THE RELATION OF SPRING POLLEN RELEASE TO WEATHER IN FAIRBANKS, ALASKA

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Abstract

Twenty-three years of pollen data for Fairbanks have been analyzed and related to meteorological data (temperature, wind, relative humidity and precipitation). The purpose of this research is to develop quantitative statistical relationships between weather parameters and the timing and magnitude of pollen release for four taxa native to the Fairbanks area (birch, alder spruce and grass). During the spring and early summer in Fairbanks, dry, sunny and breezy days are common. These conditions are ideal for establishing an unstable boundary layer and its accompanying convective circulation, which can loft large quantities of pollen into the atmosphere. The timing of pollen release varies from season to season by as many as 24 days. Growing degree days based upon daily maximum temperatures and daily minimum relative humidity are the parameters which best define the timing of the onset of significant pollen release. The day-to-day concentration of pollen and the seasonal totals of pollen released can vary by more than an order of magnitude. Weather plays an important part in this because the release of pollen is a result of a drying process accompanied by turbulent circulation, which disperses the pollen.

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Chapter 1. Introduction

Between 10 and 20% of the population suffers from pollen allergies (Ronneberger et al. 2002; Cookson 1987; Mannino et al. 2002; Nathan et al. 1997). Pollen released from various taxa native to the Fairbanks area cause allergic reactions which can range from very minor problems to life threatening ones. The timing of the pollen release in the Fairbanks area varies among the four taxa and from season to season (Anderson 1986). For a given taxon, the concentration of pollen in the atmosphere during the period of pollen release can vary by an order of magnitude from day to day. Similarly, the total volume of pollen released in a season can vary by an order of magnitude from one year to another (Anderson 1984b).

A large number of studies of the relation of meteorological parameters to pollen release have been conducted in Europe, Australia, Japan and South America (Altinas et al. 2004; Bartková-Šĉevková 2003; Celenk et al. 2009; de Morton et al. 2011; Fehér and Járai-Komlódi 1998; Galán et al. 1995; Hernández-Ceballos et al. 2011; Hobday and Stewart 1973; Peternel et al. 2006; Ribeiro et al. 2008; Spieksma et al. 1985; Stach et al. 2007, 2008). All of these studies found that temperature was the most important factor in pollen release. The results of these studies differed with regard to other factors (humidity, precipitation, wind and hours of sunshine).

Studies of pollen concentrations have taken varied approaches. Bartková-Šĉevková (2003) analysed pollen concentrations for *betlua, Poaceae* and *Ambrosia artemisiifolia* during their respective pollination seasons in Bratislava, Slovakia in 1995 and 1997. The correlation between average daily pollen concentration (grains/m^3), average daily temperature, average daily relative humidity and total rainfall in 24 hours was calculated. Temperature was positively correlated (correlation coefficients between 0.37 and 0.67) and humidity was negatively correlated (correlation coefficients between 0.14 to -0.42). Rainfall was not significantly correlated.

Celenk et al. (2009) gathered daily pollen concentration data for 66 taxa in northwest Turkey from 1 January 2003 to 31 December 2004. The concentration data was plotted on a pollen calendar, a bar graph showing 10-day average pollen concentration over the course of a year. The characteristics of the pollen seasons of the nine most important taxa were calculated. The length of the pollen season was determined by summing the number of days with pollen concentration above a significant allergenic value. The relations between the daily pollen concentrations and average daily temperature, relative humidity and wind speed and total daily precipitation were examined for nine of the taxa (*Pinus sp.*, *Olea sp.*, *Platanus sp.*, *Cupressaceae/Taxaceae*, *Quercus sp.*, *Poaceae*, *Moraceae*, *Urticaceae* and *Castanea sp.*) The correlations between these four parameters and the nine taxa pollen concentrations varied. For all four meteorological parameters, there were both positive and negative correlations with pollen concentrations for the nine taxa. Relative humidity was negatively correlated with *Platanus sp.*, *Poaceae*, *Urticaceae* and *Castanea sp.*, it was positively correlated with *Moraceae*. For pollen grains of the *Urticaceae* family, there was a significant positive correlation between pollen concentrations and mean temperature and wind speed. For pollen grains of *Castanea sp.*, there was a negative correlation with mean temperature, wind speed and relative humidity. It was speculated that the differences in correlations were due to distinct source regions associated with various air flow patterns, the ability of the grains of certain taxa to remain aloft for longer periods than others and fluctuation of pollen production due to biannual or triennial cycles.

De Morton et al. (2011) analyzed grass pollen concentrations in Melbourne, Australia for 16 seasons. Days with high pollen concentrations occurred with offshore continental flow. Onshore maritime flow suppressed pollen concentration. The length of the pollen seasons varied from 47 days to 118 days. Land use in the area was an important factor. Extensive clearing of land or the planting of grass taxa over large pastures both increased pollen concentrations.

Fehér and Járai-Komlódi (1998) examined the relation of A*mbrosia* daily pollen concentration in Budapest, Hungary to various weather parameters. As have others, they found that high temperature (~>20°C), low humidity (~<30%) and sunny weather promote pollen release. These values of temperature and relative humidity are akin to those used in forecasting wildfire behavior (Schroeder and Buck 1970). Fehér and Járai-Komlódi (1998) did not develop specific thresholds for these parameters. Instead, they developed equations based upon multiple regression analysis. Cyclonic weather and rain suppressed pollen release. In addition, they found that the daily temperature range (maximum temperature minus minimum temperature) was more important than any other factor related to temperature.

Galán et al. (1995) demonstrated that two areas, London, UK and Cordoba, Spain, with significantly different climates (mid latitude maritime and subtropical continental) have differing relations between pollen concentrations and weather factors. In London, maximum and average temperatures are the factors most strongly correlated with pollen concentration. At Córdoba, the positive correlation between temperature and pollen concentration holds from the onset to the peak of the pollen season. After the peak, the correlation becomes negative. At Córdoba, there is a strong negative correlation between relative humidity and pollen concentration, whereas at London, the correlation is weakly negative.

Hernández-Ceballos et al. (2011) utilized a network of pollen measuring stations in southwest Spain to analyze olive (*Olea spp.*) pollen transport dynamics. Particular attention was directed to nine episodes of high pollen concentrations. Peak olive pollen concentrations in these episodes ranged approximately from 500 to 7,700 grains/m^3. Synoptic surface maps and surface weather observations (temperature, relative humidity, rainfall, wind direction and wind speed) were used in conjunction with the hybrid single particle Lagrangian integrated trajectory model (HYSPLIT) to calculate kinematic backward trajectories of pollen arriving at measuring stations (Draxler and Hess 1998; Draxler et al. 2005). Due to the significant differences in the prevalent taxa between distinct upwind areas, source regions were an important factor affecting the taxa and quantities of pollen observed. The largest pollen influxes were from the south. The other important source was to the west of the station network. Correlations between olive pollen concentrations with temperature and rainfall were not particularly strong. Correlation coefficients for all possible combinations of pollen concentration, temperature and relative humidity were never more than 0.4.

The importance of differences between source regions was pointed out by Dingle (1953). Three of the four taxa studied in this research – alder, birch and spruce – are ubiquitous around Fairbanks. In comparison to these, grasses are the prevalent taxon over relatively much smaller areas. The grass pollen concentrations, which are much smaller than those of the other three taxa, reflect this.

Hobday and Stewart (1973) collected data on (1) hospital admissions of children in Perth, Australia, (2) fungal and pollen counts and (3) local weather conditions. They investigated interrelationships between these three factors. They found a significant association between reduction of asthma attendance and (1) increased atmospheric ionization three days before, (2) increased atmospheric pressure two days before and (3) increased temperature one day before.

Peternel et al. (2006) examined *Ambrosia* pollen concentration at a network of three inland measuring sites in northern Croatia during three seasons (2002-2003). There was a positive relation between high temperatures in June and an early onset of the pollen season.

Ribeiro et al. (2008) studied hourly distributions of allergenic airborne pollen in the city of Porto, Portugal and found that the pollen concentration of some species typically was at a maximum in the morning and for other species in the afternoon. Specifically, they found that *Urticaceae*, *Cupressaceae*, *Acer spp.* and *Plantago* spp. pollen concentrations were higher in the morning than at other times. *Alnus* spp. (alder) and *Betula spp.* (birch) pollen was mostly present in the afternoon. The highest concentration of *Poceae* (grasses) was observed in the evening. *Olea europaea* and

Pl*atanus spp.* pollen was present at similar concentrations at all hours of the day and night.

All of the taxa in Ribeiro et al.'s (2008) study exhibited a rise of pollen concentration in the morning, when humidity is decreasing and wind is increasing. Those taxa having higher pollen concentrations in the morning have delicate pollen anthers which quickly dry and release small grains that are readily dispersed. As evening approaches, humidity typically rises and flow in the boundary layer becomes less turbulent. The taxa with higher concentrations in the afternoons have pollen which readily adapts to increased humidity, and become heavier as it absorbs moisture. The lessening of turbulent mixing allows this pollen to settle into a smaller volume of air.

Spieksma et al. (1985) observed large and highly irregular variations in *Poaceae* (grasses) pollen concentration in Leiden, The Netherlands from day to day and from hour to hour. They developed a successful technique to prepare a daily forecast of pollen concentrations in three broad categories, based mostly on daily forecasts of maximum temperatures and to a lesser extent on expected daily rainfall. The total annual pollen release in Leiden in the years 1977-1981 varied by less than a factor of two, but the distribution of high pollen concentration days varies considerably from year to year. Thus, Spieksma et al. (1985) concluded that long term prediction of the time of the start of the grass pollen season and of the intensity and course of the season was not yet possible.

Stach et al. (2007) examined episodes of high concentrations of *Ambrosia* pollen at Poznań, Poland using backward trajectory analysis to establish the likely locations of source regions. They found that *Ambrosia* pollen episodes reaching a maximum concentration in the morning occurred when air flow was from the south. During those episodes in which peak concentrations were in the afternoon the air mass arrived from an easterly direction. Stach et al. (2007) surmised that the morning peak concentrations resulted from long range transport over one or more days, followed by night time cooling and settling. The average daily *Ambrosia* concentrations in the episodes analyzed were similar for both easterly and southerly flow. Since there was loss of pollen due to evening and night time settling in southerly events, the initial pollen load was much larger than in easterly events. This behavior is to be expected because the areas south of Poznań have large, established *Ambrosia* populations capable of releasing very large amounts of pollen. The pollen in easterly events appears to have originated from areas relatively close to Poznań.

Stach et al. (2008) found that *Betula spp.* (birch) pollen seasons in Poland and the United Kingdom were related to phases of the North Atlantic Oscillation (NAO) as well as meteorological conditions in both the year before pollinations and in the same year that pollen is released. At Poznań, there are significant correlations between *Betula* season severity and temperatures, rainfall and averages of the NAO in the year before pollination. At Worchester, there were significant positive correlations between the *Betula* season severity and temperatures and averages of the NAO in the winter and spring before pollen release. At both Worchester and London, there were negative correlations between *Betula* season severity with the same variables from the year before

Little work on pollen release has been done in Alaska. Durham (1941) gathered samples on slides set in Juneau, Fairbanks and Nome during July, August and September in 1939. He obtained pollen concentrations from five taxa: grasses, chenopod, pine, sedge and sage. The largest concentrations were for grasses – which Durham (1941) noted had a well-defined pollination season during the first two weeks of July at Juneau and Fairbanks and during the last week of July and the first half of August at Nome. Durham found the most pollen in Nome and the least in Fairbanks. Since the period in which Durham acquired data was well after the usual pollen season in Fairbanks this result is not surprising.

Anderson (1984a, 1984b, 1985, 1986) gathered pollen and spore concentration in Anchorage, Fairbanks, Palmer, Juneau and Whitehorse. He developed pollen calendars, which graphically display pollen concentration of several taxa vs. the calendar date.

Fathauer et al. (2004) developed similar pollen calendars for the four taxa examined in this study. These calendars show that different taxa have distinct seasons. Other investigators have developed similar pollen calendars for taxa other than those investigated in this study (Mitakakis and Guest 2001; Docampo et al., 2007). Of the four taxa for which Anderson gathered data in Fairbanks, birch is the first to release pollen, followed by alder, spruce and grasses, respectively. The grasses release pollen weeks after the other taxa, which all begin pollen generation in the year before release (Alden 1985). Grasses produce pollen in the same year as it is released. Since grasses must complete the entire process of pollen generation in one season, rather than two, their pollen is not ready for release until mid summer, rather than in May and early June.

Anderson (1986) first considered the process of green-up in Fairbanks, which is the rapid transformation of Interior Alaska from the brown colored landscape at the end of winter to spring green as the leaves of deciduous trees burst forth. Green-up of deciduous taxa occurs close to the time of pollen release, and is a similar process because the opening of leaf buds is similar to the opening of pollen buds. Anderson noted that green-up is sudden enough to assign a single calendar data for its occurrence.

Thoman and Fathauer (1998) used green-up dates for Fairbanks for the years 1974 and 1976 through 1998 (J Anderson and R Elsner, 1998, personal communication), and applied statistical correlation tests of the green-up dates vs. a number of temperature indices calculated from meteorological data taken at Fairbanks International Airport (1974-1998). The most successful results were obtained using a form of growing degree day. A similar approach had been taken by Perry et al. (1987) to predict harvest dates of apples. The growing degree day (GDD) was calculated by using the maximum temperature (T_{max}) for a day in °C for each calendar day, beginning on 1 March of each year, for 24 years of data. If T_{max} =< 0°C, then for that calendar date GDD = 0°C. The sum of all calendar day growing degree days from 1 March through the date of green-up for each year was calculated. The mean GDD total (ΣGDD) to green-up was 401°C, the standard deviation (σ) was 44°C and the coefficient of variance (CV = σ/ΣGDD) was 0.11.

This result suggested that thermal indices could be applied in the same manner to determine the date of pollen release for various taxa. Indeed, similar thermal indices have been used to calculate the day of pollen release (Anderson 1986), and to determine the effect of temperatures on annual shoot growth of white spruce (*Picea abies*) (Bergan 1983).

Fathauer et al. (2004) analyzed 23 years of daily pollen concentration data (in grains/m^3) for four taxa in Fairbanks. The spring and summer environment in Fairbanks in particular, and in the sub-arctic in general, differs from that of the mid latitudes, primarily due to the extended period of sunshine. During dry, relatively cloud-free weather, pollen buds have many hours of drying time. During cloudy, rainy weather, there is little if any drying of pollen buds. Some of the 23 years in this study had extended periods of low concentrations and others had large concentrations released in a few days, with a very large maximum concentration.

Chapter 2. Materials and Methods

Daily pollen and spore concentrations for 39 taxa were gathered by J Anderson at the University of Alaska in 1978 and 1981-2002. The data for the years 1978 and 1981 were gathered using a Durham gravimetric sampler. The data for the years 1982 through 2002 were gathered using a Burkard 7-day volumetric sampler, located on the roof of the Arctic Health Research Building at the University of Alaska Fairbanks (Figure 1). The sampler was located about 10 m above ground level. The Durham and Burkard samplers were run side by side for eight years. The data from these samplers was highly correlated (Anderson 1991). Daily pollen concentrations for the four locally most important taxa – birch (*Betula papyrifera*, mostly, and *B. glandulosa*), alder (*Alnus crispa*), white spruce (*Picea glauca* and *P. mariana*) and grasses (*Gramineae*, mostly, *Calamagrostis canadensis*, *Bromis inermis* and *Hordeum jubatum*) were gathered for the pollen seasons of 1978 and 1981 through 2002 - a total of 23 years. The present study analyzes the pollen concentrations of these four taxa.

Figure 1. The Burkard 7-day volumetric sampler. (Photo courtesy of J Anderson).

Burkhard samplers have been used for decades. The Burkhard sampler is a wind-oriented, aspirated sampler which gathers airborne particulates on a coated slide. Pollen *counts* are done manually using a microscope (Hirst 1952; Altinas et al. 2004). Pollen *concentration* is calculated by dividing the number of pollen grains (the pollen count) by the volume of air which passes through the sampler during the sampling period. Anderson's data was taken over a 24 hour sampling period. It therefore represents the daily average concentration. It does not provide information regarding fluctuations of pollen concentration over shorter periods of time, e.g., hourly. The total pollen release for a season is the sum of all of the daily pollen concentrations for the season. Figure 2 shows images of birch and spruce pollen grains. Figure 3 shows images of grass and alder pollen grains.

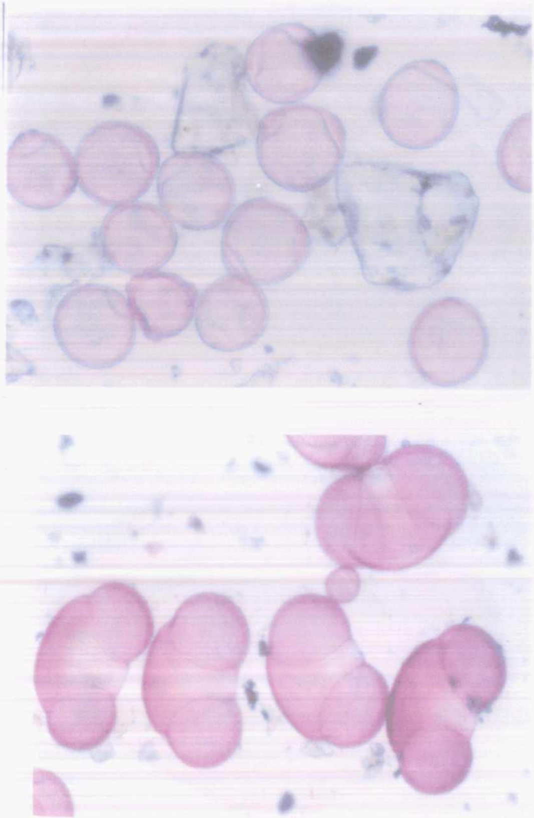


Figure 2. Birch pollen grains and spruce pollen grains. Birch pollen grains (top) are approximately 0.025 mm in diameter. Spruce pollen grains (bottom) are about 0.11 mm in length. Both are stained here. In nature both are yellow in color. (Pictures courtesy of J Anderson).

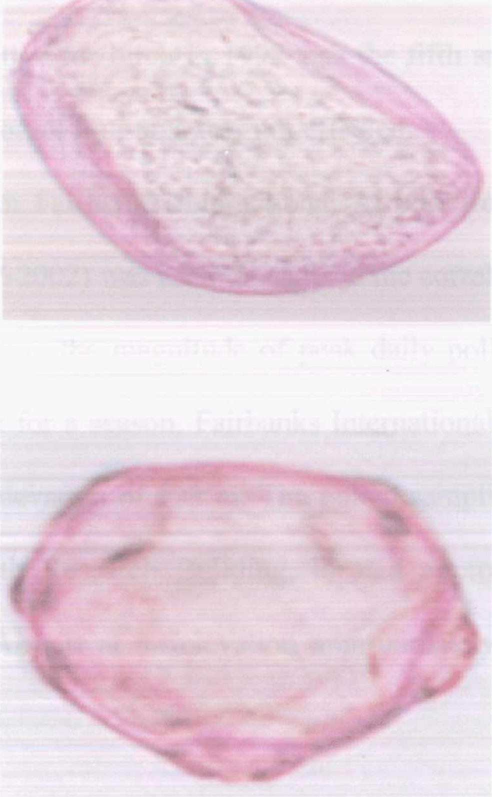


Figure 3. Grass pollen grain and alder pollen grain. Typical grass pollen grains (top) are approximately 0.025 to 0.035 mm in diameter (Geisler 1945). Typical alder pollen grains (bottom) are approximately 0.015 to 0.020 mm in diameter (Ronneberger et al. 2002). (Pictures courtesy of J Anderson).

There was one period in Anderson's data in which only one pollen count was taken over several days: 15-27 May 1992. In this case, Anderson divided the total pollen count by the number of days to yield an average daily concentration for the period. The average daily concentration was entered for all days in the period. As a result, the onset dates for both birch and alder, and the magnitude and date of the peak daily concentration for birch, had to be estimated. The 1992 season release of alder was the fourth largest in the record, and the release for birch was the fifth smallest in Anderson's record. The estimated peak concentration for birch in 1992 was the fifth smallest in the record. The total season release data for all four taxa was not effected.

Weather data from Fairbanks International Airport from the National Climatic Data Center (NCDC 1977-2002) was used to evaluate the correlations between the timing of significant pollen release, the magnitude of peak daily pollen concentration and the cumulative pollen release for a season. Fairbanks International Airport is located at 64° 49′ N 147° 51′W at an elevation of 133 m. The pollen sampling was performed on the roof of the Arctic Health Research Building, located approximately 5 km north of Fairbanks International Airport at an elevation approximately 50 m above the airport (Figure 4).

Figure 4. Google map of the pollen sampling site and surrounding areas, and the National Weather Service (NWS) station at Fairbanks International Airport.

During the summer pollen season in Fairbanks, the air is typically well mixed from 1 to 3 km above ground level during the afternoon hours (NCDC 1978-2002). Thus, due to close proximity and the well mixed nature of the air mass during the warmest and most windy part of the day, the weather data from Fairbanks International Airport can be presumed to be closely representative of meteorological conditions at the pollen sampling site.

Plotted daily values of pollen concentration, temperature, relative humidity, wind speed and precipitation vs. Julian date were examined for each taxon for the 23 individual seasons for which pollen data was available. Based on this examination and on the known processes of pollen development, release and transport, the parameters which were selected for investigation were daily high temperatures (T_{max}>20°C), minimum relative humidity (RH_{min}<30%), little or no precipitation (RR<1mm) and peak wind gusts (VV>12m/s).

Plant health is considered important in this analysis. The great variation in pollen release in Fairbanks from one season to the next reflects how sensitive plant health, and therefore pollen release, is to external forces. As previously mentioned. birch, alder and spruce, pollen generation begins in the summer of the year before its release while grass pollen is released in the same summer that it is formed. The portion of the year when active growth is in progress in Fairbanks extends from May through September. Favorable temperature and precipitation during this period promote pollen development. Thus, temperatures and precipitation from May through September were chosen to be among the meteorological factors relevant to the health of the four taxa in this study.

The period of plant dormancy in Fairbanks begins in late September and ends in April as the temperatures are below and above freezing, respectively, for at least part of the day. Winter temperature was assumed to be important to taxa such as spruce, birch and alder which form pollen above the winter snow cover. Since grass pollen is formed close to the ground, and grass is under the snow for most of the winter, temperature during the winter months was assumed to be relatively unimportant to grass pollen production.

Over-winter accumulated precipitation minus sublimation and evaporation determines the amount of water available to plants in spring (Mölders et al. 2003a, 2003b). In this study, sublimation is assumed to be small compared to the total precipitation and is therefore neglected. This assumption is based upon National Weather Service (NWS) precipitation and snow core measurements of the water content of the snow pack at Fairbanks International Airport (NCDC 1978-2002). Although the amount of precipitation water content lost by sublimation from the snow pack over winter varies from one year to another, it is not considered significant in this study.

Following the transition from the winter season, when temperatures are continuously below freezing, to spring, when snowmelt begins, the loss of the water content from the snow pack is largely due to evaporation. This loss can be significant. Eaton and Wendler (1982) calculated that the snowpack at Fairbanks in the spring of 1980 lost one third of its water content due to evaporation.

Computation of the water available from snowmelt in the spring in Fairbanks is not a simple procedure. All meteorological factors being similar, the time required to melt a large snow pack is longer than for a smaller snow pack. Thus, it can be argued that there is more evaporative moisture loss in large snow packs. Numerical studies (Mölders and Walsh 2004) show that snow-pack thickness affects soil temperature. Thus, the variation in snow pack thickness may affect pollen production and release.

Further complicating the matter, birch, alder, spruce and grasses around Fairbanks have differing zones of growth, primarily as a function of elevation (USGS 1979). Finally, as is the case in much of the world, precipitation in the Fairbanks region is augmented with increasing elevation.

Therefore, the over-winter precipitation measured at Fairbanks Airport in this study is considered an index, not as a precise measure of the water from snowmelt which will infiltrate the ground and be available for plant growth. Above normal over winter precipitation is considered to provide more water for plant growth then below normal over winter precipitation.

Once pollen has been formed, its release is initiated by drying – a rapid process that can take place within only 1 to 2 hours. Thus, the time interval for examination of meteorological parameters relevant to pollen release shifts from the months during which pollen is formed to one day at a time at the beginning of the period of pollen release.

Lowering humidity and rising temperature are the principal meteorological parameters involved in the pollen drying process. Humidity rises in conjunction with precipitation. Wind serves to dislodge pollen grains and to transport them. The NCDC climatological normals tables for Fairbanks International Airport show that May is the windiest month of the year (Table 1).

Figure 5 shows the average pollen count for each calendar day, based on the 23 years of pollen data available. Birch is the earliest and largest pollen release, followed by successively later and smaller releases of alder, spruce and grass pollens. May is the month when most of the pollens from birch, alder and spruce are released.

Table 1. Average monthly wind speed at Fairbanks Airport based on data 1952 – 2002 (51 years).

Month	Monthly average wind speed (m/s)
January	1.3
February	1.7
March	2.4
April	3.0
May	3.4
June	3.2
July	3.0
August	2.7
September	2.7
October	2.4
November	1.7
December	1.3

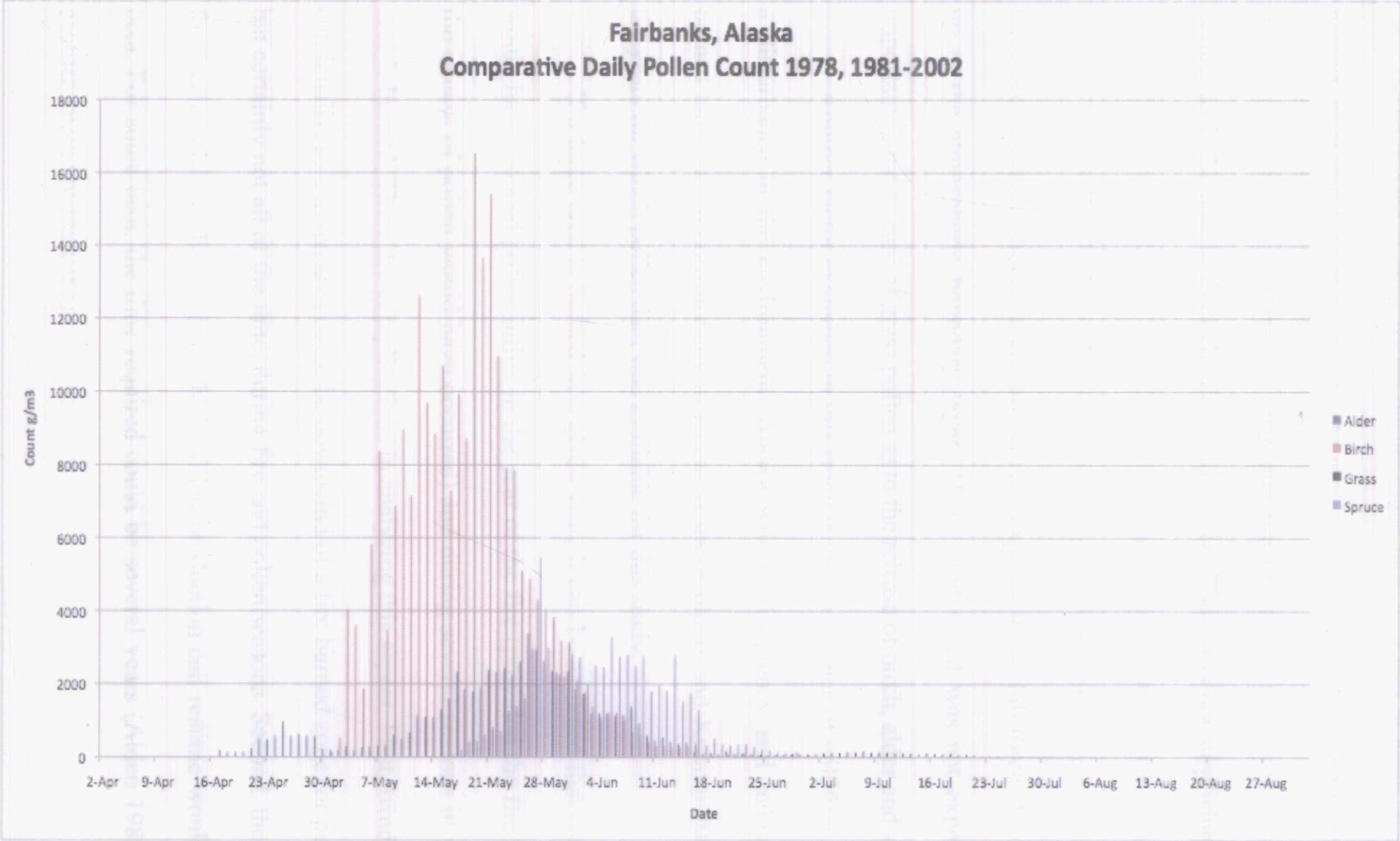


Figure 5. Average daily pollen concentrations for birch, alder, spruce and grass (grains/m³) for 1978 and 1981 – 2002.

The release of grass pollen occurs much later than that of birch, alder and spruce, namely from mid June through July. As previously mentioned, the entire process of grass pollen generation is confined to only one season, rather than commencing the year before, as is the case with birch, alder and spruce. Thus, it is not surprising that having a late start of formation, grass pollen is released later than the other three taxa in this study.

Grass pollen buds are located much closer to the ground than those of the other three taxa examined in this study, and are not exposed to the full force of the wind farther up in the atmospheric boundary layer. Thus, wind speed was not expected to be as important to the release of grass pollen as to the release of birch, alder and spruce pollen.

Another factor examined in this study is the occurrence of wildfires. Wildfires are a disturbance in the environment. Alaska wildfire frequency and intensity, and area burned have varied considerably in recent years (Mölders and Kramm 2007), including the years for which pollen data was available for this study.

If a large area is burned in a given year, it can be assumed that areas downwind would have reduced pollen influx in the year of the fire (provided the fire burned before the release of pollen would have occurred) and during several seasons in years after the area is burned. There are complications in analyzing this aspect. First, wind flow changes continually, so a given area could be downwind of a fire burned zone for part of the time, but certainly not all of the time, during fire and pollen seasons. Second, the time required for regeneration to the stage at which pollen production can resume would vary among taxa. For some taxa, the time required could be several years (Alden 1985; Owens and Molder 1979; Owens 1985).

Statewide data for acres burned each year shows great variation from year to year. For the years in this study, large areas (>5,000 km^2) in Alaska were burned in: 1977, 1988, 1990, 1991, 1997 and 2002. The area burned in 1977 would not be producing pollen in 1978, which is the first year of pollen data in this study. The cumulative pollen release for all four taxa in the two years following large fire seasons ranged from less than 5,000 (1999) to almost 25,000 (1989).

A good deal of work has been done to investigate pollen trajectories (Bacles et al. 2006; Belmonte et al. 2008; Chamecki et al. 2009; Fotiou et al. 2011; Gassmann and Pérez 2006; Gassmann and Gardiol 2007; Izquierdo et al. 2011; Rousseau et al. 2004; Šikopariga et al. 2009; Skjøth et al. 2009; Sofiev et al. 2006). These studies investigated trajectories in scales ranging from mesoscale, as in sea-breeze circulations to large synoptic scale transport from the mid latitudes in the northern hemisphere to the north pole. There is one theme common to them all: while pollen grains can be transported over very large distances, the fraction of grains, which remain in the air decreases rapidly with time. Hence, the reduction of pollen flux from fire burned areas was not considered relevant to this study.

Considerable damage can be done to plants by insects and diseases – both of which recur periodically (Holsten et al. 2001). For example, the spruce budworm *(Choristoneura spp.)* is a significant pest to Fairbanks area white spruce (Holsten et al. 1999). Its infestations can run from 2 to 5 years, and are followed by dramatic and rapid population declines. Such infestations are difficult to factor into a biometeorological study. Their occurrence appears related to natural limits to their duration rather than to meteorological factors.

Data on insect infestations statewide (U. S. Forest Service 1977-2002) shows great variation in various insect pests from year to year during the years covered by this study. Large infestations destroyed more than 1,200 km^2 of spruce in 14 of the 23 years of this study. The total spruce pollen release measured at Anderson's sampler in the year following each of these infestations ranged from 607 to 7,446 grains/m^3. The mean season release for spruce pollen during Anderson's study was 2,938 grains/m^3. Infestations of birch, alder and aspen destroying more than 400 km^2 occurred in 4 years of the study (1980, 1986, 1987 and 1991). The season releases in the following year (1981, 1987, 1988 and 1992) ranged from 2,755 to 26,717 grains/m^3 of birch pollen and from 1,664 to 4,599 grains/m^3 of alder pollen. The mean season release of birch pollen measured by Anderson was 10,155 grains/m^3, and 2,965 grains/m^3 for alder.

Werner (2010) set insect traps at the Bonanza Creek Long Term Ecological Research Area (LTER), which is located 24 km southwest of the location of Anderson's pollen sampler at the University of Alaska Fairbanks. Werner (2010) counted the number of three pest species: the spruce beetle, the *Ips* beetle and the larch beetle. His data covers the years 1975-2007 and 2010 – which include all of the years investigated in this study. The spruce beetle (*Dendroctonus rufipennis*) and *Ips* beetle (*Ips spp.*) infest white spruce. The larch beetle does not infest any of the taxa in the study. Werner did not gather data on insects, which infest birch or alder. While Werner's data only includes two pests of one of the taxa in this study, its obvious advantage is that it was gathered at a site close to

Anderson's sampler, so it is presumed to be representative of insect populations that would affect white spruce in Fairbanks. Werner counted large numbers (>1,800) of the combined spruce and *Ips* beetles in 1984, 1985 and 1986. If these infestations had an impact, the spruce pollen would have been reduced in the following seasons – i.e. 1985, 1986 and 1987. Surprisingly, there was not a large decrease in spruce pollen collected at Anderson's sampler in these years. In the three years following infestations at LTER, the combined spruce pollen releases measured by Anderson were 1,438, 307 and 7,446 grains/m^3, respectively. The mean season spruce pollen release during Anderson's study was 2,938 grains/m^3. If the infestations of spruce in 1984, 1985 and 1986 had really caused a large decrease in spruce pollen, the release should have decreased substantially by 1987, after three consecutive years of infestation. In fact, the spruce pollen release in 1987 had increased to more than twice the mean spruce pollen concentration in the 23 years in which data was collected. In conclusion, it appears that neither statewide nor the nearby LTER insect infestations would correlate using standard analysis of variance (Wilks 2006) to any consistent effects on the pollen that Anderson collected at the University of Alaska. The infestations of spruce pests were followed by years with very large ranges of spruce pollen releases.

Chapter 3. Results and Discussion

The dates of green-up in Fairbanks vary considerably. Figure 1 illustrates green-up dates in Fairbanks for 1978 and 1981-2002 – the same years of the pollen data used in this study. The green-up dates in the 23 years of data range from April 29 through May 25 – a range of 27 days. The length of this time is surprising. Fairbanks summers are short and intense, and flowering plants have little time to lose. Nonetheless, the four taxa in this study exhibit a similar tolerance for a large range of dates on which pollen release can begin. This tolerance is not exhibited in some other taxa in Fairbanks. For instance, the Siberian crab apple (*Malus baccata*) flowers very briefly, in the first 10 days of June (author's personal observation 1983-2012).

Figure 6. Green-up dates in Fairbanks in 1978 and 1981-2002.

Significant pollen release is defined in this study as pollen concentration at or above a level generally accepted to pose a risk to people with pollen allergies (Hobday and Stewart 1973; Nathan et al. 1997). The thresholds for significant pollen concentration used in this study are listed in Table 2.

Table 2. Thresholds for significant pollen concentration (grains/m^3).

Birch	50
Alder	30
Spruce	20
Grass	4.0

The first day on which pollen concentration of a taxon reaches its threshold is defined in this study as the date of the onset of pollen release of that taxon. Table 3 lists the earliest and latest dates of the onset of pollen release of the four taxa.

Table 3. Earliest and latest dates of the onset of significant pollen release.

Taxon	Earliest release date	Latest release date
Birch	April 30	May 23
Alder	May 2	May 24
Spruce	May 15	June 6
Grass	June 14	July 6

Plots of total pollen release by year of individual taxa are shown in Figures 7 to 10. These plots reveal great differences from one year to another, as well as large ranges over the 23 years for which data was available. The ranges are (in grains/m^3): grass: 25-260; spruce: 607-7,446; alder: 1,252-5,719; birch: 1,366-26,717. Further, in some years, there appeared to be only a weak linkage or none at all, between various taxa. This finding suggests that statistical regressions for different taxa differ considerably. For example, as shown in Table 4, the 2001 grass pollen release was at a medium level (171 grains/m^3 total release for the season compared to a mean season release of 161 grains/m^3), while alder, spruce and birch were decidedly low (1,451, 929 and 2,565 grains/m^3, respectively). The total season pollen releases for all four taxa combined are shown in Figure 11.

Table 4. Total 2001 season pollen release vs. mean season pollen release (grains/m^3).

Taxon	2001 Season Release	Mean Season Release
Grass	171	161
Alder	1,451	2,965
Spruce	929	2,938
Birch	2,565	10,155

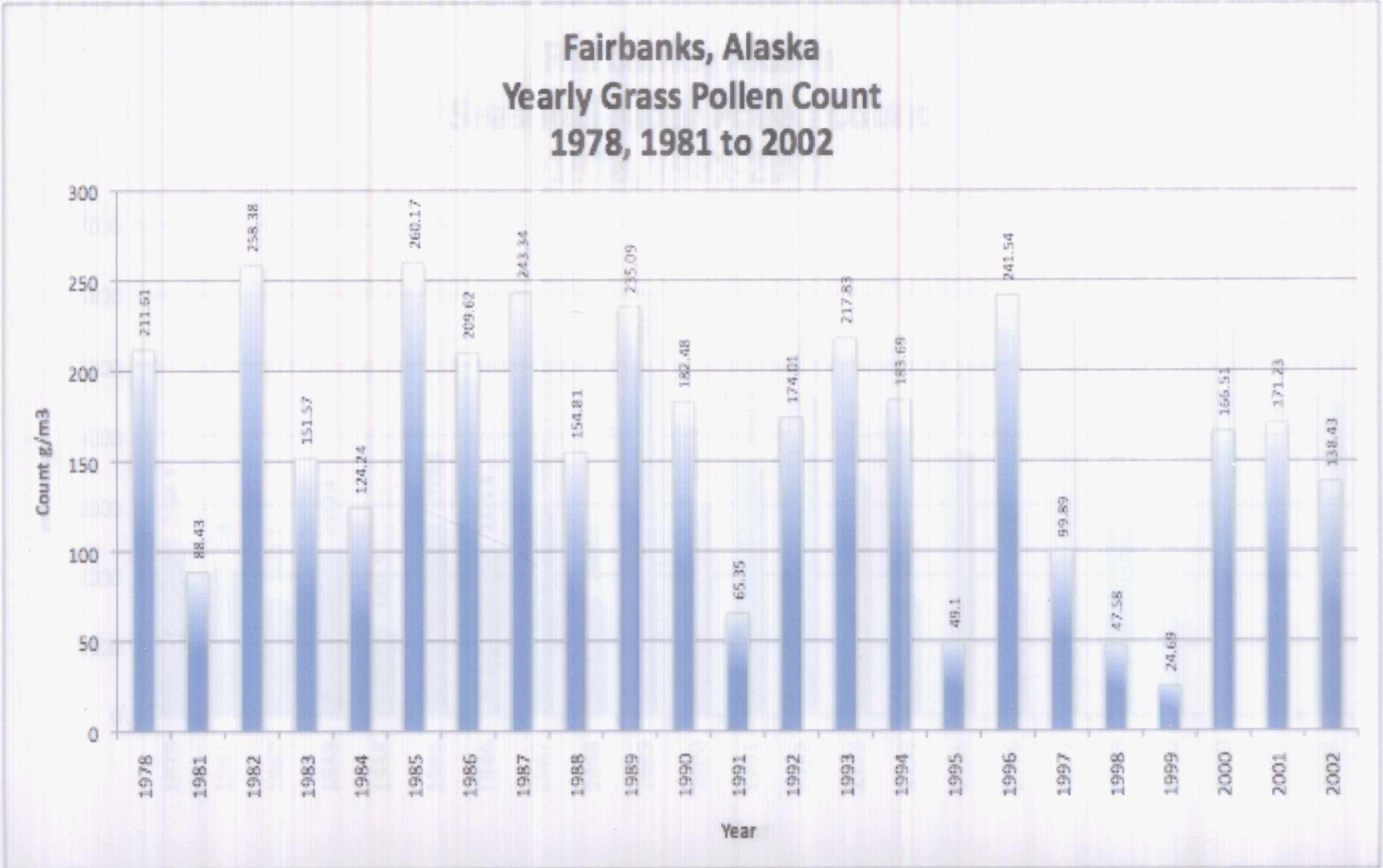


Figure 7. Cumulative seasonal grass pollen concentration in 1978 and 1981–2002.

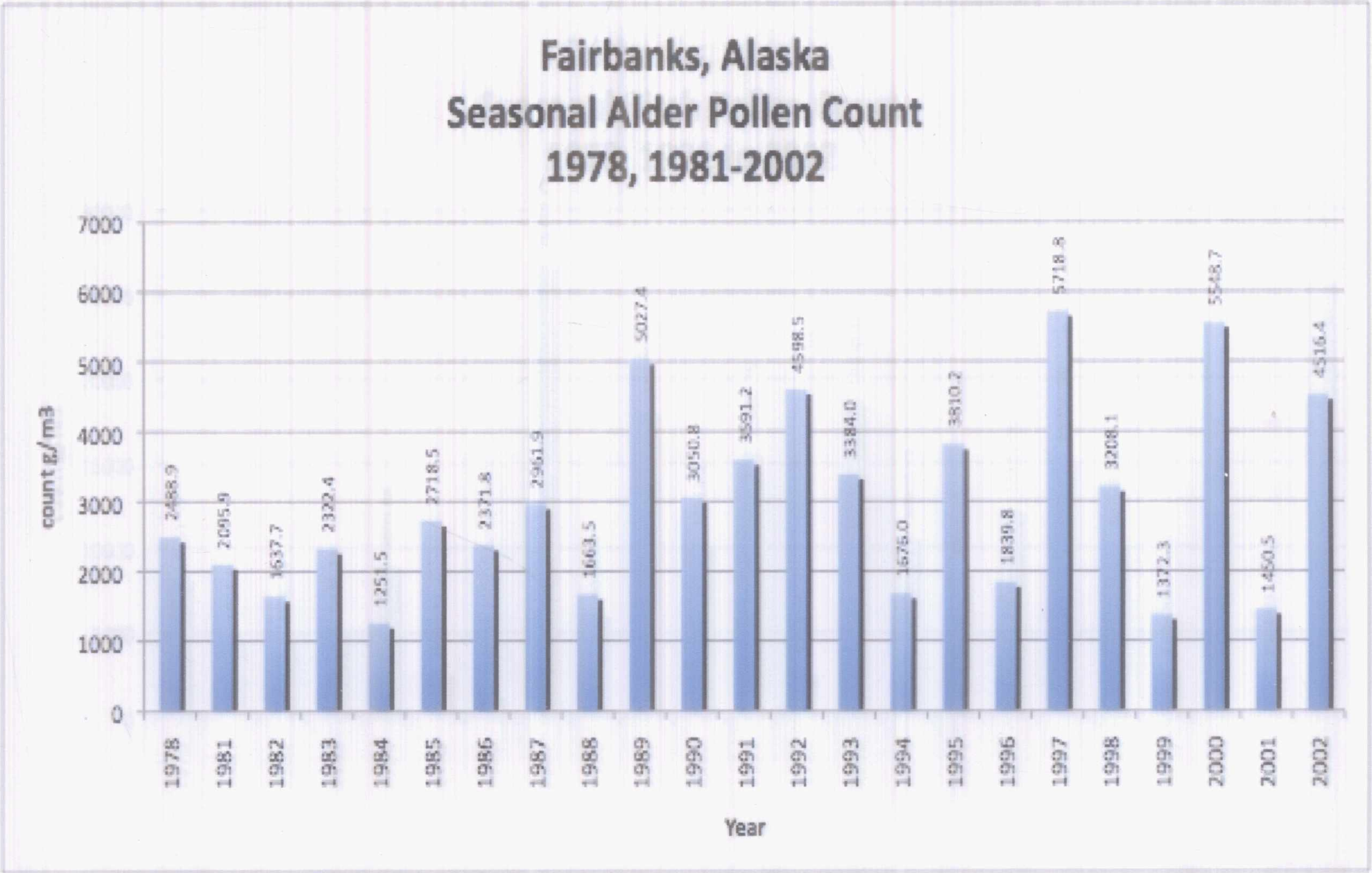


Figure 8. Cumulative seasonal alder pollen concentration in 1978 and 1981–2002.

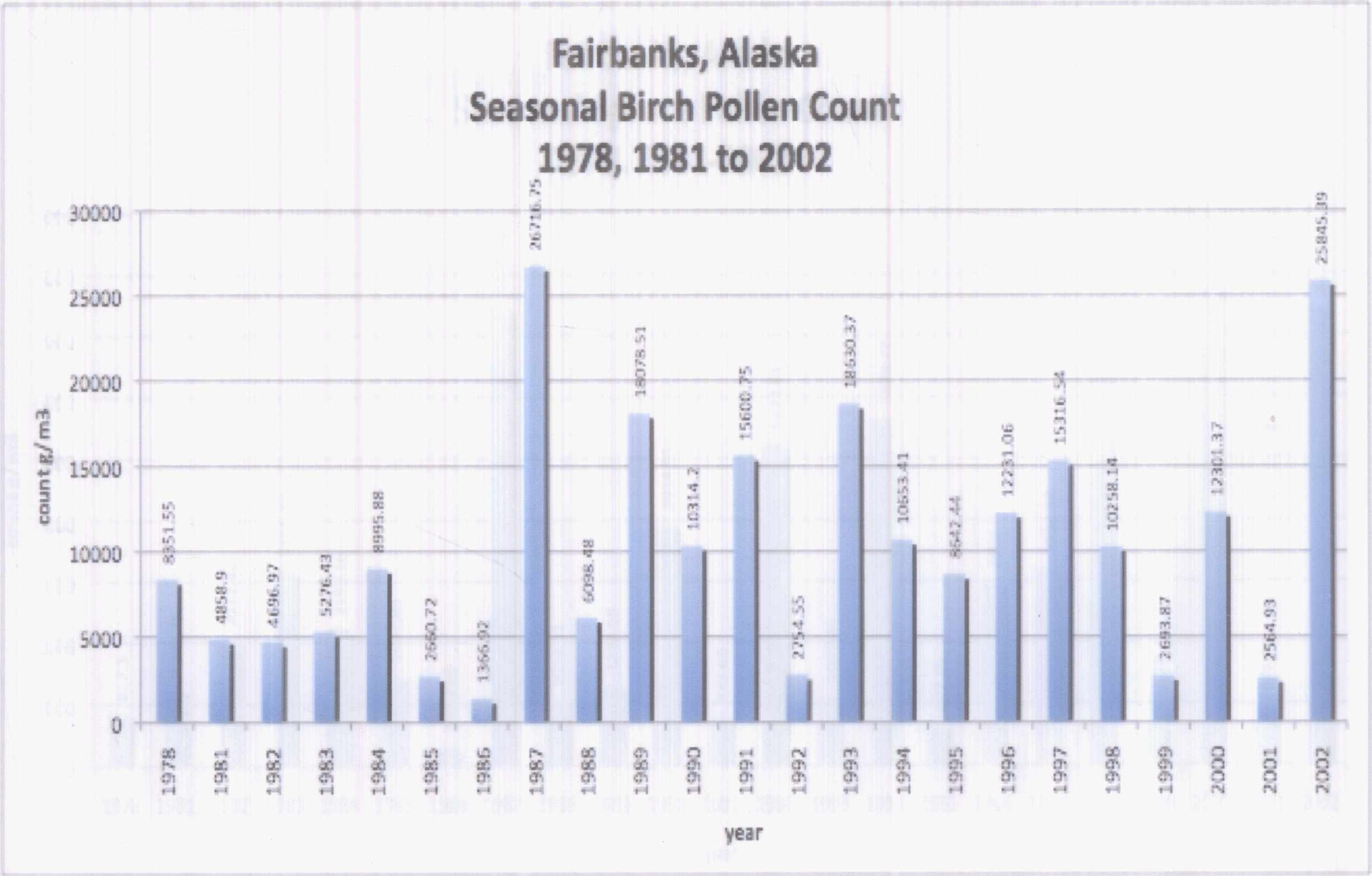


Figure 9. Cumulative seasonal birch pollen concentration in 1978 and 1981–2002.

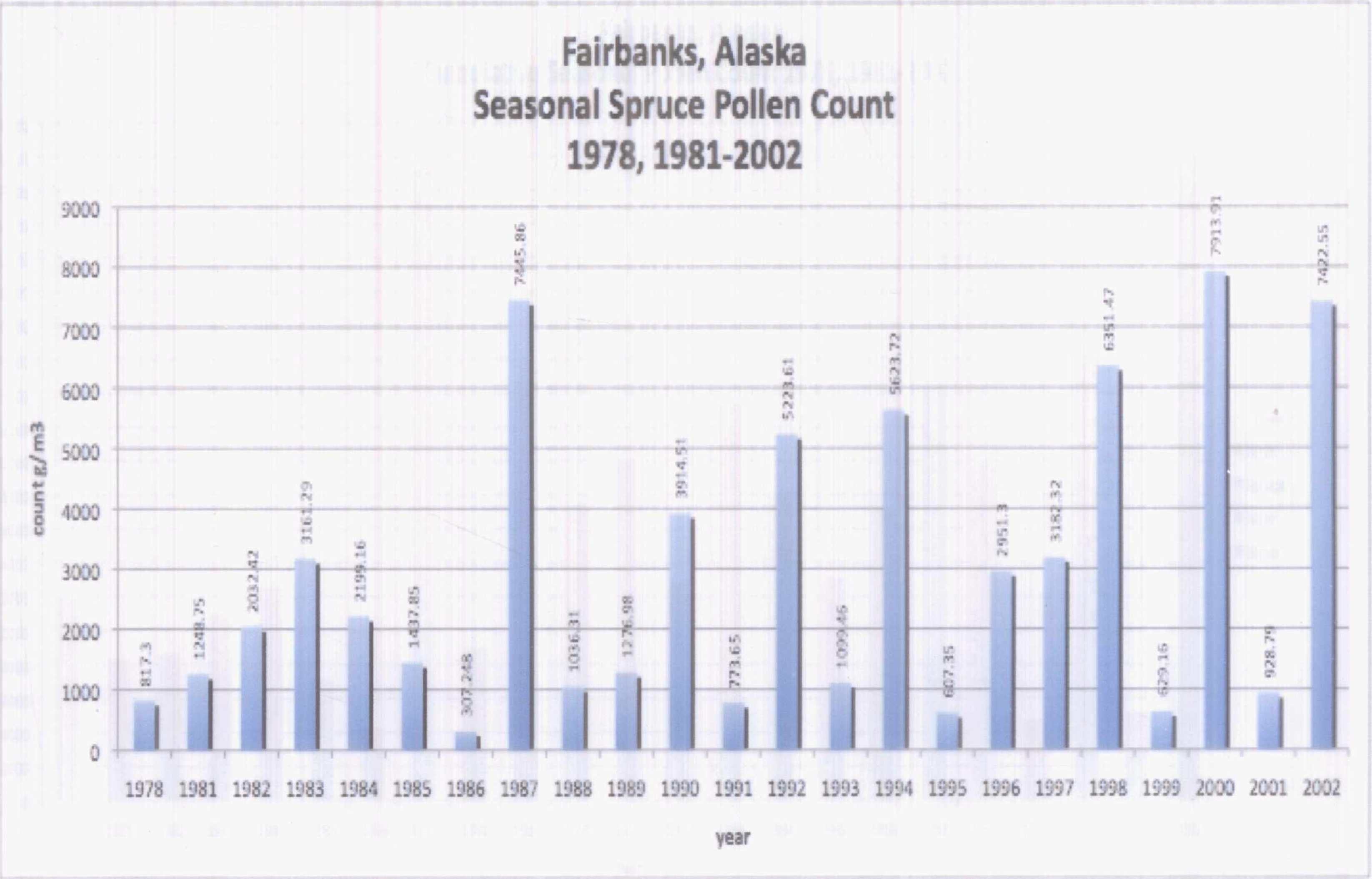


Figure 10. Cumulative seasonal spruce pollen concentration in 1978 and 1981–2002.

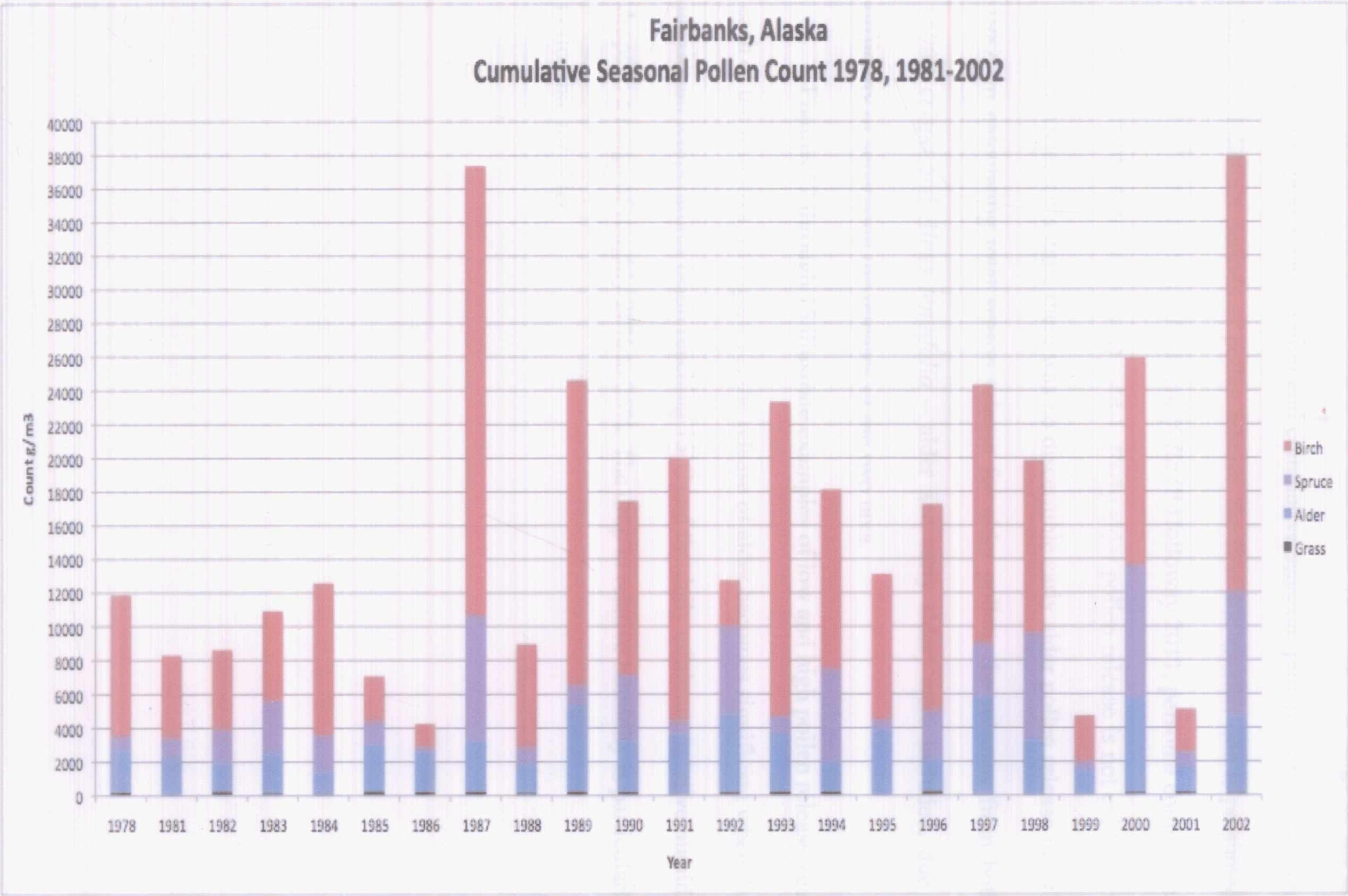
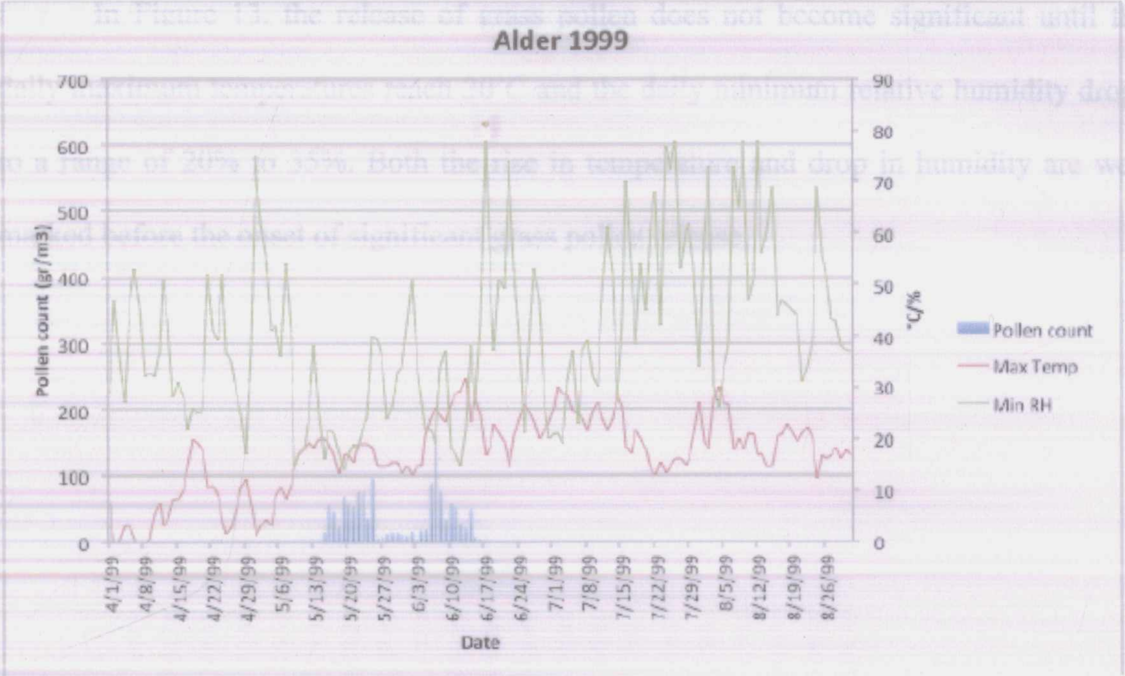


Figure 11. Cumulative seasonal pollen concentration in 1978 and 1981–2002.

The average timing of pollen seasons of the four taxa in this study is evident in Figure 6. Plots of daily pollen counts for individual years show a range of the onset of pollen release, peak concentration and cumulative seasonal pollen counts. The alder data shows two distinct periods of pollen release, the first and smaller one is presumed to be the release of a subspecies, *Alnus tenuifolia* (P Holloway 2011, personal communication). Anderson dubbed this taxon early alder. Early alder pollen release is not evident in some years; in Anderson's data, there was no discernible early alder pollen release in 1978 and 1982. In calculating total season release for alder pollen, the releases from both taxa (*Alnus crispa* and *Alnus tenuifolia* – alder and early alder) were included, due to the difficulty of separating the releases of the two taxa.

Figures 12 through 15 illustrate examples of low and high pollen release years for each of the four taxa. In Figure 12, the release of alder becomes significant when daily maximum temperatures begin reaching 15˚C and the daily minimum relative humidity drops to a range of roughly 20% to 25%. The drop in relative humidity is particularly noticeable for alder.



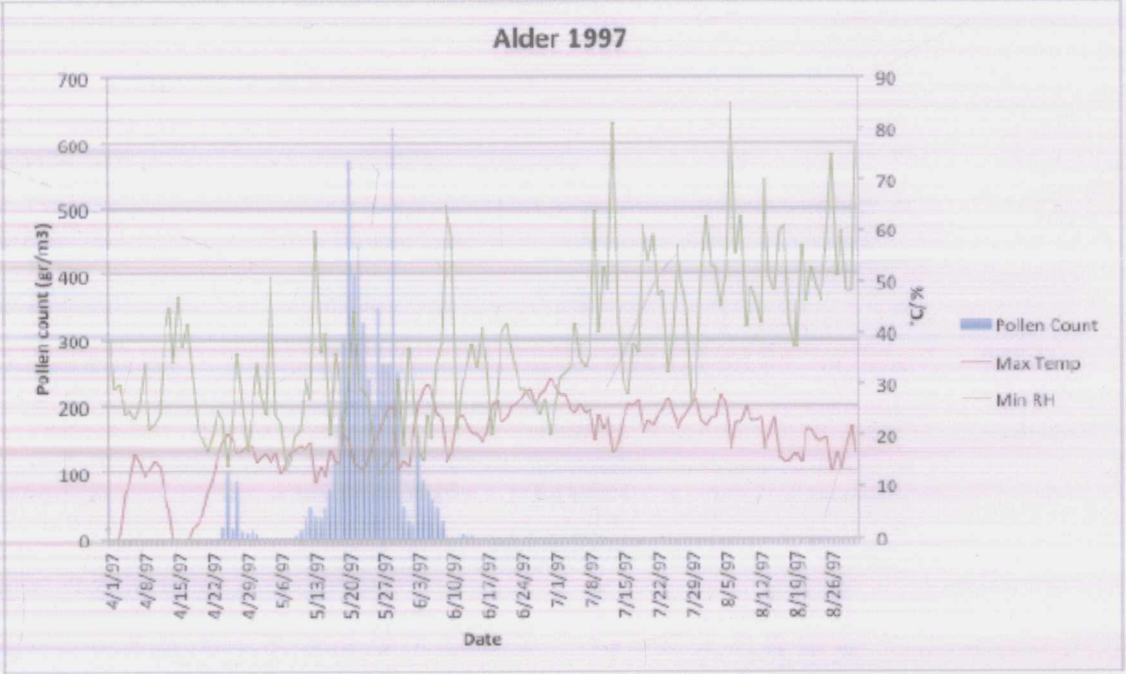


Figure 12. Alder pollen, temperatures and relative humidity in 1999 and 1997. 1999 was a low pollen release year. 1997 was a high pollen release year.

In Figure 13, the release of grass pollen does not become significant until the daily maximum temperatures reach 20°C and the daily minimum relative humidity drops to a range of 20% to 35%. Both the rise in temperature and drop in humidity are well marked before the onset of significant grass pollen release.

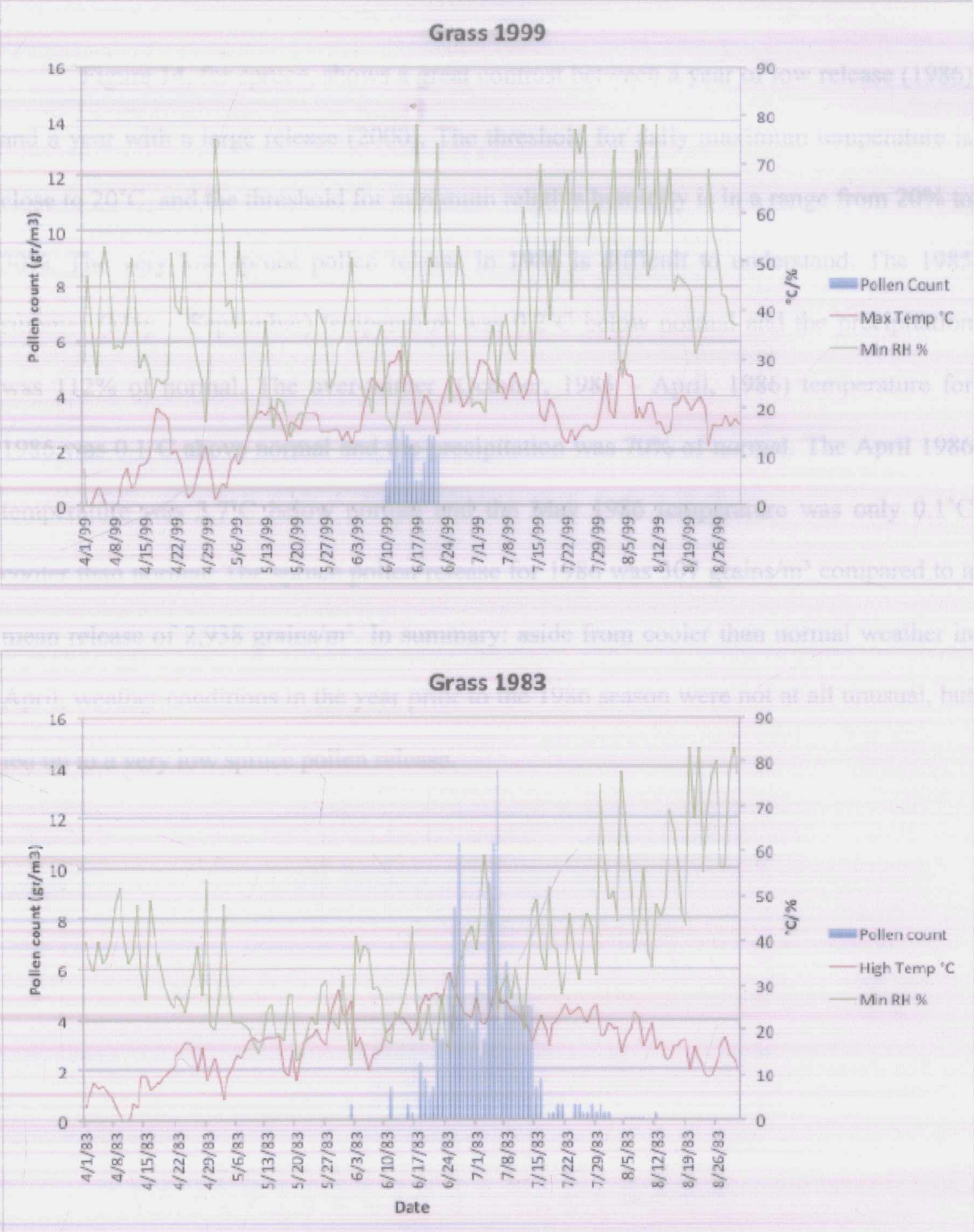


Figure 13. Grass pollen, temperatures and relative humidity in 1999 and 1983. 1999 was a low pollen release year. 1983 was a high pollen release year.

Figure 14, for spruce, shows a great contrast between a year of low release (1986) and a year with a large release (2000). The threshold for daily maximum temperature is close to 20˚C, and the threshold for minimum relative humidity is in a range from 20% to 30%. The very low spruce pollen release in 1986 is difficult to understand. The 1985 summer (May – September) temperature was 0.2˚C below normal and the precipitation was 112% of normal. The over-winter (October, 1985 – April, 1986) temperature for 1986 was 0.1˚C above normal and the precipitation was 70% of normal. The April 1986 temperature was 3.7˚C below normal and the May 1986 temperature was only 0.1˚C cooler than normal. The spruce pollen release for 1986 was 307 grains/m³ compared to a mean release of 2,938 grains/m³. In summary: aside from cooler than normal weather in April, weather conditions in the year prior to the 1986 season were not at all unusual, but led up to a very low spruce pollen release.

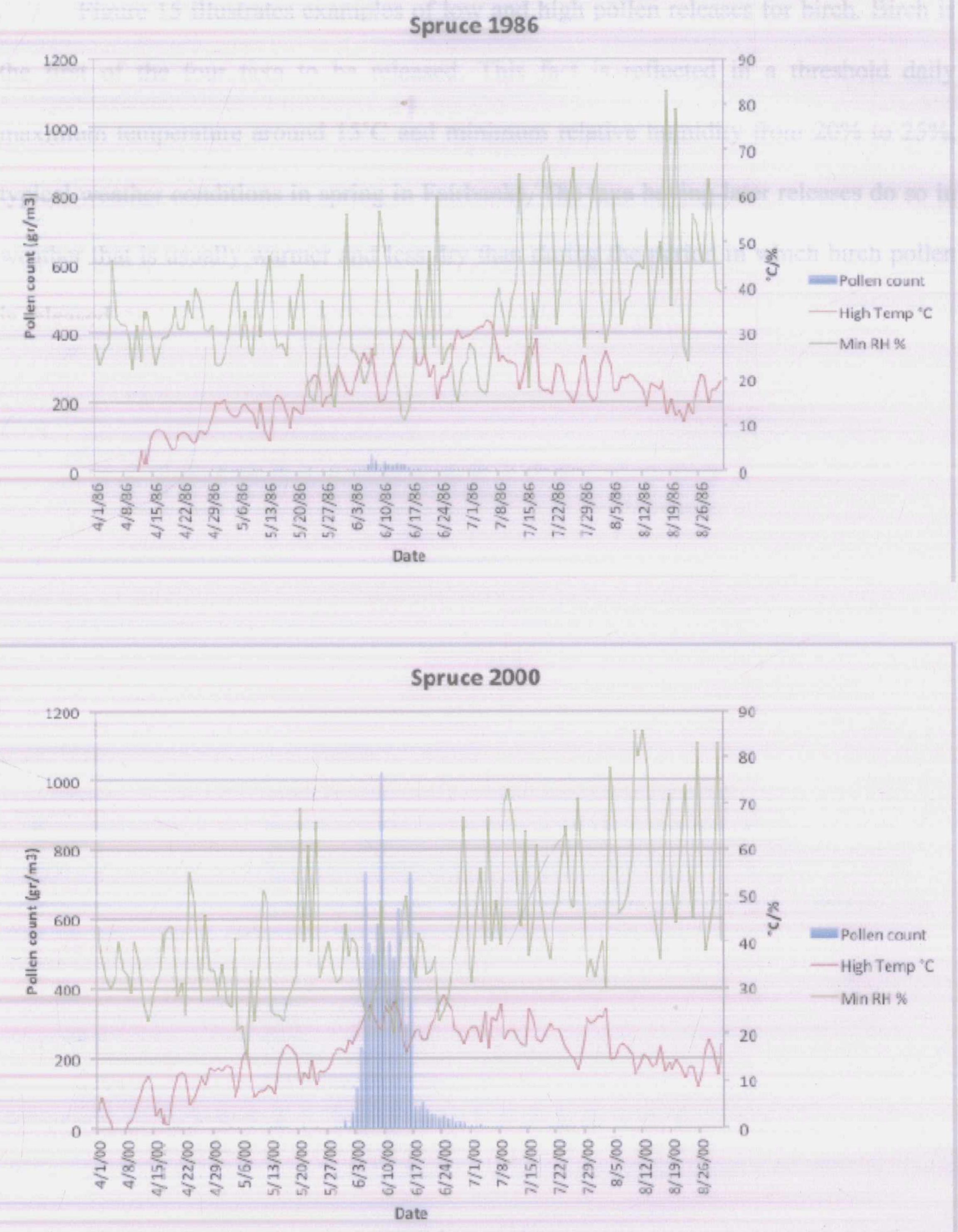


Figure 14. Spruce pollen, temperatures and relative humidity in 1986 and 2000. 1986 was a low pollen release year. 2000 was a high pollen release year.

Figure 15 illustrates examples of low and high pollen releases for birch. Birch is the first of the four taxa to be released. This fact is reflected in a threshold daily maximum temperature around 15˚C and minimum relative humidity from 20% to 25%, typical weather conditions in spring in Fairbanks. The taxa having later releases do so in weather that is usually warmer and less dry than during the period in which birch pollen is released.

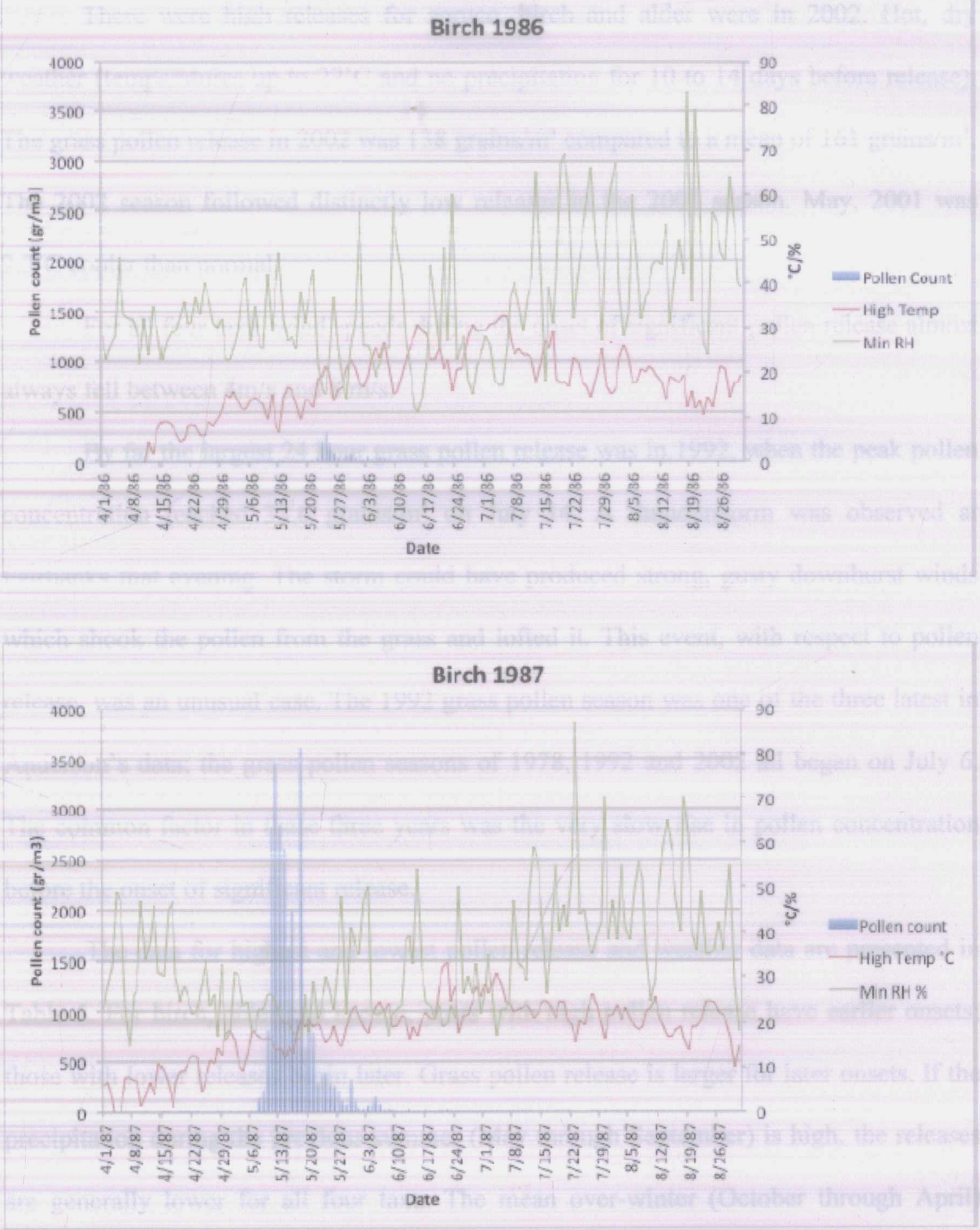


Figure 15. Birch pollen, temperatures and relative humidity in 1986 and 1987. 1986 was a low pollen release year. 1987 was a high pollen release year.

There were high releases for spruce, birch and alder were in 2002. Hot, dry weather (temperatures up to 27°C and no precipitation for 10 to 14 days before release). The grass pollen release in 2002 was 138 grains/m^3 compared to a mean of 161 grains/m^3. The 2002 season followed distinctly low releases in the 2001 season. May, 2001 was 2.3°C cooler than normal.

For all four taxa, wind speeds during the onset of significant pollen release almost always fell between 4m/s and 8 m/s.

By far the largest 24 hour grass pollen release was in 1992, when the peak pollen concentration reached 33.6 grains/m^3 on July 14. A thunderstorm was observed at Fairbanks that evening. The storm could have produced strong, gusty downburst winds which shook the pollen from the grass and lofted it. This event, with respect to pollen release, was an unusual case. The 1992 grass pollen season was one of the three latest in Anderson's data; the grass pollen seasons of 1978, 1992 and 2002 all began on July 6. The common factor in these three years was the very slow rise in pollen concentration before the onset of significant release.

The data for highest and lowest pollen release and weather data are presented in Table 5. For birch, alder and spruce, years with high pollen release have earlier onsets; those with lower releases begin later. Grass pollen release is larger for later onsets. If the precipitation during the previous summer (May through September) is high, the releases are generally lower for all four taxa. The mean over-winter (October through April) temperature seems to have no discernible effect on pollen release in the spring. If the over-winter precipitation is high, the pollen release in the spring tends to be high. Warm

Aprils (mean temperature >3°C above normal) lead to higher pollen release for the season, except for grasses. Warm Mays (mean temperatures >2°C above normal) tend to lead to larger pollen releases for birch and alder.

Table 5. Highest and lowest season releases and corresponding weather data. Temperatures are mean temperatures.

	Birch Max	Birch Min	Alder max	Alder min	Spruce Max	Spruce Min	Grass Max	Grass Min
Year	1987	1986	1997	1984	2000	1986	1985	1999
Concentration grains/m^3	26,717	1,367	5,719	1,139	7,914	307	260	25
Onset day	5/8	5/23	5/11	5/19	5/30	6/6	6/5	5/11
Temp. prev. summer (˚C)	12.7	11.8	11.9	12.4	12.6	11.8	12.3	12.3
Precip. prev. summer (mm)	166	198	169	169	188	198	152	240
Over-winter temp. (˚C)	-11.0	-13.9	-15.0	-12.9	-13.9	-13.9	-13.0	-13.9
Over-winter precip. (mm)	87	68	78	126	109	68	136	43
April temp. (˚C)	1.7	-4.4	1.9	-0.9	-0.1	-4.4	-6.2	0.4
May temp. (˚C)	10.5	8.8	9.4	8.4	6.9	8.8	8.2	8.3
June temp. (˚C)	16.6	17.0	17.3	16.4	16.4	17.0	14.3	16.3

Based upon what parameters seemed most promising, scatter plots and best fit lines were prepared for the total season release of all four taxa vs. the average temperature of the summer (May through September) of the previous year and the over-winter (October through April) precipitation. These best fits are presented in Figures 16 through 19. Figures 20 through 23 show scatter plots of spring weather to the total season pollen release.

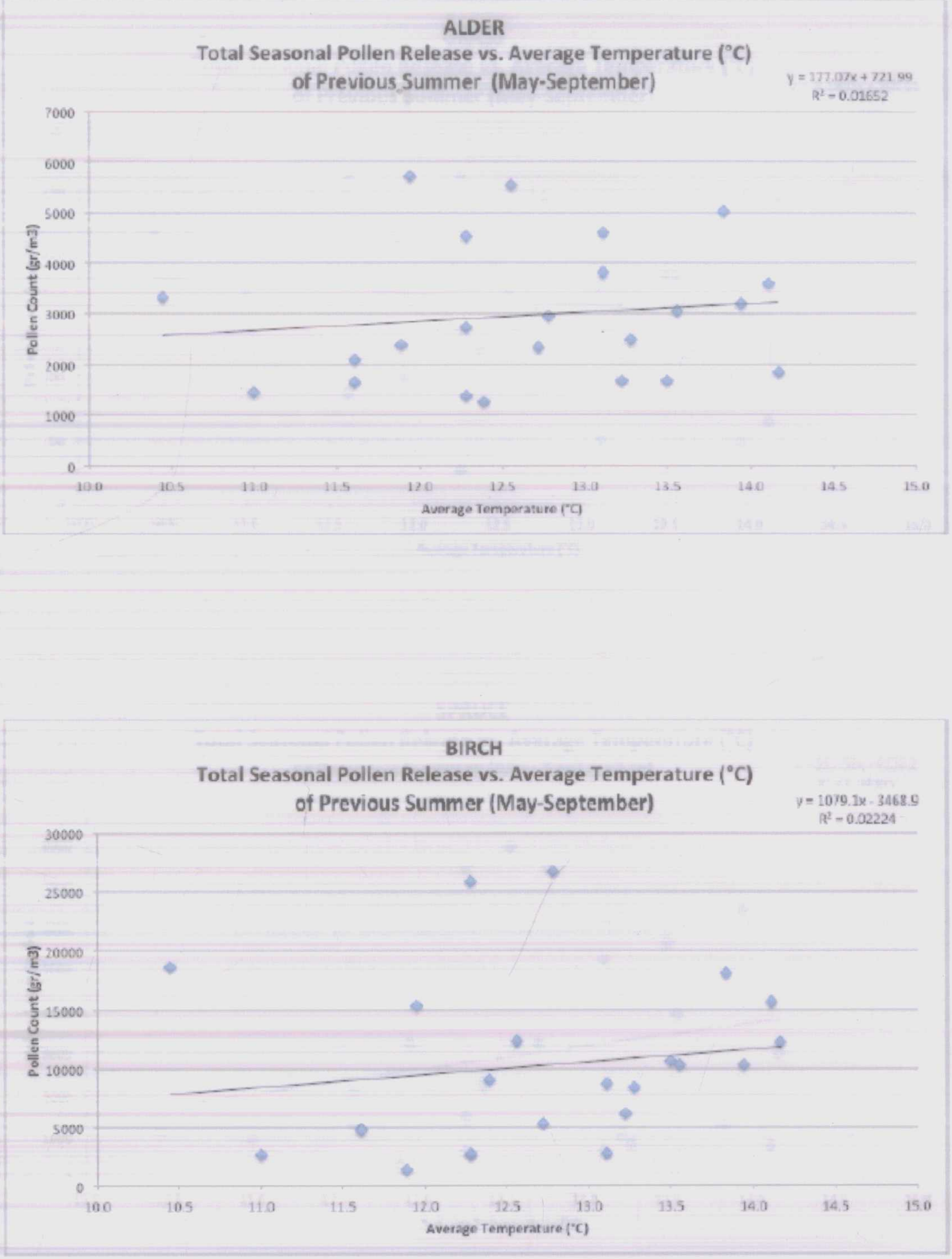
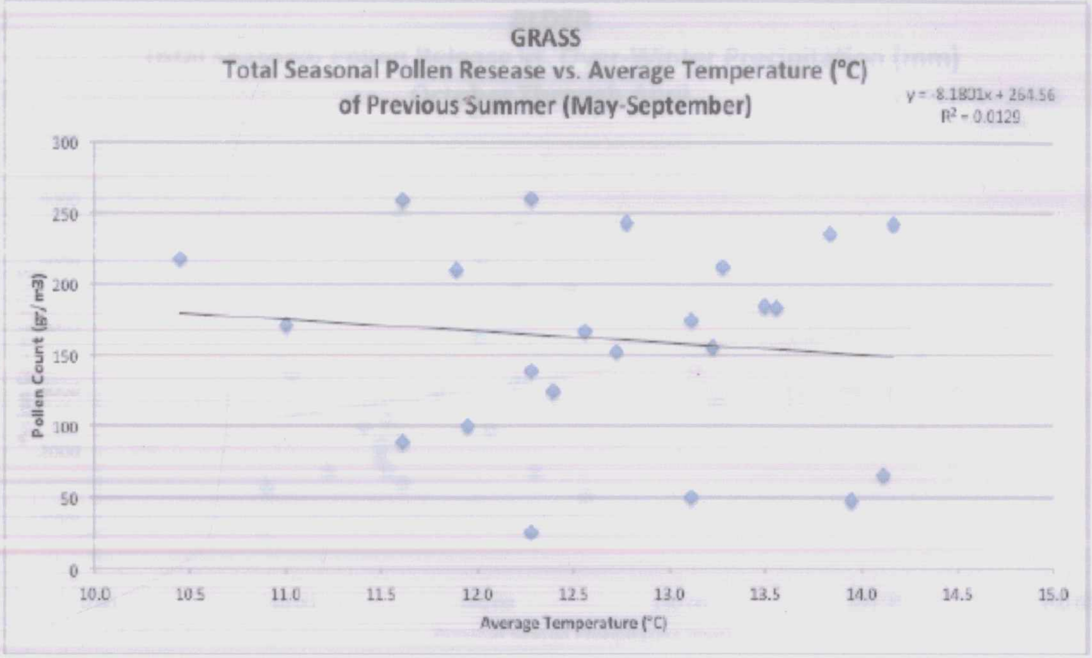


Figure 16. Alder and birch pollen vs. mean temperature of the previous summer.



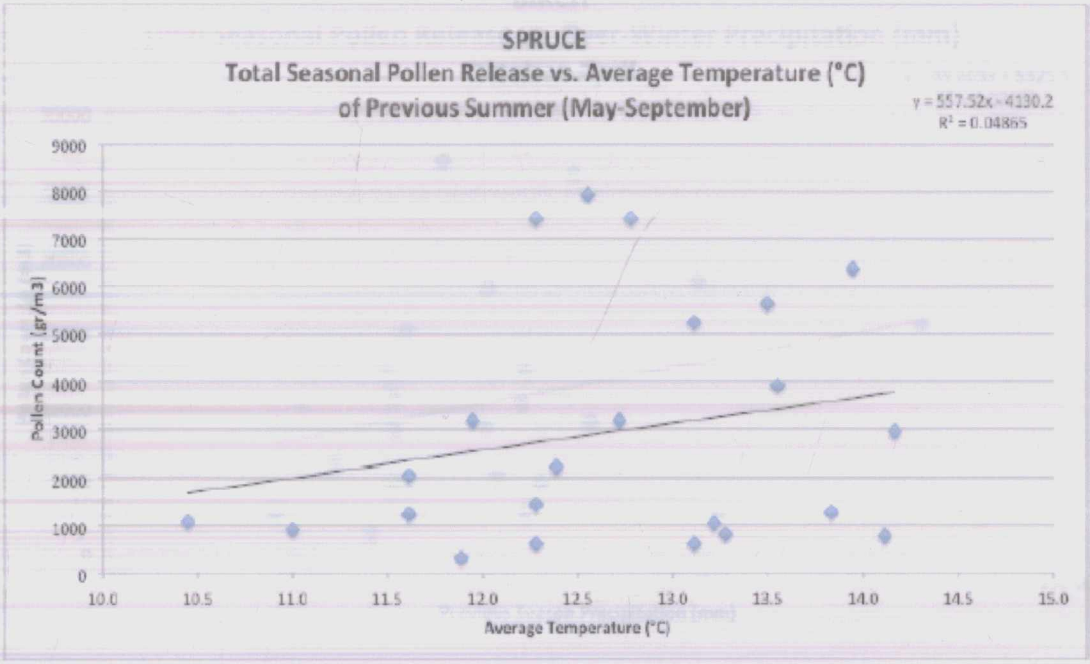
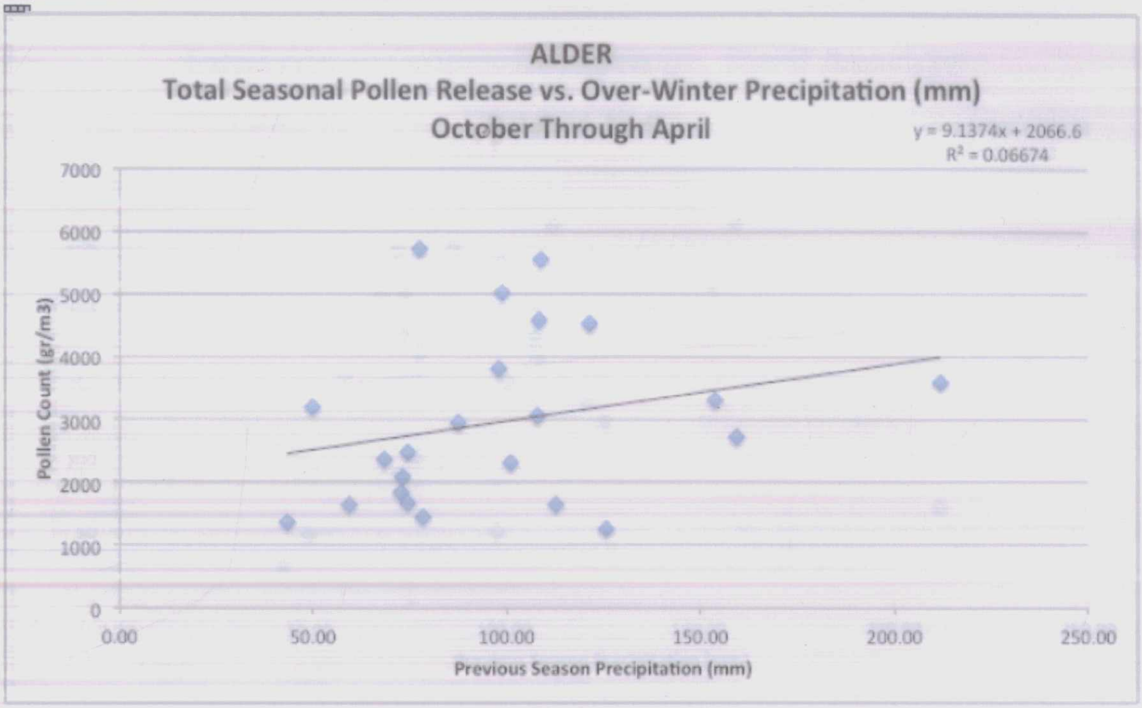


Figure 17. Grass and spruce pollen vs. mean temperature of the previous summer.



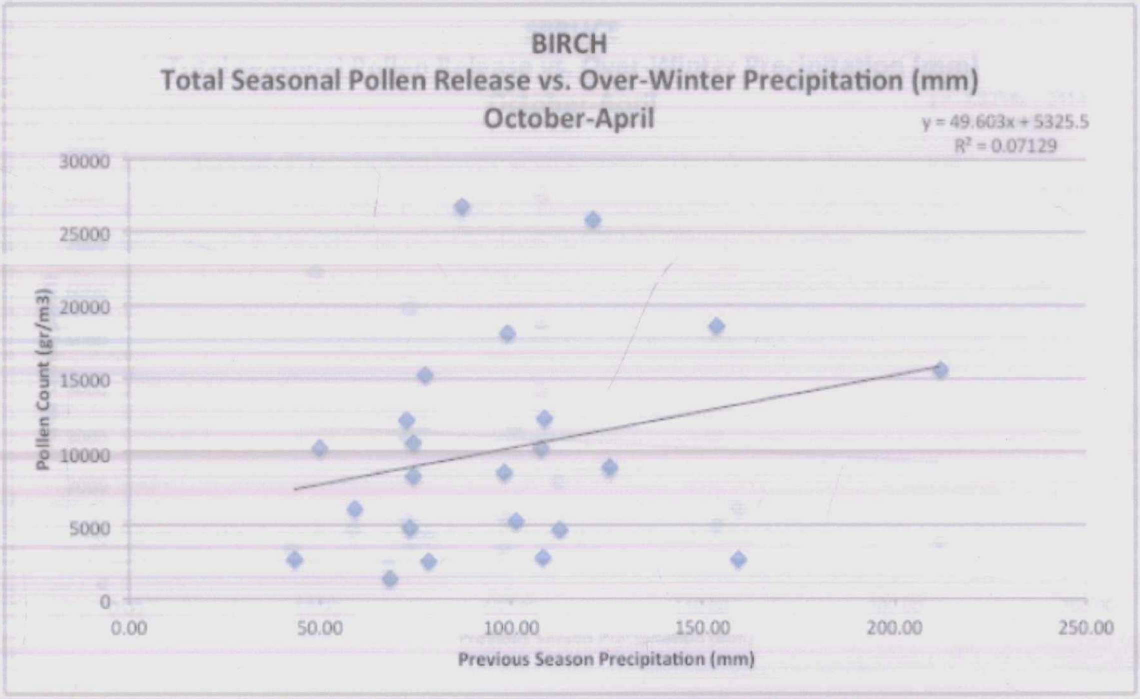


Figure 18. Alder and birch pollen vs. over-winter precipitation.

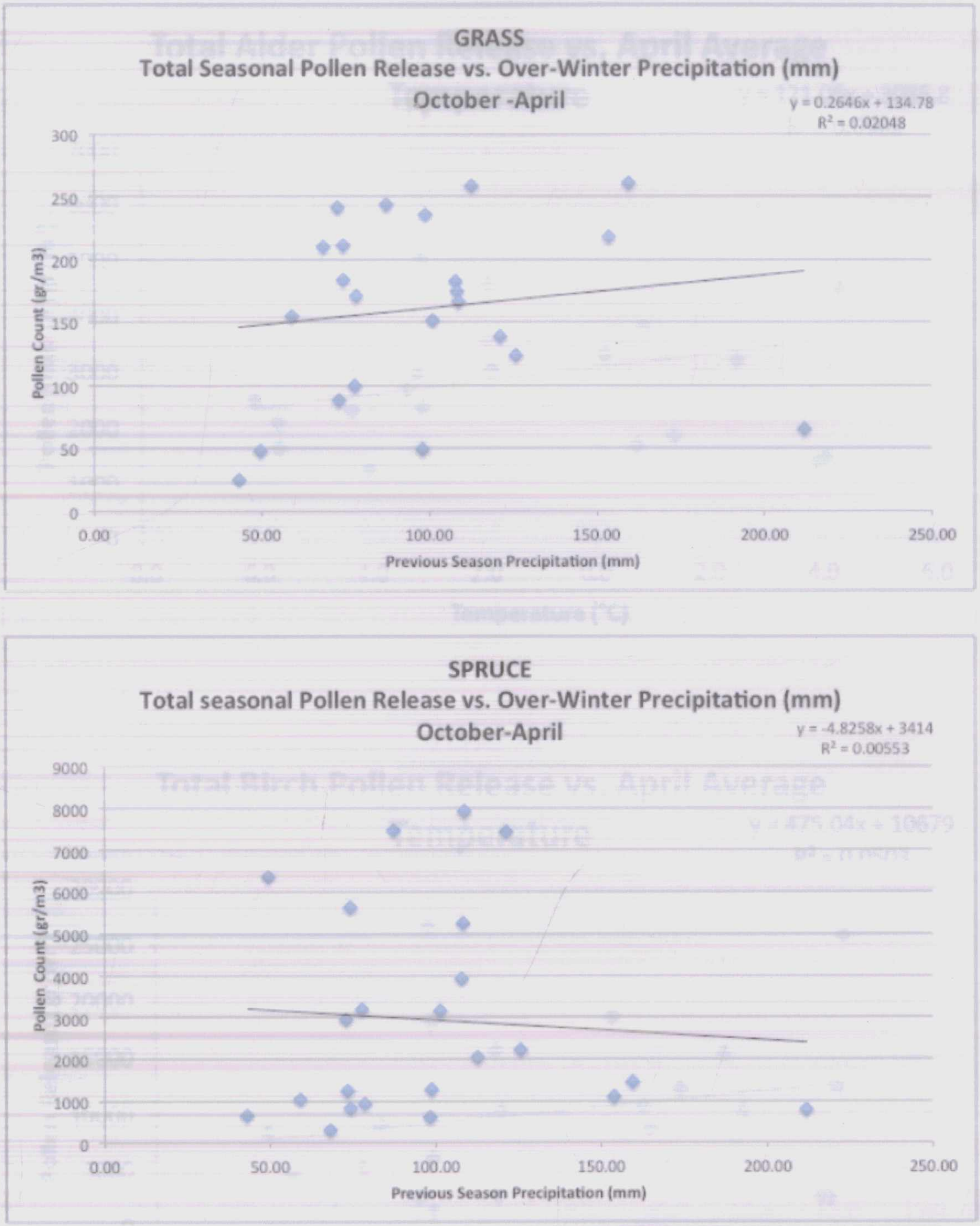
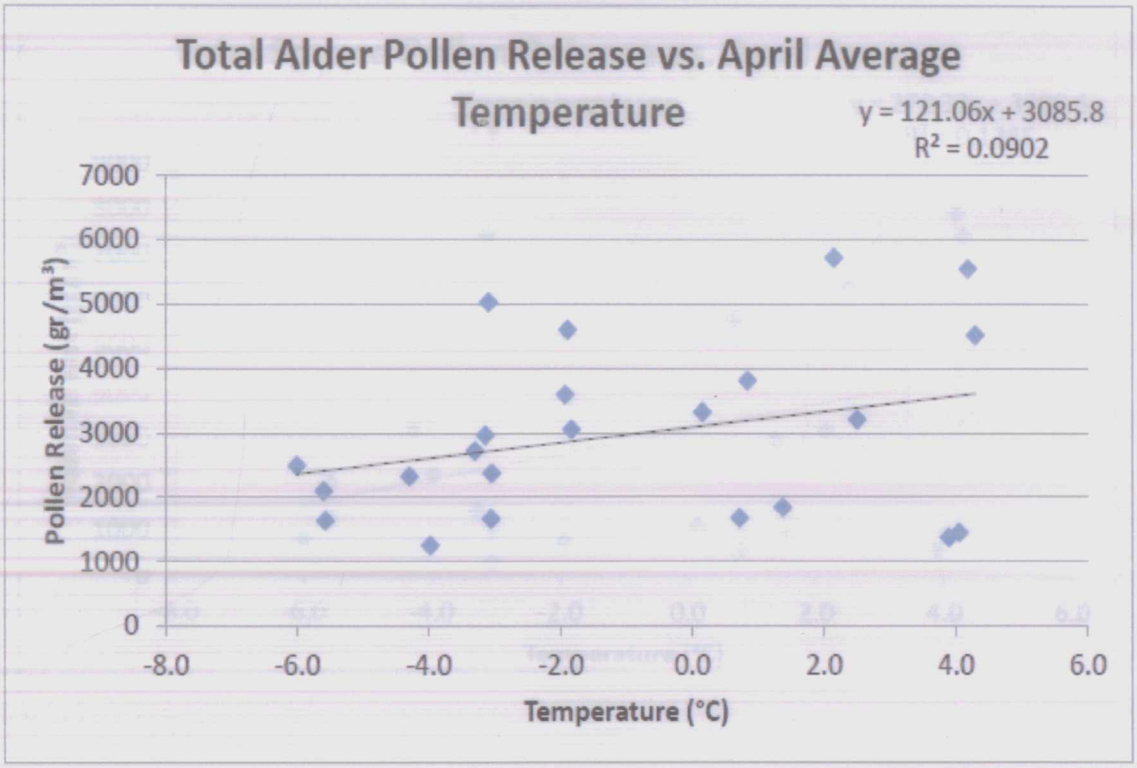


Figure 19. Grass and spruce pollen vs. over-winter precipitation.



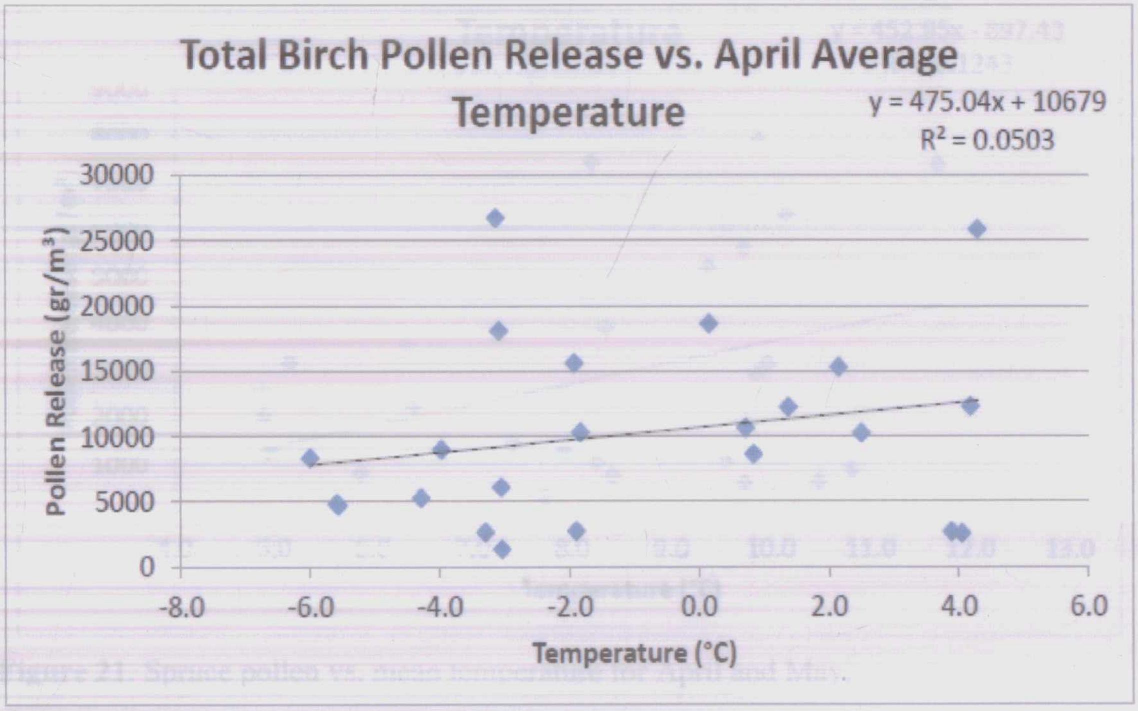
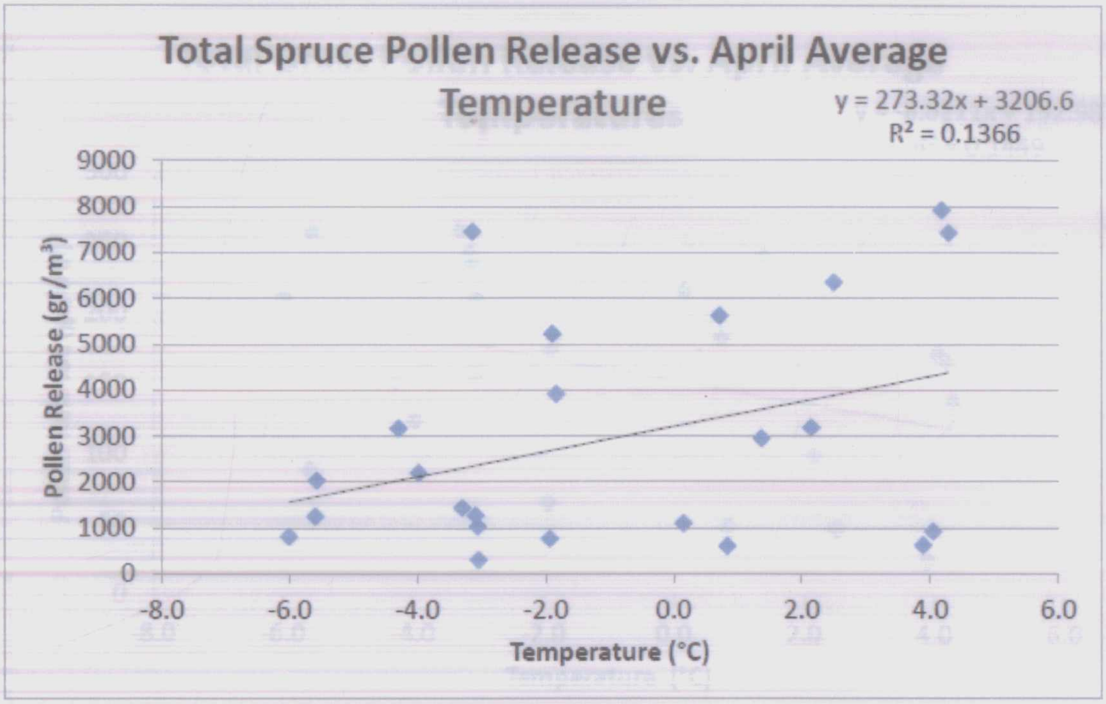


Figure 20. Alder and birch pollen vs. mean April temperature.



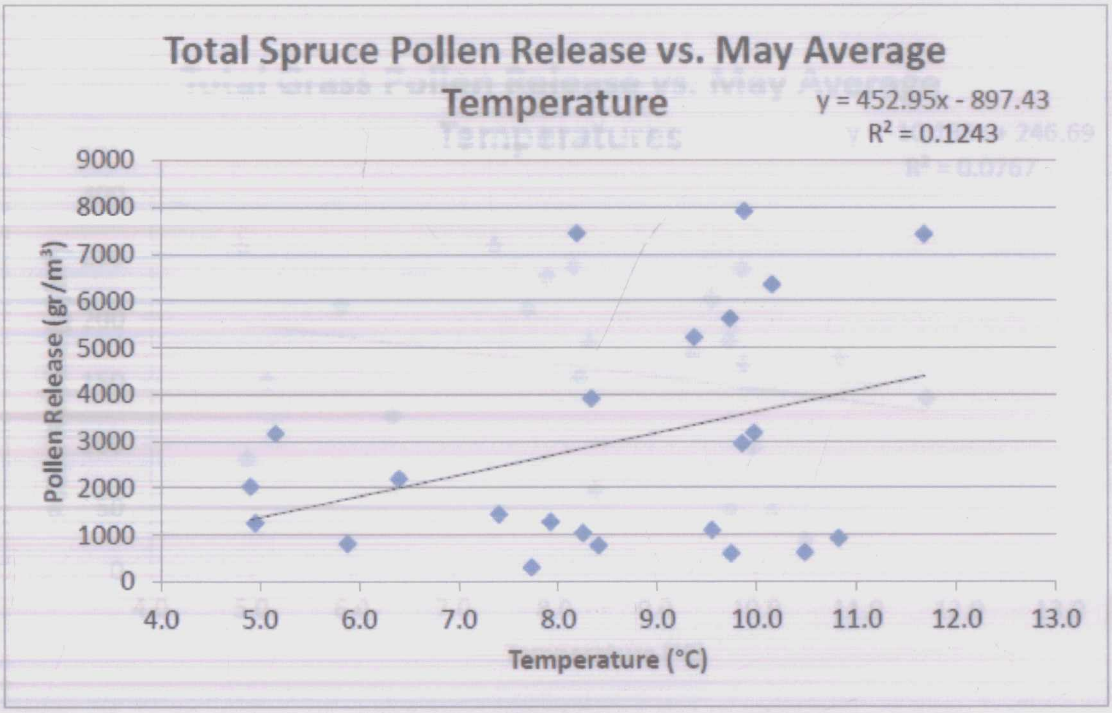
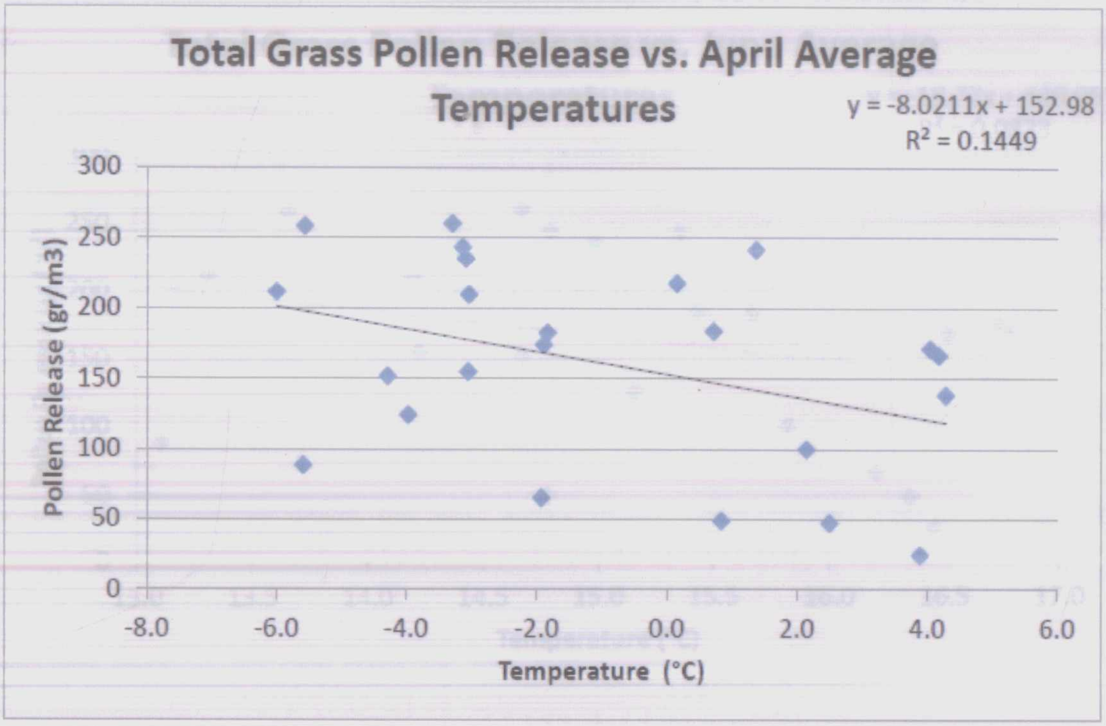


Figure 21. Spruce pollen vs. mean temperature for April and May.



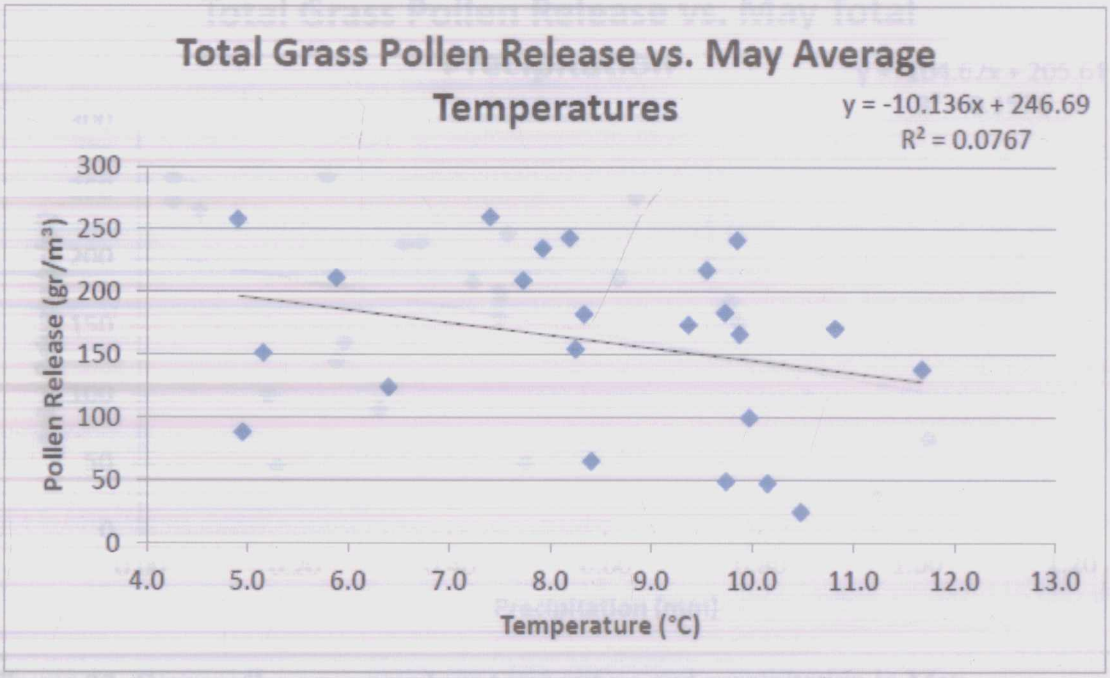


Figure 22. Grass pollen vs. mean temperature for April and May.

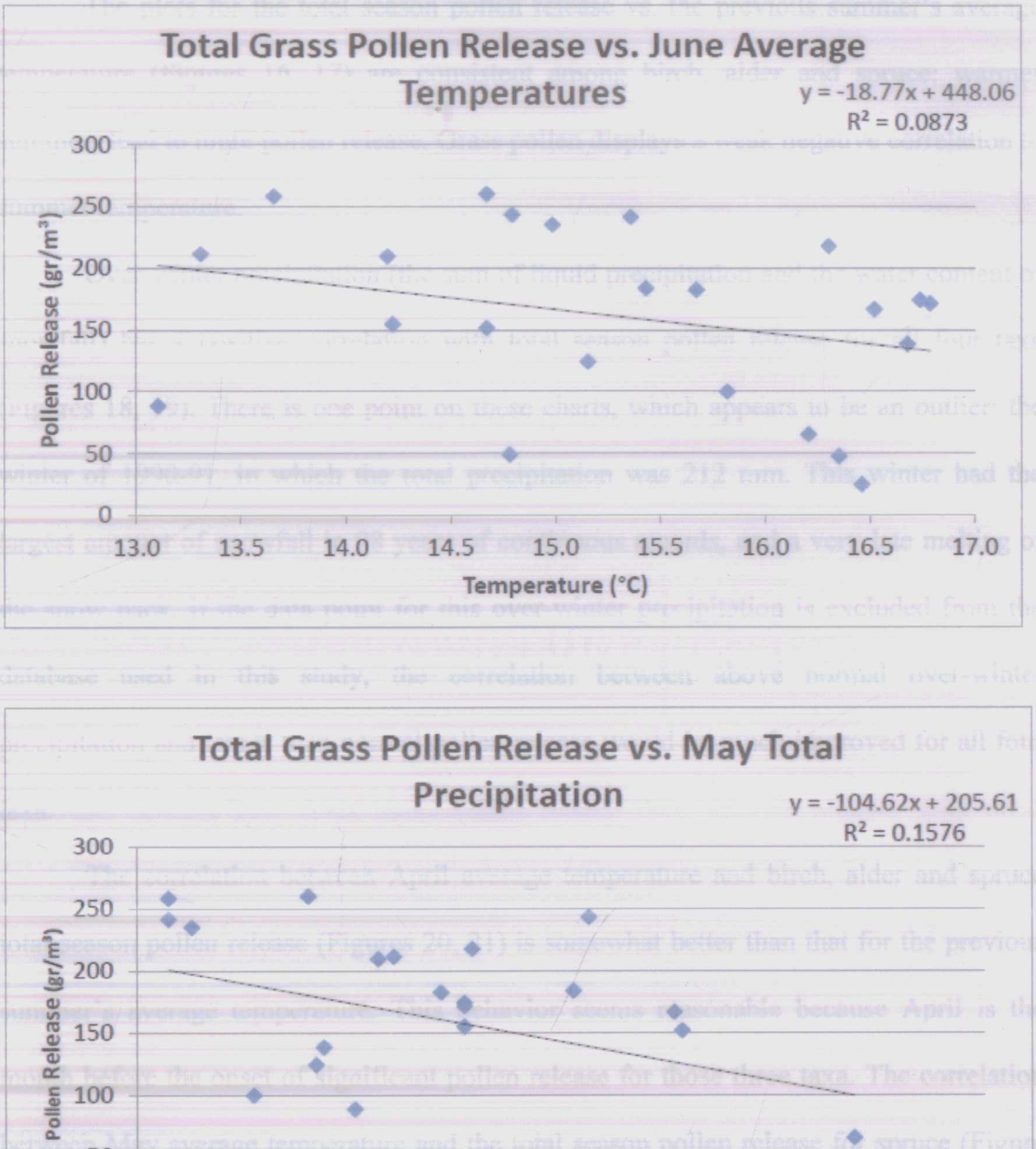


Figure 23. Grass pollen vs. mean June temperature and precipitation in May.

The plots for the total season pollen release vs. the previous summer's average temperature (Figures 16, 17) are consistent among birch, alder and spruce: warmer summers lead to more pollen release. Grass pollen displays a weak negative correlation to summer temperature.

Over-winter precipitation (the sum of liquid precipitation and the water content of snowfall) has a positive correlation with total season pollen release for all four taxa (Figures 18, 19). There is one point on these charts, which appears to be an outlier: the winter of 1990-91, in which the total precipitation was 212 mm. This winter had the largest amount of snowfall in 98 years of continuous records, and a very late melting of the snow pack. If the data point for this over-winter precipitation is excluded from the database used in this study, the correlation between above normal over-winter precipitation and larger than normal pollen release would be much improved for all four taxa.

The correlation between April average temperature and birch, alder and spruce total season pollen release (Figures 20, 21) is somewhat better than that for the previous summer's average temperature. This behavior seems reasonable because April is the month before the onset of significant pollen release for those three taxa. The correlation between May average temperature and the total season pollen release for spruce (Figure 21) is similar to April's correlation for this taxon.

This result is consistent with the findings of Fehér and Járai-Komlódi (1998), that the daily temperature range gives the best correlation between temperature and pollen release. Spring and summer days in Fairbanks with higher than normal maximum temperatures can be expected to have more of a range between daily high and low temperatures than cool days which are prone to have less of a range.

The charts of the total season release of grass pollen (Figures 22, 23) go in the opposite direction: the correlations with April, May and June average temperatures and for May precipitation are all negative. The only parameter with which grass has a correlation similar to those for the other taxa is over-winter precipitation. Clearly, grass pollen release responds to weather in a manner considerably different from the way in which birch, alder and spruce respond. This behavior could be expected. Both the pollen generation season and the growing environment of grass are quite different from those of the other three taxa.

The response of the grass pollen release to weather seems counter intuitive. The plots indicate that cool, dry weather in the two months leading into the release season of late June through July favor more pollen release than warmer weather with more precipitation. Indeed, dry summer weather in Fairbanks tends to be warm, while rainy summer weather tends to be cool.

Pollen release can be viewed on several time scales. The first part of this study has emphasized the seasonal scale (roughly one year in advance of pollen release). This scale emphasizes the magnitude of the seasonal pollen release. The monthly or weekly time scale emphasizes the timing of the onset of significant pollen release (Kasprzyk 2008, 2009). In this study, the approach of Thoman and Fathauer (1998) was used to develop GDD, base 0°C, for the onset dates of significant pollen release for the four taxa in this investigation. In addition, the values of GDD for green-up date in Fairbanks were calculated for the same 23 years as those for which pollen data was available. The values obtained are in Table 6. Note how close the green-up data obtained in this study are to the values obtained by Thoman and Fathauer (1998). The years in the respective studies overlap. In this study, the years 1978 and 1981-2002 (23 years) were used. In Thoman and Fathauer (1998), the years 1974 and 1976-1998 were used (24 years, 19 in common with this study). Both studies used the same approach employing the GDD (growing degree day, base 0°C).

Table 6. Growing degree days vs. pollen onset dates and green-up dates, based on pollen data from 1978 and 1981-2002 and on green-up data from 1974 and 1976-1998.

Taxon	Mean GDD total GDD (°C)	Standard deviation σ (°C)	Coefficient of Variance (GDD/σ)
Alder	471	72	0.15
Birch	403	47	0.12
Grass	1,319	251	0.19
Spruce	643	60	0.09
Green-up	401	42	0.10
Green-up – Thoman and Fathauer (1998)	401	44	0.11

Following this, the mean Julian (JD_{mean}) dates for: (1) the onset of significant pollen release for each of the four taxa and for (2) green-up were calculated. The mean maximum daily temperatures matching each of these Julian dates (T_{maxjd}) were tabulated.

The number of growing degree days (GDD_{tmaxjd}) corresponding to each T_{maxjd} were calculated. Since the base of each GDD_{tmaxjd} is 0°C. $GDD_{tmaxjd} = T_{maxjd}$. Each standard deviation was divided by its corresponding GDD_{tmaxjd} to yield the number of days ($D_{1\sigma}$) within a range of one standard deviation of each Julian date. This calculation is intended to provide a measure of predictability of the dates of the onset of significant pollen release of each of the four taxa and of green-up. These statistics are tabulated in Table 7.

Table 7. Predictability of pollen onset dates and green-up dates.

Taxon	Mean day of event (JD_{mean})	Corresponding growing degree days (GDD_{tmaxjd}) (°C)	Days within one standard deviation ($D_{1\sigma}$)
Alder	May 15	16.1	4
Birch	May 11	15.0	3
Grass	June 26	23.3	11
Spruce	May 25	18.3	3
Green-up	May 11	15.0	3

Examination of pollen and weather data for each taxon and each season revealed that the threshold daily maximum temperature values for the onset of significant pollen release are lower for the earlier releasing taxa, (birch and alder), near 15°C, and close to 20°C for the later releasing taxa (spruce and grass). The threshold values of daily minimum relative humidity are quite low for birch and alder (typically 20% to 25%), typically from 20% to 30% for spruce and 20% to 35% grass. The average minimum relative humidity on the day of the onset of significant pollen release is 25% for birch, alder and spruce and 33% for grass. Since grass pollen must begin generation in the same year as it is released, it requires more time before significant grass pollen to begin. July weather in Fairbanks has the highest monthly normal temperature of the year and has more precipitation (55 mm) and thus a larger mean humidity (71%), than May (54%) and June (56%). The normal monthly temperature and precipitation data for Fairbanks are shown in Table 8. Strong winds (>10 m/s) are not required for significant pollen release.

Table 8. Average monthly temperature and precipitation in Fairbanks May - July.

Month	Average monthly temperature (°C)	Average monthly precipitation (mm)
May	8.9	17
June	15.2	35
July	16.3	48

Proceeding from the effect of weather on pollen release on seasonal and monthly time scales, the weather during days with very high pollen releases was considered. Individual days of very high releases were selected, and the afternoon Fairbanks soundings for those days were examined. These soundings are shown in Figures 24 through 27.

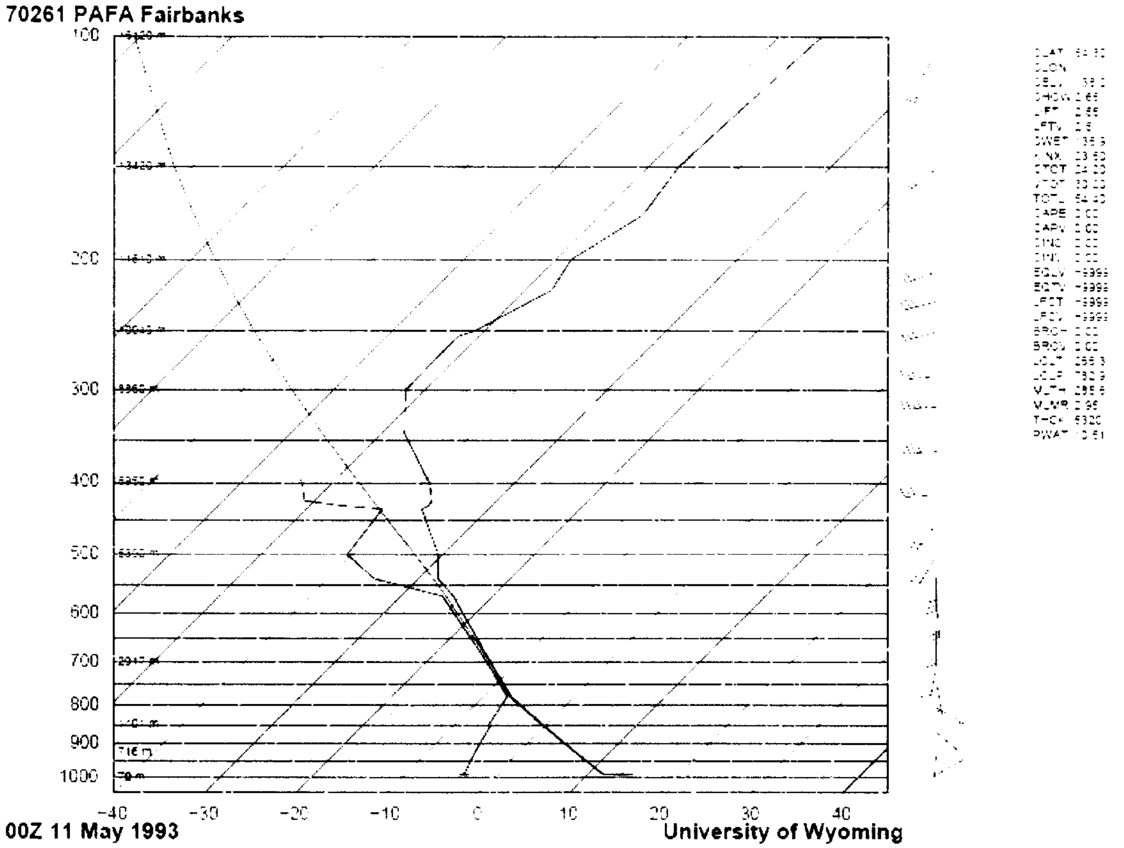


Figure 24. Skew-T chart for Fairbanks at 00 UTC 11 May 1993. There is a mixed layer approximately 2,000 m deep. The high temperature that day was 16°C. The minimum relative humidity for the day was 27%. The average birch pollen concentration on that day was 969 grains/m^3. There was no alder, spruce or grass pollen present. The concentration of birch pollen on the evening of 10 May 1993 rose to a potentially lethal level (author's personal observation, 1993).

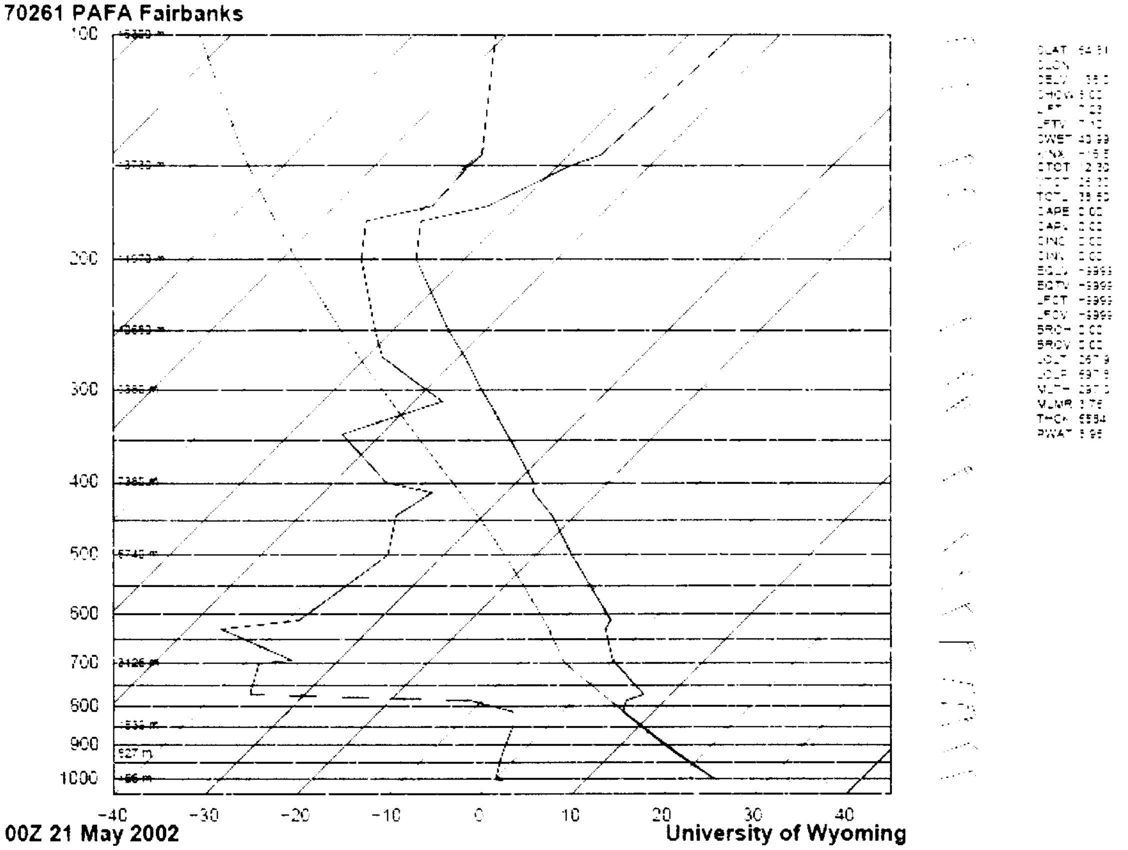


Figure 25. Skew-T chart for Fairbanks at 00 UTC 21 May 2002. There is a mixed layer approximately 2,000 m deep. The temperature inversion just above the mixed layer would limit further upward mixing. The air mass was very dry. The high temperature that day was 27°C. The minimum relative humidity for the day was 18%. The birch pollen count on that day was 9,299 grains/m³ the highest pollen count for any taxon in the 23 years of Anderson's data.

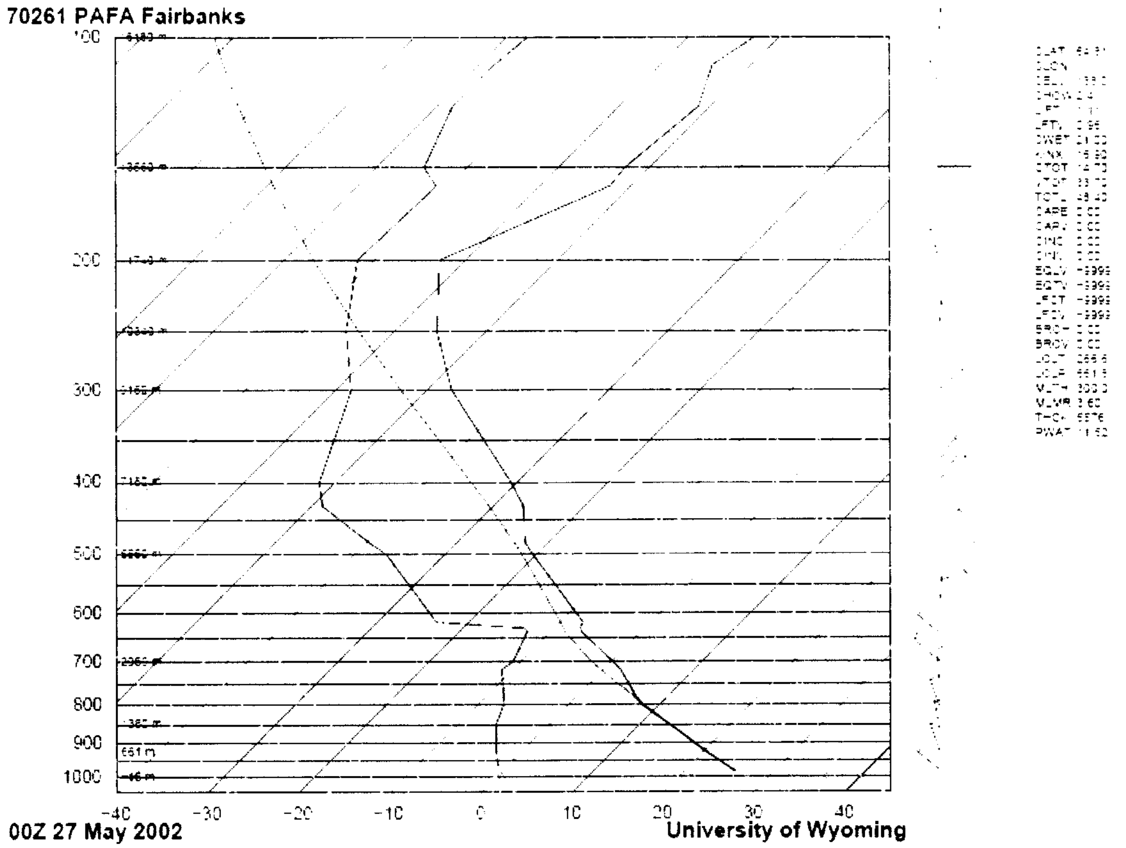


Figure 26. Skew-T chart for Fairbanks at 00 UTC 27 May 2002. There is a mixed layer approximately 4,000 m deep with a thin, more stable layer on top. The air mass was quite dry. The high temperature that day was 27°C. The minimum relative humidity for the day was 18%. The alder pollen count on that day was 623 grains/m³. The spruce pollen count on that day was 2,880 grains/m³, the highest count for spruce in Anderson's 23 years of data.

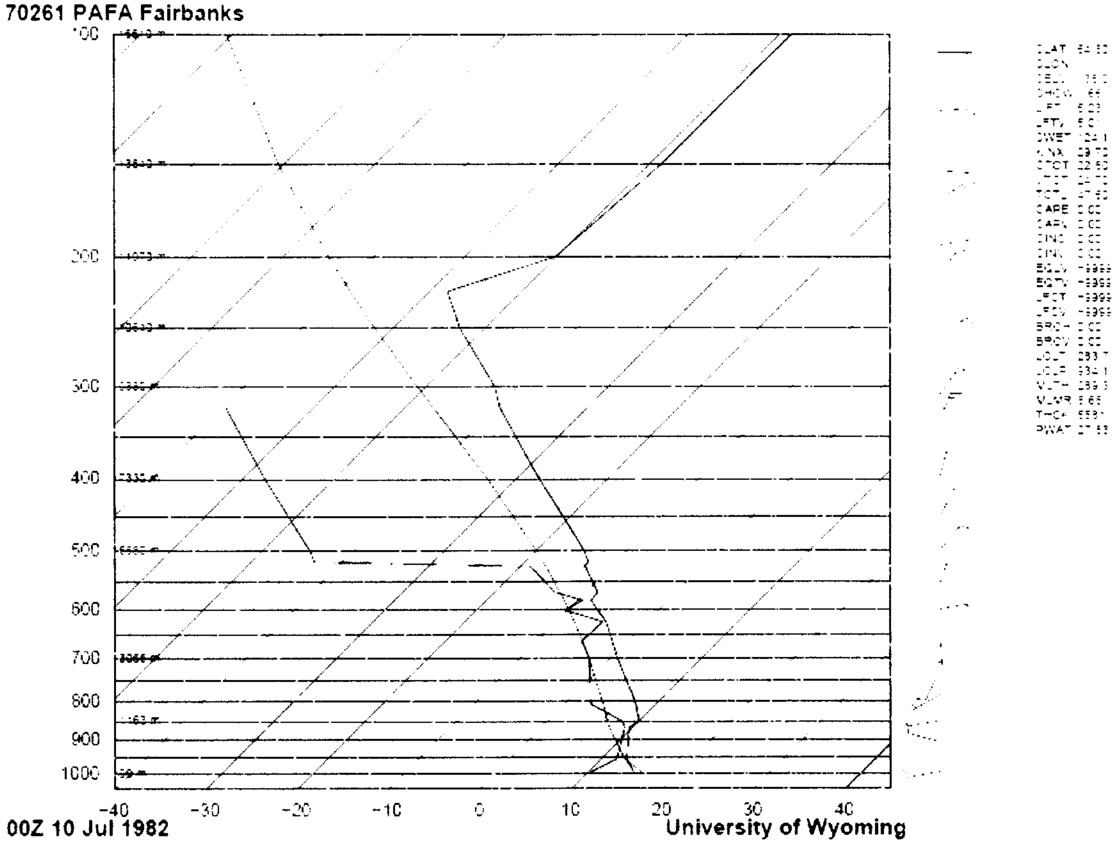


Figure 27. Skew-T chart for Fairbanks at 00 UTC 10 July 1982. There is a shallow mixed layer approximately 500 m deep. The air mass was moist. The high temperature that day was 21°C. The minimum relative humidity for the day was 57%. The high temperatures on the three preceding days were: 28°C, 31°C and 30°C. The grass pollen count on that day was 24.3 grains/m^3.

On the high release days, daily maximum temperatures above 25°C on those days, or on several days before, were common factors. So was relative humidity below 30%. The high release of birch pollen on 10 May 1993 came during a period of daily high temperatures of 12°C to 18°C. The total rainfall for 6-10 May was 9 mm. The deciding factor in that case appears to have been rapid drying and a deep unstable, surface based layer.

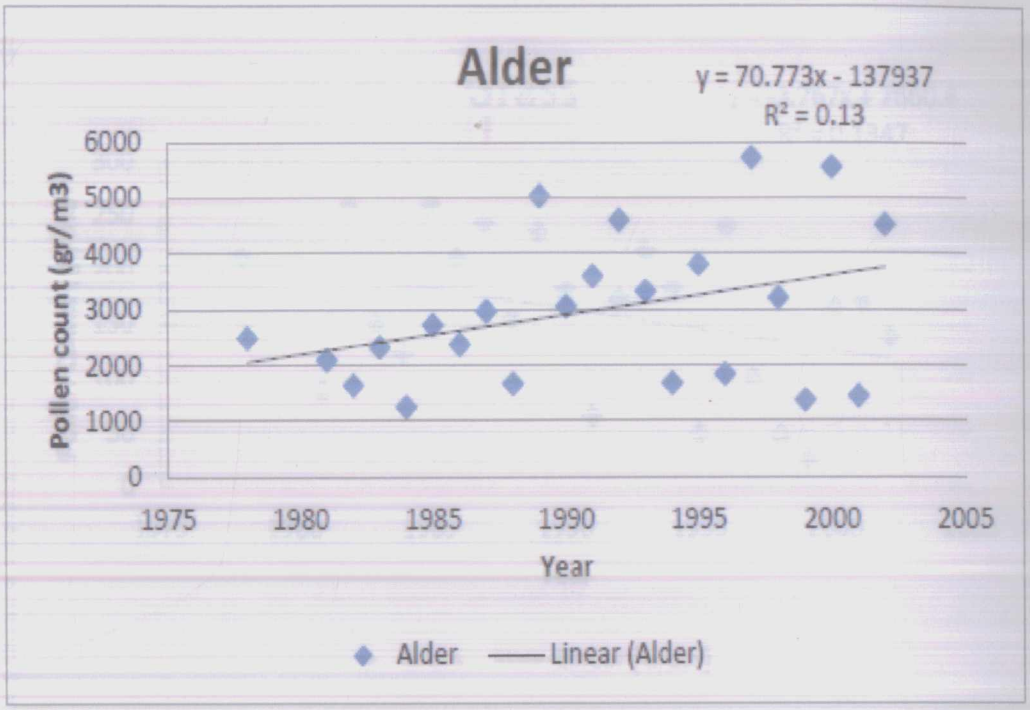
An important process, which can take place several times during the pollen seasons, is removal of pollen from the air by rainfall. The rainfall required to significantly reduce pollen concentrations is small – typically 1 mm to 5 mm for birch and alder, 3 mm to 6 mm for spruce, and 5 mm to 20 mm for grass. The higher rainfall rate required for spruce, compared to birch and alder is due to the larger size of the spruce pollen grains. Since grass releases its pollen at a time of year when precipitation is more than twice of what it is in May, its pollen must be able to release and to remain airborne during weather with higher humidity and rainfall than the weather in which birch, alder and spruce release and remain airborne. Recovery of pollen concentrations following removal by rain can be rapid – only a day or two free of rainfall are required for this recovery. However, rain free weather following a decrease in pollen concentration does not assure a significant recovery of the amount of pollen in the air. Removal of nearly all of the pollen in the air is not possible until the time that the end of the pollen season is near. In most seasons, a small amount of pollen lingers for days or for as long as two to three weeks after pollen concentration drops below levels of clinical concern.

There are changes in pollen concentration that occur in a time scale of hours (Barnes et al., 2001; Käpylä 1984; Ribeiro et al. 2008). The patterns of these changes vary from one taxon to another. Study of changes in an hourly time scale requires hourly pollen and weather data. Anderson (1986) gathered Fairbanks birch pollen concentration data for ten days in 1983 (May 12-17 and May 20, 25, 30 and-31) on a 2 hour interval.

There were very large circadian changes in birch pollen concentration, some as large as an order of magnitude within 24 hours. The maximum daily concentrations occurred mostly at mid-day or early evening, particularly for days with high maxima. Such large fluctuations in pollen concentration are clinically significant. Anderson's data showed that such large circadian fluctuations are more likely on hot and breezy days than on cool, calm days.

Sassen (2008) used a different technique to observe variations in pollen concentration. Polarization (0.694 μm) lidar observations indicated large variance of pollen concentrations over periods of minutes, particularly within a turbulent boundary layer. The magnitude of these variations was much greater than changes in pollen concentrations averaged over 24 hours. Thus, as in the case of the evening of 11 May 1993 (Figure 24), local pollen concentrations can be much larger than conventional time-averaged samples.

Beyond the hourly, daily, monthly or seasonal scales are longer term, decadal responses of pollen release to changes in weather (Anderson 1986; Emberlin et al. 1997, 2002). These responses are outside of the scope of this study and they are important to investigate for the purpose of foreseeing the impacts of a changing climate to the environment. Figures 28 and 29 display a trend toward greater pollen release in birch, alder and spruce that Anderson (1991) noted in the shift to more pollen production after 1986, as is also shown in Figure 11. A number of investigators (Emberlin et al. 1997; Emberlin et al. 2002; Frei and Gassner 2008; Hartman and Wendler 2005; Jäger et al. 1996; Jato et al. 2009; Ziska et al. 2009) have observed a trend toward higher temperatures leading to more pollen production. The trend in grass pollen release is toward less pollen release. As this study has repeatedly found, grass pollen release differs from that of the other taxa.



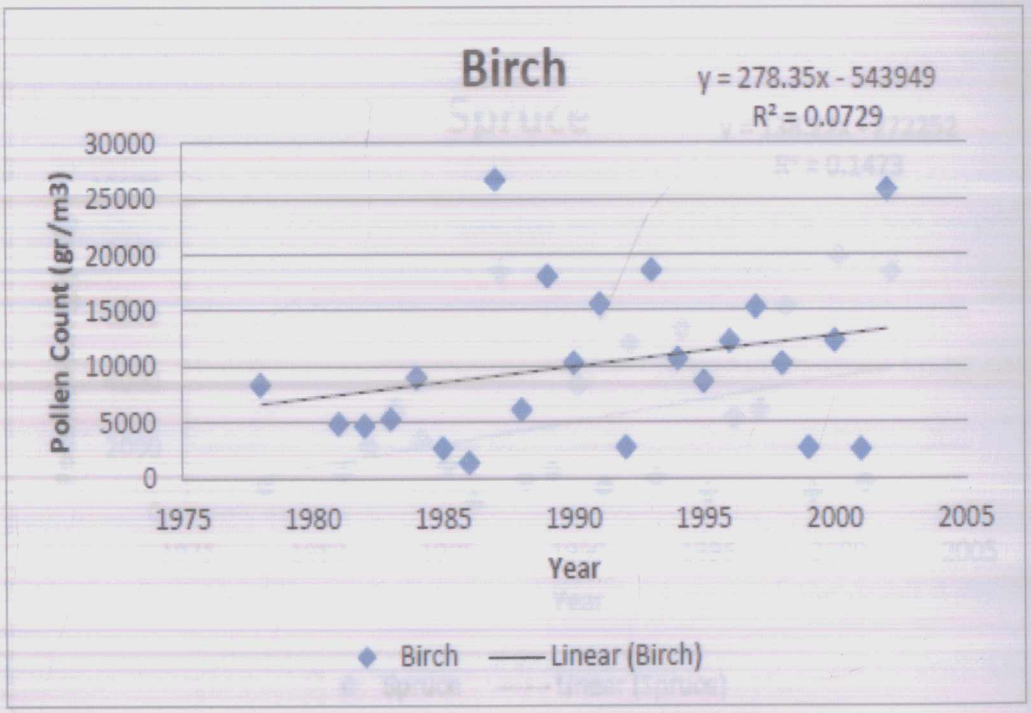


Figure 28. Scatter plots and trend lines for alder and birch pollen.

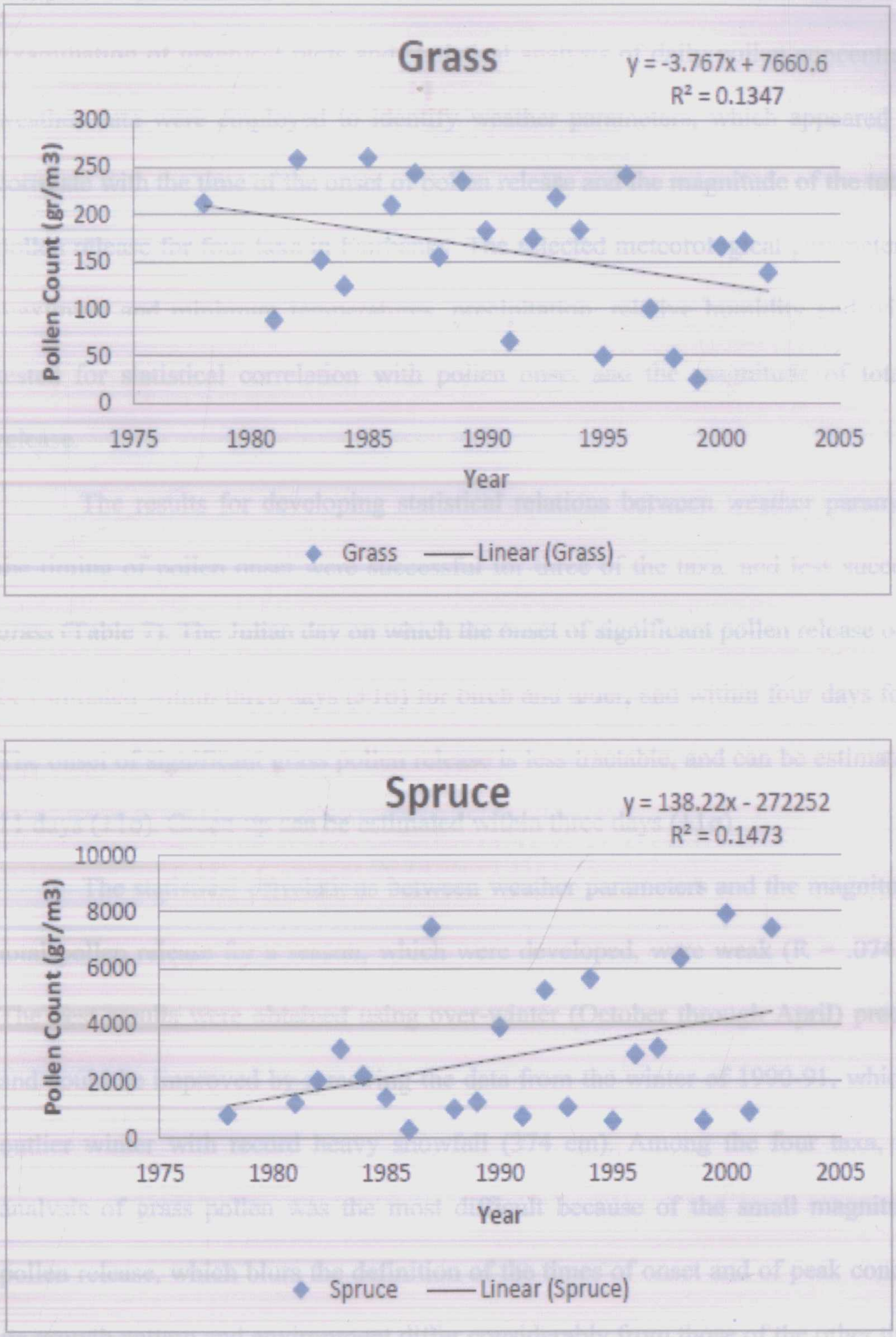


Figure 29. Scatter plots and trend lines for grass and spruce pollen.

The plots of total pollen release by year of individual taxa show great differences from one year to another and among taxa. In some years, there is little if any linkage between taxa. The diverse response to weather of the four taxa in this study strongly suggests that statistical correlations between pollen and weather for each taxon will be quite different from the correlations for the other three.

For all four taxa, there appears to be a number of important biological processes at work, which occur over varying time periods – from seasons down to hours – which are too difficult to account with weather parameters covering weeks, months or seasons.

Plots of daily pollen concentration and weather data for a year with high pollen release and for a year with low pollen release were prepared for each of the four taxa in order to identify the weather characteristic of such years, particularly for years with high pollen release likely to be of clinical concern. Thresholds of temperature and relative humidity leading to significant pollen release were identified by inspection of plots for each of the 23 seasons of pollen concentration, minimum relative humidity, and maximum temperature for each taxon.

Four days with very large pollen concentrations were chosen for analysis using weather data for the selected day and several days prior to it. In addition, the skew-T charts for Fairbanks on the afternoon of the days with very large pollen concentrations were examined to identify air mass structure found on such days. Pollen concentration might be expected to be diluted in very deep (more than 3 km) mixing layers, but this dilution did not appear to be an important factor. The depth of the mixing layer on summer days in Fairbanks varies by a factor of roughly three. The pollen concentrations can vary by more than one order of magnitude.

Yearly statewide data for acres burned in wildfires and for acres of land destroyed by insect infestations were examined. In addition, insect data obtained at the Bonanza Creek Long Term Ecological Research (LTER) area near Fairbanks were examined. It appears that neither the statewide and nearby LTER insect infestations, nor the acreage burned in wildfires correlated to any consistent effects on the pollen collected at Fairbanks. It was concluded that the precipitation of pollen is rapid enough, and wind flow is sufficiently changing, such that the impact of wildfires and insect infestations would be significant only if these events occurred within a distance of less than approximately 20 km of a pollen sampling site.

Examination of pollen concentration and precipitation revealed that the amount of precipitation needed to remove a significant portion of pollen in the air is not large – typically from 1 mm to 6 mm for birch, alder and spruce, and 5 mm to 20 mm for grass. Recovery of pollen concentration after rainfall can occur in a day or two.

The trends in the magnitude of seasonal pollen releases were examined for all four taxa over the 23 years for which pollen data were available. The trend toward increasing pollen release of birch, alder and spruce over recent years is consistent with the findings of Anderson (1986) and others. Seasonal grass pollen release has trended downward during the same 23 years for which data were available. As was the case with the correlation with weather over seasonal or monthly time scales, grass pollen release differs markedly from the patterns exhibited by birch, alder and spruce.

The weather during the pollen season in Fairbanks differs from that in the mid latitudes primarily because of the long hours of sunlight during the spring and summer in Fairbanks. Based on limited data of 2-hourly pollen concentrations, the diurnal pattern of pollen concentration in Fairbanks appears to be most affected by temperature and relative humidity, and typically reaches its maximum level in the afternoon or early evening.

The diurnal patterns of pollen concentration in various mid latitude and subtropical areas elsewhere in the world vary considerably among different taxa, as noted by Ribeiro et al. (2008). This appears to be related to plant adaptation to warm, dry continental climates, for instance, Spain. Some taxa have diurnal cycles of concentration similar to those in Fairbanks. Others appear to be less tolerant to the heat of afternoons and thus do not release pollen until the onset of relatively cooler weather in the evening.

In dry, warm climates such as Spain, Croatia and Turkey, for instance, pollen seasons vary considerably among taxa. Pollen release in such regions can occur from January through October. In Croatia, for example, alder releases pollen from January through March, birch from March through May, grasses from April through August and ragweed from August through October (Peternal et al. 2006).

Total pollen releases in these areas is similar to those in Fairbanks. In Croatia, Peternal et al. (2006) measured total season release of ragweed pollen ranging from approximately 1,000 grains/m^3 to 25,000 grains/m^3. In Fairbanks, Anderson measured total season release of birch pollen from 1,367 grains/m^3 to 26,717 grains/m^3.

The diversity of taxa in sub-arctic areas such as those around Fairbanks is less than it is in lower latitudes. If pollen concentration data for more taxa in the region around Fairbanks were gathered, differing diurnal patterns might be found. Diurnal patterns in pollen concentration can be significant during large release days. Pollen fluctuations within a span of one day can be of considerable clinical concern. Due to the rigor of winters in Fairbanks, annual pollen seasons are confined to April through mid August.

The 23 years of Fairbanks pollen data are clearly not sufficient to develop a forecasting system. The standard requirement for such work is 30 years (Kutner et al. 2005; Panovsky and Brier 1965; Wilks 2006). A credible model for forecasting pollen release would need 20 or more years of data for training and another 10 years or more for validation. Anderson (1986) found some correlation between temperatures in the weeks following floral bud initiation and the amount of birch pollen released in Anchorage and Fairbanks in the following spring. His analysis was based on three years of data. The temperature parameter was a choice of (1) the temperature in the two weeks following floral bud initiation, (2) the following two weeks, or (3) the month following initiation.

Clearly more data are needed, and indeed, there are. Pollen data has been gathered at the Tanana Valley Clinic starting in the year 2000 (Harry 2000-2012). The taxa for which the clinic gathers pollen include all four investigated in this study plus willow, poplar/aspen, weeds and mold.

The two sampling sites differ. The clinic is in an urban environment 7 km southeast of Anderson's site, which is in a rural to suburban area on the University of Alaska campus. The elevation of Anderson's sampler site is about 50 m above the elevation of the clinic. Anderson's sampler was about 10 m above above ground level. The sampler at the clinic is approximately 25 m above ground level.

Anderson used Durham and Burkhard samplers. Most of Anderson's data (21 of 23 years) was taken from the Burkhard sampler. At the clinic, a Rotorod sampler has been used. A comparison of the data from the Burkhard and Rotorod samplers (Heffer et al. 2005) found that the Burkhard pollen counts were up to 2 times higher than counts obtained using the Rotorod. Inspection of Anderson's data for birch pollen concentration for the years 2000 through 2002 and the data from the Rotorod at the clinic in the same years somewhat agrees with this conclusion (Table 9).

Table 9. Total birch pollen measurements of the Burkhard and Rotorod samplers for 2000 through 2002.

Year	Burkhard sampler	Rotorod sampler
2000	12,264	10,353
2001	2.492	2,388
2002	25,752	12,132

The results in Table 9 suggest that the differences in sampling locations and sampling instruments are large enough to require recalculation of statistical relations for the data from the clinic. At the same time, inspection of the three years of data from Anderson and the clinic shows that the two sets of data are in good agreement on the onset and the end of large pollen releases. Anderson consistently took readings at 8 AM.

Readings at the clinic are taken later in the morning or at mid day (S Harry 2012, personal communication). Thus, Anderson's data, taken before the diurnal increase of pollen begins, represent the pollen concentration from the day before. The clinic data are often offset several hours from Anderson's data, thus mixing the pollen concentration from the day before with pollen concentration of the day on which the reading is taken. This difference plays a role in the day to day series of readings, but has no effect on the total pollen release for a season.

Other investigators (Davies and Smith 1973; Marakra et al. 2011; Smith and Emberlin 2005; Stark et al. 1997; Subiza et al. 1992; Taira 2000) have endeavored to develop pollen forecasting systems. All of these have faced limits on the length of the pollen data record. One of the most useful tools that could be used in future pollen modeling and forecasting development would be a longer period of a consistently recorded data – a need common to many of the natural sciences.

As noted by DellaValle et al. (2012), Estrella et al. (2006) and Herzmann et al. (2008), pollen data needs to be gathered in a well designed spatial network for serious modeling to be accomplished. The network must be randomly designed to support sound climatology studies (PaiMazumder and Mölders 2009). Such a network is a need common to many of the natural sciences.

Pollen calendars for several Fairbanks taxa have been developed, and can be of benefit to people with pollen allergies to plan their activities in spring and early summer. Further improvement in understanding correlations between weather and pollen release can very likely be advanced through the use of multivariate statistical analysis. Consistent data gathered over a reasonably long period of time would surely support this. Work to improve forecasts of pollen over the time scales of several weeks, several days and several hours would yield great clinical benefits to society.

References

Alden, J., 1985: *Biology and management of white spruce seed crops for reforestation in subarctic taiga forests.* Bulletin 69 Agricultural and Forestry Research Station University of Alaska Fairbanks, xii+51pp.

Altinas, D. U., G. B. Karakoç, M. Yilmaz, M. Pinar, S. G. Kendirli, and J. Çakam, 2004: Relationship between pollen counts and weather variables in east-Mediterranean coast of Turkey. Clin *& Devel Immun.,* **11**, 87-96.

Anderson, J. H., 1984a: A survey of allergenic airborne pollen and spores in the Fairbanks area. *Ann Allerg.,* **52**, 26-31.

_____, 1984b: Allergenic airborne pollen and spore research in Alaska and adjacent Canada. *Circumpolar Health,* **84**, 96-102.

_____, 1985: Allergenic airborne pollen and spore in Anchorage, Alaska. *Ann Allerg,* **54**, 390-399.

_____, 1986: Testing hypotheses regarding airborne pollen onset dates and pollen season severity in Anchorage and Fairbanks. Research report from the Palynology Laboratory University of Alaska Fairbanks, 23 pp.

_____, 1991: Long-term monitoring of airborne pollen in Alaska and the Yukon: possible implications for global change. *Proceedings International Conference on the Role of Polar Regions in Global Change*, Fairbanks, AK, University of Alaska Fairbanks, 453-459.

Bacles, C., A. J. Lowe, and R. A. Ennos, 2006: Effective seed dispersal across a fragmented landscape. *Science*, **311**, 628.

Barnes, C. F. Pacheco, J. Landuyt, F. Hu, and J. Portnoy, 2001: The effect of temperature, relative humidity and rainfall on airborne ragweed pollen concentrations. *Aerobiologica,* **17**, 61-68.

Bartková-Ščevková, J., 2003: The influence of temperature, relative humidity and rainfall on the occurrence of pollen allergens (*Betula, Poaceae, Ambrosia artemisiifolia*) in the atmosphere of Bratislava (Slovakia). *Int J Biometeorol.*, **48,** 1-5.

Belmonte, J., M. Alarcón, A. Avila, E. Scialabba, and D. Pino, 2008: Long-range transport of beech (*Fagus sylvatica* L.) pollen to Catalonia (north-eastern Spain). *Int J Biometeorol.,* **52**, 675-687.

Bergan, J., 1983: Temperaturens virkning på årlige toppskuddlengder hos gran i Troms. (Effects of temperature on annual shoot growth of *Picea abies* (L.) Karst in Troms). *Medd Nor inst skogforsk*, **38,** 1-15.

Celenk, S., Y. Canitez, A. Bicakci, N. Sapan, and H. Malyer, 2009: An aerobiological study on pollen grains in the atmosphere of north-west Turkey. *Environ Monit Assess.*, **158**, 365-380.

Chamecki, M., C. Meneveau, and M. Parlange, 2009: Large eddy simulation of pollen transport in the atmospheric boundary layer. *Aerosol Sci.,* **40**, 241-255.

Cookson, J. B., 1987: Prevalence rates of asthma in developing countries and their comparison with those in Europe and North America. *Chest,* **91**, 97S-103S.

Davies, R. R., and L. P. Smith, 1973: Forecasting the start and severity of the hay fever season. *Clin Allerg.,* **3**, :263-267.

DellaValle, C. T., E. W. Triche, and M. L. Bell, 2012: Spatial and temporal modeling of daily pollen concentrations. *Int. J. Biometeorol.*, **56**, 183-194.

de Morton, J., J. Bye, A. Pezza, and E. Newbigin, 2011: On the causes of variability in amounts of airborne grass pollen in Melbourne, Australia. *Int. J. Biometeorol.*, **55**, 613-622.

Dingle, N., 1953: Pollen counts and the hay fever problem. *Science,* **116**, 64-65.

Docampo, S., M. Reicio, M. M. Trigo, M. Melgar, and B. Cabezudo, 2007: Risk of pollen allergy in Nerja (southern Spain): a pollen calendar. *Aerobiologia*, **23**, 289-299.

Draxler, R. R., and G. D. Hess, 1998: An overview of the HYSPLIT-4 modeling system for trajectories, dispersion, and deposition. *Aust Meteor. Mag.,* **47**:295-308.

_____, B. Stunder, G. Rolph, and A. Taylor, 2005: HYSPLIT-4 user's guide. NOAA Air Resources Laboratory. iv+57pp.

Durham, O. C., 1941: Atmospheric Allergens in Alaska. *J. Allerg.*, **12**, 307-309.

Eaton, F., and G. Wendler, 1982: The heat balance during the snow melt season for a permafrost watershed in Interior Alaska. *Arch. Met. Geoph. Biokl. Ser A*, **31**, 19-33.

Emberlin, J., J. Mullins, J. Corden, W. Millington, M. Brooke, M. Savage, and S. Jones, 1997: The trend to earlier birch pollen seasons in the U.K.: a biotic response to changes in weather conditions? *Grana*, **36**, 29-33.

_____, M. Detandt, R. Gehrig, S. Jaeger, N. Nolard, and A. Rantio-Lehtimäki, 2002: Responses in the start of the *Betula* (birch) pollen seasons to recent changes in spring temperatures across Europe. *Int. J. Biometeorol.*, **46**,159-170.

Estrella, N., A., Menzel, U. Krämer, and H. Behrendt, 2006: Integration of flowering dates in phenology and pollen counts in aerobiology: analysis of their spatial and temporal coherence in Germany (1992-1999). *Int. J. Biometeorl.*, **51**,49-59.

Fathauer, T., J. Anderson, and N. Mölders, 2004: Analysis of Pollen and Climatological Data for Application in Public Health Information. *Proceedings of 55th Arctic Science Conference*, Anchorage, AK, University of Alaska Fairbanks.

Fehér, Z., and M. Járai-Komlódi, 1998: A new weather factor predicting airborne pollen concentration: Péczly's macroscopic weather types. *Aerobiologia*, **14**, 171-177.

Fotiou, C., A. Damialis, N. Krigas, J. M. Halley, and D. Vokou, 2011: *Parietaria judaica* flowering phenology, pollen production, viability and atmospheric circulation, and expansive ability in the urban environment: impacts of environmental factors. *Int. J. Biometeorol.*, **55**, 35-50.

Frei, T., and E. Gassner, 2008: Climate change and its impact on birch pollen quantities and the start of the pollen season an example from Switzerland for the period 1969-2006. *Int. J. Biometeorol.*, **52**, 667-674.

Galán, C., J. Emberlin, E. Dominguez, R. Bryant, and F. Villamandos, 1995: A comparative analysis of daily variations in the Gramineae pollen counts at Córdoba, Spain and London, UK. *Grana,* **34**, 189-198.

Gassmann, M. I., and C. F. Pérez, 2006: Trajectories associated to regional and extra-regional pollen transport in the southeast of Buenos Aires province, Mar del Plata (Argentina). *Int. J. Biometeorol.*, **50**, 280-291.

_____, and J. M. Gardiol, 2007: Weather conditions associated with the potential for pollen recirculation in a coastal area. *Meteorol. Appl.*, **14**, 39-48.

Geisler F., 1945: *A pollen study of thirty-two species of grasses*. Butler University Botanical Studies, 7-6, 65-73..[Available online at http://digitalcommunications.butler.edu/botanical/vol7/issl/6.]

Harry, S., 2000-2012: Pollen counts for Fairbanks, Alaska. [Available online at: http://www.bannerhealth.com/Locations/.]

Hartman, B., and G. Wendler, 2005: The significance of the 1976 Pacific climate shift in the climatology of Alaska. *J. Clmate,* **18**, 4824-4839.

Heffer, M. J., J. K. Ratz, J. K. Miller, and J. D. Day, 2005: Comparison of the Rotorod to other air samplers for the determination of *Ambrosia artemisiifolia* pollen concentrations conducted in the Environmental Exposure Unit. *Aerobiologica,* **21**, 233-239.

Hernández-Ceballos, M. A., H. Garcia-Mozo, J. A. Adame, E. Domínguez-Vilches, B. A. De la Morena, J. P. Bolivar, and C. Galán, 2011: Synoptic and meteorological characterization of olive pollen transport in Córdoba province (south-western Spain). *Int. J. Biometeorol.*, **55**, 17-34.

Herzmann, D. E., J. D. Wolt, and R. Arritt, 2008: Representativity of a mesoscale network for weather-related factors governing pollen dispersal. *Int. J. Biometeorol.* **52**, 617-624.

Hirst, J. M., 1952: An automatic volumetric spore trap. *Ann. Appl Biol.*, **39**, 257-265.

Hobday, J. D., and A. J. Stewart, 1973: The relationship between daily asthma attendance, weather parameters, spore count and pollen count. *Aust NZ J Med.*, **3**, 552-556.

Holsten, E., P. Hennon, L. Trummer, and M. Schultz, 2001: Insects and diseases of Alaskan forests. USDA For. Serv. Gen. Tech. Rept. R10-TP-87. 242pp.

_____, R.W., Their, A. S. Munson, and A. S. Gibson, 1999: Forest insect & disease leaflet 127. USDA For. Serv. Leaflet 127.12pp.

Izquierdo, R., J. Belmonte, A. Avila, M. Alarcón, E. Cuevas, and S. Alonso-Pérez, 2011: Source areas and long-range transport of pollen from continental land to Tenerife (Canary Islands). *Int. J. Biometeorol.*, **55**, 67-85.

Jäger, S., S. Nilsson, B. Berggren, A. M. Pessi, M. Helander, and H. Ramfjord, 1996: Trends of some airborne tree pollen in the Nordic countries and Austria, 1980-1993. *Grana,* **35**, 171-178.

Jato, V., F. J. Rodriguez-Rajo, M. C. Seijo, and M. lJ. Aira, 2009: Poaceae pollen in Galicia (N.W. Spain): characterization and recent trends in atmospheric pollen season. *Int. J. Biometeorol.*, **53**, 333-344.

Käpylä, M., 1984: Diurnal variation of tree pollen in the air in Finland. Grana **23**, 167-176.

Kasprzyk, I., 2008: Non-native *Ambrosia* pollen in the atmosphere of Rzeszów (SE Poland); evaluation of the effect of weather conditions on daily concentrations and starting dates of the pollen season. *Int. J. Biometeorol.*, **52**, 341-351.

_____, 2009: Forecasting the start of the *Quercus* pollen season using several methods – the evaluation of their efficiency. *Int. J. Biometeorol.*, **53**, 345-353.

Kutner, M. H., C. J. Nachtsheim, J. Neter, and W. Li, 2005: *Applied Linear Statistical Models*, 5th ed. McGraw-Hill Irwin. xxvii+1396pp.

Marakra, L., I. Matyasovszky, M. Thibandon, and M. Bonini, 2011: Forecasting ragweed pollen characteristics with nonparametric regression methods over the most polluted areas in Europe. *Int. J. Biometeorol.*, **55**, 361-371.

Mannino, D. M., D. M. Homa, L. J. Akinbami, J. E. Moorman, C. Gwynn, and S. C. Redd , 2002: *Surveillance for Asthma – United States, 1980 – 1999.* CDC Surveillance Summaries, MMWR 51(SS01), 1-13.

Mitakakis, T. Z., and D. I. Guest, 2001: A fungal spore calendar for the atmosphere of Melbourne, Australia, for the year 1993. *Aerobiologia,* **17**, 171-176.

Mölders, N., U. Haferkorn, J. Döring, and G. Kramm, 2003a: Long-term investigations on the water budget quantities predicted by the hydro-thermodynamic soil vegetation scheme (HTSVS) – Part I: Description of the model and impact of long-wave radiation, roots snow, and soil frost. *Meteorol. Atmos Phys.*, **84**, 115-135.

_____, _____, _____, and _____, 2003b: Long-term investigations on the water budget quantities predicted by the hydro-thermodynamic soil vegetation scheme (HTSVS) – Part II: Evaluation, sensitivity, and uncertainty. *Meteorol. Atmos. Phys.*, **84**, 137-156.

Mölders, N., and G. Kramm, 2007: Influence of wildfire induced land-cover changes on clouds and precipitation in Interior Alaska – a case study. *Atmos. Res.*, **84**, 142-168.

Mölders, N., and J. Walsh, 2004: Atmospheric response to soil-frost and snow in Alaska in March. *Theor. Appl. Climatol.*, **77**, 77-105.

Nathan, R. A., E. O. Meltzer, J. C. Selner, and W. Storms, 1997: Prevalence of allergenic rhinitis in the United States. *J. Allergy Clin. Immunol.*, **99**, S808-S814.

NCDC, 1977-2002: Local climatological data for Fairbanks, AK. [Available online at http://www.ncdc.noaa.gov.]

Owens, J. N., and M. Molder, 1979: Sexual reproduction of white spruce (*Picea glauca*). *Can. J. Bot.*, **57**, 152-169.

_____, 1985: Cone and seed biology. *Proceedings Conifer Tree Seed in the Inland Mountain West Symposium*, Missourla, MT, 14-31.

PaiMazumder, D., and N. Mölders, 2009: Theoretical assessment of uncertainty in regional averages due to network density and design. *J. of Appl. Met. and Clim.*, **48**, 1643-1666.

Panovsky, H. A., and G. W. Brier, 1965: *Some applications of statistics to meteorology*, first ed. Pennsylvania State University, ix+224p.

Perry, K. B., S. M. Blankenship, and C. R. Unrath, 1987: Predicting harvest date of 'delicious' and 'golden delicious' apples using heat unit accumulations. *Agri. and For. Meteorol.*, **39**, 81-88.

Peternel, R., J. Čulig, J. Hrga, P. Hercog, 2006: Airborne ragweed (*Ambrosia artemisiifolia* L.) pollen concentrations in Croatia, 2002-2004. *Aerobiologia,* **22**, 161-168.

Ribeiro, H., M. Oliveira, and I. Abreu, (2008) Intradiurnal variation of allergenic pollen in the city of Porto (Portugal). Aerobiologia 24:173-177

Ronneberger, O., H. Burkhardt, and E. Schultz, 2002: General-purpose object recognition in 3D volume data sets using gray-scale invariants – classification of airborne pollen-grains recorded with a confocal laser scanning microscope. *Proc. 16th inter. Conf. Pattern Recognition,* ***2,*** IEEE, 290-295.

Rousseau, D. D., D. Duzer, J. L. Etienne, G. Gambon, D. Jolly, J. Ferrier J, and P. Schevin, 2004: Pollen record of rapidly changing air trajectories to the north pole. *J. Geophys. Res.*, **109**, D06116, 7p.

Sassen, K., 2008: Boreal tree pollen sensed by polarization lidar: depolarizing biogenic chaff. *Geophys. Res. Lett.*, 35:L18810.

Schroeder, M. J., and C. C. Buck, 1970: Fire Weather. USDA Forest Service Agriculture Handbook 360, v+229p.

Šikoparija, B., M. Smith, C. A. Skjøth, P. Radišić, S. Milkovska, S. Šimić S, and J. Brandt, 2009: The Pannonian plain as a source of *Ambrosia* pollen in the Balkans. *Int. J. Biometeorol.*, **53**, 263-272.

Skjøth, C. A., M. Smith, J. Brandt, and J. Emberlin, 2009: Are the birch trees in southern England a source of *Betula* pollen for North London? *Int. J. Biometeorol.*, **53**, 75-86.

Smith, M., and J. Emberlin, 2005: Constructing a 7-day ahead forecast model for grass pollen at north London, United Kingdom. *Clin. Exp. Allerg.*, **35**, 1400-1406.

Sofiev, M., P. Siljamo, H. Ranta, and A. Rantio-Lehtimäki, 2006: Towards numerical forecasting of long-range air transport of birch pollen: theoretical considerations and a feasibility study. *Int. J. Biometeorol.*, **50**, 392-402.

Spieksma, F. T. M., A. V. D. Assem, and B. J. A. Collette, 1985: Airborne pollen concentration in Leiden, the Netherlands, 1977-1981. *Grana,* **24**, 99-108.

Stach, A., M. Smith, C. A. Skjoth, and J. Brandt, 2007, Examining *Ambrosia* pollen episodes at Poznań (Poland) using back-trajectory analysis. *Int. J. Biometeorol.*, **51**, 275-286.

_____, J. Emberlin, M. Smith, B. Adams-Groom, and D. Myszkowska, 2008: Factors that determine the severity of *Betula* spp. pollen seasons in Poland (Poznań and Krakow) and the United Kingdom (Worchester and London). *Int. J. Biometeorol.*, **52**, 311-321.

Stark, P. C., L. M. Ryan, J. L. McDonald, and H. A. Burge, 1997: Using meteorological data to predict daily ragweed pollen levels. *Aerobiologia* **13**, 177-184.

Subiza, J., J. M. Masiello, J. L. Subiza, M. Jerez, M. Hinojosa, and E. Subiza, 1992: Prediction of annual variations in atmospheric concentrations of grass pollen. A method based on meteorological factors and grain crop estimates. *Clin. and Exp. Allerg.*, **22**, 540-546.

Taira H., H. Teranishi, and Y. Kenda, 2000: Male flowering index can predict the annual airborne pollen count of *Cryptomeria* japonica at different altitudes. *Allerg. Int.*, **49**, 175-181.

Thoman, R., and T. Fathauer, 1998: An Investigation into estimating green up dates around Fairbanks Alaska using thermal indices. *Proceedings of 49th Arctic Science Conference*, Fairbanks, AK, University of Alaska Fairbanks.

U. S. Forest Service, 1977-2002: Forest Health Conditions in Alaska. [Available online at http://www.fs.fed.us/r10/spf/thp/.]

USGS, 1979: Fairbanks, Alaska vegetation and land cover. Alaska vegetation and land cover series Map L-208.

Werner, R. A., 2010: Total Number of Beetles per Trap. [Available online at http://www.lter.uaf.edu.]

Wilks, D. S., 2006: Statistical *Methods in the Atmospheric Sciences*, second ed. Elsevier, xvii+627pp.

Ziska, L. H., P. R. Epstein, and W. H. Schlesinger, 2009: Rising CO_2, climate change, and public health: exploring the links to plant biology. *Environ. Health Perspec.*, **117(2)**,155-158.