (1932), Davidson (1941) and Jones and Brown (1951) all emphasised the importance of temperature for anthesis. Cocks (1958) considered humidity to hinder anthesis, whereas Gregor (1928) thought that humidity promoted it. Thus there are a great number of factors concerned with the development of the grass and the later stage of anthesis.

This analysis has highlighted that the sites have a varied response to the variables of mean and accumulated temperatures and rainfall in relation to time.

One of the main problems in predicting the start of the season concerns the varying physiological response of the various grass species to environmental factors. Over 150 grass species exist in Britain and these all have a varying response to temperature, rainfall, photoperiod etc. The different species of grasses flower at different times during the season. *Anthoxanthum pratensis* and *Anthoxanthum ordoratum* flower early, whereas *Phleum pratense* flowers much later in the UK (Godron 1873, Beddows 1931). One annual grass species is an exception to this orderly sequence - *Poa annua* - which flowers all year round.

It has long been reported that the flowering process in perennial grasses is initiated by a species-specific critical day length in the period February to May (Cooper 1952, Ryle and Langer 1963). Some species require prior exposure to a period of cold temperatures before they become sensitive to photoperiod (Roy and Peacock 1972). The models for London and Derby show the importance of temperatures during the spring in the next stage of development. In the next development stage the stem apex develops into an inflorescence initial (Ryle 1972) and the rate of this is temperature dependent. There is a temperature below which development will not proceed (Beddows 1968, Roy and Peacock 1972) which is lower for the earlier flowering grasses (which are initiated in February) than for the late flowering grasses (which are initiated in May). The lack of significance of spring temperatures at Cardiff, as discussed earlier (Section 6.2.1.b) could either be that temperatures in Cardiff during this period are sufficiently high as a result of the warming influence of the North Atlantic Drift, or alternatively it could be that there is an abundance of early flowering grasses in the Cardiff source area which respond to temperatures in February (as apparent from the Cardiff predictive model). This would also explain the earlier start to the season in comparison with the other sites, as has been discussed in chapter 4.

Once the inflorescence has expanded, flowering awaits a warm dry day with a light breeze (Godron 1873, Anslow 1963, Emecz 1962). Some inflorescences complete their flowering in a single day but most take several days for all the flowers in the head to open. The critical meteorological parameters for each stage prior to flowering vary for each species and thus it is difficult to forecast when flowering is going to start when there are great number of species concerned.

Overall, the three models, enabling the prediction of the start of the grass pollen season within 4 days of the actual start date on 100%, 77% and 61% of occasions at London, Cardiff and Derby respectively, are considered to be adequate in the forecast of the start of the grass pollen season at the three sites.

6.3 MODELLING THE SEVERITY OF THE SEASON

6.3.1 Methods

Results presented in chapter 4 suggested that the severity of the individual grass pollen seasons depend partly on the weather conditions during the late spring when the pollen forms in the anthers, partly on the weather during anthesis, and partly on the amount of grassland in the source area. An estimate of the severity of the season can be made from a combination of some of these factors.

The severity of the season was modelled using correlation and multiple regression. However,to use these methods the pollen data has to be normally distributed. When the data was plotted it was found to be skewed at all three sites and therefore it was square rooted in order to produce a normal distribution.

The same meteorological variables were used as for the modelling of the start of the season (see section 6.2.1). That is, daily average temperatures compiled to monthly means, accumulated temperatures as day degrees above 5.5°C, and total monthly precipitation. The start of season dates were also included in the analysis. When the monthly aggregated meteorological variables were correlated with the seasonal totals to establish relationships and then used in the multiple regression analysis, a relatively low level of explanation was achieved. Therefore the meteorological variables were aggregated into 10 day periods calculated back 200 days from July 31st. July 31st was selected as very few counts over 50 grains/m^3 of air occur after this date, and highest counts occur in either June or July. It also represents the main period of anthesis. The 10 day aggregated variables that appeared most significant following correlation tests were then incorporated into a stepwise multiple regression analysis.

6.3.1.a London

As for the modelling of the start of the season, the 1960s data was not included in the predictive modelling as a result of the differences in the magnitude of pollen from the 1960s to the present. The model was therefore based on data from the 1970s onwards.

The meteorological data for the analysis was taken from two meteorological stations, one located outside the urban area at Rothamsted, representing conditions in the rural source area, and one located closer to central London representing conditions in the inner urban area (as mentioned in section 6.2.1.a).

When variables based on monthly aggregates were used the correlations were not significant and when incorporated into a stepwise multiple regression analysis a regression model could not be established.

When the meteorological data was aggregated into 10 day periods a model with a Rsq value of 91.5% was achieved using the actual start date (according to the sum75 definition), accumulated temperatures 12-21 June and 24 March-2 April and total rainfall 2-11 February. It was found that accumulated temperatures and rainfall during the late winter and spring were important along with accumulated temperatures during anthesis. The actual start date was also important in that seasons with late starts tended to have a lower overall annual grass pollen sum ($r=-0.639$, $p<0.01$). In chapter 4 (section 4.2.3.a) it was also shown that seasons that had cool temperatures in June, had their highest total catches in July, and comparatively low overall totals.

Square root of the
Cumulative catch for season = 246.413 - 1.266a - 0.372b - 0.204c - 0.152d

a = actual start date (sum75 definition)
b = accumulated temperatures 24 March-2 April (Heathrow)
c = total rainfall 2-11 February (Heathrow)
d = accumulated temperatures 12-21 June (Heathrow)

An important feature of this model is that meteorological variables at Rothamsted did not prove to be significant. This is probably because the temperatures at Heathrow were more similar to those of Central London, and seasonal severity is more a function of the weather during anthesis which is best reflected by weather conditions closer to the pollen monitoring site.

When the actual totals were plotted with the predicted totals it was found that, using this model it was possible to predict the total seasonal catch by June 21st (Fig 33). On 71% of occasions the total seasonal catch was predicted within 500 grains of the actual total. The only two years when there was a greater than 1500 grains difference between the actual total and the predicted total was in 1970 and 1972. In 1970, this was probably because the period 12 - 21 June had accumulated temperatures 83 Day°C above the period average leading to above average grass pollen totals.

6.3.1.b Cardiff

As there were not so pronounced fluctuations in the total grass pollen catch at Cardiff over the period 1962-1992 as there were in the start of season dates at Cardiff, the complete data set was incorporated into the model.

When the monthly aggregated meterological variables were processed through the stepwise multiple regression analysis an Rsq value of 33% was achieved using total rainfall for April and accumulated temperatures for May. The equation for this model was:

$$\textbf{Square root of total cumulative catch for season} = 39.31 + 0.209a + 0.165b$$

a = total rainfall in April
b = accumulated temperatures in May

Using the 10 day aggregated meteorological variables covering the period from 150 days from July 31st an Rsq value of 53.4% was achieved with rainfall 2-11 June, and accumulated temperatures 3-12 April and 13-22 May.

When analysing the meteorological data aggregated into 10 day periods covering the period from 200 days from July 31st, the relative importance of mean temperatures and accumulated temperatures was tested. Using mean temperatures with total rainfall and start dates an Rsq value of 52.6% was achieved. The Rsq value of 52.6% was achieved using total rainfall 2-11 June, mean temperatures 3-12 April and mean temperatures 13-22 May. It appeared that temperatures in the preseason period and rainfall during the time of anthesis were important.

In order to increase the level of explanation further, both mean and accumulated temperatures were incorporated into the stepwise multiple regression analysis. The meteorological variables for the period of 200 days up to 31st July were included, thus taking account of weather conditions in January and February. The 150 day lag model only took account of the weather conditions from March and therefore excluded the importance of the winter chilling of the soil. The best model produced by the stepwise multiple regression analysis only contained accumulated temperatures and rainfall. An Rsq value of 96.9% was achieved using the variables as shown in the equation below:

Square root of
Cumulative catch for season= -41.997 + 0.434a + 0.267b - 1.69c - 0.151d + 0.638e + 0.348f + 0.157g + 0.329h - 0.35j + 0.181k

a = total rainfall 2-11 June
b = accumulated temperatures 13-22 May
c = accumulated temperatures 22 February - 3 March
d = total rainfall 4-13 March
e = actual start date (sum75 method)
f = accumulated temperatures 23 April - 2 May
g = total rainfall 23 April - 2 May
h = accumulated temperatures 3 - 12 May
j = total rainfall 13-22 January
k = total rainfall 12-21 February

The most significant variables were rainfall in June and accumulated temperatures in May, these two variables alone accounted for 53% of the variance.

In a similar way to the start of the season, temperatures and rainfall during the late winter and spring months also appeared to be important as this is the main period of grass development.

A factor to note about Cardiff, when comparing it with other sites is that total rainfall was more important than temperature, as compared with for example at London and Derby where temperature was a more influencing variable. This was also found in the prediction of the start of the season. This could be a result of Cardiff having a more maritime climate and therefore more heavily influenced by rainfall (as discussed in 6.2.1.b and 6.2.1.d).

When the actual totals were plotted with the predicted totals (Fig 34), on 73% of occasions the predicted total were within 500 grains of the actual total. The largest divergences between predicted totals and measured totals were in 1962 and 1963 when there were more than 3500 grains difference.

6.3.1.c Derby

The whole data set 1969-1992 was used to develop the model at Derby. When the monthly aggregated meteorological variables were incorporated into the stepwise multiple regression analysis an Rsq value of 48.6% was achieved using accumulated temperatures in March and total rainfall in June. This suggests that accumulated temperatures were important in influencing grass development in the spring, and then rainfall had an influence on the amount of pollen that was released in June during the main period of anthesis. The regression equation is shown below.

Square root of cumulative
catch for season = 94.654 - 0.22a - 0.119b

a = accumulated temperature in March
b = total rainfall in June

In order to increase the level of explanation, the meteorological data was aggregated into 10 day periods, the most significant variables were incorporated into the stepwise multiple regression analysis. An Rsq value of 98% was achieved using the following variables:

Square root of
Cumulative catch for season= 83.582 - 0.48a + 0.642b - 0.73c + 0.371d
- 0.35e - 0.503f

a = accumulated temperatures 14-23 March
b = total rainfall 3-12 May

c = total rainfall 24 March - 2 April
d = accumulated temperatures 13-22 April
e = accumulated temperatures 3-12 April
f = accumulated temperatures 23 January - 1 February

Unlike London and Cardiff, accumulated and mean temperatures and rainfall once the season had started did not seem to be important at Derby. Liem (1980) examined the effect of temperature on the anthesis of several species of *Gramineae* and noted that maximum temperatures of around 20°C proved most favourable for pollen production. Maximum temperatures during June and July were correlated with the annual grass pollen sums. The correlations did not prove particularly significant, and when included in the model did not improve the level of explanation. Temperatures during the early stages of grass development at the end of the winter had a significant influence on the total pollen sum in a similar way to the influence that they had on the start of the season.

Using this model the total cumulative grass pollen catch for the season was predicted by May 13th. Predictions could not be made for 1969, 1970 and 1971 due to a lack of accumulated temperature data during the period 13-22 April. On 84.2% of occasions the predicted total was within 500 grains of the actual total. The main differences in predicted and actual totals occurred in 1981 and 1988 following a particularly wet period at the end of March in both years (Fig 35).

6.3.1.d Discussion

These models have shown that similar factors influence the start date and the total seasonal catch, ie. temperatures at the end of winter and the beginning of spring, and temperatures and rainfall during spring. At London and Cardiff the total seasonal catch was also dependent on when the season actually started, however this was not significant at Derby. Also at both London and Cardiff weather conditions during the period of anthesis were significant, however this was not apparent at Derby.

The influence of temperature on the total cumulative grass pollen count may be divided into three components. It will firstly effect the development of pollen within the grasses during the preseason period. Secondly it will effect the release of pollen from the anther, and thirdly influence the dispersal of pollen from the source area to the sampling site. Davies and Smith (1973b) 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 the pollen grains are exposed within the anther, high temperatures will aid in drying grains and then their release. Thus, it can be assumed that ideal conditions for high annual pollen sums would be; warm temperatures in the preseason period and high temperatures and dry conditions during anthesis. The importance of these variables have been shown in the models.

The models for the total seasonal catch have a higher level of explanation than the start of season models because the problem of the variation in the time of flowering is not important here as the total seasonal grass pollen catch takes account of all species irrespective of when they flower.

The main problem with these models is that the total cumulative catch is based on mean daily counts and therefore does not take into account the highs and lows during the day. It also does not predict when the highest total pollen catches are going to occur, for example it does not give any information on whether the majority of pollen will be released in June or July? and when in these months? This would be useful information in the timing of clinical trials and in the alleviation of symptoms. The models do however provide information on whether or not the season will have a higher or lower annual total than average. These problems will be discussed in more detail in section 9.4.

6.4 SUMMARY

The forecast models for the start and severity of the season at the three sites provide a useful basis for forecasting at a relatively early stage in the year. The models also have the advantage of an empirical base which has monitored the biological response of the various grass species to variations in climate. Although it would be better to include phenological changes and also variations in source area, it would be extremely difficult to quantify the relationships between phenology and environment for a mixture of species, and therefore difficult to develop theoretical models on this basis. By using empirical models, if there are any shifts in either the climate or the pollen spectrum, these can be incorporated into the models and the models then adjusted to account for these changes.

Comparison of the Start of the Grass Pollen Season Predicted from the Regression Model with the Actual Values for London 1970-1990

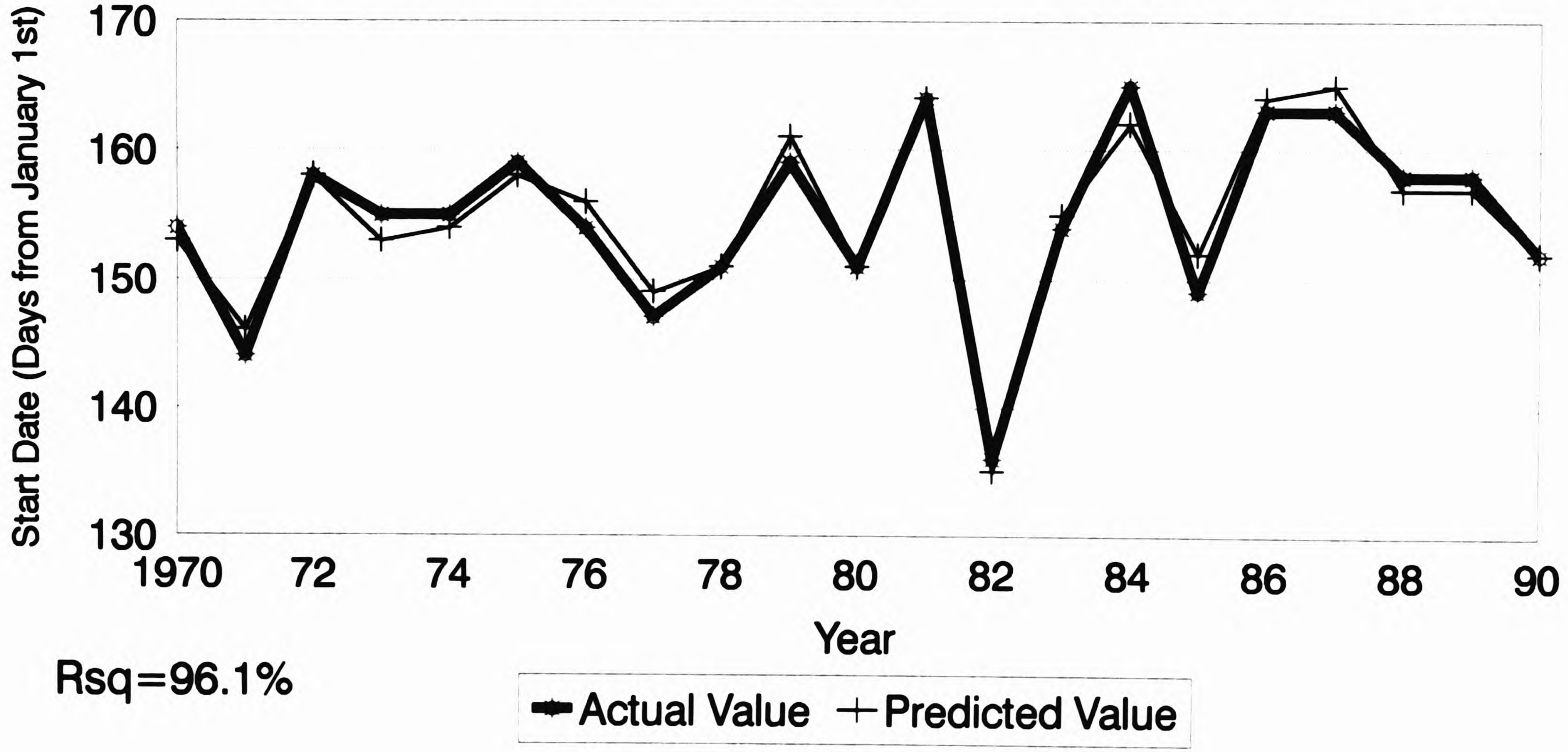
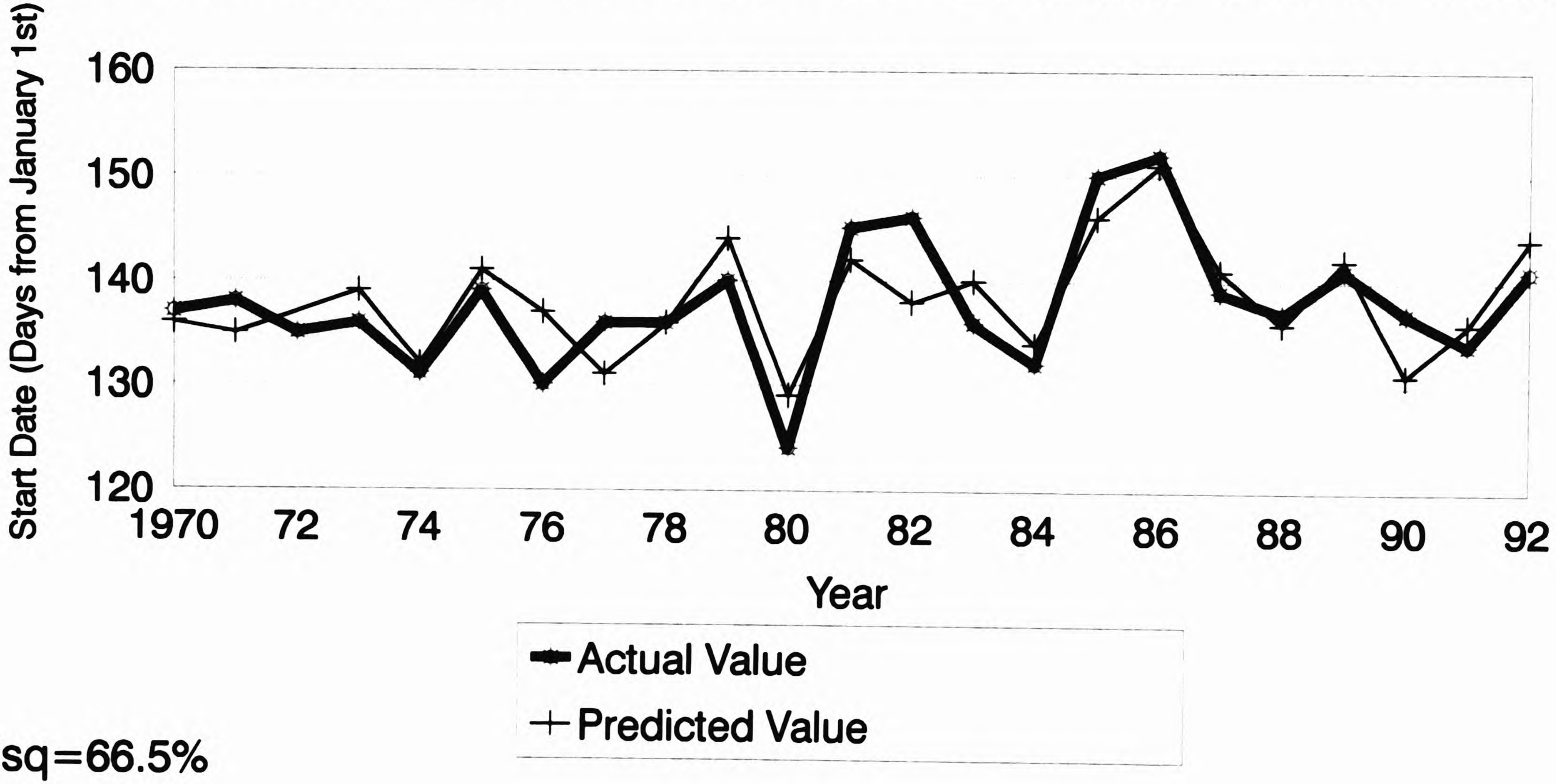


FIG 30

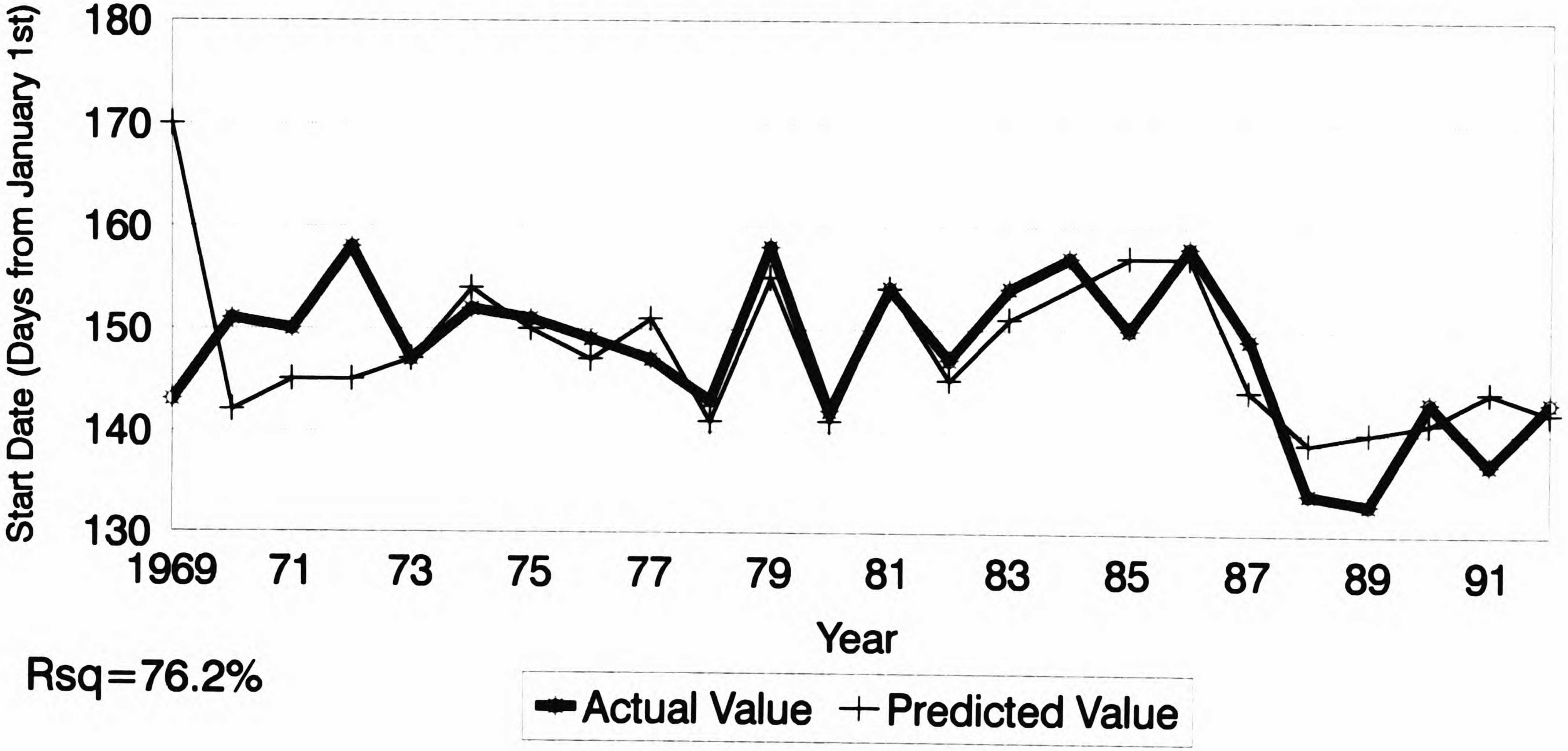
Comparison of the Start of the Grass Pollen Season Predicted from the Regression Model with the Actual Values for Cardiff 1970-1992



Rsq=66.5%

FIG 31

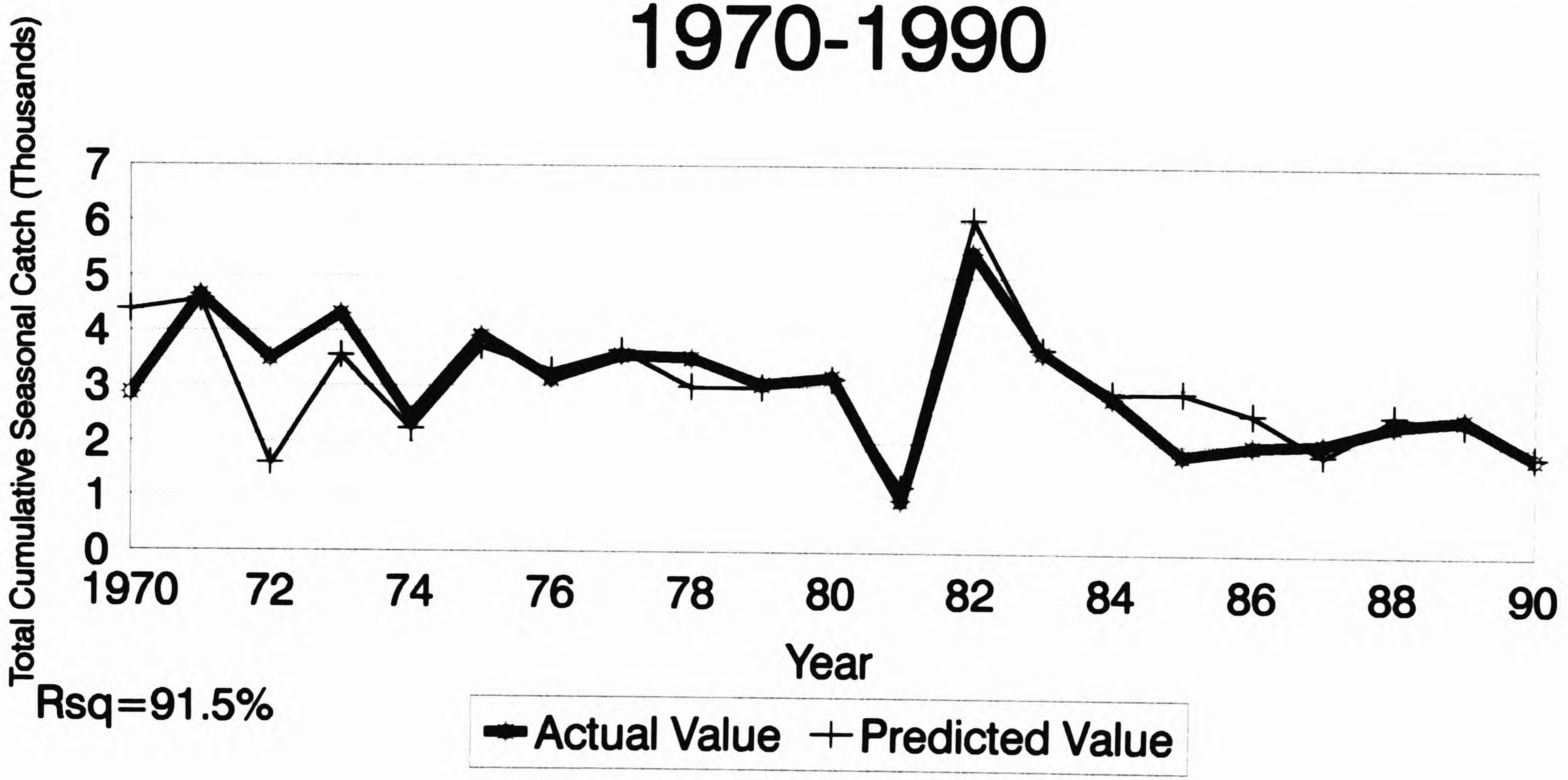
Comparison of the Start of the Grass Pollen Season Predicted from the Regression Model with the Actual Values for Derby 1969-1992



Rsq=76.2%

FIG 32

Comparison of the Total Seasonal Grass Pollen Predicted from the Regression Model with the Actual Values for London 1970-1990



Rsq=91.5%

FIG 33

Comparison of the Total Seasonal Grass Pollen Predicted from the Regression Model with the Actual Values for Cardiff
1962-1992

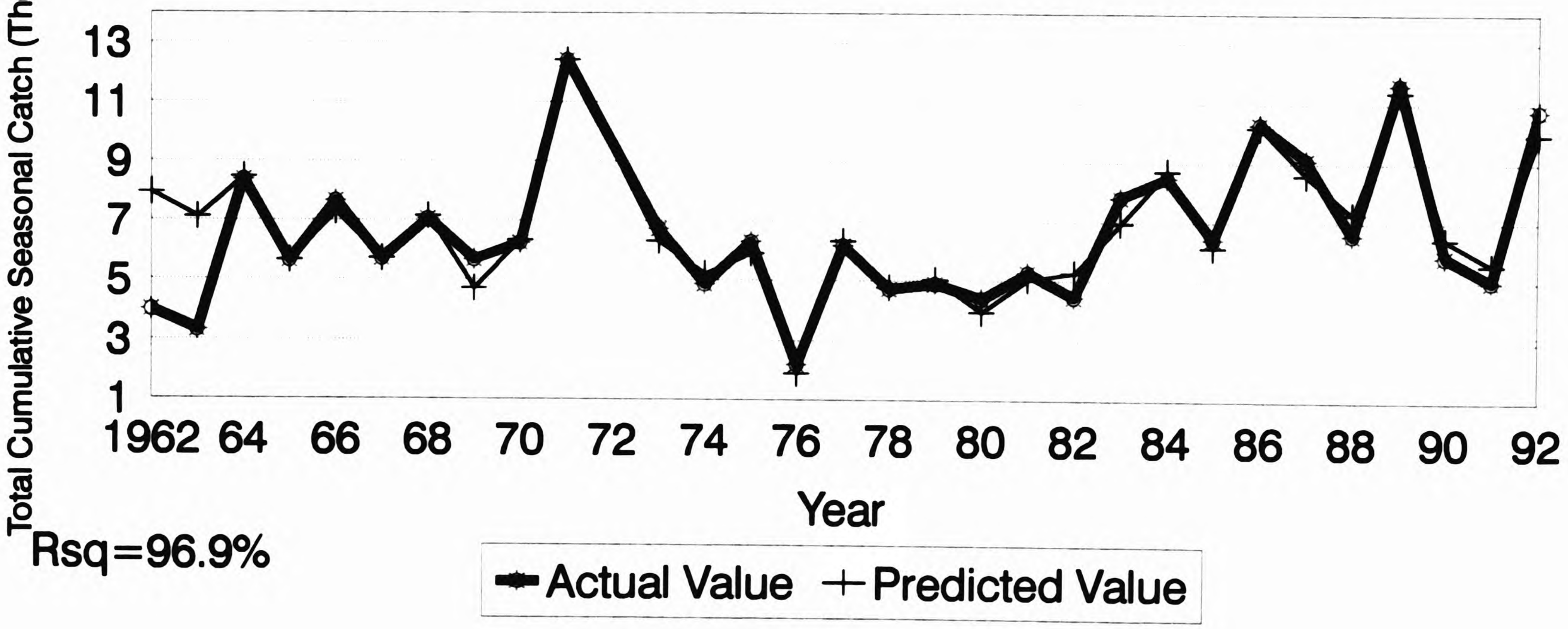
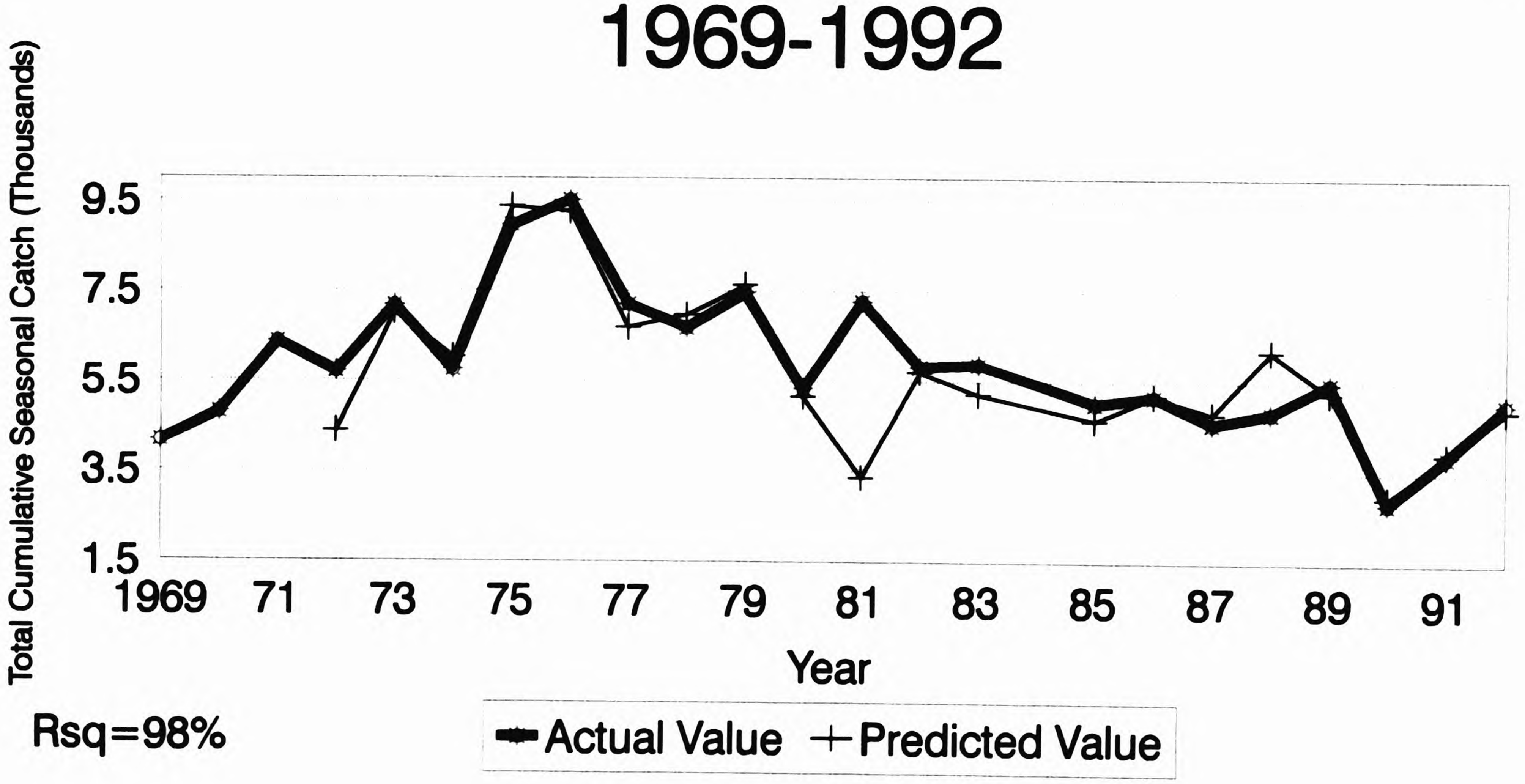


FIG 34

Comparison of the Total Seasonal Grass Pollen Predicted from the Regression Model with the Actual Values for Derby 1969-1992



Rsq=98%

FIG 35

CHAPTER 7 - MODELLING THE START AND SEVERITY OF THE BIRCH POLLEN SEASON AT THE THREE LONG TERM DATA SITES IN THE UK

7.1 INTRODUCTION

Betula pollen is a major source of early springtime allergic rhinitis particularly in Northern Europe. Despite this, very few attempts have been made at predicting the characteristics of the birch pollen season. The literature review (section 2.5) has discussed the few works that have been presented. Andersen (1980) reported that birch pollen production was influenced by precipitation in the preceding April. Bringfelt *et al* (1982) used regression analysis to predict the start of the birch pollen season with an efficiency of 80%. Andersen (1991) developed a model using Utah phenoclimatology chill units and growing degree-hours to predict the first bloom in birch. Larsson (1993) used the cumulated activity method to predict the start, peak and end of the pollen season for birch (amongst other species). These studies were all different, using various methods such as; multiple regression analysis, cumulated activity method, the use of chill units and growing degree hours etc. They were also based mostly on birch pollen concentrations in Scandinavia. Up until 1993, no work on *Betula* concentrations had taken place in the UK. In 1993 Emberlin *et al* (1993a) built models to predict the start, severity and duration of the birch pollen season in London over a period of 30 years. In this study the start of the season was predicted with an explanation of 62% using mean temperatures in February and March, and the severity of the season was predicted with an explanation of 42% using mean temperatures in April.

Chapter 5 has shown that annual birch pollen sums and start dates vary from year to year and from site to site and that when considering annual sums, the biennial flowering pattern of the species must be considered. Faust (1989) suggested that the main controls on the timing of the flowering of *Betula* pollen are; the weather during the preceding late summer and autumn, winter chilling/vernalisation and spring weather.

This chapter aims to establish the main controlling variables on the characteristics of the birch pollen season in the UK, and to develop models to predict more accurately the start and severity of the birch pollen season in advance at three sites based on long term data sets of between 23 and 30 years in length. The statistical method used for the modelling is multiple regression analysis, and as discussed in section 6.1, due to the lack of data at the EAN(UK) short term data sites it is not possible to develop the models for the entire EAN(UK) network. The performance of the models in the forecasting of the characteristics of the birch pollen season will be tested on the 1993 and 1994 season and presented in chapter 8. The models will then be tested on the EAN(UK) data to establish their efficiency at modelling on a regional basis.

7.2 MODELLING THE START OF THE SEASON

7.2.1 Methods

Various authors have discussed the influence on the birch pollen season of weather in the late summer and autumn, winter chilling and spring weather (Chandler 1925, 1937, Brown 1960, Kramer and Kozlowski 1979, Faust 1989), as will be discussed in section 7.2.1.d. When building predictive models it is important to consider a great number of variables in order to include the previous seasons weather during the pollen formative period. When trying to build a predictive model for the start of the birch pollen season based on data for the period 1960s to 1992 at London, Cardiff and Derby, the parameters used were mean daily temperatures and total rainfall. Emberlin *et al* (1993a) reported that variables such as relative humidity, wind direction and velocity were significant in the prediction of day to day variations once the season had started, but they did not contribute to the prediction of broad seasonal patterns. Other variables such as sunshine hours and synoptic situation are themselves correlated with temperature and rainfall.

Section 6.2 considering grass pollen, and also the study by Emberlin *et al* (1993a) on birch pollen, both showed that meteorological variables aggregated into monthly periods did not produce a particularly high level of explanation. For this analysis 10 day aggregated variables calculated 150, 200 and 250 days from the mean start date were analysed. The lag times were chosen in order to include weather in the previous spring, winter and autumn. Where linear relationships occurred between the variables and the start of season dates, the significant aggregated variables were processed through a stepwise multiple regression analysis to identify the parameters which caused most variation.

7.2.1.a London

The collection of the data over the period 1961-1993 has been discussed in section 5.2.1. Analysis of variance of the pollen data showed the data to be similar throughout the 3 decades (despite the change in the location of the trap), therefore, unlike the previous modelling of the start of the grass pollen season, the whole data set was used for the period 1961 to 1992, with a break of three years between 1984 and 1986.

When modelling the start of the birch pollen season using monthly aggregated meteorological variables, Emberlin *et al* (1993a) achieved an Rsq value of 61.8% using February and March mean temperatures. When 10 day aggregated meteorological variables were used calculated 200 days from the mean start date, an Rsq value of 99.2% was achieved using the variables shown in the equation:

$$\mathbf{Sum75\ Start = 132.788 - 3.63a - 4.01b + 0.19c - 0.28d + 0.35e + 1.6f - 0.24g + 1.23h - 0.17j - 0.1k}$$

a = mean temperatures 5-14 February (Heathrow)
b = mean temperatures 25 February - 6 March (Rothamsted)
c = total rainfall 26 November - 5 December (Heathrow)
d = total rainfall 6 - 15 January (Rothamsted)
e = total rainfall 27 September - 6 October (Rothamsted)
f = mean temperature 6-15 December (Rothamsted)
g = total rainfall 16-25 January (Heathrow)
h = mean temperature 15-24 February (Heathrow)
j = mean temperature 7-16 March (Rothamsted)
k = total rainfall 6-15 April (Rothamsted)

Using this model it was possible to predict the start of the season before April 16th ie.the mean start date for the period 1961-1993. This prediction in some years will therefore not be made until the season has actually started unless a 30 day weather forecast is used, in which case the start of the season can be predicted by March 16th. In this situation the level of accuracy will depend upon the accuracy of the long term weather forecast. If the total rainfall 6-15 April is removed from the stepwise regression, an Rsq value of 98.5% is achieved using the same variables as in the equation above:

Sum75 Start = 131.37 - 3.47a - 4.44b + 0.2c - 0.27d + 0.38e + 1.47f - 0.27g + 1.38h - 1.0j

(The alphabetical coding represents the same 10 days aggregated periods as in the previous equation).

Using this model the sum75 start to the season was predicted by March 17th with an explanation of 98.5%. The significant meteorological variables suggest that rainfall in the autumn is important in providing sufficient moisture for future development. Temperatures at the beginning of December were important for chilling also important in the spring for spurring on the start of the season. Temperatures throughout the whole of February and half of March proved significant and this agrees with the predictive model of Emberlin *et al* (1993a).

The actual start of season dates were plotted with the predicted start of season dates (predicted using the latter equation with the omission of rainfall for the period 6-15 April)(Fig 36). It was found that the predicted start date was within 2 days of the actual start date on 92.3% of occasions. The only two years when there were more than two days difference in start dates was in 1963 and 1972 when there was a difference of 26 days and 15 days respectively. The very late predicted start to the season in 1963 was a result of cooler and drier than normal conditions in the preseason period, however temperatures 2.2°C above average in the period 7-16 March spurred on the start of the season and thus lead to a much earlier start than had been predicted. In 1972 the opposite happened in that there were above average temperatures and rainfall throughout the preseason period, however cooler than average temperatures during the period 7-16 March leading to a later start to the season than had been predicted.

7.2.1.b Cardiff

The entire data set 1963-1992 was used in the modelling of the start of the birch pollen season at Cardiff.

Using 10 day aggregated variables calculated from the mean start date an Rsq value of 95.7% was achieved using the variables shown in the equation:

$$\textbf{Sum75 Start} = 104.46 - 4.57a + 0.39b + 2.1c - 2.83d + 0.33e + 2.5f + 0.19g - 0.09h$$

a = mean temperatures 3-12 April
b = total rainfall 13-22 January
c = total rainfall 24 November - 3 December
d = mean temperature 12-21 February
e = total rainfall 24 March - 2 April
f = mean temperature 2-11 February
g = total rainfall 14-23 March
h = total rainfall 23 January - 1 February

The main problem with this model was that a prediction could not be made until April 12th, unless a long term weather forecast was used, in which case a prediction could be made by March 13th. If the mean temperatures for the period 3-12 April were removed an Rsq value of 66% was achieved and a prediction made by April 3rd using the following equation:

$$\textbf{Sum75 Start} = 82.76 + 0.52a - 2.04b + 0.3c + 0.23d$$

a = total rainfall 24 March - 2 April
b = mean temperatures 12-21 February
c = total rainfall 13-22 January
d = total rainfall 24 November - 3 December

As the level of explanation achieved using this model was only 66%, and it only provides a prediction of the start date 10 days before the mean start date, it is suggested that a prediction based on the previous model and using a long term weather forecast would be more accurate, and the previous model will be used in chapter 8 when testing the models. Unlike at London, temperatures or rainfall in the autumn did not prove to be significant, neither did temperatures in the winter, however rainfall in late November was important. Temperatures did not prove to be important until the spring. Temperatures throughout February, and then at the beginning of April were important in spurring on the release of pollen. A possible reason for the lack of significance of winter temperatures in the model could be that as a result of warmer coastal temperatures the birch trees do not enter into the full phase of dormancy and therefore do not require a chilling period to break it.

The model predicted the start of the season within 3 days of the actual start on 62% of occasions, and within 5 days of the start on 83% of occasions. The years with the greatest differences between the predicted and actual start dates were at the beginning of the monitoring period ie. 1963, 1964 and 1965 when there was a difference of 15 days, 11 days and 7 days respectively (Fig 37). In all 3 years this was a result of dry conditions in late autumn/early winter followed by particularly cool, wet conditions in the spring. It is interesting to note from section 5.2.3.b that 1964 and 1965 were also years with low annual birch pollen sums, and relatively late start dates.

7.2.1.c Derby

Using the meteorological data in the form of 10 day aggregated periods calculated 200 days from the mean start date (April 20th), the level of explanation achieved when stepwise multiple regression analysis was performed on the data was 85.4%.

$$\textbf{Sum75 start} = 126.57 - 2.68a + 0.19b - 2.73c - 1.58d + 0.17e$$

a = mean temperatures 31 January - 9 February
b = total rainfall 2-11 December
c = total rainfall 31 January - 9 February
d = mean temperature 20 February - 1 March
e = total rainfall 21-30 January

As was the case at Cardiff, temperatures during the autumn and winter were not significant, however rainfall at the beginning of December was important. Spring temperatures were important, particularly those at the beginning and end of February.

By using this model the start of the birch pollen season can be predicted by March 2nd, ie. approximately 7 weeks before the mean start date. A prediction was made within four days of the actual start date on 65% of occasions, and within six days of the actual start date on 80% of occasions (Fig 38). The years which showed most variation between the actual and the predicted start dates were 1970, 1971 and 1991 with a difference of 12 days, 10 days and 23 days respectively. In 1991 this was probably due to a very wet period 2-11 December, followed by a cold and dry start to February, however this cold spell was broken at the end of February with temperatures during the period 20 February to 1 March 1.9°C above average.

7.2.1.d Discussion

The physiology of temperate zone trees and their environmental response has been studied for many years. Chandler in 1925 recognised that during late autumn trees entered a dormant period during which inhibitors accumulated in the budscales and prevented growth. Kramer and Kozlowski (1979) reported that growth could not be resumed until a period of chilling had taken place. In 1937 Chandler and others established that a daily average temperature range of 0-7.2°C was most effective for this chilling. Brown (1960) noticed that intermittent warm periods reversed the chilling and the tree then reverted to dormancy. In this way, temperatures during the late autumn and winter have an influence on bud development and the production of pollen and thus would have an overall effect on the potential of the annual birch pollen sum. In 1989, Faust reported that the actual time of bloom in the spring was dependent on spring temperatures as warm temperatures are required for bud growth.

This analysis has highlighted the varied response the start of the season has to mean temperatures and rainfall at the individual sites. Temperatures in February, and rainfall during the last week of November and first week of December appear significant at all three sites. The response to spring, particularly February, temperatures has been suggested in previous work (Faust 1989, Spieksma *et al* 1989, Frenguelli *et al* 1992, Emberlin *et al* 1993a), however no research has highlighted the significance of winter moisture. It is possible however that winter moisture is autocorrelated with winter temperatures in that the presence or absence of water implies warmer or cooler temperatures. London is the only site at which winter temperatures are significant, this does not necessarily contradict the importance of the chilling factor on the development of the *Betula*, but merely suggests that spring temperatures are more important in determining the start of the season, and the weather in the late summer and autumn is perhaps more important for the determination of the potential pollen sum within the bud.

The three models enabled the prediction of the start of the birch pollen season within four days of the actual start on 92%, 76% and 65% of occasions at London, Cardiff and Derby respectively, and this is regarded as providing an adequate forecast of the start of the season

7.3 MODELLING THE SEVERITY OF THE SEASON

7.3.1 Methods

A consideration when trying to predict the severity of the season concerns the alternation of 'high' and 'low' years in pollen abundance which is not consistent and therefore makes prediction very difficult. Previous work by Emberlin *et al* (1993a) met with little success in the prediction of the severity of the birch pollen season in London over the period 1961-1990. An Rsq value of 41.5% was achieved using a combination of summer, winter and spring temperatures, and spring rainfall.

Chapter 5 showed that at all three sites there was an increasing trend in annual sums of birch pollen, particularly since the mid 1980s. A trend towards warmer springs from the mid 1980s was also obvious along with a decline in March and April rainfall, however these relationships were not statistically significant. The annual pollen sums at Cardiff and Derby showed more of an alternating flowering pattern than at London, however these alternating patterns were not explained as being a response to weather conditions, as fluctuations in weather patterns did not occur.

Work by Chandler (1925, 1937), Brown (1960) and Kramer and Kozlowski (1979) (discussed in section 7.2.1.d) reported the importance of winter chilling on the growth and development of buds. Apart from at London, winter chilling did not appear to have a significant influence on the start of the birch pollen season, and therefore its influence on the severity of the birch pollen season was examined. In the development of a predictive model for the total annual sums, the parameters used were mean daily temperatures, total rainfall and start of season dates. The meteorological variables were aggregated into 10 days periods calculated 150, 200 and 250 days from April 30th in order to include weather conditions in the previous spring, winter and autumn, and thus test the significance of winter chilling. April 30th was selected as at all 3 sites by this time in most years the majority of birch pollen has been released.

When modelling the severity of the season the variables in the form of 10 day aggregated periods and the start of season dates were correlated with the annual sums. Where linear relationships existed the significant variables were incorporated into stepwise multiple regression analysis to identify the parameters which caused most variation. In order to do this however, the pollen data was transformed by a method of square rooting in order to produce a normal distribution on which parametric methods could be used.

7.3.1.a London

As for the modelling of the start of the birch pollen season, the complete data set 1961-1992 was included in the predictive modelling. It was discussed in section 7.2.1.a how the meteorological data was taken from two stations, one representing Central London and one representing the rural source area, and also there was a break in the pollen data record, years 1984-1986 being omitted from the analysis.

When modelling the annual birch pollen sums using monthly aggregated meteorological variables, Emberlin *et al* (1993a) achieved an explanation of 41.5% using a combination of summer, winter and spring temperatures and rainfall in March and April (as mentioned previously). When 10 day aggregated meteorological variables were used calculated 250 days from April 30th with the start of season date, an Rsq value of 69.7% was achieved using the variables shown in the equation:

Square root of the
Cumulative catch for the season = 155.583 + 0.215a - 0.971b - 0.467c

a = total rainfall 1-10 April (Heathrow)
b = start of season date
c = mean temperatures 12-21 March (Rothamsted)

Thus, mean temperatures in March in the rural source area, rainfall in the early stages of anthesis, and the date on which the season started all appear to have an influence on the annual birch pollen sum. This therefore did not provide evidence for the influence of winter chilling on pollen development.

When the actual totals were plotted with the predicted totals it was found that using this model the annual birch pollen sum could be predicted as soon as the birch pollen season started (Fig 39). On 70% of occasions the total seasonal catch was predicted within 500 grains of the actual total. The only two years when there was a large difference in the actual and predicted total was in 1987 and 1988 when the predicted value were 1473 and 1869 grains less than the actual value respectively. In 1988 the highest annual birch pollen sum of the 27 year period was experienced with 4310 grains.

7.3.1.b Cardiff

When the meteorological variables were correlated with the annual birch pollen sums for 1963-1992, there was very little evidence of any relationships. When the meteorological variables in the form of monthly aggregated periods were used in a stepwise regression analysis the result was not significant. Using the meteorological data in the form of 10 day aggregated variables calculated from April 30th, an Rsq value of 17.1% was achieved using rainfall during the period 1-10 April:

$$\textbf{Square root of total cumulative catch for season} = \mathbf{28.545 + 0.8a}$$

a = total rainfall 1-10 April

This would not provide an accurate prediction of the total annual sum, and therefore on the basis of the analysis employed, a prediction cannot be made.

7.3.1.c Derby

When the meteorological variables in the form of monthly aggregates were correlated with the annual birch pollen sums for the period 1970-1992, mean temperatures in March were particularly significant. The significant variables were incorporated into the stepwise multiple regression analysis and an Rsq value of 65.9% was achieved:

$$\textbf{Square root of total cumulative catch for season} = 156.432 - 0.97a - 3.328b$$

a = start of season date
b = mean temperatures for March

When the actual annual pollen sum was plotted with the predicted annual pollen sum, the predicted value was within 500 grains of the actual value on 81% of occasions (Fig 40).

The 10 day aggregated variables calculated from April 30th were incorporated into the stepwise multiple regression however the result of this was not significant.

7.3.1.d Discussion

The forecast models for the severity of the birch pollen season have a relatively low level of explanation at all three sites, particularly at Cardiff. The annual birch pollen sums at the three sites are influenced mainly by either mean temperatures or rainfall in the period immediately preceding anthesis and the start of season date. In the models, weather conditions in the preceding autumn, winter and early spring do not appear to influence the total annual pollen sums. Despite work by Chandler (1925), Brown (1960) and Kramer and Kozlowski (1979) suggesting their influence on bud growth and development, the actual pollen production appears to be independent of this on the basis of this analysis. Emberlin *et al* (1990) reported on the course of the weather during the season as a control on the release and dispersal of the pollen from the trees, and this is confirmed in the three models.

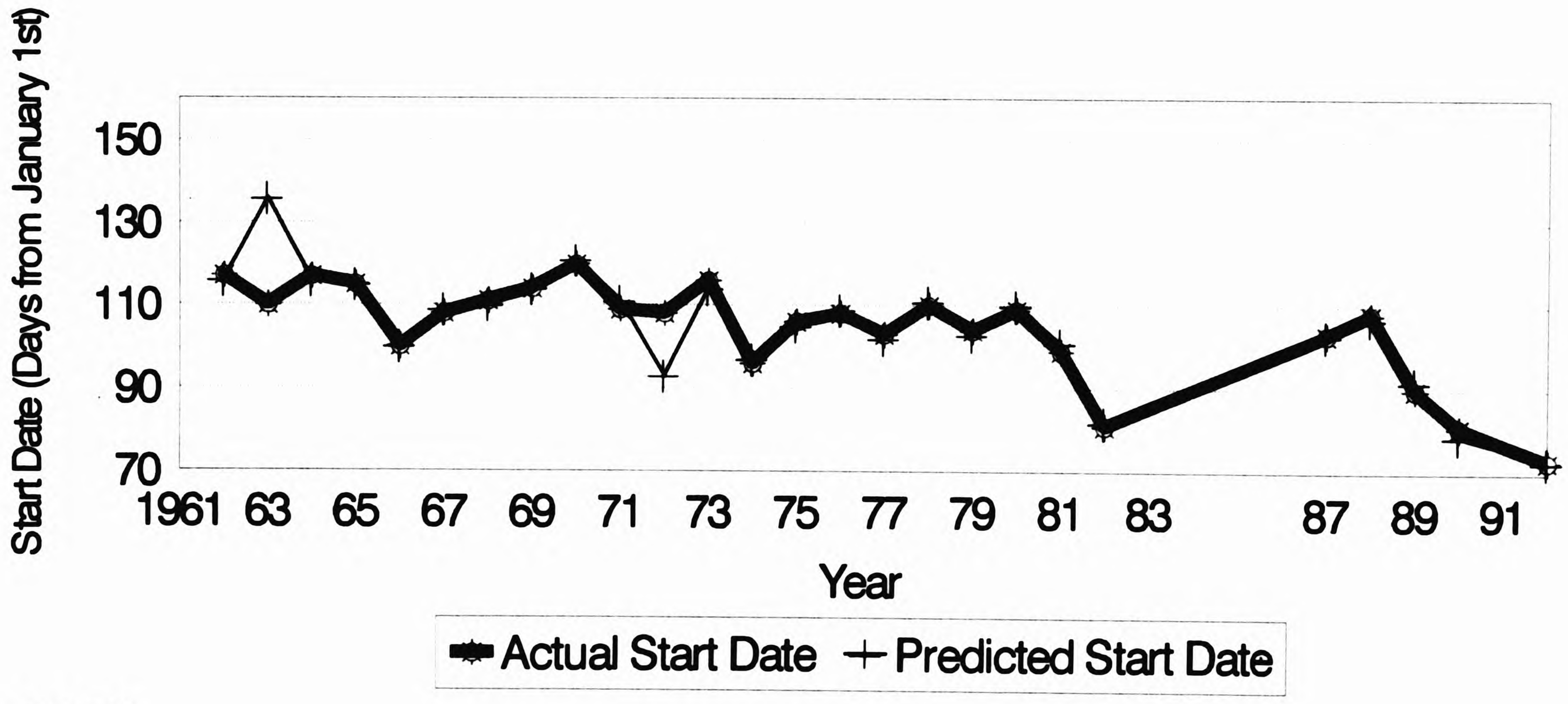
The poor level of explanation achieved by the models is likely to be as a result of the biennial flowering pattern, and the great variation in annual sums from year to year. Attempts were made to normalise the counts and thus minimise the annual variation using the methodology of Moseholm *et al* (1987) (as also used by Norris-Hill 1992) using the equation:

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

where np = the normalised count
p = the raw pollen count
Σp = the years total pollen count

however as the variation in some cases from year to year was so great, this did not improve the value of the models. Section 5.2.3.d discussed how the alternating flowering pattern of the tree occurs as a result of the production of auxins and gibberellines affecting bud development. From the models, it can be suggested that, due to the lack of significance of preseasonal temperatures, pollen production within the buds is determined by the amount of hormone produced in the preceding year, and this is determined irrespective of autumn and winter temperatures. Once the pollen has been produced within the buds, it is the actual day on which the season starts and the temperatures and rainfall at the early stages of anthesis that influence the dispersal of pollen.

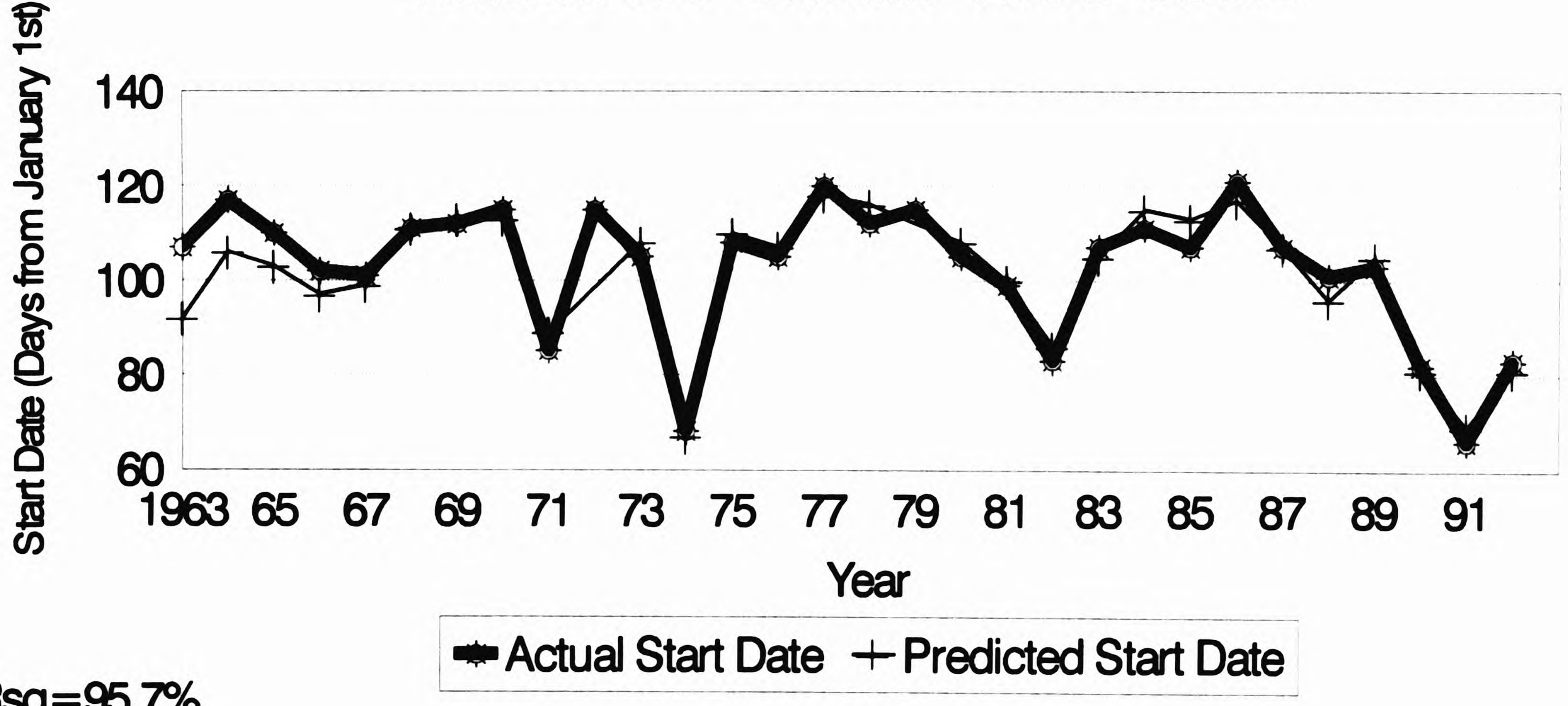
Comparison of the Start of the Birch Pollen Season Predicted from the Regression Model with the Actual Values for London 1961-1992



Rsq=98.5%

FIG 36

Comparison of the Start of the Birch Pollen Season Predicted from the Regression Model with the Actual Values for Cardiff 1963-1992

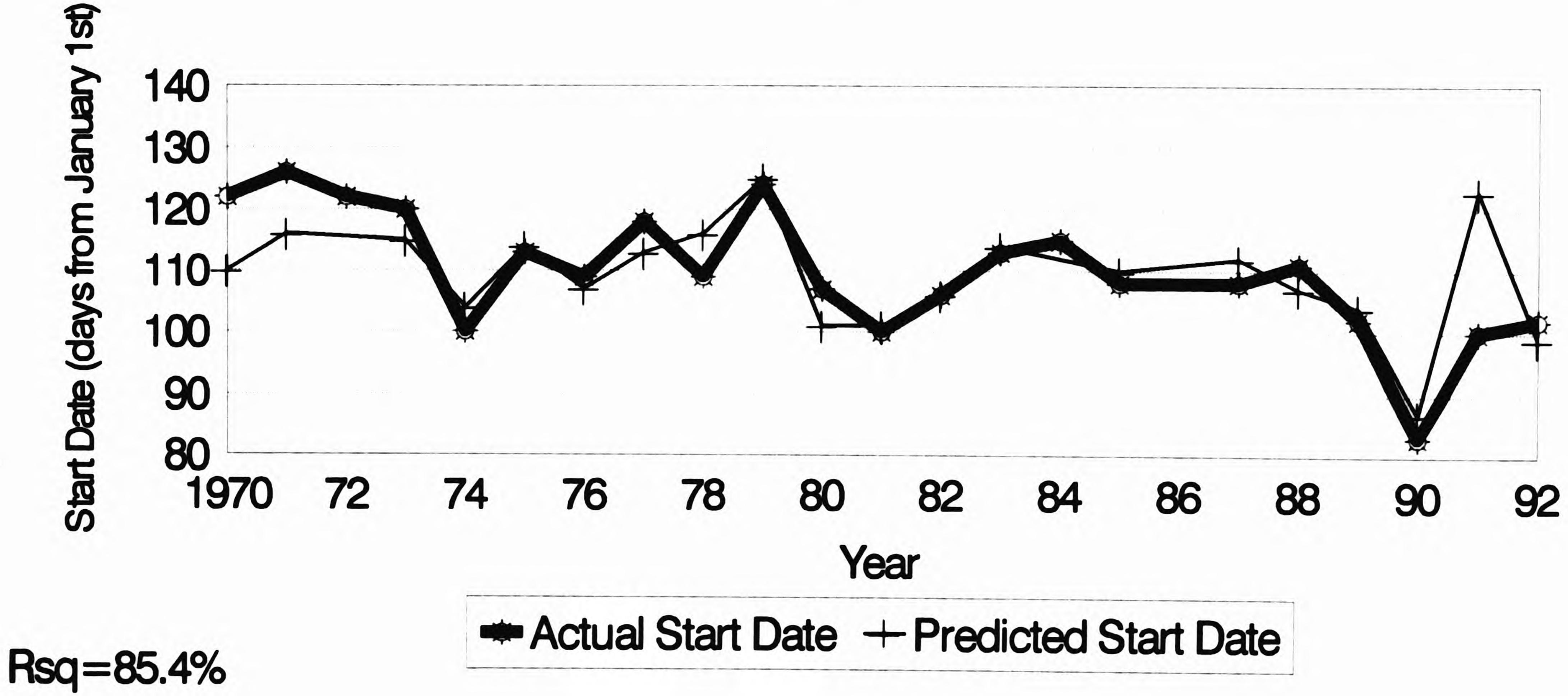


Rsq=95.7%

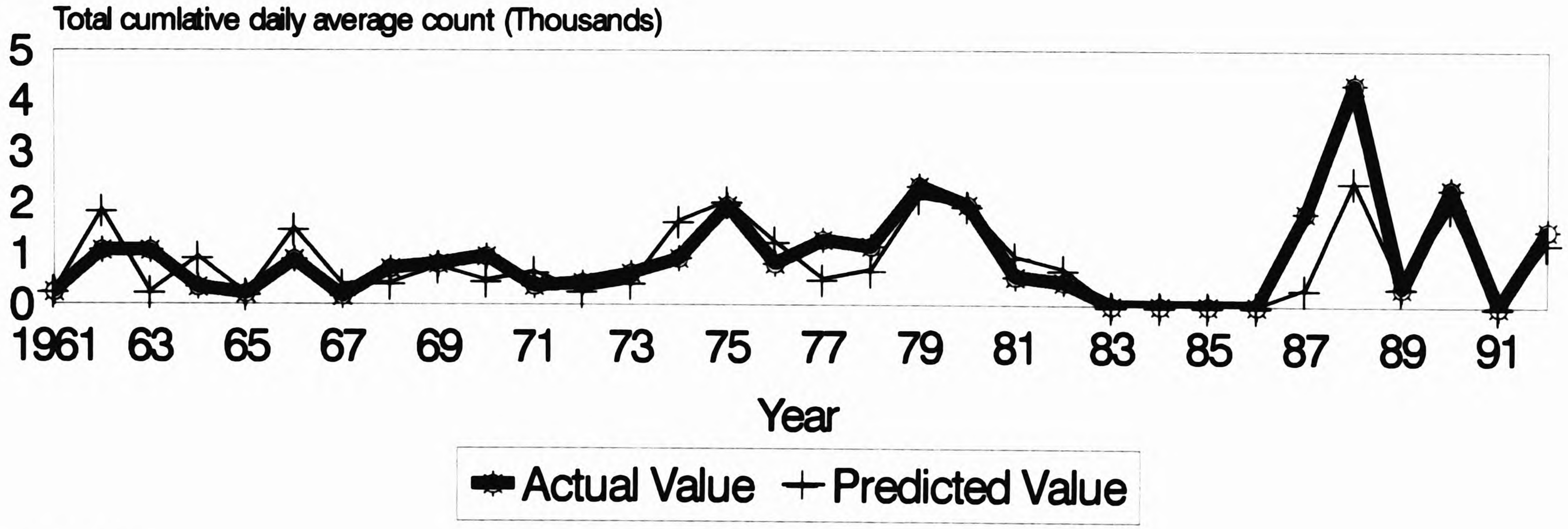
FIG 37

FIG 38

Comparison of the Start of the Birch Pollen Season Predicted from the Regression Model with the Actual Values for Derby 1970-1992



Comparison of the Total Seasonal Birch Pollen Predicted from the Regression Model with the Actual Values for London 1961-1990

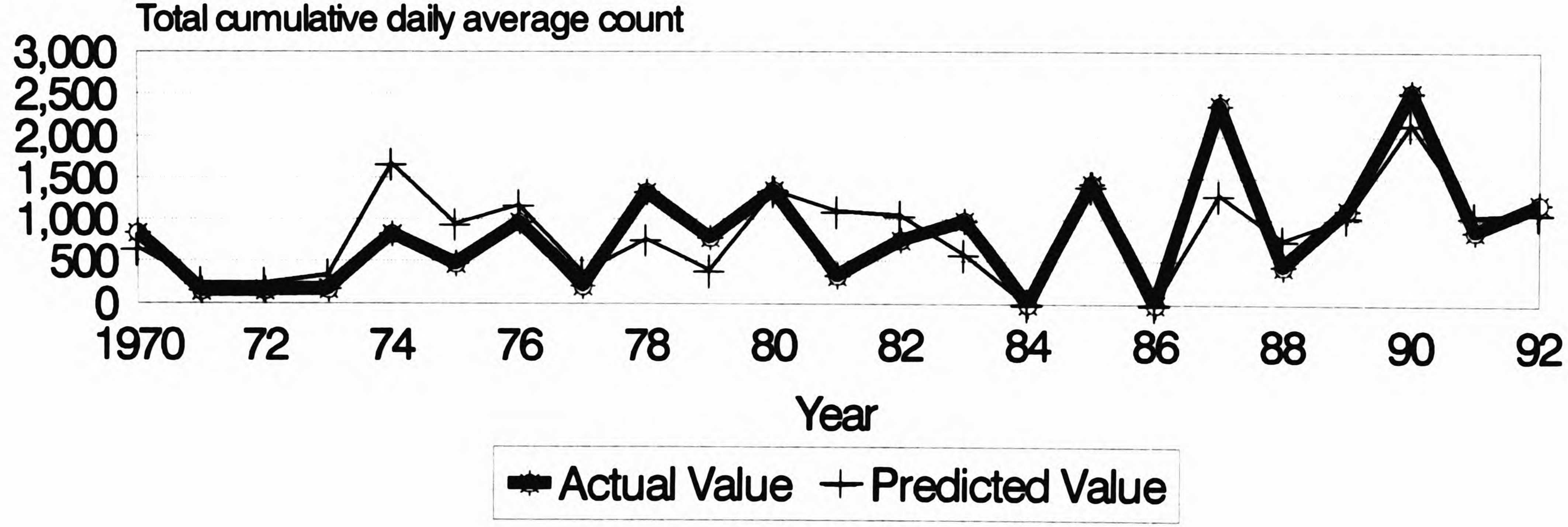


Rsq=69.7%

FIG 39

FIG 40

Comparison of the Total Seasonal Birch Pollen Predicted from the Regression Model with the Actual Values for Derby 1970-1992



Rsq=65.89%

CHAPTER 8 - THE APPRAISAL OF THE FORECAST MODELS AND THEIR APPLICATION REGIONALLY

8.1 INTRODUCTION

The efficiency of the forecast models presented in chapters 6 and 7 was tested by applying them to the data for 1993 and 1994. This chapter aimed to first test the reliability of the grass and birch pollen models at London, Cardiff and Derby in the estimation of the start and severity of the grass pollen season and the start of the birch pollen season. Secondly, as a result of the short data span at the short term EAN(UK) sites it was not possible to statistically model the characteristics of the various pollen seasons. As a result of this, the data from the short term EAN(UK) sites was incorporated into the models to assess their use in forecasting the start of the grass pollen season on a regional basis. Due to the great variation in source strengths at the individual EAN(UK) sites (Table VII, chapter 4) and their influence on the total seasonal catch, the models were not used to predict the severity of the season.

8.2 TESTING THE MODELS ON THE 1993 AND 1994 GRASS AND BIRCH POLLEN DATA

8.2.1 Start of the Season

8.2.1.a Grass Pollen

The models used to forecast the start of the grass pollen season at London, Cardiff and Derby have been presented in section 6.2. The equations which have been selected as providing the best estimate of the start of the season are:

For London:

Sum75 start = 190.95 - 0.55a + 0.91b - 0.26c - 0.62d + 0.79e - 0.53f - 0.1g

Rsq = 96.1%

a = accumulated temperatures 24 May-3 June (Rothamsted)

b = total rainfall 24 February-5 March (Rothamsted)

c = total rainfall 14-23 February (Rothamsted)
d = total rainfall 24 February-5 March (Heathrow)
e = accumulated temperatures 14-23 February (Rothamsted)
f = accumulated temperatures 15-24 January (Heathrow)
g = accumulated temperatures 15-24 April (Heathrow)

For Cardiff:

$$\textbf{Sum75 start} = 143.58 - 1.22a + 225b - 0.104c$$

Rsq = 66.5%

a = mean temperatures 19-28 February
b = total rainfall 10-19 April
c = total rainfall 30 January-8 February

For Derby:

$$\textbf{Sum75 start} = 147.32 + 0.43a - 0.213b + 0.574c$$

Rsq = 76.2%

a = total rainfall 8-17 May
b = accumulated temperatures 28 April-7 May
c = accumulated temperatures 18-27 January

The meteorological data was incorporated into the models to test their reliability. The results are shown in the tables (Table XVI and Table XVII).

The discrepancy in the predicted and the actual start dates (Table XVI) at London in 1993 was probably a result of low rainfall during the period 14 February to 5 March with only 0.7% of average rainfall at Rothamsted in the period 14-23 February, and 40% and 14% at Heathrow and Rothamsted respectively during the period 24 February - 5 March. It is possible that dry conditions at this time retarded the growth of the grasses and therefore lead to a later start date than had been predicted, although a difference of 8 days is still regarded as being an adequate forecast. The fact that the predicted start date was earlier than the actual start date is better than if it had been later, in that clinical trials can proceed without having missed the real start to the season.

Table XVI. Actual Start Dates for the Grass Pollen Season and Start Dates Predicted from the Regression Equations for London, Cardiff and Derby in 1993

Site	Actual Start Date (Sum75 method)	Predicted Start Date (Sum75 method)	Number of days difference between actual and predicted dates
London	143	135	8
Cardiff	127	145	18
Derby	142	146	4

(Dates presented as the number of days from January 1st)

At Cardiff there was a large difference between the actual start date and the predicted start date. This difference is too large to be regarded as providing an adequate forecast for the start of the season. When looking at the significant meteorological data it appears that the later start to the season than predicted is likely to be a result of there being particularly wet conditions in the period 10-19 April (195% of normal rainfall) resulting in the provision of sufficient moisture for grass development.

In 1994 (Table XVII), the predictions for the start of the season at London and Cardiff can be regarded as being very accurate, however the difference of 15 days at Derby infers this to be an unreliable forecast. The much earlier start to the season than predicted was probably a result of accumulated temperatures during the period 28 April-7 May being 27.38 Day°C above the period average (1969-1992) and thus bringing on an earlier start to the season.

Table XVII. Actual Start Dates for the Birch Pollen Season and Start Dates Predicted from the Regression Equations for London, Cardiff and Derby in 1994

Site	Actual Start Date (Sum75 method)	Predicted Start Date (Sum75 method)	Number of days difference between actual and predicted dates
London	156	156	0
Cardiff	139	137	2
Derby	135	150	15

(Dates presented as the number of days from January 1st)

It would be advisable when applying these models to future data to have the long term averages for the aggregated meteorological variables so that anomalies can be checked annually, and the model adjusted accordingly. One of the problems with applying the models to future data is that the significance of the variables may alter, for example as was the case at Derby in 1990 (as discussed in section 4.2.3.c). In this year a lower than average pollen sum was the result of drought conditions and a change in the climatic response from a negative correlation with rainfall, to a positive correlation with rainfall. It is therefore important not to rely on the few significant variables, but to monitor strong deviations from the mean in all of the variables in order to assess the 'normality' of the season on which the model is to be based.

8.2.1.b Birch Pollen

The models used to forecast the start of the birch pollen season at London, Cardiff and Derby were presented in section 7.2. As in the testing of the models for the start of the grass pollen season, the meteorological data for 1993 and 1994 was incorporated into the models to assess their reliability. The equations that have been selected as providing the best estimate of the start of the season were:

For London:

Sum75 Start = 131.37 - 3.47a - 4.44b + 0.2c - 0.27d + 0.38e + 1.47f - 0.27g + 1.38h - 1.0j

Rsq = 98.5%

a = mean temperatures 5-14 February (Heathrow)
b = mean temperatures 25 February - 6 March (Rothamsted)
c = total rainfall 26 November - 5 December (Heathrow)
d = total rainfall 6 - 15 January (Rothamsted)
e = total rainfall 27 September - 6 October (Rothamsted)
f = mean temperature 6-15 December (Rothamsted)
g = total rainfall 16-25 January (Heathrow)
h = mean temperature 15-24 February (Heathrow)
j = mean temperature 7-16 March (Rothamsted)
k = total rainfall 6-15 April (Rothamsted)

For Cardiff:

Sum75 Start = 104.46 - 4.57a + 0.39b + 2.1c - 2.83d + 0.33e + 2.5f + 0.19g - 0.09h

Rsq = 95.7%

a = mean temperatures 3-12 April
b = total rainfall 13-22 January
c = total rainfall 24 November - 3 December
d = mean temperature 12-21 February
e = total rainfall 24 March - 2 April
f = mean temperature 2-11 February
g = total rainfall 14-23 March
h = total rainfall 23 January - 1 February

For Derby:

Sum75 start= 126.57 - 2.68a + 0.19b - 2.73c - 1.58d + 0.17e

Rsq = 85.4%

a = mean temperatures 31 January - 9 February
b = total rainfall 2-11 December
c = total rainfall 31 January - 9 February
d = mean temperature 20 February - 1 March
e = total rainfall 21-30 January

The results of incorporating the 1993 and 1994 meteorological data into the models is shown in the tables below (Table XVIII and Table XIX).

Table XVIII. Actual Start Dates for the Birch Pollen Season and Start Dates Predicted from the Regression Equations for London, Cardiff and Derby in 1993

Site	Actual Start Date (Sum75 method)	Predicted Start Date (Sum75 method)	Number of days difference between actual and predicted dates
London	92	112	20
Cardiff	91	324	233
Derby	90	112	22

(Dates presented as the number of days from January 1st)

The discrepancy in the predicted and actual start dates at the three sites in 1993 is quite extreme, and in all cases the models do not provide a reliable forecast for the start of the season (Table XVIII). At Cardiff the predicted start date was 324 days from January 1st, this figure alone makes a nonsense of the model. The peculiar predicted start date at Cardiff was a result of an extremely wet period at the end of November and the beginning of December when 390% of normal rainfall fell, this therefore caused extreme disruption to the model. At Derby, the much earlier start to the season than predicted was a result of mean temperatures 1.6°C above average and rainfall 2.7% of average during the period 31 January - 9 February, thus spurring on the start of the season.

Table XIX. Actual Start Dates for the Birch Pollen Season and Start Dates Predicted from the Regression Equations for London, Cardiff and Derby in 1994

Site	Actual Start Date (Sum75 method)	Predicted Start Date (Sum75 method)	Number of days difference between actual and predicted dates
London	98	102	4
Cardiff	109	167	58
Derby	109	86	23

(Dates presented as the number of days from January 1st)

In 1994, like 1993, there was a great difference between the predicted and the actual start of season dates at Cardiff and Derby (Table XIX). At Cardiff, this is probably a result of very wet weather during the period 14-23 March with 224% of average rainfall and cooler than average temperatures during the period 3-12 April leading to a later predicted start. A start date prediction of 167 days from January 1st however is not feasible as this would mean that the season did not start until June 18th, and in every year in the 30 year data set, the birch pollen season is over by then. At Derby the later start to the season than predicted was a result of a cold spell during the period 20 February - 1 March with mean temperatures 1.8°C below average.

From the evidence provided by the two years worth of data, it appears that the models are not successful in predicting the start of the birch pollen season, particularly at Cardiff and Derby. Unfortunately, the birch pollen seasons in 1993 and 1994 were not typical flowering years in that 1993 had extremely high birch pollen totals, and this was followed in 1994 with extremely low birch pollen totals. In 1993, Derby experienced its highest annual birch pollen total on record, and London experienced its second highest. Although this does not fully explain the reason why the models do not provide accurate results, it does show how the 1993 and 1994 seasons were different from the normal, and therefore gives a possible reason for the lack of reliability of the predictions.

8.2.2 Severity of the Grass Pollen Season

The various models to predict the severity of the grass pollen season have been presented in section 6.3. The models selected as providing the most accurate forecast are summarised below:

For London:
Square root of the
Cumulative catch for season = 246.413 - 1.266a - 0.372b - 0.204c - 0.152d
Rsq = 91.5%

a = actual start date (sum75 definition)
b = accumulated temperatures 24 March-2 April (Heathrow)
c = total rainfall 2-11 February (Heathrow)
d = accumulated temperatures 12-21 June (Heathrow)

For Cardiff:
Square root of
Cumulative catch for season= -41.997 + 0.434a + 0.267b - 1.69c - 0.151d
+ 0.638e + 0.348f + 0.157g + 0.329h - 0.35j + 0.181k
Rsq = 96.9%

a = total rainfall 2-11 June
b = accumulated temperatures 13-22 May
c = accumulated temperatures 22 February - 3 March
d = total rainfall 4-13 March
e = actual start date (sum75 method)
f = accumulated temperatures 23 April - 2 May
g = total rainfall 23 April - 2 May
h = accumulated temperatures 3 - 12 May
j = total rainfall 13-22 January
k = total rainfall 12-21 February

For Derby:

Square root of

Cumulative catch for season = 83.582 - 0.48a + 0.642b - 0.73c + 0.371d - 0.35e - 0.503f

Rsq = 98%

a = accumulated temperatures 14-23 March
b = total rainfall 3-12 May
c = total rainfall 24 March - 2 April
d = accumulated temperatures 13-22 April
e = accumulated temperatures 3-12 April
f = accumulated temperatures 23 January - 1 February

The results of incorporating the meteorological data and the start of season dates into the models is shown in the tables below (Table XX and Table XXI).

Table XX. Actual Total for the Grass Pollen Season and the Total predicted from the Regression Equation for London, Cardiff and Derby 1993

Site	Actual Total	Predicted Total	Number of grains difference between actual and predicted totals
London	1997	2026	29
Cardiff	7130	8118	988
Derby	5919	4194	1725

(Totals recorded as cumulative counts for the period May, June, July and August)

The models were fairly accurate for London and Cardiff in 1993, the prediction for London was very close to the actual value, and the prediction for Cardiff was less than one standard deviation from the actual value (Table XX). At Derby the underestimate of the predicted total is likely to have been caused by the above average accumulated temperatures during the period 14-23 March, 3-12 April and 13-22 April (with 23.36 Day°C, 10.5 Day°C and 17.5 Day°C respectively above the period average) and a particularly dry period during 3-12 May, which could have lead to higher pollen production than was expected.

In 1994 there was greater variation between the actual and predicted values (Table XXI). At London this was likely to have been caused by a later than average start date. Higher than average spring rainfall at Cardiff is likely to have caused a lower total than was predicted. The annual total at Derby was less than one standard deviation from the actual total and therefore this was regarded as being a fairly reliable forecast.

Table XXI. Actual Total for the Grass Pollen Season and the Total predicted from the Regression Equation for London, Cardiff and Derby 1994

Site	Actual Total	Predicted Total	Number of grains difference between actual and predicted totals
London	1607	585	1022
Cardiff	5225	7014	1789
Derby	5564	4047	1517

Although in both 1993 and 1994 at the three sites there was often between 1000 and 1800 grains difference between the predicted and the actual totals, the models were useful in that they predicted whether or not the seasonal total was lower or higher than average and thus gave an indication of the actual severity of the season. For example in 1993, the models accurately predicted that at London and Cardiff the seasonal totals would be lower than and greater than the average respectively. In 1994 the models accurately predict that at London and Derby the seasonal totals were lower than average. It is this level of information that is more important than the actual number of grains, as the actual number of grains collected at a site is very dependent on local conditions, for example wind direction, site topography and location, altitude and situation of the trap etc. It has been found that if two traps are placed next to each other on the same roof the counts will vary between traps (Jane Norris-Hill personal communication), and therefore an accurate prediction of the actual number of grains is not necessary as this would only represent conditions on the roof of one building rather than giving a more general picture. More important is a model that will predict the overall severity of the season, and whether the season will be more or less severe than the average. The models presented here can be regarded as providing sufficiently accurate information to enable such a forecast.

8.2.3 Discussion

Overall the forecast models for the start and severity of the grass pollen season at London, Cardiff and Derby have been shown to provide a fairly reliable prediction, although in years which experience extreme weather conditions during the significant periods, the forecast models become less reliable, and therefore they need to be monitored carefully. The models to predict the start of the birch pollen season were not as successful. Whether this was a response to the alternating flowering pattern of birch, or whether it was a result of the years 1993 and 1994 being untypical in their seasonal pollen catch is a matter for future study.

8.3 APPLICATION OF THE GRASS POLLEN MODELS FOR REGIONAL FORECASTING

8.3.1 Methods of Grouping the EAN(UK) Sites

The length of the data at the EAN(UK) sites ranged from 7 years at Edinburgh, to two years at Taunton and Chester (Table IX, chapter 4). In order to increase the geographical range of the data sets, the data since 1987 from Cardiff and Derby was also incorporated into the tests. The majority of predictive statistical tests, including multiple regression analysis, rely on there being a large number of data points, in this case years of data, on which to perform an analysis. The more data points there are, the more accurate the end result will be. Unfortunately, the EAN(UK) data covers the same period of time ie. 1987-1994 and therefore even if the sites were grouped together to incorporate all of the data, there could only ever be 8 years worth of data as the years would overlap. In order to incorporate all of the data from the EAN(UK) sites, the sites were grouped together and then the data was tested on the models based on the long term data sets at Cardiff and Derby in order to assess their reliability of forecasting the start of the season on a regional basis. The regression model for London was not used, as the pollen site was located in a large urban area, and none of the other pollen sites, despite some of them being in urban areas, are considered to be as urban as London and thus under the influence of a climatic urban heat island effect.

Various attempts were made at grouping the sites. The first method of grouping the sites was related to the percentage of grassland in the surrounding area. The sites were divided into two groups depending on whether there was less than or greater than 65% of grassland within a 40km radius of the site;

Group 1 - Isle of Wight, Taunton, Preston, Invergowrie
Group 2 - Cardiff, Leicester, Derby, Chester, Edinburgh

(NB. Belfast was not included as a result of lack of land use data).

The sites were also grouped on the basis of less than 65% of grassland in an 80km radius of the sites;

Group 1 - Isle of Wight, Cardiff, Preston, Invergowrie
Group 2 - Taunton, Leicester, Derby, Chester, Edinburgh

The main problem with this method was that although the sites within the groups may have similar amounts of grassland in their surrounding area, they did not have similar climates, for example Derby and Leicester have a relatively warm and dry climate in comparison with Edinburgh where the climate is much cooler and wetter. Chapter 4 showed there to be a greater correlation between the start of the season and climatic variables than land use patterns, and therefore this was not an adequate method of grouping the sites, unless climatic variables are also incorporated in some way.

The other methods of grouping the sites concentrated on grouping them according to similarities in pollen data characteristics or climate. The second attempt at grouping the sites was based on grouping the sites in relation to their start of season dates through analysis of variance tests. The main problem with this method was that the analysis of variance was based on the variation in the means between a number of samples, in this case sites. As there were only a few years worth of data at a few of the sites, for example, 3 years at Preston, Belfast and Invergowrie, and 2 years at Taunton and Chester, the mean start dates at these sites cannot be taken as being particularly representative, and therefore it was not statistically sound to group the sites purely on this basis. Also, this method did not take into consideration the factors that actually influence the start of the season, ie. climate.

The third grouping method used concerned the shape of the pollen curves. Curves of variation in start dates, daily average counts, 5 day running means of daily average counts and cumulative counts were drawn for the individual sites for each year in order to establish any similarities in the grass pollen season characteristics between the sites. There was great variation between the sites in each year, and also great variation at the individual sites from year to year. The amount of variation made it very difficult to establish any coefficient of similarity between the curves, and therefore the sites could not be grouped in this way.

The final grouping method was based on an analysis of variance test incorporating the start of season dates, the mean monthly temperatures for January, February, March and April and the total monthly rainfall for January, February, March and April. The sites were therefore grouped according to similar spring climates and similar start of season dates. The results of the analysis of variance test yielded 3 groups;

Group 1 - Isle of Wight, Taunton, Cardiff
Group 2 - Leicester, Derby, Chester
Group 3 - Belfast, Edinburgh, Invergowrie

(Preston was omitted due to the absence of meteorological data).
As it turned out, the sites were in fact grouped into 'southern', 'central' and 'northern' sites.

8.3.2 Testing the Models

Meteorological data from the short term data sites was used in the models to assess their use regionally. Unfortunately there was no long term data set for the north and therefore this region remains unmodelled. When the data was used in the models, the mean values of the significant meteorological variables for the 3 sites in the group were used, and thus it was the mean value for the sites that was predicted, thus producing a mean regional start date value.

8.3.2.a Southern Areas

The model for the start of the season was based on the regression equation for Cardiff (see section 8.2.1.a). When for a particular year there were 3 sets of data, the mean values for the significant variables at Cardiff, Isle of Wight and Taunton for the period 1988-1994 were used in the regression equation. 1987 was not tested as there was no data for Taunton in this year, and the pollen data at the Isle of Wight was collected using a Rotherham Trap and was considered to be incompatible with the rest of the data set. Table XXII shows the results.

Table XXII. Actual Mean Start Dates for the Southern Region and Mean Start Dates Predicted from the Regression Equation for Cardiff 1988-1994

YEAR	Actual Mean Start Date	Predicted Mean Start Date	Number of days difference between the actual and predicted values (actual - predicted)
1988	145	134	11
1989	140	141	1
1990	137	130	7
1991	143	136	7
1992	139	142	3
1993	133	143	10
1994	139	136	3

(Start dates represented as the number of days from January 1st)

(Regional prediction based on meteorological data for Isle of Wight, Taunton and Cardiff).

In most cases there was less than 7 days difference between the actual mean values and the predicted mean values. The start of the season date varied locally from site to site, as discussed in chapter 4, in response to variations in local climate, topography, altitude, site situation etc. By predicting a mean start date for the region, a general idea was provided of when the season started, although local variation in start dates would have existed. A prediction of the mean start date within 7 days is regarded as being adequate for a regional prediction.

8.3.2.b Central Areas

The model for the start of the season in the central areas was based on the regression equation for Derby (see section 8.2.1.a). Meteorological data from Derby, Leicester and Chester was used in the model for the period 1990-1993 in the same way as for the southern regional forecast model. Unfortunately, due to lack of meteorological data at Leicester, the model could not be tested for a longer period, and in 1994 a lack of both Leicester and Taunton meteorological data did not allow for a regional prediction (Table XXIII).

Table XXIII. Actual Mean Start Dates for the Central Region and Mean Start Dates Predicted from the Regression Equation for Derby 1990-1994

YEAR	Actual Mean Start Date	Predicted Mean Start Date	Number of Days Difference between the Actual and Predicted Values (actual-predicted)
1990	143	140	3
1991	143	149	6
1992	145	143	2
1993	144	156	12

(Regional prediction based on meteorological data for Leicester, Derby and Chester).

The regression model based on the long term data set for Derby enabled a mean prediction of the start of the season in the central region within 6 days of the actual mean start date for most years. In 1993, the poor level of prediction was a result of a very wet period at Chester during 8-17 May resulting in a disruption to the regression equation and hence a lower level of significance to the prediction. As was the case with the southern regional prediction, a prediction at this level is regarded as adequate in providing a good regional forecast for the start of the season.

8.3.3 DISCUSSION

The models used for the prediction of the start of the season in the southern and central areas gave a good general guide to when the season would start. In these comparisons the mean start date for the region was predicted, and due to local variation between sites (discussed earlier 8.3.2.a), this is probably adequate information on which to base the timing of clinical trials, pharmaceutical advertising campaigns etc.

Care must be taken in the use of these regional prediction models, in that it must be remembered that they produce predictions for the mean start date for a region, and variations will take place between one site and the next. Also, as the models are based on the long term models for Cardiff and Derby, the results were more representative of sites in the close vicinity of these two sites, than for sites further away. An example of this is in the modelling of the central sites where Derby and Leicester have similar dry, and relatively warm climates as compared with Chester which although being warm, is a much more maritime site. Consideration of this must be taken when incorporating other sites into the network modelling.

CHAPTER 9 - CONCLUSIONS

9.1 INTRODUCTION

This research has determined the regional variations in annual grass and birch pollen concentrations and start of season dates over the period 1988-1994, at a number of sites located throughout the United Kingdom. Trends in annual grass and birch pollen concentrations and start of season dates were also identified at three sites in the United Kingdom with a long range of data; London, Cardiff and Derby. The trends were analysed in detail with meteorological and land use information, and where relationships existed, models were developed which forecasted annual concentrations and start of season dates. The models for Cardiff and Derby were also used to enable the regional prediction of the mean start of season dates.

This chapter will discuss the conclusions made concerning the start and severity of the grass and birch pollen seasons. An appraisal of the research will be made, highlighting problems inherent in a study of this sort. Finally, suggestions will be made for future research that could take place involving the pollen, meteorological and land use data used in this study, and also the potential of the information resulting from future years monitoring.

9.2 MAIN CONCLUSIONS OF THE RESEARCH

9.2.1 Conclusions on the Start and Severity of the Grass Pollen Season

There is a great contrast in the trend in start of grass pollen season at the three long term data sites; London showing a trend towards later start dates, and Cardiff and Derby showing a weak trend towards earlier start dates, particularly since the mid 1980s. At London, it may be that a trend towards later start dates is a result of a decline in pollen abundance. The development of the Greater London area has extended the distance between the grassland area and the pollen monitoring site, thus resulting in later starts to the season. The sites have a varied response to the meteorological variables. At Cardiff and Derby there was evidence of earlier start dates being a function of increased spring temperatures, and decreased May rainfall.

Models were developed to predict the start of the grass pollen season at the 3 long term data sites. The start of the grass pollen season accounted for 96.1%, 66.5% and 76.2% of variation in the data at London, Cardiff and Derby respectively, using mean temperatures, accumulated temperatures over 5.5°C and rainfall variables aggregated into 10 day periods. When the models were tested on the 1993 and 1994 season, the differences between the actual and predicted start dates were 8 days and 0 days at London, 18 days and 2 days at Cardiff, and 4 and 15 days at Derby. Large differences between the predicted and actual values, for example at Cardiff in 1993 and Derby in 1994, were probably caused by extreme weather conditions in the preseason period, which disrupted the model. Prolonged periods of either good or bad weather in the preseason period are frequently sufficient to influence the timing of the start of the season. The models confirmed the importance of temperatures at the end of January and early February in the first stages of grass development. Temperatures and rainfall during the spring at all 3 sites proved to be important probably in influencing the development of the stem apex into the inflorescence initial. The importance of the variables closer to the actual start date varied between the sites, with high rainfall being important at Cardiff and high accumulated temperatures important at London and Derby in the completion of initial development, the opening of the flower heads and the release of pollen from the anthers.

Variations exist in the trends in annual grass pollen concentrations at London, Cardiff and Derby. At London and Derby there was a clear decline in annual grass pollen concentrations with time, whereas at Cardiff the trend was more varied. These trends in annual grass pollen sums related closely to trends in land use patterns over the 24-32 year period. When the annual pollen sums at all three sites were analysed together, there was no synchronisation in 'high' and 'low' years, thus emphasising the varied response to meteorological variables at the 3 sites. At London high annual grass pollen concentrations were characteristic of years with warm spring mean monthly temperatures and low rainfall in the spring and early summer. At Cardiff, the annual grass pollen sum had little, if any, relationship with mean monthly early spring weather. The relationship between the variables appears to vary over the period (1969-1992) at Derby, and this highlights problems inherent when trying to forecast the annual pollen sum in a particular year.

Models were developed to predict the annual grass pollen sum at the 3 long term data sites. The meteorological variables that influenced that start of the grass pollen season were also important in determining the annual grass pollen total, ie. temperatures at the end of winter and the beginning of spring, and temperatures and rainfall during the spring. At London and Cardiff the total grass pollen catch for the season was also determined partly by when the season actually started. The models explained 91.5%, 96.9% and 98% of the variability respectively at London, Cardiff and Derby. When the models were tested with the 1993 and 1994 meteorological data, they were relatively accurate in predicting whether or not the season was going to be more or less severe than the average at the 3 sites. As the actual total pollen catch varies so much locally as a result of situation, location and altitude of the trap etc. the models were regarded as providing an adequate estimate of the severity of the grass pollen season at the 3 sites.

Analysis of the eleven EAN(UK) sites showed a variation in the start of season dates at the various sites, and between the sites. There did not appear to be any significant relationships between mean and accumulated temperatures and rainfall, and start of season dates at any of the sites, although this could be a result of there being too few years data at the majority of the sites. Long lag times in the start of the season occur in years with cool mean spring temperatures. There was little evidence of any definite direction in the progression of the start of the season, although this could have been because there were only 3 years in which there was data available at a sufficient number of sites to enable the establishment of a pattern.

In a similar way to the start of season dates, the annual grass pollen sum varied between the EAN(UK) sites. There was a combined relationship between plant physiology and climate in the influence of the total seasonal catch. There was evidence of a stronger relationship with climate than at the long term data set sites; high pollen production years were characteristic of years with warm springs and dry starts to the summer.

A positive correlation was found between annual grass pollen sums and the percentage of grassland in the source area. Areas with a high percentage of grassland in the source area tended to have high annual pollen sums, and a greater number of days experiencing counts greater than 50 grains/m^3 of air.

Due to the lack of both pollen and meteorological data at the EAN(UK) sites and thus the statistical restrictions imposed, it was not possible to develop models to predict the start of the grass pollen season at the EAN(UK) sites. In order to counteract this problem, the sites were grouped regionally as a result of analysis of variance tests. The long term models for Cardiff and Derby were tested on the mean significant meteorological variables for the region in order to assess their use regionally. In the southern region, over the years 1988-1994, the model for Cardiff predicted the mean regional start date to within 7 days of the actual mean start date, in 72% of cases. In the central region, the long term model for Derby predicted the mean regional start date to within 6 days of the actual mean start on 75% of occasions. Therefore, the models provided a good estimation of when the season was going to start. Information of this sort would be adequate in the timing of clinical trials and pharmaceutical advertising campaigns etc.

9.2.2 Conclusions on the Start and Severity of the Birch Pollen Season

There was an overall trend towards an earlier start to the birch pollen season at all 3 long term data sites over the study period. This trend was particularly pronounced after the mid 1980s, and correlated with a trend towards warmer spring mean temperatures.

Models were developed to predict the start of the birch pollen season at the 3 long term data sites, the models accounted for 99.2%, 95.7% and 85.4% of the variation at London, Cardiff and Derby respectively. The research revealed that the sites had a similar response to meteorological variables ie. mean temperatures and rainfall, although as a result of the effects of local climate, the timing of the response was slightly different. All 3 sites responded to mean temperatures in February and March, and rainfall during the last week of November and the first week of December. The importance of rainfall in the winter was autocorrelated with temperature in that days with rainfall were usually warm, and hence the presence or absence of rainfall implied warmer or cooler temperatures which would bring on the extension of, or the end of dormancy. Late winter and spring temperatures were important in determining the actual time of bloom as warm temperatures were required for bud development. When the models were tested on the data for 1993 and 1994, they did not prove particularly successful at Cardiff and Derby, despite the high levels of explanation achieved by the equation. It is possible that this was because 1993 and 1994 were not normal flowering years in that 1993 was one of the highest flowering years on record, and 1994 was an exceptionally low flowering year. The model for London proved more reliable, possibly as a result of London being a dense urban area and therefore not as influenced by the prevailing dispersal patterns and hence the alternating flowering rhythm of the birch tree. This is a matter for further investigation and will be discussed later (section 9.4).

All 3 sites showed a similar trend in annual birch pollen sums, that is they all showed a trend towards an increase over the 24-32 year period. This trend was most pronounced from the mid 1980s. The mid 1980s were characteristic of warm January, February, March and April mean temperatures, and also a decline in rainfall in March and April, thus providing ideal dispersal conditions.

Models were developed to predict the severity of the birch pollen season on the basis of climatic factors, however they achieved a relatively low level of explanation at all 3 sites. The poor level of explanation is likely to be a result of the biennial flowering pattern and thus the great variation in annual sums from year to year. It is possible that pollen production within the buds is determined by the amount of hormone produced in the preceding year, irrespective of autumn and winter temperatures. Once the pollen is produced, the actual amount of pollen released is determined by when the season starts and temperatures and rainfall during anthesis.

Biennial rhythms in birch flowering were identified. The research revealed that the pattern was more regular at the more rural sites ie. Cardiff and Derby. There was no evidence of any synchronisation in 'high' and 'low' years at the 3 sites. This, along with the fact that weather patterns were not rhythmic, leads one to believe that fluctuations in annual birch pollen sums were due mainly to the production of gibberellines and auxins and occur regardless of prevailing weather patterns, although weather conditions during the period of anthesis would be important in determining the release of pollen.

Analysis of the start of the birch pollen season between the EAN(UK) sites showed great variation. Unfortunately a lack of data restricted the analysis, and therefore variations in lag times could only really be investigated for the years 1992-

1994. On the basis of this data it was found that generally long lag times occur in cooler years.

Annual birch pollen sums at the EAN(UK) sites varied from year to year and also between sites. Considering the short range of data, biennial rhythms were evident over the period 1987-1994 at those sites for which data was available, although as some of the sites only had two or three years of available data no conclusions could be made at this stage based on the EAN(UK) sites until further years monitoring has taken place.

9.3 AN APPRAISAL OF THE RESEARCH

Whilst undertaking the research, several key difficulties have become evident.

The first problem concerns the question of how representative is the pollen concentration data derived from sampling a small quantity of air from a single sampling point? The efficiency of the Burkard volumetric spore trap was considered in chapter 3. Hirst (1953) reported that the trapping efficiency varies with wind speed, and for wind speeds of about 1m/sec sampling efficiency is 100%, however the efficiency declined with increasing wind speed. Pollen concentrations recorded under high wind velocities will thus be under estimated. Considerable differences in pollen abundance can occur both horizontally and vertically within regions (Bryant *et al* 1989, Emberlin and Norris-Hill 1991). This together with trapping efficiency and other sources of variation, means that the defined start dates are indicative rather than real, and one must be careful that the explanation does not exceed the capacity of the data.

The second problem concerns the forecasting of the start of the grass pollen season. In Britain approximately 150 different species of grasses exist. Different species of grass have varied responses to climate, and therefore flower at different times. For example, *Anthoxanthum pratensis* is an early flowering species compared to *Phleum pratense* which flowers much later on in the season and *Poa annua* which flowers all year round (see chapter 6). The analysis of the severity of the grass pollen season suggests that either the climatic response of a particular species can vary over a period of time, or a change in the grass seed mix can lead to a dominance or absence of a particular species resulting in a grass population with a different response to climate than it had previously. This altered climatic response over time makes forecasting difficult.

9.4 SUGGESTIONS FOR FUTURE RESEARCH

This research was based on intact pollen grains. During the last ten years the existence of micronic and submicronic allergen bearing particles has been demonstrated for grass pollen (Stewart and Holt 1985, Spieksma *et al* 1990). These particles may originate from plant material or may form by combination or reactions with air pollutants. The origins and significance of these smaller sized particles is not fully understood but it is known that they contribute to symptoms especially during the early and late phases of seasons (Spieksma *et al* 1990). In London particularly, where there has been a decline in the grass pollen count, increases in vehicle exhaust pollutants, especially suspended particulate matter, may have enhanced the importance of this fraction. Agarwal *et al* (1981) reported that pollen counts do not always correlate with the allergen load of the atmosphere. It is therefore possible that although at London the concentrations of grass pollen have declined during the study period the allergenicity of the grass pollen grains has increased because of the interaction with air pollutants. (Emberlin *et al* 1993b). A suggestion for future research therefore should concentrate on a more detailed analysis of this micronic and submicronic allergen bearing fraction and its relation to hayfever symptoms.

There is a further need to decide on an international definition for the start and other characteristics, (eg. length, severity) of the pollen season. Chapter 3 has highlighted the many different approaches to defining the start of the season. Research into establishing the best method of defining the characteristics of a pollen season would be useful for both allergists and agriculturalists in all European countries. The availability of the EAN database could permit future comparative research on long term data sets between countries.

Poor results were achieved for the prediction of the annual birch pollen totals in this analysis. There is a need to look in more detail at biennial flowering rhythms and the dispersal characteristics of birch and other trees. The results suggested that biennial rhythms appear to be more pronounced in rural areas than urban areas. This was possibly a result of the prevailing dispersion patterns making urban monitoring areas too far away from the pollen source, thus not as influenced. Very little work has been done on birch pollen and therefore with these and other European long term data sets, and also those that exist in Europe (Spieksma *et al* unpublished), it is now possible to extend this study. This type of study has increased in importance because of the increase in the incidence of birch pollen allergy, particularly in the Scandinavian countries (Eriksson *et al* 1984).

Further research could be done on the use of phenology particularly in grass pollen forecast models. Driessen and Moelands (1985) traced the phenology of the early and late flowering grasses to explain the different timing of species on the basis of their response to climatic factors. Keynan *et al* (1989) forecast the flowering of grasses using phenology alone and found that results of such a survey yielded good predictions of when flowering of a given species in a region would start. This research was done in Israel, and in most other countries, particularly within Europe, phenological investigation would probably pose too time consuming. Also, in a country like the UK which has a varying topographies and local climates, you would need the studies to take place in a large number of different places. Therefore although it would be useful, it would not be very cost effective. Ideally frequent measurements of climatic, pollen and phenological information recorded from the early spring would be necessary to be able to study the factors influencing pollen production.

The final suggestion is for a more detailed study of daily concentrations over a long period of time. Previous research has modelled daily concentrations of grass pollen on a short term basis (Norris-Hill 1992 PhD Thesis). With the availability of these long term data sets, more accurate modelling of daily concentrations could take place. The models for the prediction of the severity of the grass pollen season presented in this study considered the total seasonal catch and were based on mean daily counts. Mean daily counts do not take into account the 'highs' and 'lows' during the day. Morrow Brown (1992) has suggested that symptoms are related more closely to diurnal or nocturnal peak concentrations than to the average for 24 hours. This analysis did not allow for daily or diurnal forecasting, neither did it provide information on when the severest period was going to be ie. will it be most severe in June or July? when in June or July? The research did however provide information on whether or not the season was going to be more or less severe than the average season. This information would be useful to GPs in prescribing medication, and also to pharmaceutical product managers. Future research would therefore consider the daily analysis of the long term data sets in order to enable the prediction of day to day variations in the pollen catch, and the prediction of the timing of peak pollen concentrations.

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