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THE INFLUENCE OF TEMPERATURE AND CLIMATE CHANGE ON THE TIMING OF POLLEN RELEASE IN THE NETHERLANDS

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ABSTRACT

In the last decade it has become clear that the timing of many phenological processes, like the start of flowering and leaf unfolding in spring, have changed. The increase in temperature is believed to be the main cause. The earlier start of flowering will have consequences for the start of the pollen season, and thus for the start of the hay fever season. Millions of people world-wide will therefore experience the impact of climate change in their daily lives during spring and summer. In this paper we analyse the relation between climate parameters, especially temperature, and the start of the pollen season in the western part of the Netherlands based on daily pollen counts of the Leiden University Medical Centre and temperature measurements from 1969 till 2000 by the Royal Netherlands Meteorological Institute in De Bilt. The results indicate that there is a strong correlation between temperature and start of the pollen season. An advance of the start of the pollen season of 3 to 22 days has been observed. The potential future changes in the start of the pollen season under climate change scenarios are also discussed. Copyright © 2002 Royal Meteorological Society.

KEY WORDS: aerobiology; climate change; phenology; pollen; allergy; scenarios; temperature sum

INTRODUCTION

Recently, our understanding of climate change impacts on human health has improved significantly (Watson *et al.*, 1996; Kovats *et al.*, 2000; McCarthy *et al.*, 2001) and it has become clear that our society will face a wide variety of health impacts. McMichael *et al.* (1996) structured the effects of climate change into direct effects (exposure to thermal extremes) and indirect effects (disturbances of ecological systems, sea level rise, and biological effects of impacts of climate change on air pollution, including changes in release of pollen and spores). In the last couple of years, hay fever or *pollinosis*, has received increased attention (e.g. in the special section ‘Aeroallergens’ in the IPCC’s Third Assessment Report (McCarthy *et al.*, 2001)). The IPCC report lists several studies that analyzed the abundance of pollen and/or the start and duration of the pollen season in relation to meteorological variables or the CO_2 concentration of the atmosphere (e.g. Emberlin, 1994, 1997; Spieksma *et al.*, 1995; Ziska and Caulfield, 2000).

A large number of people suffer from hay fever or *pollinosis*, which is caused by repeated exposure to pollen grains emitted by pollinating plants.[1] The start and duration of flowering determine the potential hay fever period whereby the start and duration of the pollen season vary from year to year. Spieksma and Nikkels (1998), for example, studied the pollen season for grasses over the period 1969 to 1994 and found a difference in start date ranging from 12 May to 19 June.

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However, not all species cause strong allergenic effects. Grass pollen are the most important in causing hay fever in western Europe, due to the relatively high allergen content and the large amount of pollen (Driessen *et al.*, 1988).

1.1. Phenological processes and climate change

Since 1961 the global average surface temperature (the average of near-surface air temperature over land and sea) has increased. During the whole of the 20th century the increase has been 0.6 ± 0.2 °C (Houghton *et al.*, 2001). Also, in the Netherlands, the last two decades of the 20th century have been exceptionally warm. The mean annual temperature of the last two decades was 0.7 °C higher than the first two decades. From 1987 onwards a sudden increase in temperature was observed. The mean January to May temperatures in the 1990s were 0.7 °C higher than in the 1960s. With the exception of 1996, all winters from 1988 onwards were warm, of which several were unusually warm. We know from phenological studies that timing of phenological events, like the start of flowering, is, to a large extent, determined by climate variables (e.g. see Kramer, 1996; Walkovszky, 1998; Ahas, 1999; Cannell *et al.*, 1999; Sparks and Manning, 2000; Sparks *et al.*, 2000a,b; Zwart, 2000a; Ahas *et al.*, 2000). Plant species require a certain amount of heat to complete their development. For some species, a certain amount of chilling during winter is required for breaking bud dormancy (e.g. Kramer, 1996; Chuine *et al.*, 1999). Given this strong relation, the significant increase in global temperature should thus also be visible in long-term phenological observation series. This is also demonstrated by a large number of studies (RIVM, 1998; Sparks and Crick, 1999; Beaubien and Freeland, 2000; Zwart, 2000b; Chmielewski and Roetzer, 2001; Menzel *et al.*, 2001; Zhou *et al.*, 2001; Zwart and van Vliet, 2001). In addition to the influence of climate, other factors, e.g. day-length and soil type, also determine the start timing of phenological events. However, often the change in temperature is one of the most important explaining variables, but there is a need for a better understanding of the links between climate and the start of processes like flowering.

Standardized daily pollen measurements have been made throughout Europe in order to be able to predict the start of the pollen season, and they provide an important addition to phenological observations series, which monitor the start of flowering.

As the start of flowering, and thus pollen release, is strongly determined by temperature, we asked ourselves the following questions:

1. To what extent can the start of the pollen season be related to temperature?
2. Do historical pollen records show an earlier start of the pollen season, as has been observed by historical phenological records?
3. Is there a difference in response between different plant species/families?
4. What future changes in the start of the pollen season, and therefore in the start of hay fever complaints, can be expected in the light of future climate change?

2. MATERIALS AND METHODS

2.1. Airborne pollen data

In the whole of Europe, the pollen amount in the atmosphere is measured with standardized instruments. However, only a few stations have an uninterrupted series of pollen data dating back to the 1960s. We were able to use the pollen measurements made at the roof of the E.N.T. clinic of Leiden University Medical Centre (LUMC), formerly known as the University Hospital Leiden (52°23′N; 4°29′E). The pollen have been measured with a Hirst-type volumetric, continuous pollen trap (Hirst, 1952) from 1969 up to and including 2000. The LUMC is situated west of the city of Leiden. Dunes are located approximately 7 km West of Leiden. East of the dunes are the ‘geest’ soils with the bulb fields, and between those soils and Leiden are extensive grasslands. Northeast of Leiden are several lakes, surrounded by pasture (Lucassen, 1994).

The seasonal course of the pollen concentrations at Leiden is probably valid for the whole northwest of the Netherlands, although there is a stronger influence of local sources, which, however, is hard to estimate. The absolute values of the pollen concentration are valid for a very small area and this area depends strongly on local and regional sources. There is some pasture in front of the hospital building, but, because grasses grow everywhere, this influence should be limited.

2.2. *Errors*

According to Käpylä and Penttinen (1981), the most important sources of error of pollen traps are: (1) changes in collecting efficiency (external wind speed, size of particles and the adhesive influence on the collecting efficiency); (2) inadequate procedures, like wrong location of the trap, poor preparation of the sticky tapes, wrong determination of the air volume sampled, and wrong identifications; and (3) sampling errors (only a part of the slide that contains pollen is counted).

The main errors in measuring the real pollen concentration are: (1) inhomogeneous distribution of the pollen grains in the air, because they fly in 'pollen clouds'; and (2) unequal distribution of the pollen grains over the width of the cellophane film. This can lead to a rather big error in the case of low pollen concentrations, because just 1/14 part of the pollen grains is counted: the lower the pollen concentration, the higher the relative error.

In Leiden, no special research has been done concerning the reliability of the measurements, but others have done this. The measurement method is used by hundreds of measurement sites all over the world, and the volumetric Hirst trap is now the technique most often used in Europe; its accuracy, with daily and even bihourly data, allows correlations to be made with the weather (Laaidi, 2001).

2.3. *Species included and their measurement period*

For this study we used daily pollen counts for 14 species or families from the period 1969 to 2000: ash (*Fraxinus*), birch (*Betula*), dock (*Rumex*), elder (*Sambucus*), elm (*Ulmus*), goosefoot (*Chenopodiaceae*), grasses (*Poaceae*), juniper (*Cupressaceae*), mug-worth (*Artemisia*), nettle (*Urtica*), oak (*Quercus*), pine (*Pinus*), poplar (*Populus*), and willow (*Salix*).

From 1969 to 1976, i.e. the period during which the pollen have been measured, daily pollen counts were not made the whole year round (see Table I).

2.4. *Climate data*

Climate data came from the Royal Netherlands Meteorological Institute (KNMI) in De Bilt, which is approximately 60 km from the pollen measurement site at Leiden. Data from stations closer to Leiden were not available. Station de Bilt (number 06260; 0 m mean sea level) is located in the middle of the Netherlands (52°06′N; 5°11′E), whereas the pollen measurement site at Leiden is in the western part of the Netherlands. De Bilt is an automatic meteorological station (Benschop, 2000). For this study, we have used the mean daily temperature (°C) provided by the KNMI (Figure 1). Different calculation methods have been used in the 20th

Table I. Measurement period of pollen from 1969 to 2000

Year	Measurement period (day of the year, 1 January = day 1)	Year	Measurement period (day of the year, 1 January = day 1)
1969	99–259	1974	60–167
1970	75–259	1975	61–260
1971	73–259	1976	63–238
1972	69–245	1977–2000	Whole year
1973	71–167		

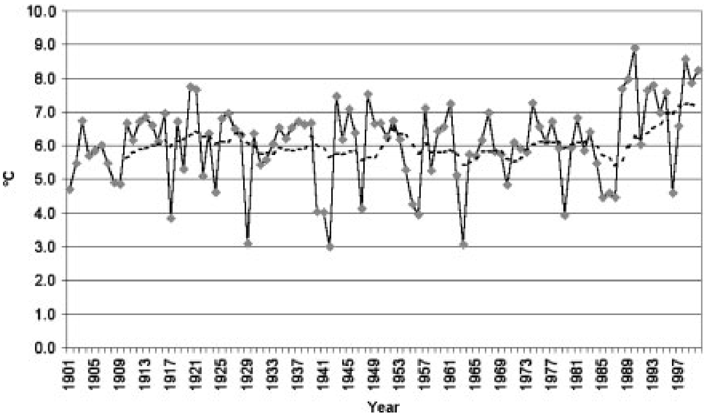

Figure 1. Mean temperature of the first 150 days in De Bilt in the 20th century (solid line) and the 10-year moving average (dotted line)

century. From 1901 to 1968 several methods were used, from 1969 to 1996 an average over 24 hourly values was taken, and from 1997 to 2000 the average of maximum and minimum temperature was used.

The mean annual temperature in De Bilt was about 0.7 °C higher in the last two decades of the 20th century compared with the first 20 years of the century. The 11 warmest years of the 20th century all occurred in the last 20 years. Summer temperatures increased in both the first and the last parts of the century, but they decreased in the 1950s. Winter temperatures did not change much until the beginning of the 1980s. From then on temperatures are clearly higher. The mean January to May temperatures in the 1990s where 0.7 °C higher than in the 1960s (see Figure 2). With the exception of 1996, all winters from 1988 onwards were warm, of which several were unusually warm.

For future daily climate data, we used the HadCM2Sa1 scenario developed by the Hadley Centre, UK Meteorological Office, which generated daily climate data for the period 1960 to 2099 (Johns *et al.*, 1997). For this study, we have used the data calculated for the grid cell longitude 2 latitude 17, in which De Bilt is located. The equilibrium climate sensitivity (DT2×) of HadCM2Sa1, i.e. the global-mean temperature response to a doubling of effective CO_2 concentration, is approximately 3.0 °C. Figure 2 shows that the temperature data of the HadCM2Sa1 scenario for the period 1960 to 2000 are not in full agreement with the observed temperatures.

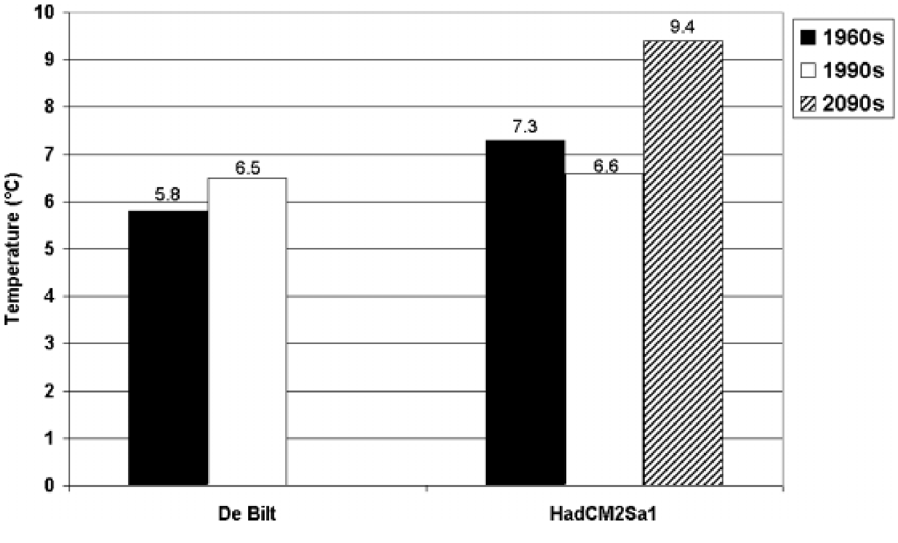

Figure 2. Observed and calculated (HadCM2Sa1 scenario) mean January to May temperature (first 150 days) in the Netherlands

2.5. *Determining the start of the pollen season*

Based on the daily pollen counts we had to derive the start of the pollen season in each year, for which we used the $\sum x$ criterion. With the $\sum x$ criterion, daily pollen counts are accumulated from a certain date. The starting date of the pollen season is the date when x pollen have been counted. The problem with this method is to determine from which date the pollen have to be counted. For each species we determined this date based on expert judgment. In the case of expert judgment we looked at the total amount of pollen measured per year. In the case of very high pollen concentrations we took 50 pollen as the threshold. If the pollen numbers were low we took 25 pollen (and in some cases even 15 pollen) as a threshold (see Table II).

2.6. *Determining the relation between pollen season start and climate variables*

A common way to determine the relation between the timing of phenological processes and climate is to find a correlation between mean temperature during a pre-defined period and the start of the process (e.g. Spieksma *et al.*, 1995; Sparks *et al.*, 2000b). Another way of finding a relation is the temperature sum (TSUM) method. Several authors have found that plants require a certain amount of accumulated heat (also called growing degree days/TSUM) to complete a developmental stage like flowering (Jones, 1992). The TSUM can be calculated by summing for each day, during a pre-defined period, the difference between the mean temperature and a certain threshold temperature:

$$D = \sum_{d=1}^{d=n} (T_{\mathrm{m}} - T_{\mathrm{t}}) \qquad \text{for } T_{\mathrm{t}} \le T_{\mathrm{m}} \le T_{\mathrm{o}} \tag{1}$$

where D(°C day) is the TSUM or growing degree days, T_{m} (°C) is the daily mean temperature, T_{t} (°C) is the threshold temperature, T_{o} (°C) is the optimum temperature, d is the day number, and n is the number of days.

With the many years of pollen data available and the observed starting dates of the pollen season, we were able to determine: (i) the TSUM required; (ii) the threshold temperature, and (iii) the date from which the TSUM should be calculated (commencement date). Based on the analysis we were able to determine whether the TSUM calculation can be used to assess the starting date of the pollen season. To determine the

Table II. Changes in observed starting dates in order of mean starting date of the pollen period (1 January = day 1)

Species	$\sum x$ criterion	Mean starting date	Mean 1970s	Mean 1990s	Difference (in days)	Years with starting date
Juniper[a]	50	60	71	51	-20^{**}	77–00
Elm[a]	25	67	79	57	-22^{**}	77–00
Poplar	25	79	84	66	-18^{**}	69–00
Willow	10	80	82	70	-12^{*}	66–76 + 79–00
Ash	50	91	92	88	-3^{ns}	74–00
Birch	25	102	106	94	-10^{***}	70–00
Oak	50	127	135	117	-18^{***}	69–00
Grasses	50	132	134	128	-6^{ns}	69–00
Dock	25	138	141	136	-5^{ns}	69–98
Pine	100	140	144	135	-9^{ns}	69–00
Nettle	50	155	158	147	-11^{**}	69–98
Elder	25	161	169	154	-15^{***}	69–72 + 75–00
Goosefoot	15	194	199	187	-12^{*}	69–72 + 75–98
Mug-worth	50	215	220	207	-12^{***}	69–98

Level of significance: ns, not significant; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

[a] For this species we compared the period 1977 to 1986 with the period 1991 to 2000 because of lack of observations before 1977.

required TSUM for each species we calculated, for each year pollen data were available, the accumulated heat in degree days at the start of the pollen season as determined by the $\sum x$ criterion for every possible combination of commencement date (date from which the TSUM is calculated) and threshold temperature. This resulted in a different TSUM for each year. Next, the mean TSUM was calculated for the whole period. Then, for each year the date was calculated at which the mean TSUM was reached and we calculated the absolute difference between the real observed starting date of a pollen season and the calculated starting date based on the given TSUM. We then selected the commencement date/threshold temperature that resulted in the lowest annual deviation between observed and calculated starting dates of the pollen season.

The threshold temperature was varied from -25 to $+15\,^{\circ}\mathrm{C}$ with a time step of $0.1\,^{\circ}\mathrm{C}$. The commencement date is varied from the first of January up to and including the earliest starting date of a season found in the pollen data set minus 14 days.

There are more species for which pollen data are available than those selected for this study; however, these species were left out of our analysis. Alder, for example, has a long beginning period with a rather low pollen concentration, and the pollination period is at the beginning of the year when temperatures are low. So calculation of the TSUM is difficult for alder and therefore also the starting dates have not been calculated. In the case of *Apiaceae, Asteraceae, Brassericaceae, Carpinus, Castanea, Fagus, Corylus* and *Aesculus* the pollen concentrations are too low for use with the $\sum x$ criterion and, therefore, with the TSUM.

2.7. Determining future changes in start of the pollen season

After we determined the TSUM, the threshold temperature and the commencement date we were able to assess potential future changes in the start of the pollen season under the climate change scenario by entering the mean daily temperatures in the model. We did this for the period 1960 till 2099.

3. RESULTS

3.1. Start of the pollen season

Table II provides an overview of the $\sum x$ criterion used, the mean starting date of the pollen season, the mean start in the 1970s, the 1990s and the difference between the two periods. From this table it becomes clear that there have been major changes in the start of the pollen season in the last few decades. Up to 22 days advance have been observed. It is interesting to note that there is a large difference in response between the different species. Some species hardly showed an advance of the pollen period. Ash, grasses, dock, and pine show an insignificant advance of under 10 days.

3.2. Relation between pollen season start and temperature

Table III provides an overview of the TSUM analyses we made for each species. It shows the best combination of TSUM, the temperature threshold and the commencement date. The mean annual deviation between the computed and observed dates of the pollen season and the R^2 are also given. Figure 3 provides an example of the fit between the observed and calculated starting date of the birch pollen season. Although the calculated dates are not in full agreement with the observed ones, the patterns observed are in full agreement. Only the year 1981 shows a substantial difference between observed and calculated. This might be because of the large amount of precipitation during the days preceding the start of the pollen season, which might have caused a substantial reduction in the amount of pollen in the atmosphere.

Most of the species show a mean annual deviation of below 5 days per year, which is an indication that the models are able to explain a large part of the variation seen in the starting dates from year to year. The last column with the high R^2 values supports this. Only ash seems to be less easy to model with the variables taken into account.

Table III. Relation between date of pollen start and mean temperature under the given $\sum x$ criteria

Species	Mean starting date	TSUM	Tthres	Commencement date	Mean annual deviation (days)	R^2
Juniper	62	123	−0.1	18	3.4	0.85
Elm	67	193	1.0	1	5.0	0.79
Poplar	79	94	3.2	25	5.0	0.87
Willow	80	199	−0.1	30	3.0	0.89
Ash	92	87	4.0	53	7.2	0.37
Birch	102	168	2.0	64	3.0	0.61
Oak	127	223	4.1	69	4.4	0.68
Grasses	132	2586	−14.6	4	2.6	0.74
Dock	138	280	4.5	73	3.0	0.75
Pine	140	214	6.3	58	2.5	0.83
Nettle	155	856	0.4	49	2.6	0.78
Elder	161	619	3.9	32	3.4	0.77
Goosefoot	194	465	8.5	109	5.8	0.37
Mug-worth	215	2587	−4.5	55	3.3	0.53

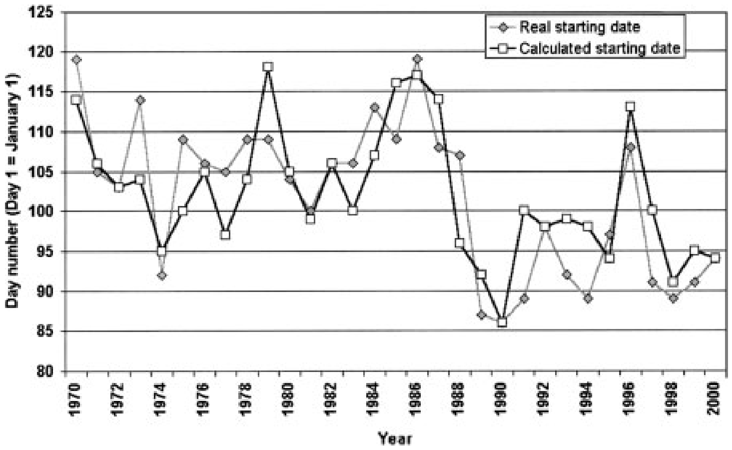

Figure 3. Observed and calculated starting dates of the birch pollen season

Our analysis resulted in a temperature threshold above the 0 °C for most species. Only grasses have a threshold of a remarkable −14.6 °C. This cannot be explained biologically. It could, however, be an indication that day length plays a significant role in determining the start of flowering. The starting dates observed are quite constant. The very low threshold means, in this case, that each day a constant amount is added to the TSUM. With the very high TSUM of 2586 the relative contribution of the observed temperature becomes less important in determining the start of the pollen season, and the relative contribution of the number of days from 1 January increases.

3.3. Potential future changes in pollen season start

Based on the TSUM variables, we can also assess the starting dates of the pollen season in those years that climate data are available but for which there are no pollen observations. It will then be possible to assess the start of the pollen season between 1901 and 1969 for which only observed climate data are available and for the period 1960 to 2099 for which scenario data are available. Figure 4 provides an example of the start of the pollen season of elder in the 20th century. Both the observed and the calculated (based on temperature data in De Bilt) starting dates have been included. The graph clearly shows that flowering advanced substantially in the last decade.

Table IV provides an overview of the actual changes between 1970 and 1990 and the potential future changes in the start of the pollen season for the species considered in this study. The table clearly shows that, under this climate scenario, species, given the TSUM models developed in the previous part of the research, face another considerable advance of the start of the pollen season. The minimum advance is 8 days for juniper, whereas species like elder will advance by 23 days. Figure 5 provides a graphical representation of the advance of three different species in the 21st century. From this figure it becomes clear that the calculated starting dates at the end of the 21st century fall outside the range of starting dates which we have seen in the past. By that time, those years that we consider to be early at this moment will be late years at the end of the century, given the assumed change in climate.

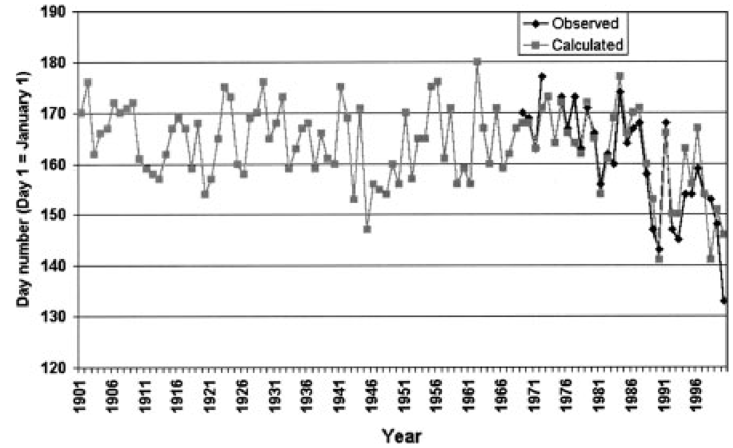

Figure 4. The start of the pollen season for *Sambucus* in the 20th century

Table IV. Advance in the start of the pollen season in two different periods. From 1970s to 1990s (observed) and from 2000s and 2090s based on HadCM2Sa1 scenario (calculated)

English name	Scientific name	Advance 1970s–1990s	Advance 2000s–2090s	Mean date
Elm	*Ulmus*	−19	−17	67
Poplar	*Populus*	−18	−20	79
Willow	*Salix*	−12	−12	80
Birch	*Betula*	−10	−13	102
Oak	*Quercus*	−18	−14	127
Grasses	Poaceae	−6	−11	132
Dock	*Rumex*	−5	−13	138
Pine	*Pinus*	−9	−20	140
Nettle	*Urtica*	−11	−16	155
Elder	*Sambucus*	−15	−23	161
Goosefoot	Chenopodiaceae	−9	−16	194
Mug-worth	*Artemisia*	−9	−15	215
Juniper	Cupressaceae	−11	−8	60
Ash	*Fraxinus*	−3	−19	92

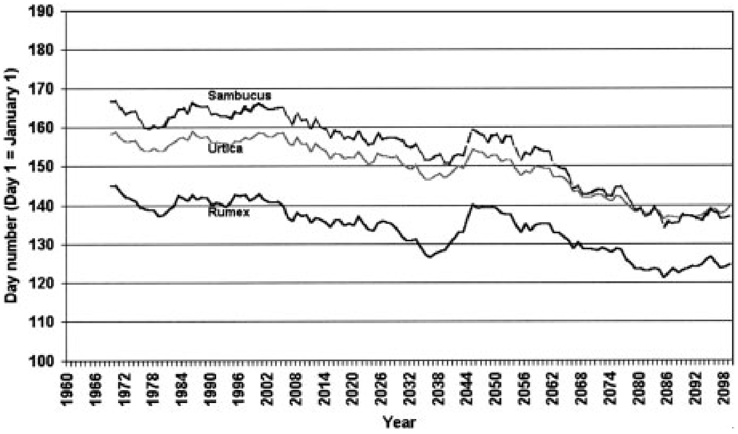

Figure 5. Start of the pollen season for *Rumex, Urtica* and *Sambucus* from 1960 to 2099 under the HadCM2Sa1 scenario (10-year moving average)

4. DISCUSSION

4.1. Temperature and pollen season start

The advance of the start of the pollen season, as observed in this study, is substantial and in close agreement with phenological records from the Netherlands, which show a similar advance of flowering over the same period (Zwart, 2000a; van Vliet and De Groot, 2001; Zwart and van Vliet, 2001).

In this study we aimed to find an explanation for the variation we observed in the start of the pollen season by looking at temperature only. In reality, other factors also determine the development speed of plants and the amount of pollen in the air. Precipitation, wind speed, and wind direction are important factors to take into account. Unfortunately, we have not been able to include these factors in this study. Nevertheless, the results indicate that temperature is able to explain a large part of the variability observed.

Despite the limitations of the data (e.g. errors made by counting the pollen and the use of climate data from De Bilt, which is about 60 km from the observation plot), the results of this study allow us to conclude that climate change will result in significant changes in the timing of the start of the pollen season. If the climate does change as projected by the scenarios, the start of the pollen season will be much more advanced than the changes that we have observed in the past century (e.g. up to 23 days).

4.2. Health impacts

People who suffer from hay fever will be confronted with a significant continuous advance of the pollen season. Whether this advance of the pollen season will directly affect hay fever symptoms is difficult to say. An important part of the seriousness of the complaints is caused by the *amount* of pollen that comes into contact with the hay fever patient. There are indications that, for some species, the amount of pollen produced has increased in past decades (Emberlin, 1997; Ahlholm *et al.*, 1998; Ziska and Caulfield, 2000), but more research is needed to see whether this is true and to determine the role of climate in this increase. The seriousness of hay fever complaints during the first days of the pollen season increases also when the duration of exposure increases. If the duration increases, less pollen is needed to cause the same complaints (called the ‘priming effect’). After a few days of exposure, the response to pollen normalizes again. With an already observed earlier start of the pollen season of up to almost 20 days and a projected future increase of up to another 20 days, this effect might increase the problems with hay fever under a changing climate (Driessen *et al.*, 1988). On the other hand, grasses, as one of the most important groups of species that cause hay fever, show only a minor advance in the start of the pollen season.

The results we presented are based on the northwestern part of the Netherlands. However, the changes in the start of the pollen season are probably not restricted to the Netherlands, as a significant advance of the flowering season has been observed in many parts of the world. Therefore, the large changes observed in the past decades and the potential large changes in the future regarding the start of the pollen season, justify, in our view, the increased interest in hay fever in the context of climate change impact assessments.

4.3. Scenario limitations

In this study we have used only one climate change scenario. In order to get a better overview of potential changes in the future, a more extensive impact assessment has to be carried out whereby several scenarios are taken into account. However, it is important to note that the scenario we used is not one of the most extreme scenarios possible. In the Third Assessment Report of the IPCC, the globally averaged surface temperature is projected to increase by 1.4 to 5.8 °C over the period 1990 to 2100 (Houghton *et al.*, 2001). In addition, based on recent global model simulations, it is very likely that nearly all land areas will warm more rapidly than the global average, particularly those at northern high latitudes in the cold season. Most notable of these is the warming in the northern regions of North America, and northern and central Asia, which exceeds global mean warming in each model by more than 40% (Houghton *et al.*, 2001).

Therefore, the HadCM2Sa1 scenario we have used in this study, with its increase in temperature of only 3 °C, is rather moderate. The observed strong advance in the start of the pollen season could thus be even stronger if the more extreme scenarios become reality. Another factor to take into account in future climate change impact assessments is that climate change is not a gradual process, whereby every year will be warmer than the year before, but that it is a process whereby colder and warmer years continue to alternate (see Figure 5).

Finally, if the projected changes in the start of the pollen season go beyond what we currently observe, we are uncertain whether species will be able to adapt to the projected changes in climate. Maybe other factors will then become limiting, which may prevent species from flowering earlier in the year. This is something that, from the ecological point of view also, is a very interesting and important subject to consider in future studies.

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NOTES

1. By inhalation, pollen gets onto the mucous membranes in the nose and, in this way, individuals with a pollen allergy get hay fever symptoms. The symptoms of hay fever are eye complaints and/or nose complaints. Eye complaints consist of scratchy, red conjunctivae and floods of tears. Nose complaints consist of scratchy burning mucous membranes, long-lasting attacks of sneezing, bright rhinorrhoea and reduced nose occurrence. Quite common are lung complaints: shortness of breath and wheezy breathing. Less common are itch in the throat, diarrhoea, Quinckes oedema and tickling cough.

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