

A mathematical model for mugwort (*Artemisia vulgaris* L.) pollen forecasts

Frank Wolf^{a,b,*}, Klaus Eckart Puls^c, Karl-Christian Bergmann^d

^a Bayreuther Institut für terrestrische Ökosystemforschung (BITÖK), University of Bayreuth, Dr.-Hans-Frisch-Straße 1-3, Bayreuth, D-95448, Germany

^b Faculty of Mathematics (FB 17), University of Paderborn, Warburger Straße 100, Paderborn, D-33098, Germany

^c Wetteramt Essen, Wallneyer Straße 10, Essen (Ruhr), D-45133, Germany

^d Allergie- und Asthma-Klinik 'Wilhelm Gronemeyer', Postfach 1280, Bad Lippspringe, D-33167, Germany

Received 18 November 1997; received in revised form 12 May 1998; accepted 20 May 1998

Abstract

Pollen forecasts are a fundamental prerequisite to obtain prophylactic measures for allergic individuals. Mugwort belongs to the most relevant allergenic pollen types after grasses and birch. An approach to modeling of mugwort pollen concentrations has not been attempted previously in Germany. A process-oriented mathematical model for the relative local daily average mugwort airborne pollen concentration was developed on the basis of pollen and weather data measured during a 6-year period. The model depends on the daily minimum and maximum temperature, amount of precipitation and atmospheric pressure, which have to and can be supplied by measurement and prediction. The comparison of modeling results and pollen counting for an additional year confirms the fitness of the model. A computer program was written, which rests upon the model and supplies daily predictions of mugwort pollen flight during the period of the weather forecast. The latter should allow a pollen forecasting period of about 5 days, with an accuracy of about 32–63% explained variance, which in view of the low mugwort pollen counts (nine grains/m³ maximum in the validation year) represents a high relative measurement error. The mathematical model may serve to improve and rationalize of present pollen forecasts. © 1998 Elsevier Science Ireland Ltd. All rights reserved.

Keywords: *Artemisia*; Pollen forecast; Mathematical model

1. Introduction

Accurate pollen forecasts are an important and fundamental prerequisite in the planning of prophylactic measures for allergic individuals, such as avoidance and short-term prophylactic measures. Patients may have less or no complaints, thereby saving costs.

Currently the German weather service (DWD), in cooperation with the German pollen information service (PID), manually combines plant observations and airborne pollen measurements with the weather forecast to provide the pollen forecast.

The aim of the work presented here (Spitzer, 1995) is to rationalize this process by use of a mathematical model. Paradigmatically, mugwort (*Artemisia*) pollen in Bad Lippspringe (North Rhine Westfalia, Germany) was investigated. Mugwort flowers from July to August in Germany and is one of the allergologically most important plants after grasses and birch (Puls and von Wahl, 1989, p. 40). Whereas pollen concentration or hay fever stress models exist for birch (Törnevik, 1982), and grasses (Spieksma, 1980; Tonkelaar, 1986; Moseholm et al., 1987; Norris-Hill, 1995), similar models for mugwort have not been developed.

Bad Lippspringe is a health resort, especially for allergic individuals, with 13500 inhabitants, 140 m above sea level, at 51° 47' north latitude and 8° 49' east

* Corresponding author. Tel.: +49 921 555632; fax: +49 921 555799; e-mail: frank.wolf@bitoek.uni-bayreuth.de

longitude. The landscape is dominated by agriculture, and is mainly flat with some hills in the west.

The genus *Artemisia* is almost exclusively represented by the one species *Artemisia vulgaris* L. in the relevant area, where it is a common wild flower. It is often found at roadsides and in rural areas in Bad Lippspringe and the environment of the pollen trap, which comprises a park and hedges.

The restriction to only one species may be a promising condition for modeling in the sense of Moseholm et al. (1987), p. 320. *Poaceae* are a family with several species that have different flowering times. In addition, *A. vulgaris* L. differs from birch by exhibiting a relatively low variation in its flowering time. This property may be considered to be another advantage for modeling.

Unfortunately, *Artemisia* pollen counts are relatively low (Table 1; Figs. 9 and 10), which causes a high relative measurement error. The low mugwort counts are a known phenomenon, investigated by von Wahl and Puls (1989). They are caused by the biologic emission rhythm of mugwort, the diurnal rhythm of wind and convection, and the usually high (more than 10 m above ground) pollen traps. Another reason may be that the genus *Artemisia* is an anemophilous exception in the eutomophilous family of the *Asteraceae*, therefore, the pollen and their release mechanism are not as sophisticated for anemogamy as it is for *Betula* or *Poaceae*.

The low *Artemisia* pollen concentrations in high traps should not mislead as to their concentration at nose height, which could be ten times higher (von Wahl and Puls, 1989). For pollen predictions of the German pollen information service, more than six grains of *Artemisia* pollen per m³ air daily mean are already assessed as a severe burden risk for pollen allergic individuals (Bergmann, 1994, p. 143).

2. Materials and methods

2.1. The data

Pollen counts in Bad Lippspringe have been made by the PID since 1988 with a Burkard trap 13 m above ground, on the roof of the Karl-Hansen Hospital. The Burkard trap is a volumetric device which sucks in a continuous air stream of 10 l per minute through a slit of 14 × 2 mm, held in the direction of the wind. The air stream passes a vaseline film, which is spanned on a cylinder with one rotation per week, to which dust and pollen adhere. The vaseline film is changed every 3 days. After preparation it is cut in strips of 1 day, which is 48 mm on the 14-mm wide film. From this, the pollen of four parallel stripes each 250 µm wide, which account for a total width of 1 mm, and 48 mm long

(the full length of 1 day), are counted under a stereo-microscope. This yields the pollen concentration in grains per m³ air (grains/m³), daily mean, because of the daily air volume of 14.4 m³ sucked in. The Burkard trap is the common instrument of European pollen measurement services (see von Wahl, 1987, p. 22 for further explanation).

For calibrating the model, all mugwort data of the seasons 1988–1993 were used. However, there are some early counts outside the main flowering seasons presented in Fig. 9; these data were never captured in a modeling approach. For evaluating the model adequacy, however, only data from the main flowering periods were used (see comparison period in Table 2). Including the periods with a few (early) pollen counts would lead to an over-estimation of the model adequacy, because of the many common pollen-free days. The early exceptions are: one grain/m³ on July 13 1988; several single peaks in the period from June 1 1990 to July 9 1990; one grain/m³ on June 11 1991; three grains/m³ on June 16 1991; eight grains/m³ on July 8 and 9 1991; one grain/m³ on June 20 1992; and one grain/m³ on July 8 1993. We assume that other pollen types that were falsely classified as *Artemisia* pollen account for the early *Artemisia* pollen, at least in June, because none of the 17–18 species of this genus which are native to Germany flowers this early (i.e. before July), as known by own observation and reference to comprehensive German flora literature (Rothmaler et al., 1990).

From the weather station of the DWD, 1 km from the pollen trap, the following nine daily parameters were obtained for 1988–1993: minimum, mean and maximum temperature, amount of precipitation, relative humidity (mean from the measurements at 08:30, 15:30 and 22:30 h CEST), atmospheric pressure at ground level (mean from the measurements at 08:30, 15:30 and 22:30 h CEST), amount of global radiation, duration of sunshine and average wind speed, 10 m above ground.

As proposed and successfully applied by Defila (1988), Klante (1989), Marletto et al. (1992) and the German pollen service, phenological data from plant observers of the environment of Bad Lippspringe should be considered for modeling the flowering season. From the central weather bureau of the DWD in Offenbach, the data from plant observers of 59 reasonable phenological phases were available for 1988–1991, and of two phases from 1988 to 1993, at the time of model calibration in 1994. The phases were the beginning of flowering of *Alnus glutinosa* (L.) Gaertn., *Anemone nemorosa* L., *Betula pendula* Roth, *Cornus mas* L., *Corylus avellana* L., *Forsythia suspense* (Thunb.) Vahl and *Galanthus nivalis* L. Unfortunately, there were no data from *Brachypodium pinnatum* (L.) P.B. or *Plantago lanceolata* L., which were also found

predictive for the flowering of *A. vulgaris* L. by Marletto et al. (1992), p. 80.

Phenological data for Bad Lippspringe were not available from plant observers but from the pollen trap, which is the same instrument used for the *Artemisia* pollen counts. The only well-defined phenological events captured by the trap, that may be useful for the prediction of mugwort flowering dates, were the airborne pollen concentration maxima (here also denoted as main flowering days) of the pollen types *Betula*, *Poaceae*, *Carpinus*, *Fagus*, *Fraxinus*, *Pinus*, *Plantanus*, *Populus*, *Quercus* and *Salix*. (*Plantago* pollen counts were performed, but are very low and have no definite maximum.)

The model was cross-validated using the corresponding and necessary (see below) weather and pollen data from 1994.

2.2. The modeling approach

In the literature a large number of trivial and more complex dependencies between the airborne pollen content and different weather parameters can be found. Not all of them could be considered in a model, because of intercorrelations and the coarse or few calibration data. One fact seems to be accepted by every investigator: warm and dry weather favors high pollen concentrations in the flowering season. But how much of the variations could be explained by this principle? For example, Törnevik (1982) found a reasonable birch pollen model dependent on the daily mean temperature only, Moseholm et al. (1987) found additional use of the relative humidity for a grass pollen model, and Norris-Hill (1995) additionally applied the maximum temperature and daily rainfall for a grass pollen model.

Our idea was to establish a basic model, with which the effect of different climatic parameters could be investigated separately. Thus, the search for relevant parameters was performed by model calibration, which seems to be a 'more natural' way, as sophisticated dependencies may be hard to find by (linear) statistics exclusively.

The model rests on a simple concentration differential equation, which was used by both Törnevik (1982) and Tonkelaar (1986). According to this equation, changes in the airborne pollen concentration C at time t at a certain location result from pollen production P (i.e. from the surrounding plants) and from dilution D (i.e. dispersal, deposition) of the airborne pollen:

$$\frac{d}{dt} C(t) = P(t) + D(t) \cdot C(t) \quad (1)$$

In contrast to Törnevik (1982), who used this approach for a birch pollen model and Tonkelaar (1986), who used this approach for a grass pollen model, the sign of $D(t)$ in Eq. (1) is chosen positive, because the

weights and signs of all components of $D(t)$ should be a result of unrestricted optimization. A positive sign would mean a self-increase of the airborne pollen, which makes no sense. The correct sign was in fact a result of optimization (Section 3.1.4), which confirmed the assumptions of Eq. (1).

Starting from Eq. (1), terms P and D had to be established, containing parametric effect functions of the different weather parameters, which should be polynoms (Fig. 7), jump functions (Figs. 3 and 6), or optimum curves (Figs. 2 and 8) (Section 2.3).

The description of all modeling approaches explored is beyond the scope of this article. The interested reader might have a look at Spitzer (1995), pp. 62–95.

2.3. Model calibration

The calibration of a model means the determination of its parameters and concrete structure (Janssen and Heuberger, 1995). This should be performed on the basis of the measurements from 1988–1993 (calibration period) and prior knowledge in the following steps.

2.3.1. Estimation of a level of plant development

This indicates the main flowering (maximum pollen concentration) day at a certain threshold and should be used as the time component in the production rate P . It should be calculated by integrating daily growth rates, which could depend on daily sunshine duration (Klante, 1989), global radiation (Strasburger et al., 1991), etc., but mainly on temperature. Assuming a linear temperature dependent growth rate yields the method of Marletto et al. (1992) and that of linear temperature sums (Fritz and Gressel, 1983; Defila, 1988; Puls, 1987). We want to investigate especially the temperature dependence of a growth rate by an optimum curve, according to experimental experience (Törnevik, 1982, p. 19; Strasburger et al., 1991, pp. 287, 399; Mohr and Schopfer, 1992, p. 449; and Fig. 2, solid line) From the three temperature parameters and other climatic parameters it should be possible to conclude a specific plant temperature (Puls, 1987, p. 35). The initiation of plant growth, and therefore the start of integration, should be defined by a temperature threshold or a phenological phase.

2.3.2. The mean pollen season

Now, the simplest realization of terms P and D in the concentration Eq. (1) was performed, which yields a pollen season without deviations around the mean season. Therefore, P should consist of a source strength and a Gaussian function in the level of plant development, as found in Section 2.3.1, with the level of plant development at the main flowering day as expected value and an additional variance parameter (Fig. 5). The deposition term should consist of one constant deposition rate only. This results in a basic model.

2.3.3. The complete model

The complete model also includes variations. Continuing from the basic model of Section 2.3.2, attempts were made to refine and improve terms P and D separately and subsequently by further parametric effect functions in different weather parameters to describe the observed pollen counts. Thus, a pollen release condition for P and effects of pollen uptake by the wind, washing out with rain and flight conditions depending on relative humidity and others for D should be investigated.

The separate parameters were estimated by minimizing the quadratic error between calculated and measured pollen concentrations, or the actual and reconstructed main flowering day in the first modeling step. On the solutions one had to decide whether a weather parameter in a certain effect function was relevant and whether other approaches had to be investigated. This decision was based on a visual inspection of the model curves and critical comparison with the measurement curves.

Such a procedure appears somewhat arbitrary, but it is a way to find out what is adequately described by a certain model structure. For example, greater rain events are rare in Bad Lippspringe (Fig. 7) but, as we found, their effect on the pollen counts could not be described (adequately) by any other climatic variable in the tested effect functions, although the improvement of the error function seemed to be negligible. The consideration of rainfall would thus yield no significant improvement, but as we are interested in the variation of airborne pollen, and thus in the washout effects, we could not ignore this influence.

2.4. Parameter optimization

The progress of the pollen season is of special interest for allergic individuals. Thus, the smoothing effect of the quadratic error as optimization criterion might be inadequate. Other error measures, such as the squared error of the gradients, which hopefully should yield a better consideration of the season dynamics, were investigated. But this led to distortions, which justified the choice of the customary quadratic error measure.

The error functions, which depend on the model parameters, are discrete and rather noisy, which is caused by the used discrete (daily) and noisy weather data. So common optimization methods using derivatives, which could only be coarsely approximated numerically, would get trapped in one of the numerous local minima. Therefore, we chose the stochastic optimization algorithm 'Simulated Annealing', which was introduced by Kirkpatrick et al. (1983). This algorithm is derived from a statistical description of (for example) crystal growing from a melt. A regular crystal is a state

of a global minimum of energy after a slow cooling process with thermodynamic equilibrium at each temperature step. The algorithm allows an increase of the cost function at a decreasing level, so that local minima may be left again. The tolerated deterioration, its decreasing rate and other parameters have to be well adapted to the problem and the progress of its solution.

'Simulated Annealing' is a powerful tool in discrete stochastic computation. Several publications, e.g. in the field of operations research, can be found concerning this topic. An overview of combinatorial algorithms including 'Simulated Annealing' is given by Lengauer (1990).

Generating new parameters, their start values and their quantity has to be well considered for each modeling approach, to ensure effective work of the optimization algorithm and to avoid mathematical fitting results without practical utility. Thus, at first only one new weather parameter or modified effect function was investigated in one optimization phase. In a final step, the relevant components were put together and their parameters had to run new optimizations.

3. Results

The modeling led to a formula for the relative daily mugwort airborne pollen concentration of Bad Lippspringe depending on the four weather parameters: minimum and maximum temperature, amount of precipitation and atmospheric pressure. Section 3.1 presents the resulting model. More details on all considered modeling approaches and the modeling process can be found in Spitzer (1995), pp. 107–130.

3.1. The model

An introductory overview of the components and mechanism of the model is given by Figs. 1–8 and their order: From the beginning of plant growth initiation (Fig. 1, paradigmatically for 1989), a positive growth rate is assumed, which depends on the minimum temperature (Fig. 2) and, from a few days before flowering, on precipitation (Fig. 3). This cumulates in a level of plant development (Fig. 4) as the time parameter of the flowering ripeness or likelihood (Fig. 5). Pollen production is then determined by flowering ripeness and a release condition (Fig. 6). The airborne pollen deposit with constant speed, could be washed out by rain events (Fig. 7) and are dispersed in relation to pressure gradients (Fig. 8). Fig. 9 shows the modeled pollen concentrations versus the counts in the calibration period 1988–1993. The model components are presented in detail below.

Table 1
Events of the mugwort pollen modeling period

	1988	1989	1990	1991	1992	1993
Plant growth initiation	9.4.	21.3.	16.2.	5.3.	6.4.	10.3.
Beginning of possible development delay	10.7.	14.7.	9.7.	18.7.	5.7.	29.6.
Beginning of modeled pollen season	23.7.	25.7.	22.7.	28.7.	19.7.	18.7.

Values represent: day.month.

3.1.1. Plant development

Plant growth is initiated on the first day of the year, when the average daily maximum temperature exceeds 13.3°C for 10 days. This defines day t_s , which is used as the start of integration in Eqs. (2) and (7) with initial condition in Eq. (8). Note that the 13.3°C, as well as the 10 days and all other model parameters mentioned in Section 3.1, are a result of optimization. The resulting days from the condition for the beginning of plant development in the calibration period are summarized in Table 1. This property seems to confirm the experience that rather than the exceeding of a single temperature peak or of a level of the seasonal trend temperature alone (yielded by smoothing over about 30 days) a few subsequent warm days are necessary for the growth initiation of plants in spring (cf. Fig. 1). But the actual biological meaning of the detected mugwort specific temperature threshold is unknown.

Among the models using phenological indicators instead of temperature for growth initiation, the best results were obtained with the maximum of the *Fraxinus* airborne pollen content of Bad Lippspringe. However, these models are less accurate. A promising result with data from the plant observers could be found with the beginning of flowering of *Forsythia suspensa* (Thunb.) Vahl in Sande, 100 m above sea level, 11 km west of Bad Lippspringe. But there were too few data (1988–1991 only) for a reasonable confirmation of this trend and for a further application in model calibration. No predictive power could be established for the two 6-year exceptions, the beginning of flowering of *Galanthus nivalis* L. and of *Corylus avellana* L. observed in Steinhagen, 110 m above sea level, 37 km north-west of Bad Lippspringe.

From day t_s , a standardized level of plant development L_{PD} , according to general growth, but especially flowering, is calculated. It should indicate the readiness for flowering and the main flowering day. L_{PD} is the numerical integral in the daily mean development velocity v_{PD} :

$$L_{PD}(t_j) = \sum_{l=s+1}^j v_{PD}(t_l) \Delta t_l \quad (2)$$

$$v_{PD}(t_l) = J_{5R}(R(t_l)) \cdot O_e(\vartheta_-(t_l)) \cdot \frac{1}{d} \quad (3)$$

The sustainable factor of v_{PD} is an optimum curve in the minimum temperature ϑ_- :

$$O_e(\vartheta_-) = \begin{cases} e^{-\frac{k(\vartheta_- - \vartheta_0)^2}{(\vartheta_- - \vartheta_m)(\vartheta_M - \vartheta_-)}} & \text{if } \vartheta_m < \vartheta_- < \vartheta_M, \\ 0 & \text{else} \end{cases} \quad (4)$$

with a minimum growth temperature of $\vartheta_m = -8.5^\circ\text{C}$, an optimum growth temperature of $\vartheta_0 = 24.5^\circ\text{C}$, a maximum growth temperature of $\vartheta_M = 35.8^\circ\text{C}$ and a distortion parameter $k = 2.142$. This infinite differentiable function is presented in Fig. 2. One can see that the minimum and maximum growth temperatures do not coat the growth interval in the used resolution. This is mainly caused by the distortion parameter: below $\approx -2.0^\circ\text{C}$ and above $\approx 35.0^\circ\text{C}$ no growth is possible. Growth rate increases with the minimum temperature above -2.0°C . A maximum growth velocity is reached at the temperature optimum $\vartheta_0 = 24.5^\circ\text{C}$. Beyond this value growth velocity decreases again and stagnates at approx. 35.0°C .

O_e may be seen as the mathematical description of a further development of the Van't Hoff curve (simplified from Törnevik, 1982, p. 19; Strasburger et al., 1991, p. 287):

$$v_{PD,H}(\vartheta) = v_0 e^{\frac{\vartheta - \vartheta_0}{\vartheta_1}} \quad (5)$$

or Arrhenius curve (simplified from Strasburger et al., 1991, p. 399; Mohr and Schopfer, 1992, p. 65):

$$v_{PD,A}(\vartheta) = v_0 e^{\frac{\vartheta_1}{\vartheta - \vartheta_0}} \quad (6)$$

Both describe plant growth or development rates and are depicted in Fig. 2, but experiments show (Törnevik, 1982, p. 19; Strasburger et al., 1991, pp. 287, 399, 401) that plant growth is ruled by an optimum law. Törnevik has satisfied this conflict using a Gaussian function, but as the empirical curves are asymmetric (the increasing parts seem to have a lower slope than the decreasing ones), we want to consider the extreme temperatures and go on from Arrhenius, Eq. (5). Thus, we prefer the description used by Eq. (4).

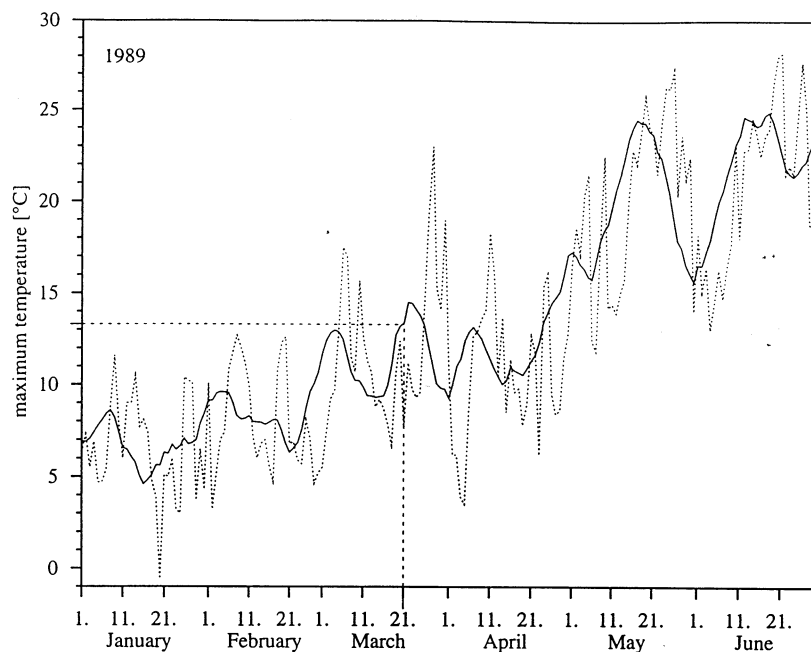


Fig. 1. Plant growth initiation 1989. Maximum temperatures in the first half of 1989 (dotted line) and averages over the following 10 days (solid line) as used for the temperature threshold of 13.3°C (horizontal line) for the beginning of plant (*Artemisia*) development, here March 21 (vertical line)

The frequency function of the minimum temperatures in the relevant period, also depicted in Fig. 2, shows that only the increasing branch of O_e is used for a description of plant development by the minimum temperature under natural conditions. This is the part which could also be described by the Arrhenius curve (Fig. 2), where a more accurate adjustment of the Arrhenius curve to O_e was avoided for optical reasons. Such surrogate would save one model parameter only. We prefer the optimum curve, because its parameters are easy to interpret and it is able to deal with exceptional temperatures more reasonably, and this is the behavior really found by experiments.

A linear increase of the growth rate can be seen in Fig. 2 between $\approx 6^\circ\text{C}$ and 17°C . This corresponds to the common linear temperature sum rules (Fritz and Gressel, 1983; Puls, 1987; Defila, 1988; Marletto et al., 1992) for predictions of a special flowering date, because of the summation for the level of development (Eq. (2)) and its meaning for the flowering ripeness function (see below). A justification for the temperature rules may be seen, because this temperature range appears with a frequency of 68%. But the temperatures below 6°C , responsible for the clear non-linear contribution of v_{PD} , appear with a frequency of 28% and, thus, could not be omitted. A linear dependency would lead to an underestimation of the effect of low temperatures. The tested direct temperature sums (from an optimized minimum) for the prediction of the main flowering day were indeed less accurate.

The preference of the minimum temperature for plant growth velocity is a result of optimization, as the parameters of Eq. (4) and all other model parameters are. We investigated a weighted mean of all three temperatures, but the weight of the minimum temperature was always the dominant one and tended to 1, whereas the others were almost 0, even if an unfavorable start vector of the weights was chosen for the minimization routine. A comparable attempt to predict the maximum of *Betula* and *Poaceae* airborne pollen content reveals the maximum temperature (and correlated weather parameters like radiation, sunshine duration and mean temperature) to be the effective variable for v_{PD} . For *Artemisia*, the minimum temperature appears to be the most important parameter determining development rate.

The standardized plant development velocity v_{PD} of Eq. (3) is influenced by an additional delay factor, J_{5R} . J_{5R} is the interpolation polynomial of 5th degree in the amount of precipitation (rain) R of day t_1 for a smooth jump up to the 2. derivative between 1 at and below 6.4 mm and 0 at and below 15.4 mm (Fig. 3), if $L_{PD} \geq 33.39$, otherwise $J_{5R} \equiv 1$. This enables a delay of plant development above a certain level of development from 13 days on average before the flowering period (Table 1), if the daily amount of precipitation exceeds 6.3 mm. The delay increases with the precipitation up to suspension at 15.4 mm daily precipitation. The extension and shift of the pollen season, because of precipitation shortly before and during the flowering period, is already known and is a result of Klante (1989).

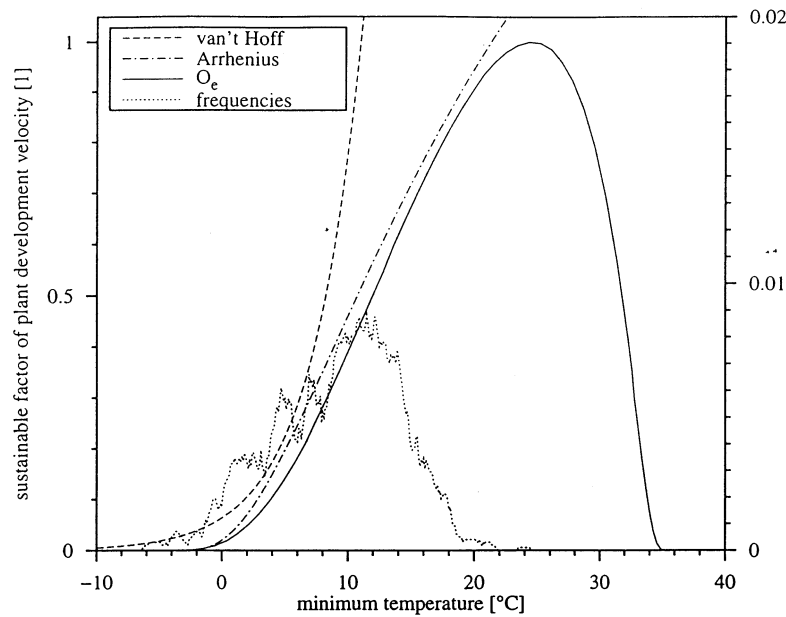


Fig. 2. The exponential optimum curve in minimum temperature, O_e (solid line, left scale) defined in Eq. (4), as the sustainable factor of plant development velocity; compared with adjusted Van't Hoff (dashed line, $v_0 = 1$, $\vartheta_0 = 11^\circ\text{C}$, $\vartheta_1 = 4^\circ\text{C}$ in Eq. (5)) and Arrhenius (dash-dotted line, $v_0 = 3$, $\vartheta_0 = -6^\circ\text{C}$, $\vartheta_1 = 30^\circ\text{C}$ in Eq. (6)) curves, left scale. The smoothed (over 1°C , i.e. ten values) frequencies of minimum temperatures (dotted line, right scale) are computed in the development period up to the end of the comparison period (Tables 1 and 2).

The frequencies of precipitation events are shown in Fig. 7 and can be compared with the effect curve in Fig. 3. Integration of v_{PD} yields the standardized level of plant development L_{PD} (Eq. (2)) which is depicted in Fig. 4 paradigmatically for 1989. There, the effect of the delay factor is demonstrated by the arrows, and the reaching of $L_{PD} \geq 33.39$ and $L_{PD} \geq L_{PD\mu}$ for the main flowering day, that means the maximum flowering likelihood (Fig. 5), at $L_{PD\mu} = 48.42$ is shown. Now, the preparations were made for the integration of Eq. (1).

3.1.2. Integration of Eq. (1)

Eq. (1) had to be integrated numerically, because the underlying data were all discrete daily values. So, time t converted to t_j [days = d], as a certain day of the year, dt converted to $\Delta t_j = t_j - t_{j-1}$, and $dC(t)$ converted to $\Delta C(t_j) = C(t_j) - C(t_{j-1})$ where the pollen concentration $C(t_j)$ of day t_j is in grains/ m^3 . Application of the simplest rule for numeric integration of Eq. (1), i.e. solution of the according difference equation, yields the recursion formula

$$C(t_j) = \frac{P(t_j)\Delta t_j + C(t_j - 1)}{1 - D(t_j)\Delta t_j} \quad (7)$$

for the local daily mean airborne *Artemisia* pollen concentration $C(t_j)$ of day t_j , with the initial condition that there were no airborne pollen at the beginning of plant development t_s

$$C(t_s) = 0 \frac{\text{grains}}{\text{m}^3} \quad (8)$$

Eq. (7) will only hold if

$$D(t_j) \neq 1 \frac{1}{d} \quad (9)$$

which will always be satisfied as becomes obvious when assuming the opposite and solving the difference equation (see also remark with Eq. (1)).

Up to now, the model, Eq. (7) is a common formula applicable for other aerosols and pollen types. The following specifications turn it into a formula which is specific for the *A. vulgaris* L. pollen of Bad Lipp-springe. This specific formula is obtained by calibrating the terms in Eq. (7) using the procedures described above. For another location, Eq. (7) must be parameterized with data specific for that location. For other pollen types the following specifications may also be qualitatively wrong. Especially for large plant groups like *Poaceae*, which is a family with several genera and species, several independent production terms P may be required.

3.1.3. The production rate

The production rate $P(t_j)$ [grains/(m^3d)] at day t_j in Eq. (7) resulted in a product of a source strength, release condition and flowering ripeness:

$$P(t_j) = P_{0,y} \cdot J_{5\vartheta}(\vartheta_+(t_j)) \cdot e^{-\frac{(L_{PD}(t_j) - L_{PD\mu})^2}{\sigma}} \quad (10)$$

The time of the pollen season is determined by the flowering ripeness or flowering likelihood of the local plant population, the third factor in Eq. (10), which is a Gaussian function in the dimension standardized level

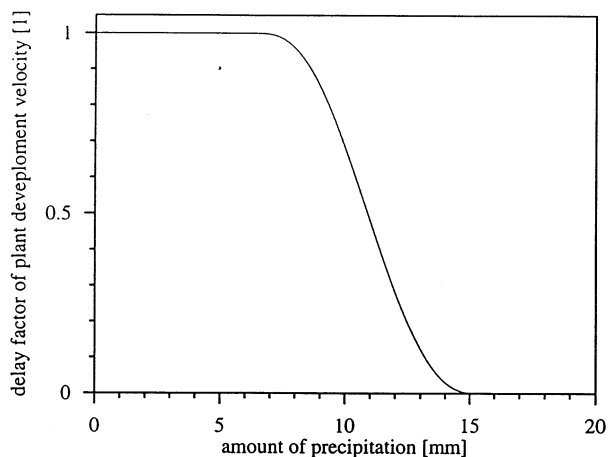


Fig. 3. Delay factor of plant development velocity by the amount of precipitation, J_{5R} of Eq. (3), which holds above a level of plant development of 33.39. For a frequency dispersion of precipitation see Fig. 7.

of plant development L_{PD} (Section 3.1.1). The flowering ripeness peaks (main flowering day) at a development level of $L_{PD,\mu} = 48.42$. $\sigma = 14.43$ defines the variance in flowering time. Fig. 5 in combination with Fig. 4 provides some insight into the distribution of flower ripeness.

Pollen release is governed by $J_{5\vartheta}$ which is the interpolation polynomial of 5th degree in the maximum temperature $\vartheta_+(t_j)$ of day t_j for a smooth jump up to the 2. derivative between 0 at and below 20.9°C and 1 at and above 21.3°C. This is a threshold condition which allows no pollen release below 20.9°C and unhindered release, restricted to the time of flower ripeness, above 21.3°C. The smooth jump between the two threshold temperatures is so sharp, that one can say there is only one threshold temperature at 21.1°C for pollen release. Fig. 6 depicts this function and the related frequency distribution in the calibration period (Table 2), which shows that a majority of 64% of the temperatures reached this threshold. With the daily mean or minimum temperature, the resulting jump ranges several degrees Celsius and the corresponding model curves were not satisfactory.

$P_{0,y}$ represents the source strength of the year y , which corresponds to the pollen production at the main flowering day. No attempt was made to model this quantity. For verification with the measured data during modeling and in the figures we used the measured maximum pollen concentration $C_{\max,y}$ of the corresponding season:

$$P_{0,y} = C_{\max,y} \cdot \frac{1}{d} \quad (11)$$

So we accept a small error, because the measured pollen concentration is a result of production and deposition, but should apply for the production only. How-

ever, this is a negligible inconsistency for the production term, being the leading component for increasing and high pollen concentrations. In the prediction program (Section 3.3)

$$P_{0,y} \equiv 100 \frac{\%}{d} \quad (12)$$

so that the model output is pollen concentration in percent of the seasonal maximum at the main flowering day.

3.1.4. The dilution rate

The dilution rate $D(t_j)$ [1/d] at day t_j in Eq. (7) contains deposition, washout and dispersion:

$$D(t_j) = d_0 + d_1 R^2(t_j) + d_2 O_5(|p(t_j) - p(t_{j-1})|) \quad (13)$$

A constant deposition velocity $d_0 = -0.9528$ 1/d reconstructs the permanent sinking process of airborne pollen grains.

Additionally, pollen concentration decreases quadratically with the amount of precipitation (rain) R . The exponent was obtained by optimization, like all other model parameters, where non-integer exponents were also allowed. This influence is weighted with $d_1 = -0.01579$ 1/(mm²d). The washing out of airborne pollen through precipitation is a well-known process (Puls, 1987, p. 39). Washout should not be understood as a resolution of pollen in rain drops, as shown by Puls and von Wahl (1989), pp. 38ff, but as a turbulent down-dragging of the airborne pollen and sticking to the wet surface. Fig. 7 shows the washout parabola and the frequency distribution of precipitation events of Bad

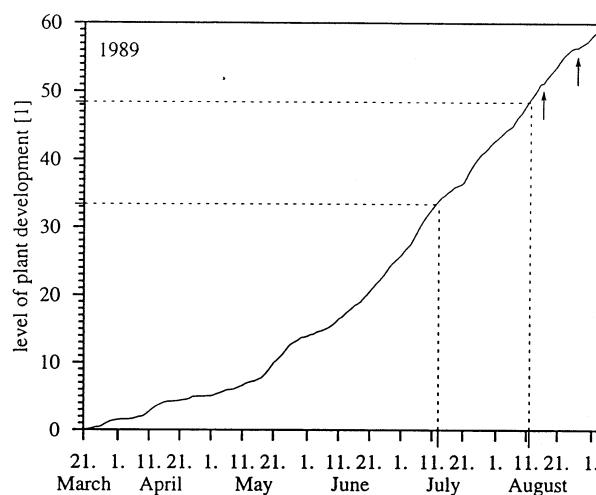


Fig. 4. Level of plant development L_{PD} , Eq. (2), for 1989, from growth initiation on March 21 to the end of the *Artemisia* pollen season. Indicated events: the beginning of possible development delay by precipitation from a level of 33.39 on July 13 and the main flowering day at a level of 48.42 on August 12. The arrows point to (almost) stagnation caused by the precipitation events on August 16 (13.0 mm) and August 27 (26.6 mm).

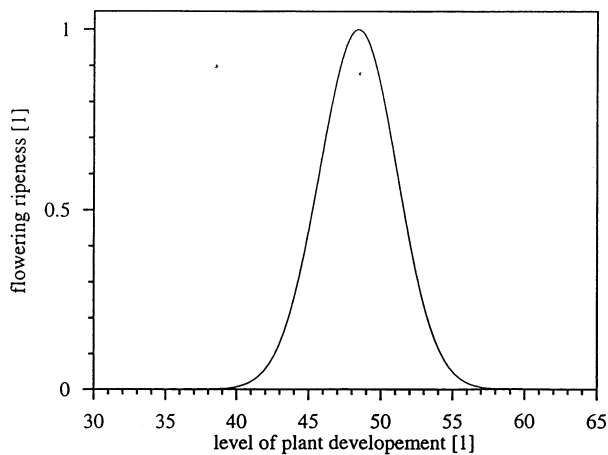


Fig. 5. Flowering ripeness as a Gaussian function in the level of plant development, third factor of Eq. (10).

Lippspringe in the studied period. Intensive rain events seldom occur, but may weight much more than the deposition d_o .

Finally, the absolute difference between the average daily atmospheric pressure $p(t_j)$ and its previous value $p(t_{j-1})$, is of importance: moderate changes of 2.0–7.1 hPa promote a thinning of the mugwort airborne pollen concentration. The strongest thinning is observed at a difference of 2.7 hPa. These are the parameters of the smooth (up to the 2. derivative) optimum function O_5 , which consist of two interpolation polynoms of 5th degree like J_{5R} from Eq. (3) or J_{5g} from Eq. (10) such that $O_5 = 0$ at and below a difference of 2.0 hPa, then O_5 follows a smooth jump to $O_5 = 1$ at 2.7 hPa with vanishing first two derivatives and decreases to 0 at and above 7.1 hPa (Fig. 8). The influence of the atmospheric pressure, denoted as dispersion, is weighted with $d_2 = -2.238 \text{ 1/d}$. Thus, its effect can be of approximately double magnitude than the constant deposition.

The dispersion effect of moderate pressure gradients may appear surprising, but it was well investigated. Different kinds of effect functions, like polynoms up to 8th degree in the direct pressure difference, or jump functions and optimum functions of 3rd and 5th polynomial degree for the decrease and the increase of the pressure were investigated, which means their parameters had to run several optimization routines with different start vectors. Some indications for a slightly emphasized thinning effect of negative pressure gradients were observed but, as a whole, the effect has an optimum curve character with the same absolute range and effect magnitude for positive and negative pressure gradients. Thus, a distinction between positive and negative gradients, and therefore eight instead of four model parameters, could not be justified.

An explanation of the dispersion effect of pressure gradients can be given on the basis of the studies of von Wahl and Puls (von Wahl and Puls, 1989, 1991).

Mugwort pollen are released in the morning, due to a biological rhythm. A high trap (more than 10 m above ground; here, 13 m) detects this pollen peak on average (a few hours) later and (about ten times) lower, than a trap at approximately plant height. The reason is a dominant diurnal course of radiation and thermal, and the existence of a stable mixing impeding inversion layer, which emerge from weather situations with low gradients of atmospheric pressure usual in the mugwort flowering time (see pressure difference frequencies in Fig. 8). The warming of the ground lets the wind and thermal rise slowly and the height of the inversion layer increases. The deposition of already released pollen and the absence of a supply of emitted pollen, because of the biologic rhythm, lets only few pollen reach the high trap.

High pressure gradients characterize through passing low pressures with high turbulence. The stronger winds and the absence of an inversion lets all emitted pollen immediately disperse in a higher air volume, but does not let it sink to the ground or whirls it up again. Pollen, which was emitted at the biological release time, can reach the trap. Summarizing, the mugwort pollen gauge of high traps equals that at low pressure gradients ($< 2 \text{ hPa}$). Here, the mixing impeding inversion layer and its diurnal course let pollen disperse in a smaller air volume, but it can easily deposit so that little pollen reaches the trap, because the inversion layer passes it after the emission maximum. An additional effect between those two scenarios, namely the defragmentation of an initially existing inversion layer, causes a dispersion promotion of the

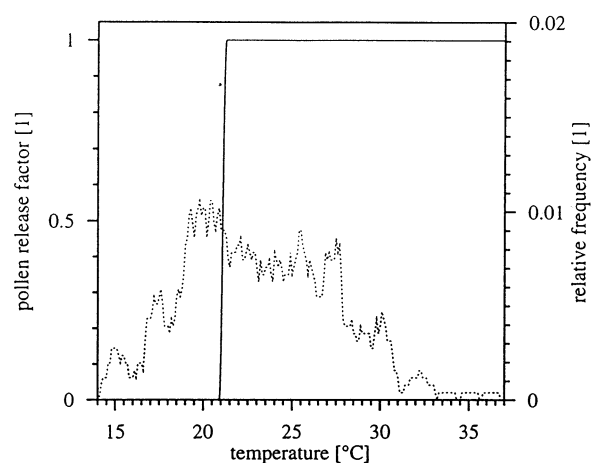


Fig. 6. Maximum temperature threshold, J_{5g} of Eq. (10), for *Artemisia* pollen release above $\approx 21.1^\circ\text{C}$ (solid line, left scale). The frequency distribution of the maximum temperature, smoothed over 1.0°C (ten values) during the calibration period 1988–1993 (255 days; Table 1) is depicted as a dotted curve (right scale).

Table 2

Comparison of measured and modelled mugwort pollen concentrations

	1988	1989	1990	1991	1992	1993	1994
Model efficiency (%)	73	85	71	86	63	16	32
RMSE (grains/m ³)	3.7	1.8	2.8	3.1	1.6	4.0	2.1
RMSE/ $C_{\max}$ (%)	12	11	10	9	16	27	24
Correlation, r^2 (%)	77	86	73	87	67	36	41
$C_{\max}$ (grains/m ³)	31	17	30	35	10	15	9
Comparison from	17.7.	20.7.	16.7.	16.7.	13.7.	17.7.	21.7.
to (day.month.)	29.8.	27.8.	28.8.	2.9.	21.8.	24.8.	12.8.
Comparison term (days)	44	39	44	49	40	39	23
Gaps in measurement	0	0	4	0	0	4	6

$C_{\max}$ is the measured seasonal maximum pollen concentration. The comparison period includes the whole modelled pollen season and the main measured season as depicted in Figs. 9 and 10 and described in the text, Section 2.1. RMSE, root mean squared error.

pollen. As a whole, this results in the effect depicted in Fig. 8. The steep increase of the curve from 2.0 to 2.7 hPa indicates a well-defined minimum gradient necessary for the inversion fragmentation.

Surprisingly, all modeling approaches including the daily average velocity of the wind proved to be unsatisfactory. This was also reported by Moseholm et al. (1987), p. 318. Perhaps the maximum peak of the wind velocity, or a measure of its dynamic, are a more suitable basis for predicting the amount of the airborne pollen, than is the average velocity.

Only the relative humidity as dispersion component, apart from pressure gradients, accounts for some of the variation in the pollen concentrations, but is not as accurate as the pressure differences. This reveals some similarities with the grass pollen models of Moseholm et al. (1987) and Norris-Hill (1995), who took humidity into consideration.

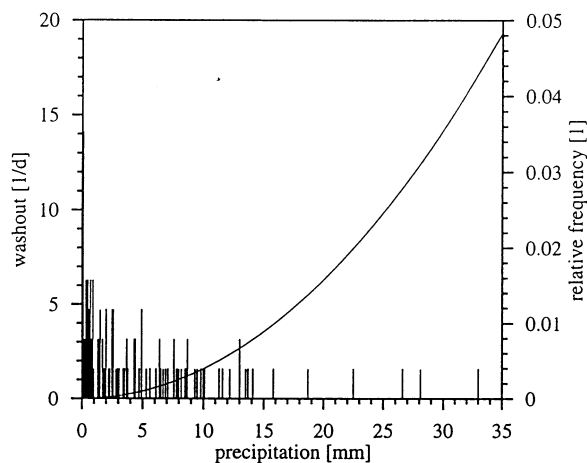


Fig. 7. Washout effect of precipitation events (solid line, left scale). Absolute contribution of the amount of precipitation to the dilution rate D of Eq. (13). The frequency function of the amount of precipitation in the calibration period 1988–1993 (255 days; Table 1) is depicted as columns (right scale); 0.0-mm precipitation appears with a frequency of 0.55.

3.1.5. Assessment of the components

In this subsection, the explanatory power of the individual model components in the calibration period 1988–1993 is compared by the model efficiency, also denoted as explained variance as it actually is for linear regressions:

$$ME = 1 - \frac{\sum_{i=1}^N (P_i - O_i)^2}{\sum_{i=1}^N (O_i - \bar{O})^2} \quad (14)$$

with the N observations O_i and predictions P_i , and the mean observation $\bar{O}$ (Janssen and Heuberger, 1995, p. 63). “Any positive value of ME can be interpreted as an improvement over the ‘nominal’ situation $\bar{O}$; the closer to +1 the better” (Janssen and Heuberger, 1995, p. 65).

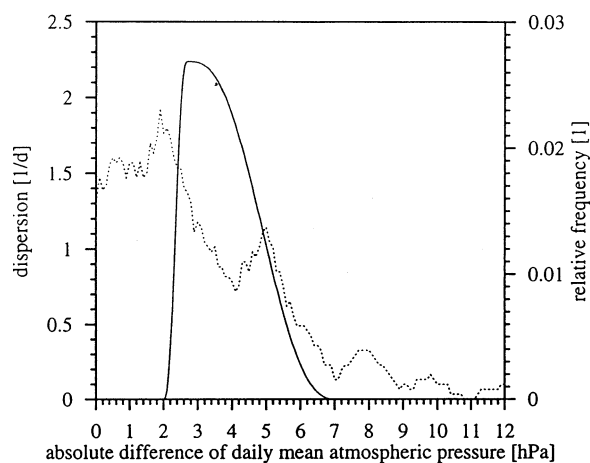


Fig. 8. Absolute dispersion effect of the absolute daily differences of atmospheric pressure (solid line, left scale). See explanations for Eq. (13). The empirical frequency of the pressure differences in the calibration period 1988–1993 (255 days; Table 1) is depicted as a dotted curve (right scale), smoothed over 1 hPa (ten values).

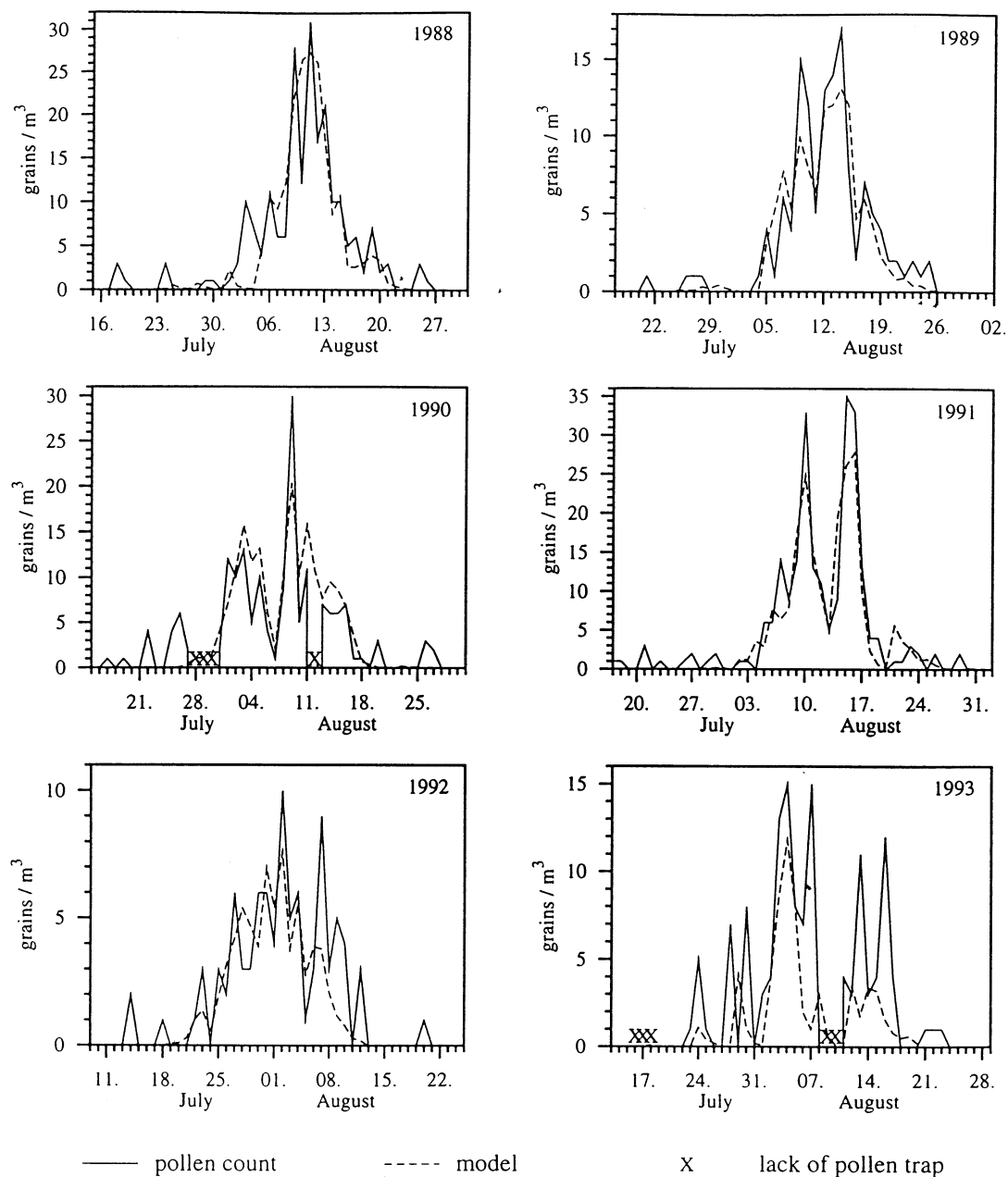


Fig. 9. Evaluation of mugwort pollen concentrations compared to the counts of Bad Lippspringe for the calibration term 1988–1993. Modeled values are multiplied with the respective value of the maximum pollen concentration (Section 3.1.3). Note the different scaling of pollen counts, to ensure best possibility of dividing the curves.

The basic model, which solves the concentration Eq. (1), consists of a pollen production Eq. (10) without a release condition and a constant deposition in Eq. (13) only. Its parameters differ slightly from the ones presented in the preceding subsections, because they were obtained from an optimization without the other components. This model, which captures no intraseasonal variations of the airborne pollen content, explains almost 50% of the variance of the *Artemisia* pollen concentrations of Bad Lippspringe in the calibration years 1988–1993 on average. An increase to 57% model efficiency was achieved taking the release condition of

Eq. (10) into account. This seems comparable to the result of Norris-Hill (1995), p. 184. An extension of the basic model by the washout effect of Eq. (13) gives an improvement to only 52% explained variance, but should be taken into account nonetheless, because of its ability to explain special dilution events not captured by other means. The basic model extended by the dispersion effect of atmospheric pressure differences yields 60% model efficiency. Therefore, this is the most meaningful component of the model with regard to the variations of airborne mugwort pollen variations in Bad Lippspringe as seen by the model efficiency.

The complete model explains 66% of the variance of the *Artemisia* pollen concentrations of Bad Lippspringe in the calibration years 1988–1993 on average. The total 255-day comparison period used for the evaluation of model performance measures includes the total model pollen season and the (main) observed pollen season (Section 2.1) and is depicted in Table 2 and in Fig. 9. Table 2 gives an overview of some different measures, judging the performance of the complete model in the distinct years. The modeling of 1993 was obviously bad, which was the same for every modeling approach. If this is not an indication of a principal error in the model concept, it may be a consequence of the low pollen concentrations, (therefore) measurement errors, or the many rain events during the season, whose appearance and effects are too sophisticated to be attributed to the amount of precipitation only.

3.2. Cross-validation

After completing the model, a cross-validation was performed using the independent data of 1994. A comparison of the retrospective prediction, i.e. model calculation using the measurements of the dependent four climatic parameters, with the measured pollen concentrations is given in Fig. 10. With respect to the damage of the pollen trap (Fig. 10), which led to a short comparison period, and the low pollen concentrations, which led to a high relative error in measurement, one can say that the seasonal interval and the essential progress of the pollen season is described by the model, but not the intra-seasonal variations. The model efficiency of 32% indicates an improvement over the nominal situation (Section 3.1.5), but is not really convincing. For the comparison term, which includes all *Artemisia* pollen counts of that year in Bad Lippspringe, and other performance measures, see Table 2.

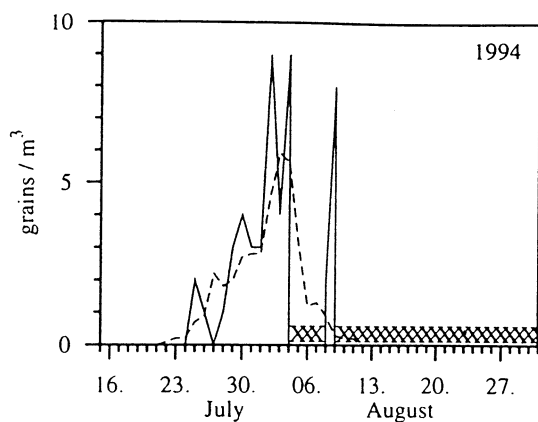


Fig. 10. Cross-validation. Retrospective evaluation of mugwort pollen concentrations compared to the counts of Bad Lippspringe in the independent year 1994. Remarks and legend as in Fig. 9.

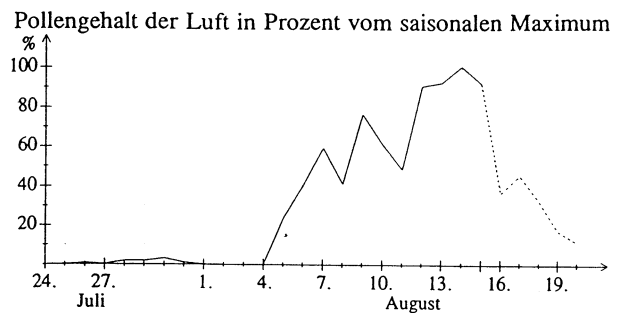


Fig. 11. Fictive pollen forecast with the prediction program for August 16 1989, paradigmatically, using the measurements of the required climatic parameters, assuming a weather and pollen forecast of 5 days (dashed part). The pollen report is not presented.

The interpretation of this result is problematic because of the low counts and trap damage, as mentioned above. If one assumes the minimum possible measurement error of only one grain/m³, all local concentration extremes in July may be wrong (Fig. 10). The conclusion we dare to draw is that with an optimal weather forecast, a mugwort pollen forecast for Bad Lippspringe on the basis of the model would have been possible in 1994, with respect to the temporal range and the essential progress of the season.

3.3. The prediction program

A computer program for PCs with MS-Windows was written as an application of the model for real mugwort pollen forecasts. The program requires as input the four relevant weather parameters from measurement (weather station, Bad Lippspringe) and forecast, which is available. Thereby, an immediate pollen forecast can be provided every day for the duration of the weather forecast.

The forecast duration was not exactly estimated, but is limited by that of the weather parameters. As stated by the German weather service (Deutscher Wetterdienst, 1993, p. 30), the minimum temperature can be predicted up to 6 days in advance, maximum temperature and a measure including the statement whether there is precipitation or not have a positive prognostic power up to 7 days in advance. We do not know the prognostic power of the amount of precipitation. The atmospheric pressure as the best predictive parameter (cf. Deutscher Wetterdienst, 1993, p. 22) was not considered in this estimate. Thus estimating the prediction time range to be 5 days appears to be warranted.

The evaluation and (graphic) output of the pollen concentration occurs as a percentage of the seasonal maximum (Fig. 11), consider Eq. (11). The beginning of the mugwort pollen season will be recognized in the program by the first exceeding of a user-defined threshold value for the pollen concentration. This threshold can be set according to experience (default

value: 2.0%). The relative pollen concentrations are related to burden classes as proposed by von Wahl (1989) and Bergmann (1994), p. 143, which may also be adjusted by the user. A sustainable allergenic content of the air is assumed (Pehkonen and Rantio-Lehtimäki, 1994) and therefore a moderate burden with possible bronchial complaints will be predicted, when the pollen concentration declines to the lowest burden class or at the end of the pollen flight season.

The program provides several options concerning the graphical output (range, size, colors, line types or shape; defaults and automatic adaptation), the storage of climatic parameters and forecast parameters (threshold for the beginning of the season, burden class borders, warning period after the last medium burden class).

4. Discussion

Several known correlations of climatic parameters and pollen counts could be confirmed and additional relations could be established. A summary of the biometeorological results is given in Figs. 1–8. A biological or meteorological interpretation of the model components is possible.

The predictive potential of accumulated temperature values has been clearly demonstrated. Those are successfully used in an “effective biological time function” (Törnevik, 1982, p. 23), in linear temperature sum rules for the prediction of a flowering event, i.e. beginning or main (Fritz and Gressel, 1983; Puls, 1987; Defila, 1988; Marletto et al., 1992), in a multiple regression analysis for the forecast of the main flowering day of *Secale cereale* L. (Klante, 1989), or as component up to the 2. power in a multiple regression model for the daily grass pollen concentration (Norris-Hill, 1995). Normally, the maximum or mean temperature was used. Here, an optimum function in the minimum temperature was accumulated as a level of plant development for a flowering ripeness function. The minimum temperature proved to be most appropriate for *Artemisia*, because of its well-defined pollen release in the morning (von Wahl and Puls, 1989) and because of the temperature use in a development level concerning the flowering ripeness. In contrast, the emission of pollen from the different grass species is possible at different times of the day (for summary see Fuckerieder, 1976, p. 58). Birch pollen were observed to be emitted from 08:00 to 22:00 h (Törnevik, 1982, p. 5).

The meaning of a plant (and site) specific release temperature was emphasized, for example, by Fuckerieder (1976), p. 67, Wachter (1978), pp. 177, 181, and Puls (1987). Minimum emission temperatures for mugwort pollen were found: 18°C (Wachter, 1978, p. 177) or 10°C (von Wahl and Puls, 1989, p. 61). Here, the

exceeding of about 21.1°C maximum temperature was found to be reliable for the mugwort pollen release. How this threshold corresponds to the mugwort plant temperature at release time in the morning is unknown.

The detected flowering delay and washout effect by precipitation is not striking, but descriptive in so far as we found no explanation of these effects by other means. The washout is a well-known effect (Puls, 1987, p. 39; Puls and von Wahl, 1989, p. 33ff). Precipitation is also used in the models of Moseholm et al. (1987) and Norris-Hill (1995). An additional influence of precipitation on acceleration of the flowering period was found. A similar effect was mentioned in the overview of Puls (1987) concerning *Olea europaea* L., and detected by Klante (1989) concerning *Secale cereale* L.

An undescribed dependency of the pollen dispersion promotion of moderate absolute differences of the daily mean atmospheric pressure from one day to the next was detected (Section 3.1.4). Hereby, the largest increase in explained variance, apart from the mean pollen season, was achieved. This is assumed to be a specific effect for mugwort or comparable herb pollen types with a biologic release rhythm in the morning, such as the *Rumex conglomeratus* group (von Wahl and Puls, 1991), measured with high (more than 10 m above ground) pollen traps. Nevertheless, it might be promising to check a similar dependency for other pollen types, as the pressure gradient is an indicator for the general weather situation.

An omission of the model is the prediction of the annual source strength. Thus, for the comparison with the pollen counts, the measured maximum pollen concentration was used (Eq. (11)). The prediction of pollen concentrations is given as a percentage of the unknown maximum pollen concentration (Eq. (12)). This means no loss of the predictive power of the model while the qualitative progress of the pollen season is of allergologic interest. Additionally, the discussion about the allergologic potential of mugwort pollen and relevant pollen concentrations respective to the height of the pollen traps with which they were estimated is of no importance for a model with no absolute pollen concentrations.

The evaluation of the mugwort pollen model accuracy is a difficult topic and difficult to compare to that of, for example, the birch pollen model of Törnevik (1982) or the grass pollen models of Moseholm et al. (1987) and Norris-Hill (1995). This is mainly due to the low mugwort pollen concentrations measured by a high pollen trap (von Wahl and Puls, 1989). Therefore a high error in detecting a representative score of the mugwort pollen and a high relative error for the count of the samples have to be assumed. The damage to the pollen trap in the validation year 1994 led to a short comparison period. With this in mind, the model efficiency of 66% explained variance in the calibration

term and 32% for the independent year 1994, which indicates at least an improvement over the nominal situation (Section 3.1.5), should be judged as a success for the modeling of the local daily relative mugwort pollen concentrations.

With the user-friendly mugwort pollen prediction program based on the developed model, a practical tool for pollen forecasts is given. The relevant climatic parameters are available from measurement and prediction. No pollen counts, plant observations or estimation of the beginning of the pollen season is necessary. This program could be modified or extended for the application of other pollen models.

The interpretation of pollen concentrations according to allergic complaints is difficult, but a correlation clearly exists (Fuckerieder, 1976, p. 71ff; Törnevik, 1982, p. 2; Kersten et al., 1995). A pollen forecast should be a forecast of the anticipated complaints, which depend not only on the current pollen concentration, but also on the airborne amount of allergenic particles and the particular time in the pollen season. The amount of the airborne allergenic particles is not correlated to meteorological parameters (Pehkonen and Rantio-Lehtimäki, 1994) and therefore hard to predict. A clever method is a direct model and prediction of the anticipated complaints by climatic parameters as proposed by Spieksma (1980). Unfortunately, we are unaware of any study relating mugwort allergenic complaints to climatic parameters. With a model for the (relative) progress of the airborne mugwort pollen concentration and the knowledge of the dependency of allergic complaints and pollen concentrations in general, a pollen forecast for allergic individuals should be possible. Therefore, a better description of the early season might be desirable (cf. Kersten et al., 1995).

The model is only locally valid for the position of the pollen trap of Bad Lippspringe or a certain environment, because of the data employed. In a further step, criteria (e.g. geographic site, height above sea level) for transferability should be investigated. Whether large-scale calculations of pollen trajectories may be a reasonable approach is doubted, because most pollen grains are deposited close to the source (Puls, 1987, p. 37).

5. Conclusion

The presented model is considered as a first successful approach to modeling mugwort pollen concentrations. Thus, a first step with respect to an objective (mugwort) pollen forecast in Germany by mathematical modeling was made. It is intended that an operational test (which was not possible earlier for reasons of organization) of the model be performed by the German weather service in the mugwort pollen season 1997.

Acknowledgements

Particular acknowledgment is entitled to Professor Dr Georg Masuch (Biology, University of Paderborn, Germany) for the deliberation on plant biology, and Professor Dr Rainer Walden (Mathematics, Technical college Bielefeld, Germany) for mathematical care. Special thanks are due to Dipl-Met Gunild Scheid for detailed information about the current practice of German pollen forecasts. Without the pollen counts of Mrs. Hansmeier from the Allergy and Asthma Hospital, the immediate data support of Mrs. Wilhelm from the German pollen service, and the measurements from the always friendly and advisory team of the DWD weather station, this work would not have been possible.

References

- Bergmann K-Ch, editor. 3. Europäisches Pollenflug-Symposium 4.-6. Februar 1994 in Bad Lippspringe. Düsseldorf: Vereinigte Verlagsanstalten, 1994.
- Defila C. Phänologische Beobachtungen und Anwendungsmöglichkeiten für die Pollenprognose. *Swiss Med* 1988;5:21–5.
- Deutscher Wetterdienst, editor. Jahresbericht 1992. Offenbach am Main: Selbstverlag des DWD, 1993.
- Fritz A, Gressel W. Zur Wetter-, insbesondere zur Temperaturabhängigkeit des Pollenfluges der Hasel, Birke und Gräser in Kärnten. *Med-Met* 1983;3:14–7.
- Fuckerieder K. Der Graspollengehalt der Luft in Mitteleuropa. München, Umweltbundesamt (Ed.) Berichte 9, 1976.
- Janssen PHM, Heuberger PSC. Calibration of process-oriented models. *Ecol Model* 1995;83:55–66.
- Kersten W, von Wahl PG, Fölster-Holst R. Pollenflugvorhersage in Deutschland. II. Medizinische Aspekte. *Allergo J* 1995;4:219–22.
- Kirkpatrick S, Gelat CD, Vecchi HP. Optimization by Simulated Annealing. *Science* 1983;220:671–80.
- Klante B. Erste Forschungsergebnisse zur Anwendung phänologischer Daten für Polleninformationsdienste. In: Kersten W, von Wahl PG, editors. 2. Europäisches Pollenflug-Symposium 17./18.03.1989. Düsseldorf: Vereinigte Verlagsanstalten, 1989:61–69.
- Lengauer T. Combinatorial Algorithms for Integrated Circuit Layout. Stuttgart: Teubner; Chichester: Wiley, 1990.
- Marletto V, Puppibranzi G, Sirotti M. Forecasting flowering dates of lawn species with air temperature: application boundaries of linear approach. *Aerobiologia* 1992;8:75–83.
- Mohr H, Schopfer P. Pflanzenphysiologie, 4th ed. Berlin: Springer, 1992.
- Moseholm L, Weeke ER, Petersen BN. Forecast of pollen concentrations of *Poaceae* (grasses) in the air by time series analysis. *Pollen Spores* 1987;XXIX(2–3):305–22.
- Norris-Hill J. The modeling of daily *Poaceae* pollen concentrations. *Grana* 1995;34:182–8.
- Pehkonen E, Rantio-Lehtimäki A. Variations in airborne pollen antigenic particles caused by meteorologic factors. *Allergy* 1994;49:472–7.
- Puls KE. Der Einfluß von Witterung und Wetter auf Blütenanlage, Pollenfreisetzung und Pollenflug. In: Kersten W, von Wahl PG, editors. 1. Europäisches Pollenflug-Symposium 20./21.03.1987. Krefeld: Medizin und Umwelt, 1987:27–47.

- Puls KE, von Wahl PG. Neue Erkenntnisse zum Einfluß des Wetters auf den Pollenflug. In: Kersten W, von Wahl PG, (Eds.) 2. Europäisches Pollenflug Symposium 17./18.03.1989. Düsseldorf: Vereinigte Verlagsanstalten, 1989:29–51.
- Rothmaler W, Schubert R, Werner K, Meusel H, editors. Exkursionsflora von Deutschland. Band 2: Gefäßpflanzen, 15th ed. Berlin: Volk und Wissen, 1990.
- Spieksma FThM. Daily hay fever forecast in the Netherlands. *Allergy* 1980;35:593–603.
- Spitzer F (after marriage: Wolf F.). Modellierung des Beifuß-Pollengehalts der Luft anhand der Daten von Bad Lippspringe und Erstellung eines Prognoseprogramms für den Pollenflug. Diploma thesis. University of Paderborn, Faculty of Mathematics, 1995.
- Strasburger E, Noll F, Schenck H, Schimper AFW, Sitte P, Ziegler H, Ehrendorfer F, Bresinsky A, editors. Lehrbuch der Botanik. Stuttgart: Fischer, 1991.
- Tonkelaar JF. Grass pollen counts in the West Netherlands as a function of the weather conditions. Ministerie van Verkeer en Waterstaat. Koninklijk Nederlands Meteorologisch Instituut, De Bilt, 1986.
- Törnevik H. An aerobiological model for operational forecasts of pollen concentration in the air. Sveriges meteorologiska och hydrologiska institut, RMK 38. Stockholm: Liber Grafiska AB/Förlagsorder, 1982.
- Wachter RKF. Der Gehalt der Luft über mitteleuropäischen Meßstellen an Pollen von *Artemisia*, *Plantago* und *Rumex*. Thesis. Technical University of München, 1978.
- von Wahl PG. Methoden der Pollenbestimmung. In: Kersten W, von Wahl PG, editors. 1. Europäisches Pollenflug-Symposium 20./21.03.1987. Krefeld: Medizin und Umwelt, 1987:16–26.
- von Wahl PG. Einordnung der Pollenkonzentrationen in Klassen - Vorschlag zu einer neuen Klassifizierung. In: Kersten W, von Wahl PG, editors. 2. Europäisches Pollenflug-Symposium 17./18.03.1989. Düsseldorf: Vereinigte Verlagsanstalten, 1989:114–117.
- von Wahl PG, Puls KE. The emission of mugwort pollen and its flight in the air. *Aerobiologia* 1989;5:55–63.
- von Wahl PG, Puls KE. Pollenemission und Pollenflug von Kräuterpollen *Artemisia vulgaris*, *Plantago lanceolata* und *Rumex* ssp. Grana 1991;30:260–4.