RMK 38

AN AEROBIOLOGICAL MODEL FOR OPERATIONAL FORECAST OF POLLEN CONCENTRATION IN THE AIR

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Abstract

Roughly 10-15% of the population in Sweden suffers from allergic reactions from airborne pollen. One of the most common allergene pollen is the one from birch (Betula verrucosa and Betula pubescens). The pollen season is limited to a period of 3-4 weeks in spring. However, the start of the season varies at most ±2 weeks from year to year. The variation of pollen dispersion during the season also varies substantially between different years. Hypothesizing that these variations are related to exogenous processes, especially climatic influence, a simplified prediction model that simulates the aerobiological process has been developed. The model has been proven to give satisfactory results and was operationally tested for the Stockholm area during springtime 1981 and 1982.

Key words

Birch, Betula, Aerobiology, Pollen forecast

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1. INTRODUCTION

1.1 The problem

The fraction of the population in Sweden, sensitive to airborne pollen is not exactly known. However, investigations that have been done indicate figures of 10-15%. This means that roughly every third household in the country is familiar with this problem.

All sorts of airborne pollen do not give allergic reactions. The majority of the symptoms observed is caused by a restricted number of pollen types. As an illustration of this statement, frequently 50% or more of the total amount of airborne pollen, yearly observed at the Palynological Laboratory Stockholm, is classified as emitted from birch, (Betula pubescens and Betula verrucosa) the source of one of the most allergenic pollen in several European countries. This limited study was chosen to consider exclusively pollen from birch.

Several investigations have clearly brought out that there is an intimate connection between observed pollen concentration in the air on one hand and present and past weather on the other hand. Among those studies that have been made we can mention: Bringfelt (1979) (birch), Reader (1975) (dogwood), Smart et al (1979), Emecz (1962), Liem and Groot (1973), Davies and Smith (1973) (grass) and Bianchi et al (1958) (ragweed).

There is also a clear relation between pollen concentration and allergic/asthmatic reactions among a population. This has been shown in several studies e g Salvaggio (1971), Engström et al (1971), Hobday and Stewart (1973), Davies (1973) and many others.

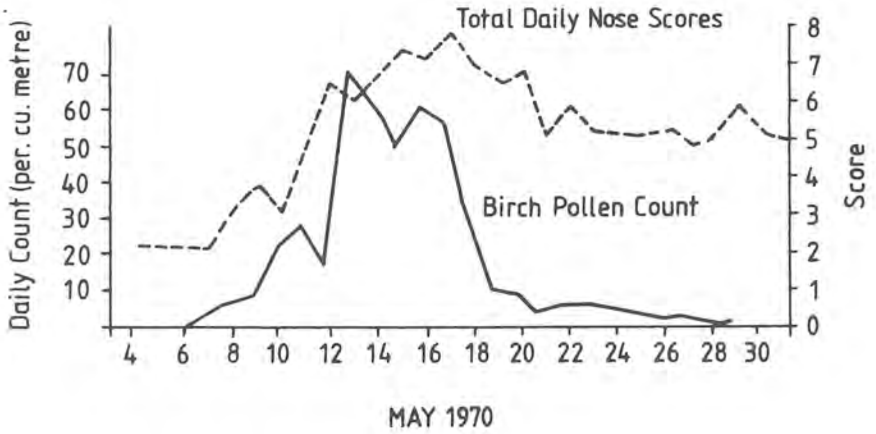

Figure 1.1 *Birch-pollen concentration in the air (Stockholm) versus allergic symptoms.*
After Engström et al (1971).

It is obvious that a pollen forecast could be of importance for an allergic person, provided he knows how to use it. Forecasting schemes for practical use have been developed by different investigators. Raynor and Hayes (1970) developed a forecasting scheme for ragweed, Davies and Smith (1973) for grass. Spieksma (1980) developed and tested a forecast procedure for grass based on subjective complainment from 150 patients instead of the measured pollen concentration in the air.

However, the crucial point in forecasting pollen concentration is evident in the above mentioned studies; The pollen forecast will never be more accurate than the weather forecast. But to make an optimal pollen prediction, it is extremely important not to ignore the fact that different meteorological variables are predicted with variable precision. The perfect prognosis method means that we estimate a relationship between a number of predictors; x_n n=1 ... and a predictand (pollen concentration) y, i e

$$y(t) = f(x_1(t) \; ..... \; x_n(t)) + \varepsilon(t), \quad \varepsilon(t) \text{ is the error at time } t \qquad (1.1)$$

Thereafter a forecast of the variables $x_1(t)$ ..... is used for a forecast of $y(t)$. But the variables $x_1(t)$ ..... are not exactly predicted but have an error $\varepsilon_k'(t)$, k=1,2 ... . The total error in $\hat{y}(t)$, i e the predicted $y(t)$, would then be an accumulation of several error terms which in fact could give, as a result, a useless forecast in $y(t)$. To avoid this problem one can restrict the functional relationship(1.1)to those predictors $x_k(t)$ that definitely are skillfully predicted, or to use the MOS-technique (Model Output Statistics) if the forecast of $y(t)$ is based on objective forecasts of $x_k(t)$. The MOS-technique, Glahn (1976) and Klein (1978) means that we establish a relationship like (1.1) but based on stored forecasted predictors $x_k(t)$ and observed values of $y(t)$. In this technique we avoid the summation of different error terms in the application stage and this technique has successfully been used in meteorological applications in USA.

In this study the MOS-technique is not used, but a *perfect prognosis based on purely daily mean air temperature, a variable that can be accurately predicted 1 à 2 days ahead and with some skill up to 4 à 5 days.*

The main purpose of this study is not only to develop a forecasting scheme, but also to make operational tests to prove that such a procedure could be a realistic forecasting tool, useful to the public. In chapter 5 the result from operational tests for 1981 and 1982 is given.

1.2 Pollendata

Measurements of pollen from birch have been made in Stockholm since 1970 with a suction sampler, the Hirst Trap, (Hirst (1952)), in the Burkard version (figure 1.2) placed on the roof at three different sites in Stockholm. Bringfelt (1979) found that the covariation between the different sites was very high leading him to the conclusion that any of them could be used as 'representative for a rather large area, at least as far as the day-to-day variations are concerned'.

In this project the forecasting problem is restricted to daily mean values. When examining hourly mean values during the dependent pollen seasons one can see a substantial variation over the hours, but these can roughly be divided into night and day values corresponding approximately to a factor of 2. (See figure 1.3).

There is no extreme diurnal variation as can be seen in grasspollen measurements but individual days show extreme variation depending upon external meteorological conditions like intensive frontal precipitation.

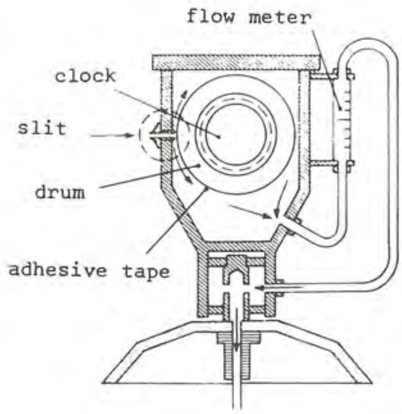

Figure 1.2 *The Burkard trap. The particles are impacted on the adhesive tape, mounted on a drum, rotating one revolution a day (or week).*

From Nilsson (1972).

In figure 1.4, daily mean values from four seasons are plotted as a function of time. Three striking features can be noticed:

1. There is a substantial variation in the mean season intensity between different years. Obviously, the source of emission must vary from year to year. This is attributed to the quality and quantity of male flowers.

2. The onset date of the pollen season is not identical from one year to another, but the recorded data indicates a variation of approximately four weeks.

3. There is a large variation from day to day during a particular season.

As we shall see in the following chapters, those three features can be treated as factors, nearly independent of each other, completely defining the problem of simulating the shedding of pollen.

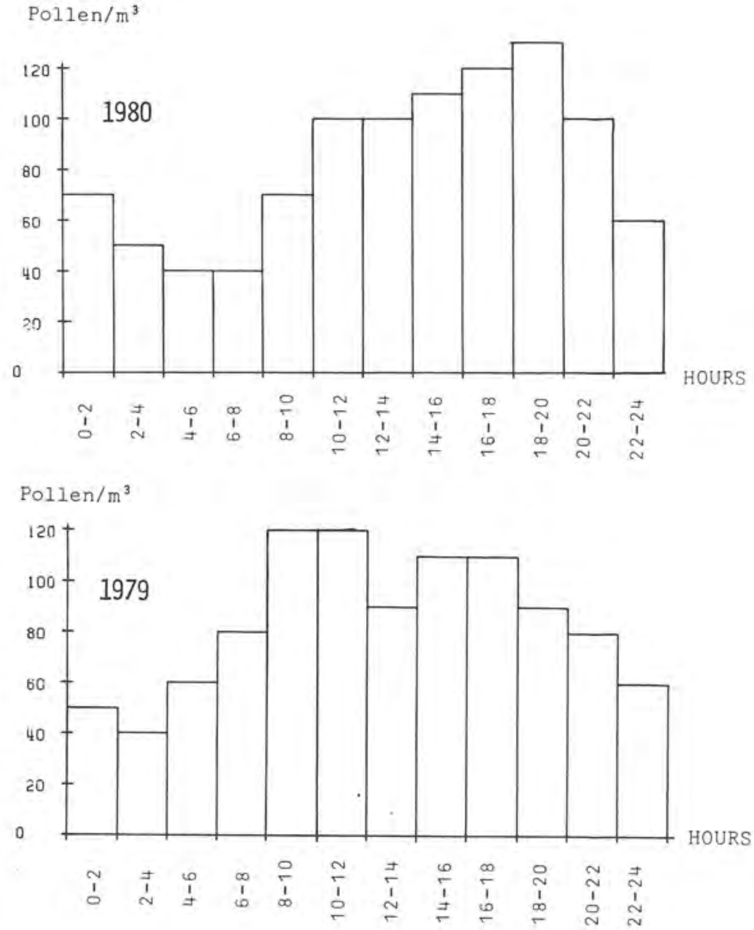

Figure 1.3 *Hourly mean values of birch-pollen during the seasons 1979 and 1980.*

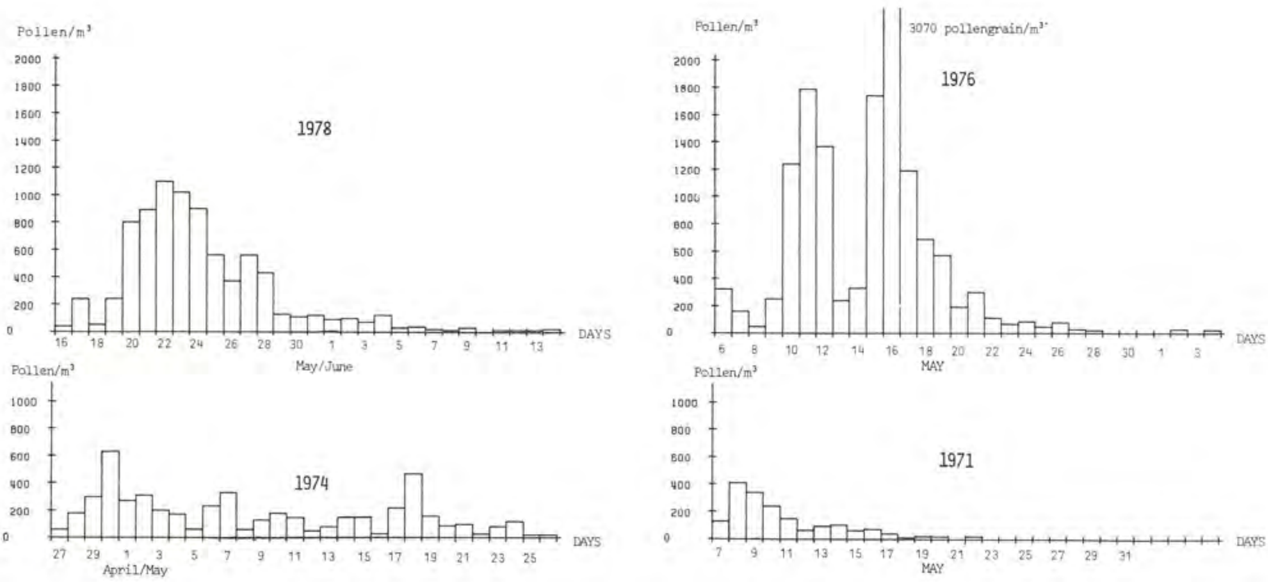

Figure 1.4 *Daily mean values of birch-pollen in Stockholm.*

1.3 The birch

The birch is of general occurrence from the southern to the northern part of Sweden. There are essentially two species, namely: Betula verrucosa and Betula pubescens. The birch occurs in most parts of the country as more than 10% of the total forest stand.

The birch has both male and female catkins on the same three. Flowering (shedding of pollen) simultaneously as busting into leaf. (Figure 1.6). Approximate date for this in different parts of the country is given in figure 1.7. The biological cycle from the flower primordia initiation until the shedding of the seed is given in figure 1.5 below. It is worthwhile to notice that the evolutionary phase in the male flowers has reached a final stage 7-8 months before bursting into blossom (Carlsson 1980). Therefore, in order to seek after external, i e meteorological factors influencing the pollen source, the weather during the preceding year must be taken into account.

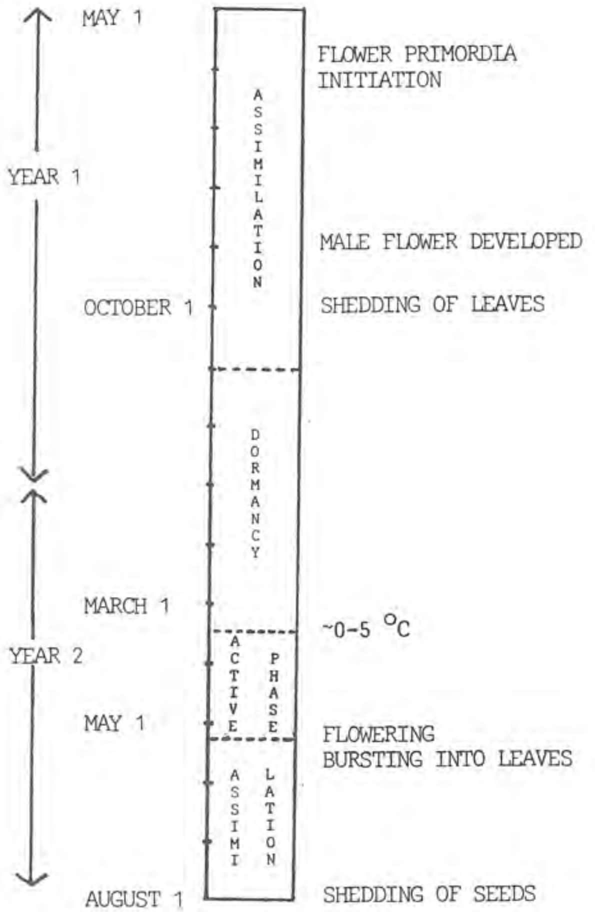

Figure 1.5 *The biological cycle of birch from flower primordia initiation until the shedding of seeds (Sweden; ~55°N).*

Figure 1.6 The flowering of birch. The female catkin (1) has passed the winter inside a bud, appears with the young leaves. The male catkin (2) on the other hand has passed the winter in a naked condition and will now be stretched.

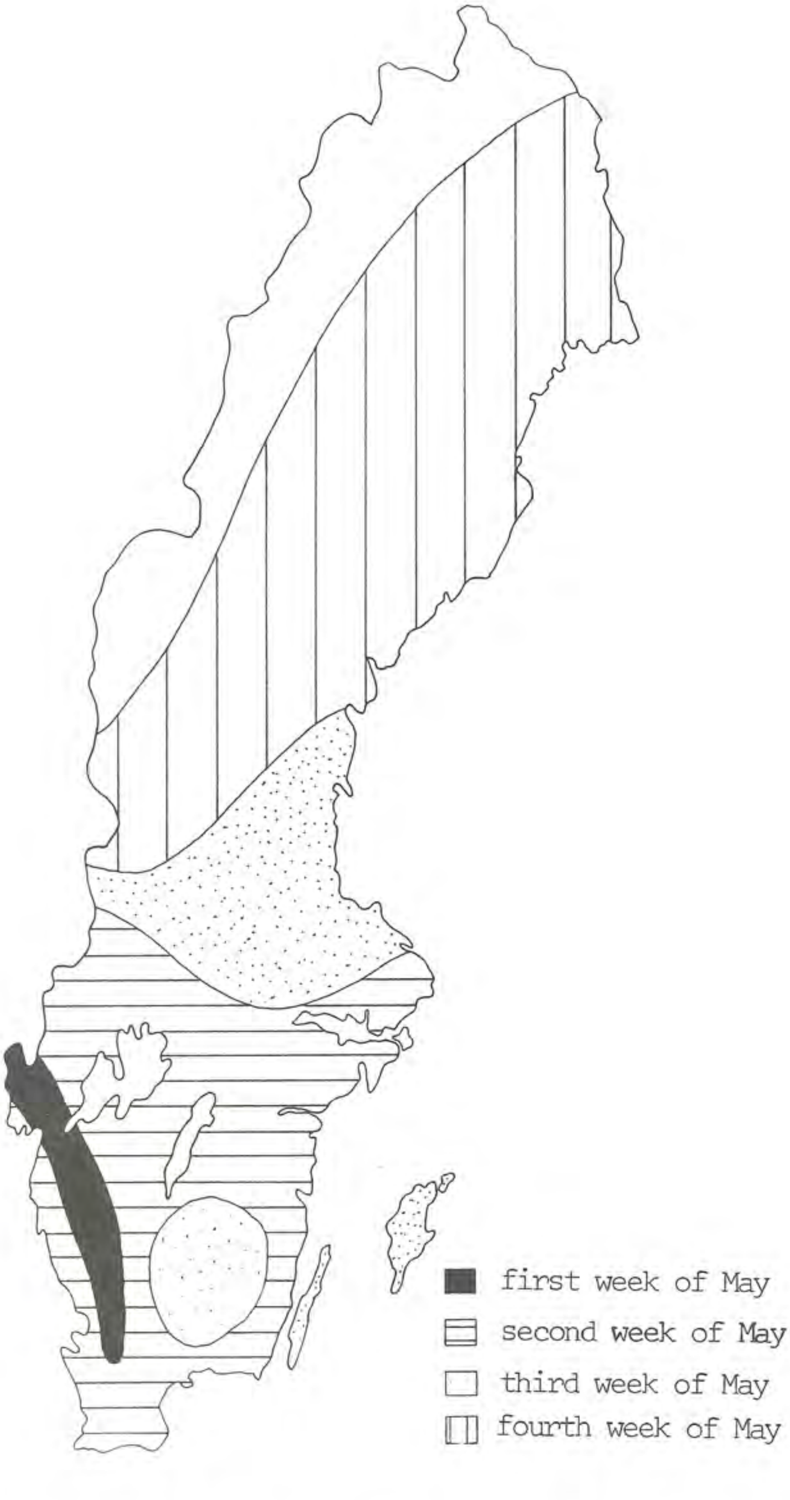

Figure 1.7 Average date for the onset of bursting into leaf (Betula verrucosa and Betula pubescens) for different sites in Sweden.

After Hultén (1971).

2. MODELLING THE POLLEN CONCENTRATION IN THE AIR

2.1 The aerobiological process

Let us examine those factors that together form the aerobiological process, governing the rate of increase or decrease of pollen in the air at a certain location and instant. The process is illustrated in figure 2.1.

A. Pollen Production (PROD). This is the primary source. It is obvious that a proper description of this effect is the pre-requisite of a successful forecasting scheme. The source strength is governed by the number of plants in the area of influence,having burst into blossom.

We have to describe the biological process affected by external forcing and simulate the evolution of a plant until the flowering.

It is likely that this process is not a function, reflecting an immediate response to weather but an accumulated effect of previous weather.

B. Pollen Release (REL). Probably there exists an immediate response to the weather when the perianth in the male flower splits and the pollen grains are exposed to the wind and transported away.

When the pollen grains are brought into the air, the atmospheric processes are:

C. Deposition (DEP). The sedimentation velocity for Betula verrucosa has been estimated by several investigators. A summary by Elsenhut (1961) shows that 2.6 cm/sec is a realistic value in calm air. Anderson (1970) reported that 34% of the pollen grain were adhering together and the average number of grains per clump was 2.9 indicating a spectrum of sedimentation velocities. However, since the vertical velocities in turbulent motion in the atmospheric boundary layer may exceed the sedimentation velocities by one and two orders of magnitude, dry deposition may differ quite a lot from a pure sedimentation process in calm air.

Dry as well as wet disposition is discussed by Tauber (1965).

D. Dispersion - Mixing and Advection (transport). The pollen grains are transported vertically by the turbulence and convective motions in the atmospheric boundary layer (Mixing; MIX) and horisontally by the mesoscale and large scale wind systems (Advection; ADV).

E. Turbulence Uptake (UP). When the pollen grains are impacted on the earth vegetation, building etc, the corrosion starts after a while. However, the pollen grains could before corrosion be brought back to the atmosphere by the turbulence.

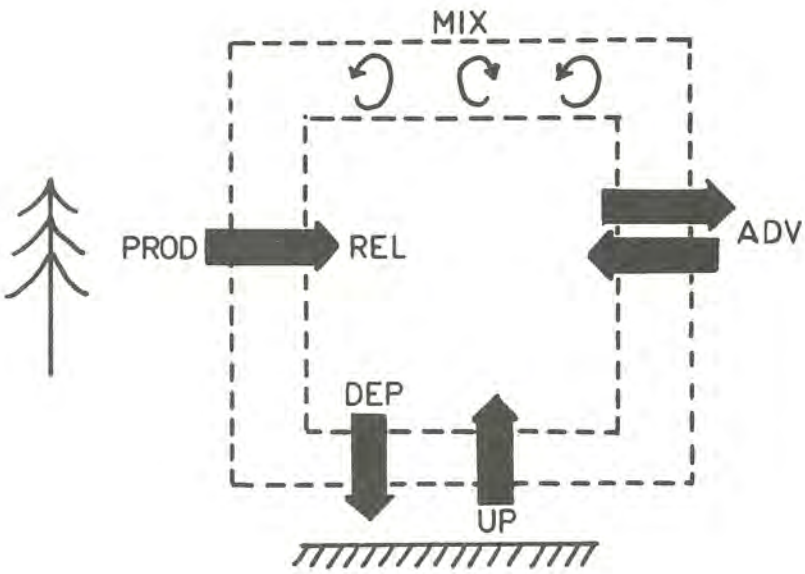

Figure 2.1 The aero-biological process governing the amount of pollen in the air.

2.2 A simplified model

It may be possible to construct a complete model that simulates all the processes that have been mentioned above. But to be used as a forecasting tool in today's weather service it would be more reasonable to make a model as simple as possible.

By making an analysis of the relative importance of the different processes we may get the maximum simplified equation still adequately reflecting the aerobiological process.

A. Pollen Production is the primary source, obviously non-linear to its nature, being zero most part of the year, varying extremely between seasons and in a particular season. There is no doubt that this must be the most important process among them all, necessary to simulate as accurately as possible.

B. Pollen Release. Liem and Groot (1973) found that release of pollen in grass is not an active but merely a mechanical process. No correlation between emergence of anthers and the release of pollen was found. In the case of Betula the flowers are exposed to the wind quite different as in the case of grass. Bringfelt (1979) found that wind was not a significant predictor for Betula but for grass. This fact suggests that in the case of Betula, the release of pollen as a pure mechanical process, is almost an effect that can be seen as constant. Therefore we let the release be proportional to the pollen production.

C. Deposition. Hirst (1953) reported that during half an hour with 1mm of rain the pollenconcentration in the air fell to 1/6 of the concentration before the rain began. During the next 18 hours, the air concentration decreased almost to zero (3 mm rain). This illustrates the crushing effect of wet deposition. However, Tauber (1965) points out that only approximately 10% of the total deposition should be attributed to wet deposition (as a mean value for longer periods). This figure is partly due to the low frequency of precipitation occurrence, partly because dry deposition rate is large. Looking at the pollen observations from Stockholm we find that very often during the final part of the different seasons half lifetime is shorter than two days without occurrence of precipitation. We also find that on the average there is only ≃ 2 days of precipitation during the intensive pollen season. Very often during this part of the year (May) the precipitation is not continuous in space and time like frontal precipitation but occurs as discrete showers. In these cases it is obvious that wet deposition plays a minor role in a well mixed lower atmosphere. In fact,during these situations the effect of washout is hardly noticable when considering daily mean values of pollen. (But, of course, the effect of washout is noticable during the precipitation period).

So, in order to simulate deposition, wet deposition is omitted and dry deposition is assumed to be proportional to the pollen concentration in the air.

D. Mixing and Advection. Bringfelt (1979) did not find the mixing depth nor the wind as significant predictors for the pollen variation of Betula. Examining the data we find occasions with extremely high concentration of pollen in the air appearing in very stable situations. But in order to distinguish the effect of non-constant dispersion we must first of all be able to separate the other important processes, especially the extremely varying production term.

Taking into account the difficulty of predicting the stability, mixing height etz, (parameters we need for calculating dispersion) differential mixing is neglected and assumed to be constant. This is not an argument for scaling but recalling the discussion in chapter 1.1 about the sum of errors, the neglection is justified for an operational model provided the mixing is not a too important process.

Koski (1967) calculated a probable range of pollen flight, making some simplified assumptions. For Betula he found the range to be 43.8 km. If we accept his calculations the pollen grains observed at a certain location have their origin in an area not too far from the observational site. If the area is rather homogeneous the weather condition in that point is representative for the area and the forecasting problem is one-dimensional, i e advection is negligable.

E. Turbulence uptake. The contribution from this effect is difficult to estimate, but short pollen seasons like 1971 and 1975 suggest that this factor is of minor importance. However, measurements are made at roof-level (~20m) and a plausible effect of turbulence uptake would be the creation of a sharp gradient in pollen concentration in the atmospheric surface layer, very near the ground. This idea is supported by figure 1.1 where we notice that subjective symptom scores are not falling as quickly as the measured pollen concentration. Investigations concerning the vertical distribution of pollen concentration ought to be done in the future in order to estimate this effect. However, in this study the effect of uptake is ignored.

To sum up, the aerobiological processes have been simplified in a maximum manner to yield an equation where the rate of increase or decrease is the effect of a production and a dry deposition term.

In a mathematical form we get the concentration equation as:

$$\frac{dC(t)}{dt} = P(t) - D \cdot C(t) \qquad (2.1)$$

where

C(t) = pollen concentration at time t

P(t) = pollen production at time t

D = dry deposition velocity

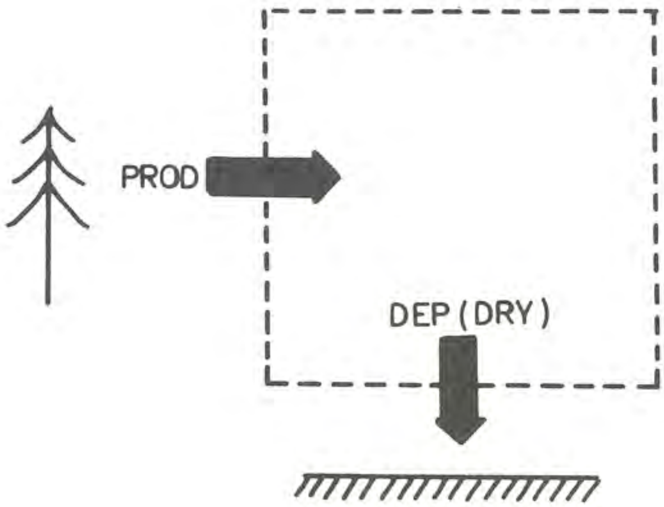

Figure 2.2 *Maximum simplification of the aero-biological process.*

3. SOLUTION OF THE CONCENTRATION EQUATION

3.1 The production term

Considering the total production in a population within an area of an approximate radius, 50-100 km, the production depends on both exogenous and endogenous conditions. If the external conditions were identical for all plants, there would still be differences in time between two specimen bursting into blossom, depending upon genetic variation, ages etc.

Figure 3.1 *An example of the variation in the production term. Although identical external conditions, the two specimen (Betula verrucosa) to the left have burst into leaves while those to the right (Betula pubesens) still show no sign of flowering.*

Taking the exogenous conditions into account the differences in behaviour between plants can be further accentuated. For instance, water supply would not be uniformly distributed over the area. The incoming energy, i e the microclimate, will also have a certain variation in the area, the distribution depending upon topography, lakes, soil types etc.

For the following discussion let us make a definition: If the weather in a tempered climate follows an idealized variation, that can be estimated by analyzing long time series, we call it normal.

This would, for instance, mean that events like sudden frost would not appear, but the variation of the weather parameters are smoothed.

The basic idea when constructing the pollen production terms is based on the following assumption:

If the weather during the spring is normal, all the processes that affect the development of a certain plant would cause, for a whole population in a fairly homogeneous, limited area, a production (frequency of flowering) that follows a Gaussian curve.

In mathematical terms, this would mean that the production is described by:

$$P(t) = P_o \cdot e^{\frac{-(t-m)^2}{2\sigma^2}} \qquad (3.1)$$

where P_o is the strength of the source, t is time, m is the date of culmination and σ is the spread of the curve. In fact, the frequency of flowering, like figure 3.2 can sometimes be observed. Landsberg (1979) suggests that this is always the case in apple crops but σ, m and P_o vary with conditions. In my assumption this behaviour is restricted to normal weather conditions, indicating that all the other factors influencing the development of a plant would be identically year after year but the weather being that factor mainly responsible for discrepancies.

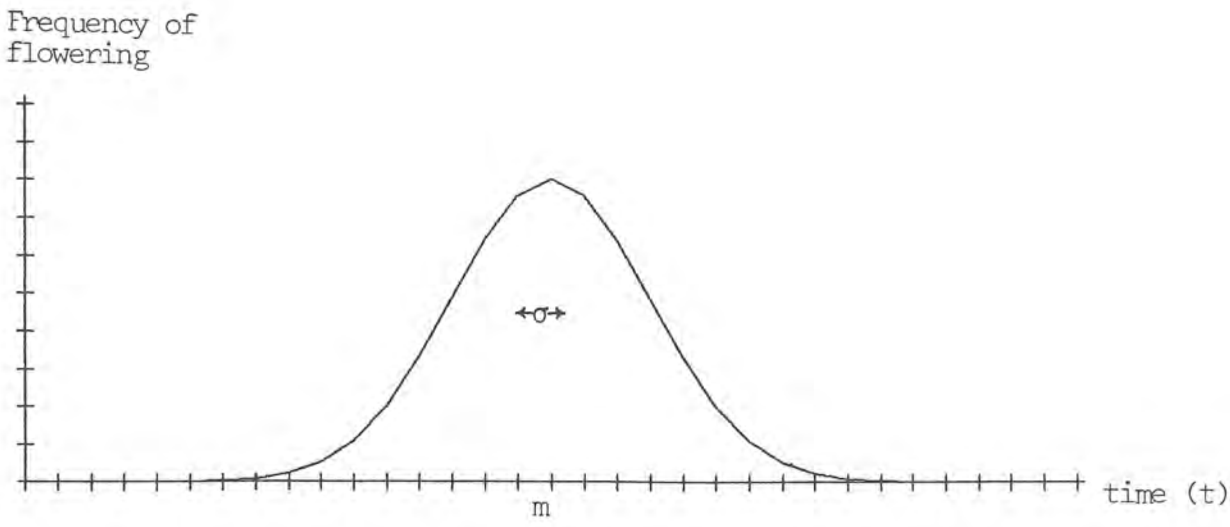

Figure 3.2 *The assumed frequency of flowering as a function of time under normal weather conditions.*

The solution of (2.1) under the normal conditions, provided that deposition is restricted to dry deposition is:

$$C(t) = D_o + P_o \cdot e^{-Dt} \cdot \int_0^t e^{-\frac{(\tau-m)^2}{2\sigma^2} + D\tau} d\tau \qquad (3.2)$$

If C(t)=0 when t=0 then $D_o = -P_o\, e^{-\frac{m^2}{2\sigma^2}}$

By setting the parameters to:

σ = 2 days

m = 10 days

D = 0.25 day^{-1}

and integrating (3.2) from 0 to t = 30 the result is given in figure 3.3.

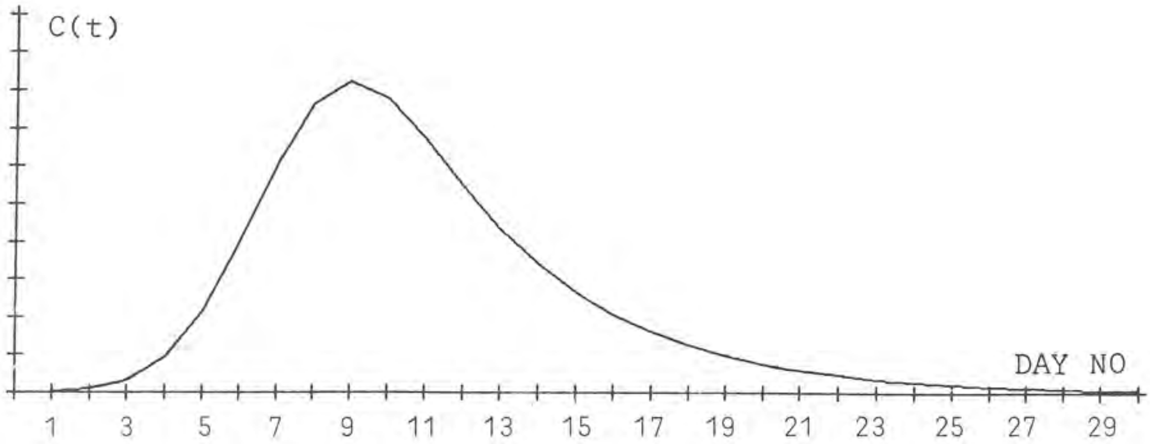

Figure 3.3 The solution of equation 3.2. Parameters given in the text.

By using the ten years of pollen data mentioned in chapter 1 (1970-1979) an estimation of the 'normal' pollen season can be made in the following way: Normalize the different years of measurements. Since the length of the seasons varies we define a season from the first observation of pollen and 30 days ahead. Transform the ten series into Principal Components (see, for example, Holmström (1978)), i e:

$$C_i^!(t) = \sum_{n=1}^{10} \beta_n(t) \cdot h_{ni} \qquad (3.3)$$

i = 1970, 1971, ..., 1979

Analyzing the first component, which by definition contains the maximum common variation in $C'_{70}(t) - C'_{79}(t)$ the result is given in figure 3.4.

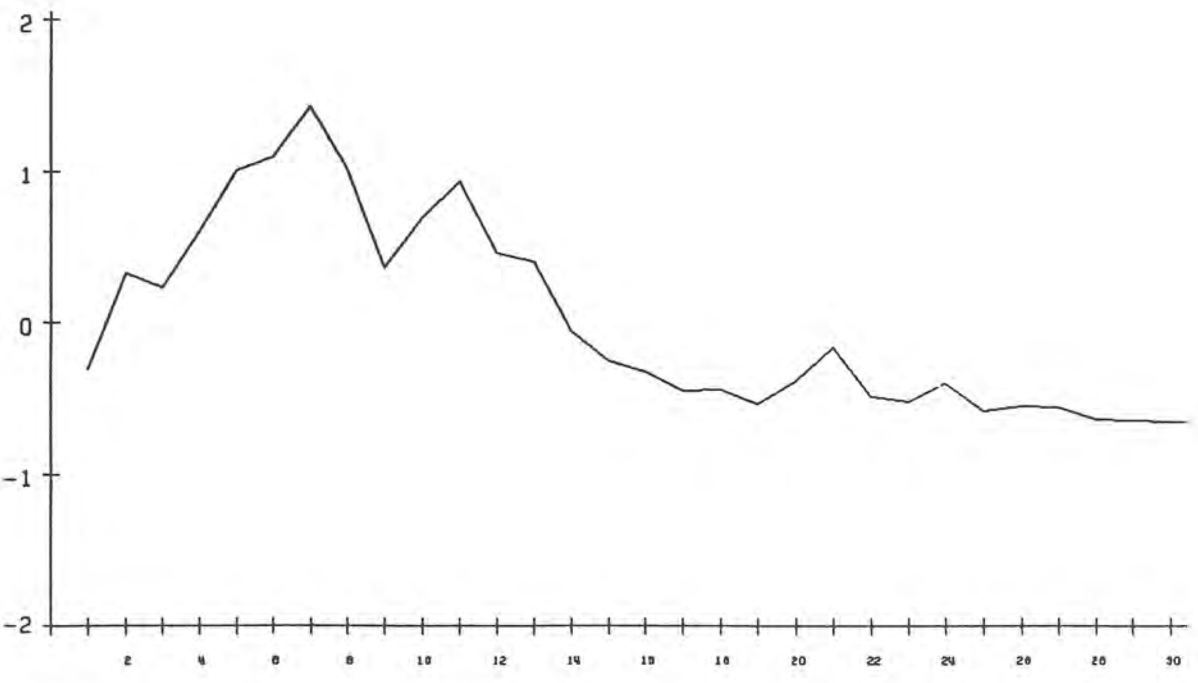

Figure 3.4 First Principal Component β_1 (t) *in eq.* (3.3).

The similarities between figure 3.3 and 3.4 are striking. In fact, we can estimate m and σ from figure 3.4 as realistic values of those parameters. We find:

$$m = 12 \text{ May}$$
$$\sigma = 2 \text{ days} \qquad (3.4)$$

Since σ = 2 this would mean that in the normal season 95% of the production is limited to a period of 8 days.

3.2 The effect of non-normal weather

A large number of investigations, concerning the effect if weather on plant growth, have been made during the last century towards finding a quantitative relationship between weather and plant response. There are, however, two or three dimensions in the structure of the relations between the forcing and the response. Livingstone and Livingstone (1913) define the dimensions as

1. Intensity.
2. Duration.
3. Quality.

As an example of quality they mention, for the photosynthesis, the necessity of having radiation within a certain waveband.

The weather and its variation cannot be described by a single timeseries, it is the combination of a number of elements that forms the complex picture, denoted weather.

Nevertheless, almost all investigators facing the problem have restricted their studies by using one or two meteorological parameters to characterize the weather. Almost without exception, the air temperature is the first one.

One of the reason for this, is, of course, that air temperature is comparatively easy to measure. Another reason is that the information given by air temperature is the reflection of the variations of other meteorological parameters like net radiation and humidity. Every meteorologist is aware of the intercorrelation between parameters. The weather is, on every scale, characterized by the feedback in the complicated system, which gives a great multicolinearity, not only in the space but also in the time domain.

A third reason to restrict an investigation to the variation of temperature is the principle of Van't Hoff and Arrhenius which state:

The velocity of most chemical reactions doubles (or somewhat more) for each rise in temperature of 10^{o}C, within a limited interval.

In a mathematical form the principle can be written:

$$\frac{dg(T)}{dt} \simeq \text{const.}g(T) \qquad (3.5)$$

$$T^{-}_{crit} < T < T_{opt}$$

Where g(T) is the velocity of a chemical reaction. T^{-}_{crit} and T_{opt} is the lower critical and optimum temperature, defining the intervall where the principle holds. The solution of (3.5) is:

$$g(T) \simeq g_0\, e^{\text{const}(T-T_0)} \qquad (3.6)$$

The value of the constant = $0.1 \cdot \ln 2$

Several investigators have made experiments in order to confirm the principle, relating it to plant growth. Early investigations were made by Koeppen (1870) and Lehenbauer (1914) studying growth of maize seedlings in relation to temperature, keeping all other environmental factors constant and varying the duration of the experiment. Some results are given in figure 3.5. The principle of Van't Hoff- Arrhenius seems to hold within the interval 18°-30°C. However beyond the point of the optimum temperature ther seems to be an inverse principle limited by the intervall $T_{opt} < T < T^{+}_{crit}$ where the latter denotes an upper critical temperature.

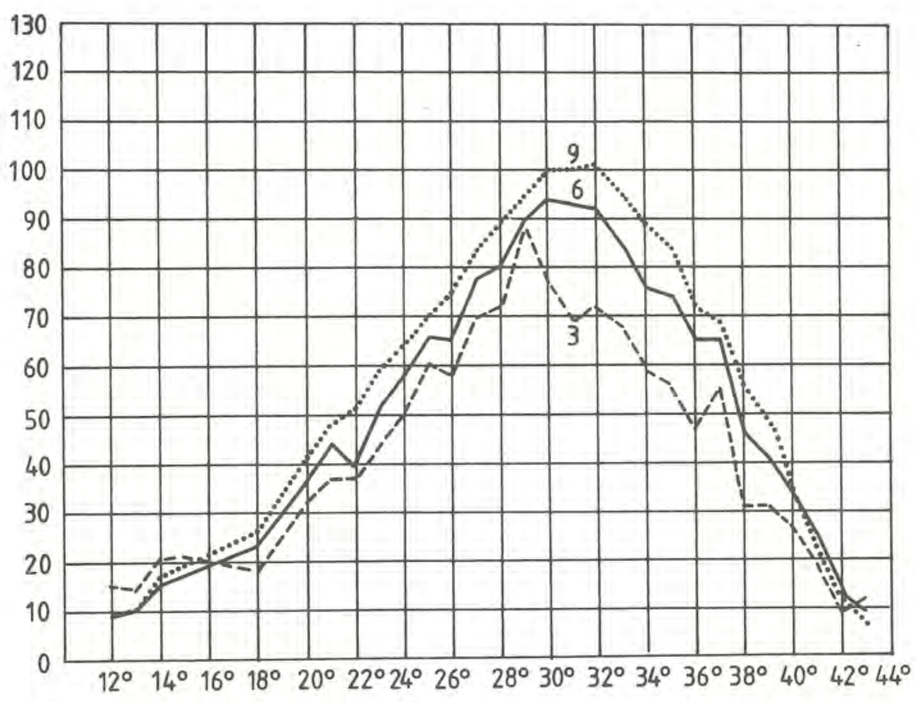

Figure 3.5 Relation of temperature to average hourly growth rate in shoots of maize seedlings, for 3, 6 and 9 hours duration respectively (1/100 millimetre). After Lehenbauer (1914)

Later investigations have shown that temperature is not the only important factor affecting growth. However, it is our wish (chapter 1.1) to (if possible) restrict the growth process to a function of purely temperature. Recalling the discussion in chapter 2.2 about advection, the conclusion was that we have a one-dimensional forecasting problem. More precisely: we are not interested in the development in one specific plant, but the mean effect in a population within a circular area with an approximate radius of 44 km. Temperature as an average for this area would probably be a meaningful climate variable when used as the driving force in a mean growth function for the population.
But it seems advisable to modify equation 3.6 slightly, still fulfilling the requirements of Van't Hoff-Arrhenius principle, but to yield an equation more in accordance with Lehenbauer's result. Define a growth function G(T) where:

$$G(T) = b_1' e^{\frac{-(T-M)^2}{2\gamma^2}} \tag{3.7}$$

Putting in (3.7) in (3.5) the approximation holds if the parameters M and γ are properly chosen.

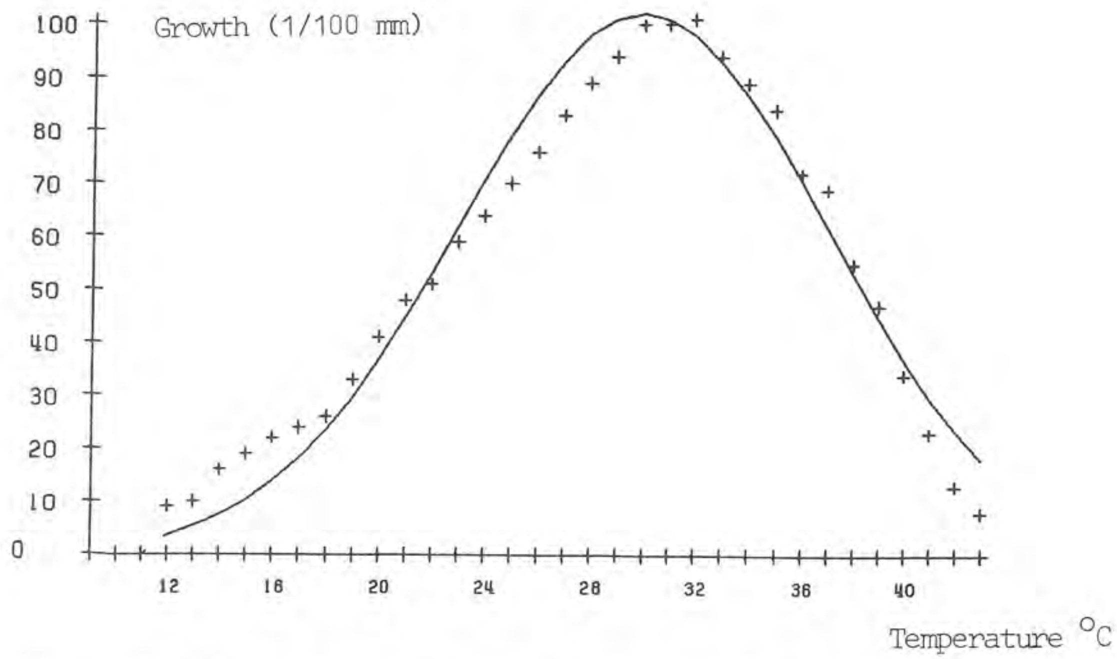

Figure 3.6 *Plus signs: 9-hours duration curve in figure 3.5.*
Drawn line: g(T) in equation (3.7)
$\gamma = 7^oC$, $M = 30^oC$.

Since the effect of duration on growth given in figure 3.5 is approximately additive, we conclude that the parameter b_1' in (3.7) is independent of the duration and the total growth within an intervall (0,t) can be described by:

$$\int_0^t G(T,\tau)d\tau = b_1' \int_0^t e^{\frac{-(T(\tau)-M)}{2\gamma^2}} d\tau \qquad (3.8)$$

However, since we intend to use the temperature,not as a continuous variable but averaged in time (daily mean), the formulation (3.7) has to be modified. If we denote the arithmetic mean operator (for an intervall I) by $(\bar{\ })$, then for an arbitrary function the identity: $\overline{f(x)} = f(\bar{x})$ would only be true for a certain class of functions or depending upon the intervall I. We know from the theorem called *Jensens´unequality* that if f(x) is a convex function in the intervall I then: $\overline{f(x)} \geqslant f(\bar{x})$. In our case we know that diurnal variation of temperature reminds of a sinusoidal wave. It can easily be shown that:

$$(2\pi)^{-1}\int_0^{2\pi} e^{-(\sin x)^2} dx < e^{-((2\pi)^{-1}\int_0^{2\pi}\sin x\, dx)^2}$$

and obviously there can be a systematic difference between $\overline{G(T)}$ and $G(\bar{T})$. For the daily mean growth rate, as a function of the daily mean temperature we therefore permit a formulation:

$$\overline{G(T)} \approx b_0 + b_1'' G(\bar{T}) = b_0 + b_1 \cdot e^{\frac{-(\bar{T}-M)^2}{2\gamma^2}} \qquad (3.9)$$

In the following, daily mean values are assumed when nothing else is said. However, in order not to confuse the reader with too many indices, the variables are treated as continoues variables. For instance: T(t) shall be interpreted as the daily mean temperature at day t.

Before continuing, there is an essential feature in the development of any organism that has to be stressed. A certain intensity, duration or quality of an environmental factor can in an early stage of plant development have the opposite effect to that in a later stage. For instance: a temperature level just above $0^{\circ}C$ would probably have no negative effect on a plant of Betula on March 15, the approximate date when the active period starts. However, the same level of temperature would undoubtly cause a negative effect on the development, if it appears just before flowering or approximately the first week of May. Considering equation 3.7 this effect implies values of M, γ and b_1' not only depending on the specific plant species we are interested in but also upon the stage of development in that specific plant species.

In a temperate climate the plant species growing in a certain area have adapted to the climate in the region, i e the different phases of development are closely related to the annual variation in weather, at least the normal variation. This means that the development in plants can be identified by the normal temperature, if we restrict ourselves to this variable.

As a first crude approximation, let M in eq (3.9) be a linear function of the normal daily mean temperature. (Assume the other parameters are constants). Hence:

$$M = M(t) = M_o + T_n(t) \tag{3.10}$$

If we define

$$T'(t) = T(t) - T_n(t) \tag{3.11}$$

we get

$$G(T,t) \approx b_0 + b_1 \, e^{\frac{-(T'(t)-M_o)^2}{2\gamma^2}} \tag{3.12}$$

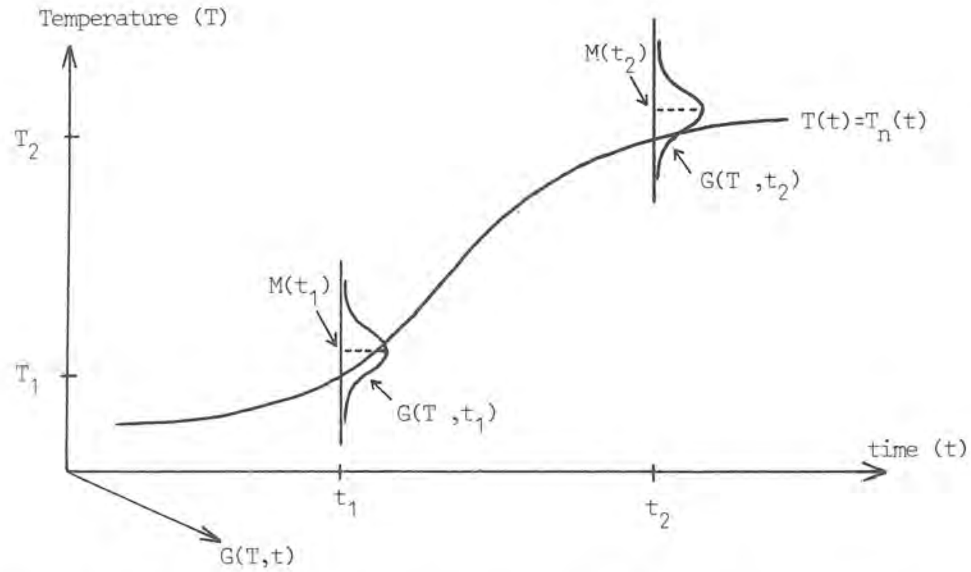

Figure 3.7 *An illustration of G(T,t) as a function of the normal temperature.*

For the following discussion we assume that there exists a function with a structure like 3.12 that can describe a general development of an arbitrary plant as a function of time and daily mean temperature.

If we define a normal development rate: $G(T_n,t)$ i e the rate we would achieve if the daily mean temperature coincides with the normal ($T'(t) = 0$), we can define a normalized development rate: $G'(T,t)$ where

$$G'(T,t) = \frac{G(T,t)}{G(T_n,t)} \tag{3.13}$$

The integral:

$$BTF = \int_{t_0}^{t} G'(T,\tau)d\tau \tag{3.14}$$

has the dimension time and represents an effective biological time function.

Looking back on eq (3.1), expressing the production as a function of time when weather is assumed to be normal, we can combine (3.1) with (3.14), replacing the time in (3.1) with the biological time (3.14).

$$P(t,T) = P_o e^{\frac{-(\int_{to}^{t} G'(T,\tau)d\tau - m)^2}{\sigma^2}} \tag{3.15}$$

Some interesting properties of P are worthwhile to mention:

- If $b_0 \geq 0$, a retrograde development is not possible. (As we shall see later on, $b_0 > 0$ in the case of Betula). This is a quite different feature of G compared with the ordinary method of temperature sums. However, the major difference is that P transforms the incoming energy, not as an absolute amount, but related to the minimum level, needed for continuing development at a certain stage of the cycle.
- The length of the period of production is independent of the total source strength P_o* while P_o may vary from year to year, it must be fixed at the start of the season i e depending on prior conditions. The length of the season, however, is perfectly determined by the weather within the season.
- The production curve follows a Gaussian curve only when temperature follows the normal or slightly deviates. Otherwise the production curve can be almost arbitrary, but, of course, depending on temperature.

* *This is true if we define the length by a relative criterion, for instance when 99% production is reached. If the criterion is absolute, i e production reaches a certain absolute level this would, of course, depend on P_o, this is discussed in chapter 4.*

4. ESTIMATION OF PARAMETERS

4.1 Pre-seasonal period

The solution of (2.1) means an integration from a certain date in late winter or early spring when the active period of the plant starts. However, in the period of development until the first pollen is discharged the effect of deposition is nil. So in this period equation (2.1) is simplified. Defining the start of the season by the criterion; $\frac{dC}{dt} > \varepsilon$ (for the first time)

$$P_o e^{-\frac{(\int_{t_o}^{t_s} G'(T,\tau)d\tau - m)^2}{2\sigma^2}} > \varepsilon \qquad (4.1)$$

t_o = date when the active period starts

t_s = starting date of pollen emission (flowering)

the parameters can be estimated. However, this is not a trivial problem from a mathematical point of view. First of all t_o must be stipulated. From earlier investigations (Carlsson, 1980, Tuhkanen, 1980) it is not perfectly clear when the integration ought to be started, but probably at the date when the daily mean temperature has exceeded 0^oC for a number of days. In this study t_o was fixed to be the date when the normal temperature in the area exceeds 0^oC approximated by March 15. A first approximation of the parameters in (4.1) can be found in the following way. From the discussion in chapter 3.1:

m = 59 (days between March 15 and May 12)

σ = 2

From figure 3.5 we can estimate $\gamma \approx 7^oC$. Analysing the dates of start in the sample described in chapter 1 this indicates a maximum value of $G'(T,t)$ not less than 1.2. This value is based on the early start in 1974 (= day no 44 after March 15) corresponding to a mean temperature about 1.2^oC above normal. As an initial guess, the parameters in $G'(T,t)$ were set to:

$$b_0 = 0,\ b_1 = 1.2,\ \gamma = 7.0^oC,\ M_0 = 5^oC \qquad (4.2a)$$

The criterion of start (4.1) can be further simplified by looking at figure 3.3 telling us that the start of the season would approximately be seven days before culmination date: m (=59)

$$\int_{t_o}^{t_s} G'(T,\tau)d\tau \approx m - 7 = 52 \qquad (4.3\ )$$

By using the definition (3.12) for $G'(T,t)$ (4.3) was solved in an iterative way, i e finding the least square minimum:

$$(t_s(n) - \hat{t}_s(n))^2 = \text{minimum} \qquad (4.4)$$

$\hat{t}_s(n)$ = estimated date of start

$t_s(n)$ = observed data of start

The estimated parameters were found to be:

$$b_0 = 0.4,\ b_1 = 0.9,\ \gamma = 5.6,\ M_0 = 4.1 \qquad (4.2b)$$

giving an estimated standard error of 2.4 days.

4.2 Seasonal period

Next step is to find the parameters when the complete equation (2.1) is used (within the season). By using a time step of one day the derivative in (2.1) is replaced by a finite difference, giving:

$$\Delta C = P(T,t) \cdot \Delta t - D \cdot C \cdot \Delta t \qquad (4.5)$$

The scheme for iterative determination of parameters looked like:

1. Initial guess D and $P_o(n)$.

2. Determine $P(T,t)\ |t_s<t<t_{end}|$ from equation 4.5 (t_{end} = time of end of season).

3. Estimate the parameters in $P(T,\tau)$ from (3.12) and (3.15) as a function of the observed temperature. Use 4.2 b as an initial guess and put initially $m = 7$ and $\sigma = 2$. Denote the estimation $\hat{P}(T,\tau)$. Use an iterative procedure to minimize $H(P(T,\tau) - \hat{P}(T-\tau))$. The choice of a function H is not trivial. In fact, a least square minimum is not suitable for the problem. In the present work H is set to the logarithm of the square error combined with subjective estimation of the minimum. This is not a satisfactory solution of the minimizing problem but the development of a general method was not possible within the framework of the project.

4. Replace $P(T,\tau)$ with $\hat{P}(T,\tau)$ in equation (4.5) giving $\Delta\hat{C}$ and determine $P_o(n)$ and D that minimizes the error $H(\Delta C - \Delta\hat{C})$.

5. Go to 2 and repeat until we have found an optimal estimation of the parameters.

Since we deal with two different phenological periods the parameters b_0, b_1, M_0 and γ are allowed to be changed, having a discontinuity at the starting date.

Hence, when $\int_{t_o}^{t_s} G'(T,\tau)\, d\tau$ has been determined in the scheme above, a repeated attempt can be made to estimate the parameters in $G'(T,\tau)$ for the pre-seasonal period.

The final estimation of parameters gave:

a) Pre-seasonal period

$$b_0 = 0.3,\ b_1 = 1,\ M_0 = 2.8,\ \gamma = 4 \qquad (4.3c)$$

b) Seasonal period

$$b_0 = 0,\ b_1 = 1.3,\ M_0 = 2.8,\ \gamma = 4 \qquad (4.6)$$

$$D = 0.4$$

The source strength $P_0(n)$ for the different years is given in table 4.1.

Table 4.1 *Total source strength P_0 for the different years, in percent of the most intensive one (1976).*

1970	50
1971	10
1972	60
1973	60
1974	35
1975	25
1976	100
1977	30
1978	45
1979	35

In figure 4.1 the modelled and observed concentrations for the different years are plotted.

As we can see there are occasions when modelled concentration largely deviates from observed, but on the whole, the essential dynamics of the process seem to be adequately described. Comprehensive seasons like 1978 and 1979 as well as extremely extended seasons like 1974 and 1977 are properly simulated.

It is worthwhile to notice that air temperature (daily mean) is the only information given to the model. The integration starts March 15 or approximately 54 days before the start of the different seasons. So some of the discrepancies that can be seen in figure 4.1 can easily be corrected (1972, 1978, 1979) by using 'the last observed' value of pollen concentration, since the error largely depends on 1-2 days error in forecasting the start of the seasons.

Finally, the model was tested on an independent sample. For 1980 the result is given in figure 4.2. Here, P_0 is estimated by the method described below. We can see from figure 4.2 that this rather extreme year is adequately described. The three local maxima, appearing this year, have been correctly depicted.

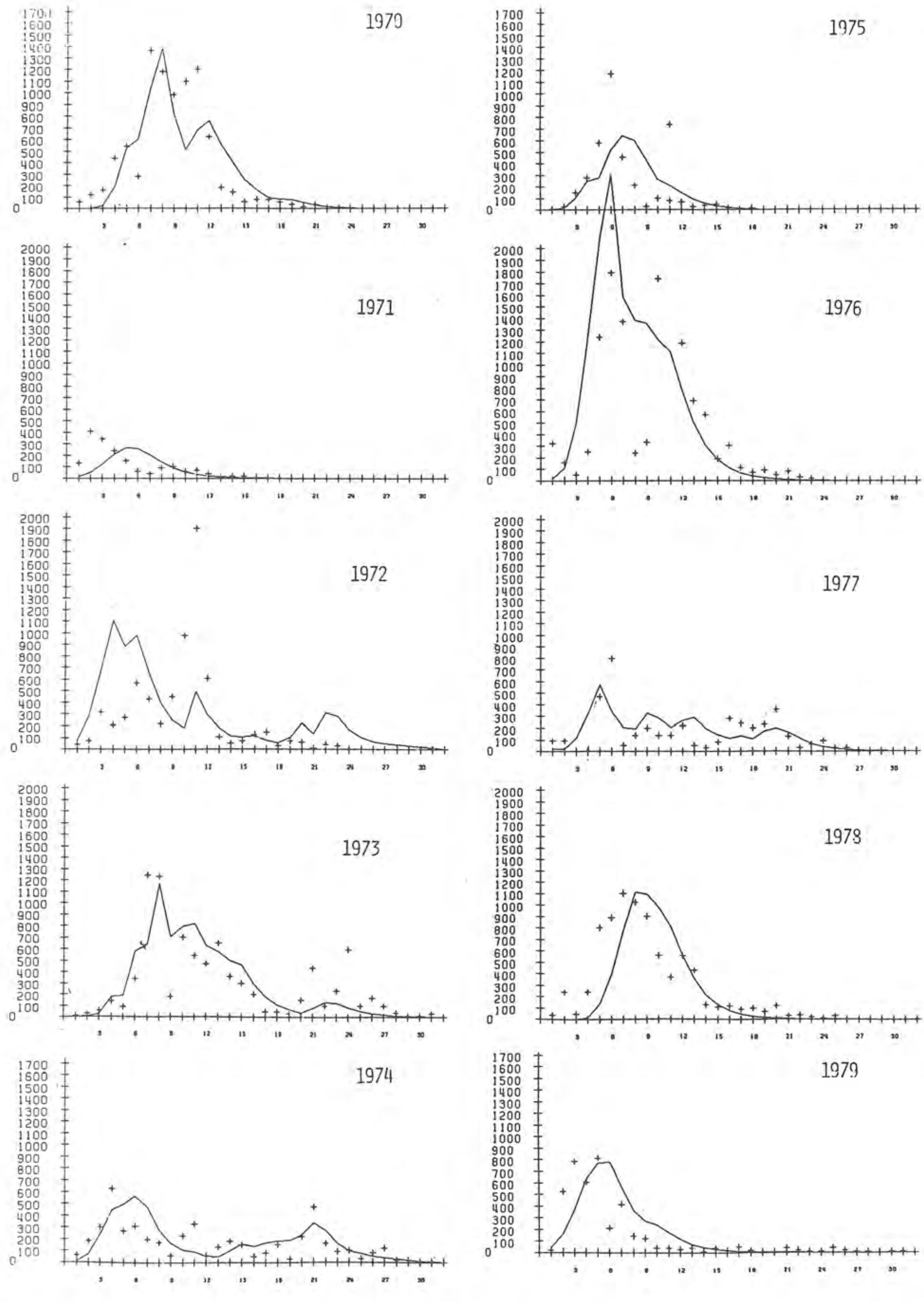

Figure 4.1 Verification of pollen forecasts. Dependent sample.
Plus signs; observations.
Solid line: modelled concentration.

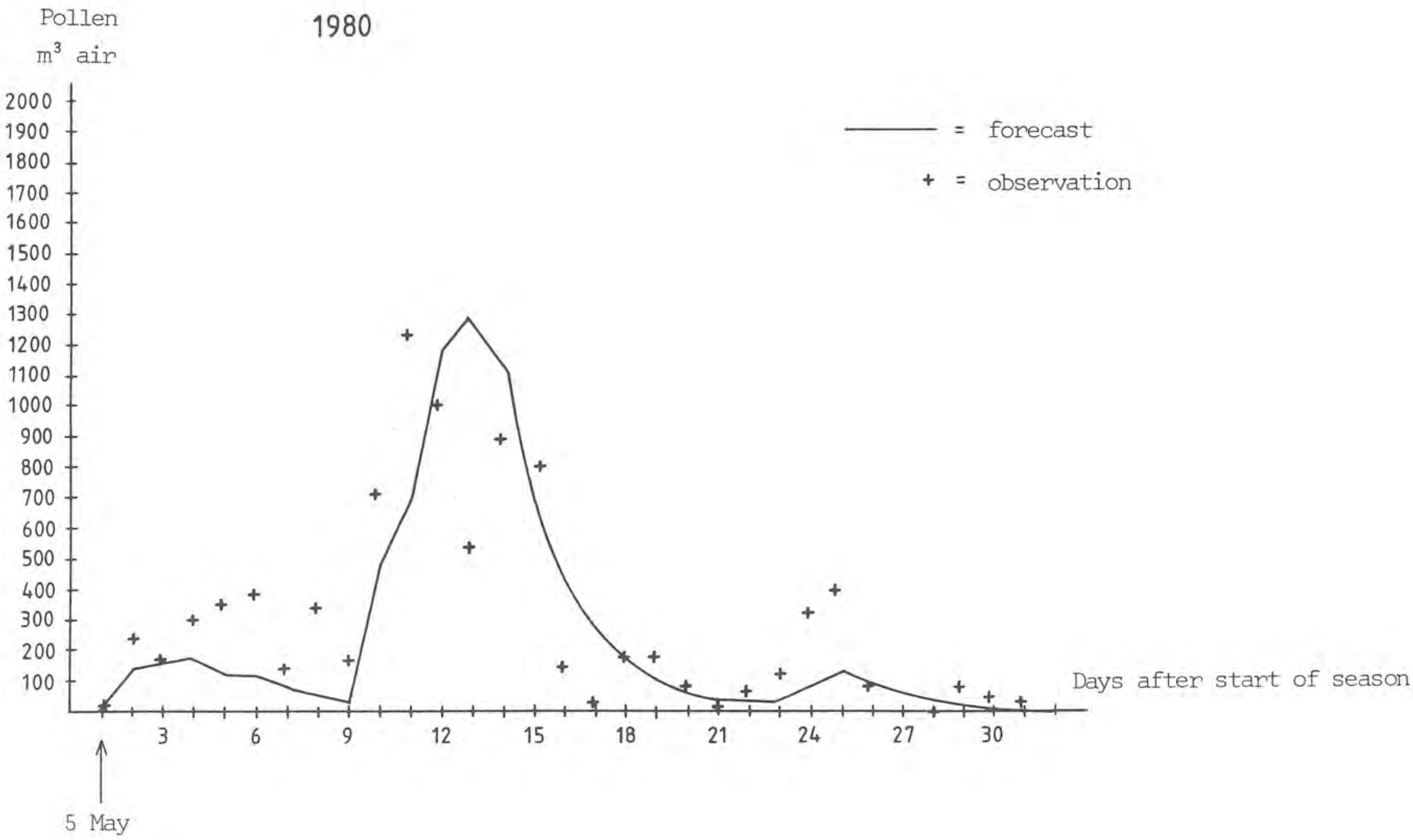

Figure 4.2 *Verification pollen forecast. Independent sample.*
Plus sign; observed pollen concentration.
Solid line: modelled pollen concentration.

4.3 The inter-annual variation of P_0

From Table 4.1 we notice that there is a substantial variation in P_0 from year to year. From the data it is clear that there exists a biennial oscillation. However, this harmonic would explain not more than 20-30 percent of the variation in P_0. This oscillation should rather be seen as an effect, superimposed on a variation that depends on external (climatic) condition. For *Picea abies* Tirén (1935) and Eriksson et al (1975) suggested that weather conditions during flower primordia initiation are of decisive importance. Lindgren et al (1977) have quantitatively shown that temperature during this period plays an important role.

For *Betula* the period of flower primordia initiation is approximately the same as the period of pollen dispersal. So $\int_{t_s}^{t_{end}} G'(T,\tau)\, d\tau$ can be used as a measure of the climate conditions during this period. The length of the pollen season, L(n), can also be used as a predictor since L(n) with a relative large accuracy can be described as a function of purely $G'(T,\tau)$. This is easily verified by using equation (3.2) and compare the length of the season when using $P_0(1971)$ and $P_0(1976)$ assumed to be extreme years. In fact, we find that L(n) as a function of $P_0(n)$ is not modified with more than two days.

Setting up a model:

$$P_0(n+1) = \beta_0 + \beta_1 L(n) + \beta_2 P_0(n) + \varepsilon(n+1).$$

Using ten years of data 1970-1979 the parameters β_0 - β_2 were determined. By using the cross validation technique a realistic estimate of the error $\varepsilon(n)$ can be found. Cross validation, Hjorth et al (1981), mean that we divide the material into K subsets using (K-1) as dependent sample and the remaining subset as independent data. By forming all the possible different combinations of the subsets all the material can be used as 'independent' data. The result is given in figure 4.3.

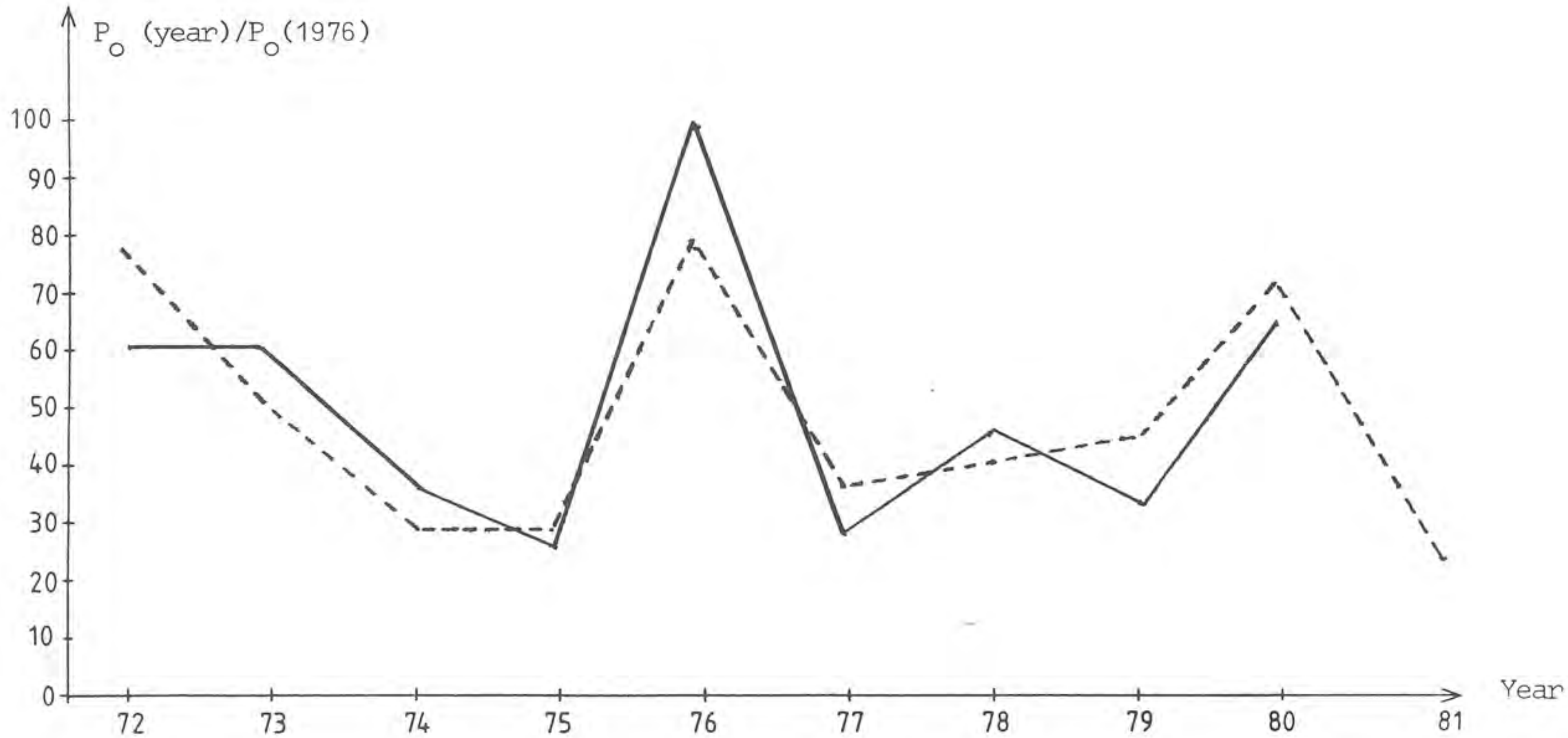

Figure 4.3 Estimated strength of birch pollen source (1972-1980) in percent of the most intensive year (1976).
Solid line: Estimation based on observed values.
Dashed line; Predicted value, described in the text.
Forecast of 1981, used in the operational test (chapter 5), is also given in the figure.

5. OPERATIONAL TESTS

In 1981 and 1982 operational tests were made in cooperation with the Palynological Laboratory, Stockholm. The forecasts were transmitted via the local broadcasting company in Stockholm. The 18th of April 1981 the first forecast was sent out telling the listeners that the birch pollen season of 1981 was going to be a very light season, the most gentle in 10 years. In fact, it turned out to be the most gentle ever observed in Stockholm. Monday to Friday the forecast was issued twice a day with projection time 5 days concerning the starting date, and when the season had started, for tomorrow (on Fridays, three days ahead).

The forecast was issued in four classes, corresponding to the international standard and the result is given in figure 5.1.

A verification of the operational tests for 1982 is given in figure 5.2.

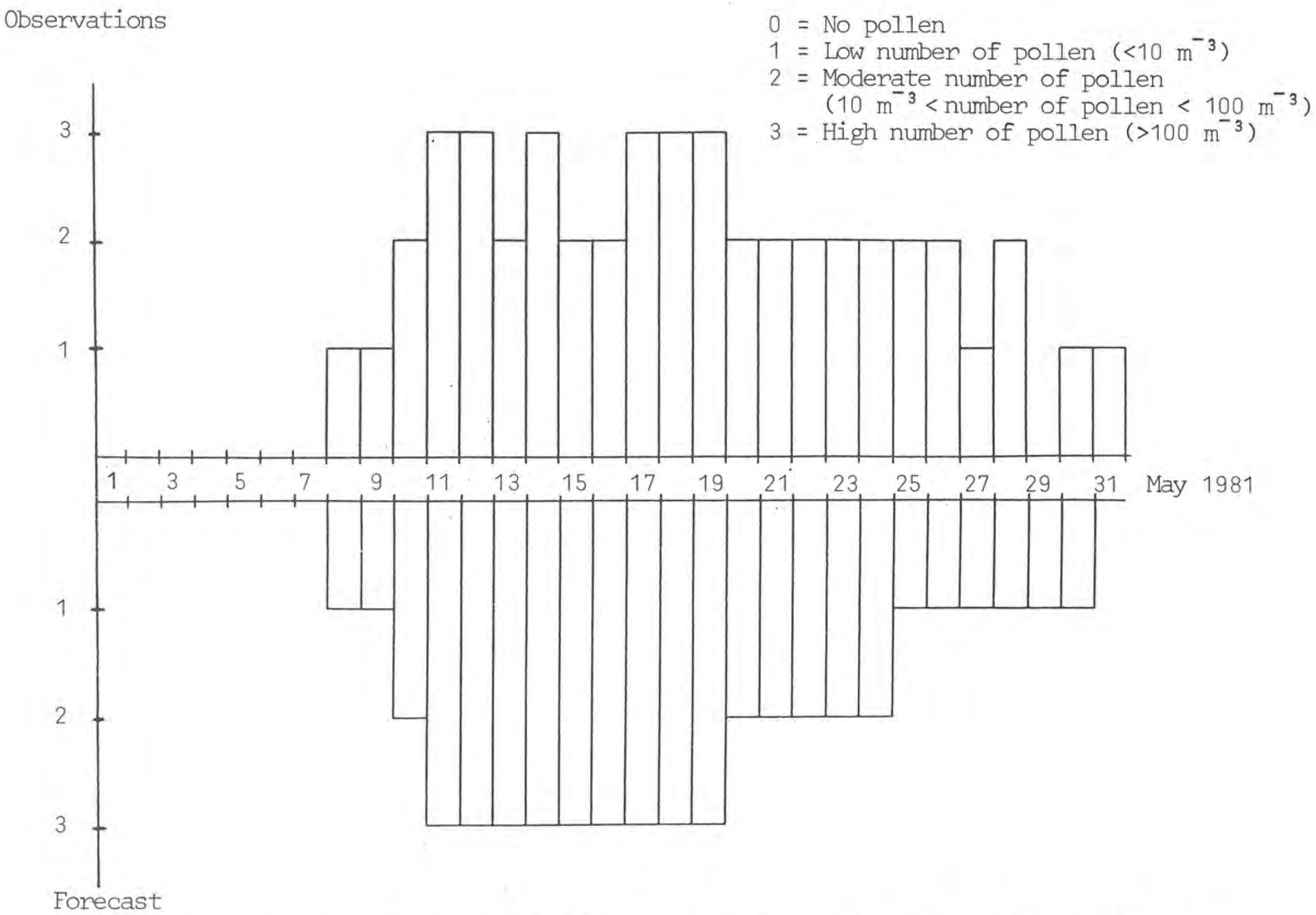

Figure 5.1 Verification of pollen forecasts (Betula) 1981 for the Stockholm area (radius ≈ 50 km).
Forecast broadcasted at 5 pm.
Projection: Pollen concentration for tomorrow.
(Friday: Pollen concentration 1-3 days ahead).

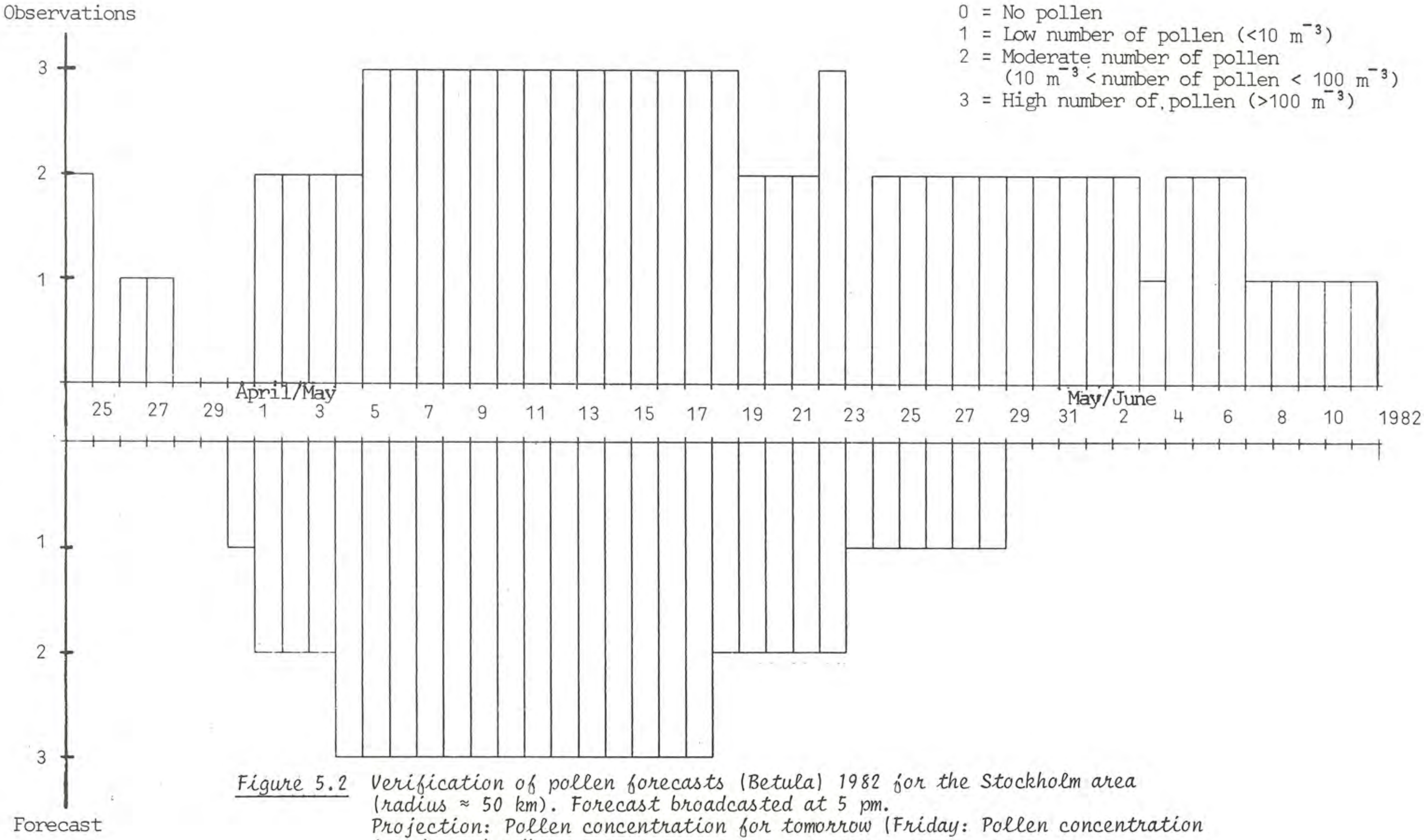

Figure 5.2 Verification of pollen forecasts (Betula) 1982 for the Stockholm area (radius ≈ 50 km). Forecast broadcasted at 5 pm.
Projection: Pollen concentration for tomorrow (Friday: Pollen concentration 1-3 days ahead).

6. CONCLUSIONS AND REMARKS

- It has become evident that reliable forecasts of pollen concentration in the air are possible to make on an operational basis.

- It has also become evident that the fundamental part of the problem is the proper description of the biometeorological production term. Given the source and a simple dry deposition as a sink, about 80% of all the variation can be explained. Of course, the direct atmospheric processes as differential dispersion, advection, release and turbulence uptake at certain instants can be very important, but those must now be seen as secondary effects and necessarily superimposed on those first.

- Having a network of pollen traps, the pollen forecasts could be a service for the whole country. In that case the advection term cen be incorporated in the model.

- Wet deposition can also be included in the model in the future. Promising experiments have been made, and this would mean not only forecast on a daily mean basis but also divided into part of the day.

- Prediction of pollen emission from other species of leaf trees like hazel, ale,oak etc would probably be possible by using the same type of model. However, the shedding of pollen from grass is presumably to some extent different, and measurements at lower levels must be done since the highest concentration occurs very near the surface.

- The success of pollen forecasts depends not only upon the quality of the predictions but also how they will be utilized. It is therefore important that information and education must necessarily take place before pollen forecasts become routine.

- A cost/benefit investigation ought to be done in order to demonstrate that an activity like this is economically and socially justified.

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