Climate Change Effects on Ragweed (*Ambrosia*) and Mugwort (*Artemisia*) Pollen Seasons in USA

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ABSTRACT

Allergenic pollen acts synergistically with common air pollutants, such as ozone, to cause Allergic Airway Disease (AAD). Climatic change is expected to affect the spatiotemporal dynamics of pollen and pollutants. So, a comprehensive prognostic modeling system, combining climate models and anthropogenic and biogenic emission models with an expanded version of the Community Multiscale Air Quality (CMAQ) model has been developed to support integrated studies of the impact of climate change on public health. The present work has employed components of this system to analyze the climate change effects on ragweed and mugwort pollen seasons across the contiguous US (CONUS). Observed airborne pollen counts from six stations from 1994 to 2010 in CONUS were studied to examine climate change effects on trends of mean and maximum daily concentrations, start and length of ragweed and mugwort pollen season. The Growing Degree Hour (GDH) model was used to establish relationships between start date and observed hourly temperatures from surrounding meteorology stations. In the 2001-2010 period, ragweed was observed to flower 2-6 days earlier and its pollen season was found to be 1-8 days longer than that in the 1994-2000 period. The mugwort pollen season at most of the studied stations also tended to start earlier and last for a longer duration. Pollen levels of both ragweed and mugwort changed differently for different stations. The optimum threshold GDH values of start dates range from 5,571 to 31,605 degree hours for ragweed and from 14,925 to 30,610 degree hours for mugwort. The optimum initial date and base temperature for the GDH model of start date were found to be August 1st and 0°C for ragweed; July 1st and 0°C for mugwort.

INTRODUCTION

Climate change has a potential effect on Allergic Airway Disease (AAD) through variability of biogenic aeroallergens like pollen, and anthropogenic aeroallergens, such as the common air pollutants ozone and particulate matter (PM)[1, 2]. Climate change has caused a rapid shift in flowering time[3] and variations of allergenic airborne pollen count from trees, weeds and grasses[4,

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[5]. Changes in spatiotemporal distribution of allergenic airborne pollen are closely associated with Allergic Airway Diseases (AAD) [6] and related rising public health costs [7].

The high allergenicity of ragweed and mugwort pollen has been reported by many researchers [8-10]. Investigations of climate change effects on distribution of allergenic pollen have typically been focused on analyses of observed airborne tree pollen counts at individual stations and their statistical relationships with local meteorology factors[11, 12]. The relationships between weed pollen levels and timing and meteorology factors have been examined based on statistical analyses of observed airborne pollen counts and meteorological factors at different stations in USA [13, 14], Poland [15, 16] and Switzerland [17]. Most of these studies showed that ragweed and mugwort pollen levels and timing are closely associated with air temperature, wind speed and relative humidity. Experiments in either a controlled field [18] or a wild open suburban area [5] found that ragweed pollen season started earlier with higher pollen productions in warming environments.

Efforts have also been made to utilize atmospheric dispersion modeling to provide detailed spatiotemporal concentration profiles of ragweed pollen [19]. A major shortcoming of dispersion modeling is that large uncertainties exist in pollen emission modules [20]. Information on trends of weed pollen levels and timing in multiple climate zones is an important aid toward understanding effects of climate change on distributions of biogenic aeroallergens. Furthermore, the dynamic start dates of ragweed and mugwort pollen seasons are crucial for generating precise emission profiles.

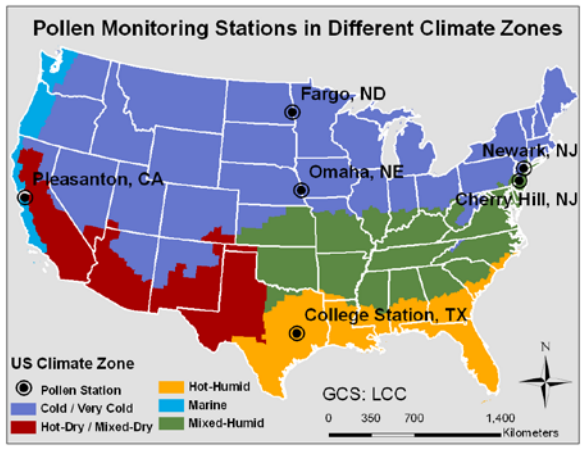
In this investigation, statistical analyses were conducted to identify trends of Start Date (SD), Season Length (SL), Annual Mean (AM) and Peak Value (PV) of daily concentrations of ragweed (*Ambrosia*) and mugwort (*Artemisia*) pollen from observed airborne pollen count at six monitoring stations across the contiguous US (CONUS). The Growing Degree Hour (GDH) model was parameterized based on observed pollen counts and hourly temperatures from surrounding meteorology stations to obtain the optimum initial dates, base temperatures and threshold GDH values.

METHODS

Data Source

Observed airborne pollen data were obtained from six monitoring stations of the American Academy of Allergy Asthma and Immunology (AAAAI). The selected stations are located at Fargo (North Dakota), College Station (Texas), Omaha (Nebraska), Pleasanton (California), Cherry Hill (New Jersey) and Newark (New Jersey). These stations were selected because (a) they have airborne daily pollen counts available for ragweed and mugwort for multiple years between 1994 and 2010; and (b) they span various representative geographical and climate zones[21] across the CONUS as shown in Figure 1. Observed hourly temperatures from 1994 to 2010 were obtained from the National Climatic Data Center (NCDC) meteorology stations nearest to the corresponding AAAAI pollen stations.

Figure 1. The geographical locations of six selected pollen monitoring stations in five major climate zones across CONUS. Map of climate zones was adapted from Baechler et al (2010)[21].



Pollen Indices

With day 1 being January 1st, the Start Date (SD) of pollen season is the day when the cumulative pollen count reaches 5% and end date when it reaches 95% of annual total count. SD was presented in the form of Day Of Year (DOY). Season Length (SL) is defined as the duration between start and end dates. Annual Mean (AM) is the mean and Peak Value (PV) the maximum daily concentration (pollen/m^{-3}) during a pollen season. Pollen data with SL of less than 7 or greater than 80 days are assumed unreasonable and excluded from further calculation. An exception was made for mugwort pollen data from the Pleasanton station because all the derived SLs from that station are between 103 and 167 days, and much longer than at other monitoring stations. Regression analyses were carried out to identify the trends of these derived pollen indices.

GDH Model

The hypothesis of the GDH model is that the trees, after having reached certain GDHs, start to pollinate (or stop pollinating), i.e. the pollen season is beginning (or ending) [22]. The GDH model is presented as (Eq.1),

$$GDH = \sum_{ID} (T_i - T_b), \qquad T_i > T_b \qquad \textbf{(Eq.1)}$$

where *ID* is the Initial Date starting to accumulate the difference between the hourly ground surface temperature T_i (°C) and the base temperature T_b (°C).

The station specific optimum GDH value for a fixed initial date and a base temperature is determined by a least square fit of the corresponding observed pollen start/end dates at that monitoring station for 1994-2010. This GDH value is utilized to calculate the modeled start/end dates and the corresponding Root Mean Square (RMS) error and correlation coefficient and *p* value with respect to the observed start/end dates. The station specific optimum initial date and base temperature are then selected based on Root Mean Square (RMS) errors.

RESULTS AND DISCUSSIONS
Trend Analysis of Pollen Indices

Results of trend analyses of ragweed pollen indices between 1994 and 2010 are presented in Figure 2. In each legend, also listed are the mean value *Ym*, trend *β*, correlation coefficient *r* and *p* value. The NaN in the legend indicates there are not sufficient data to calculate correlation coefficients and *p* values. Ragweed pollen seasons were observed to start earlier within longer season lengths. The only exception is that season lengths at the station Newark tended to be shorter. Annual mean and peak values were found to decrease at Fargo, Omaha and Cherry Hill, while increase at College Station and Newark.

Figure 2. Ragweed pollen indices and calculated trends from 1994 to 2010 for six stations in the US. Ym is the mean value, β the annual trend, r the correlation coefficient and p the significance of the trend. NaN indicates there are not sufficient data to calculate correlations coefficients and p values.

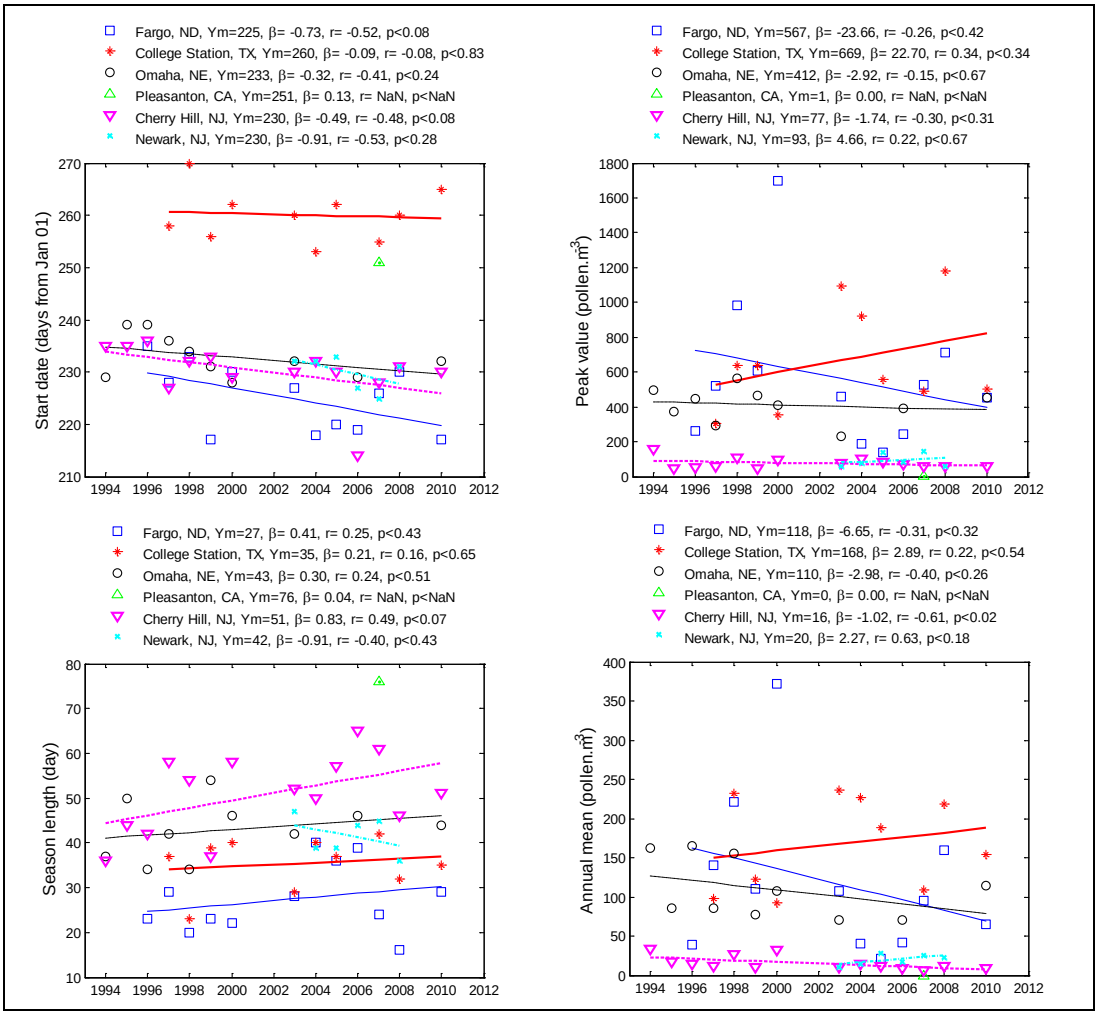
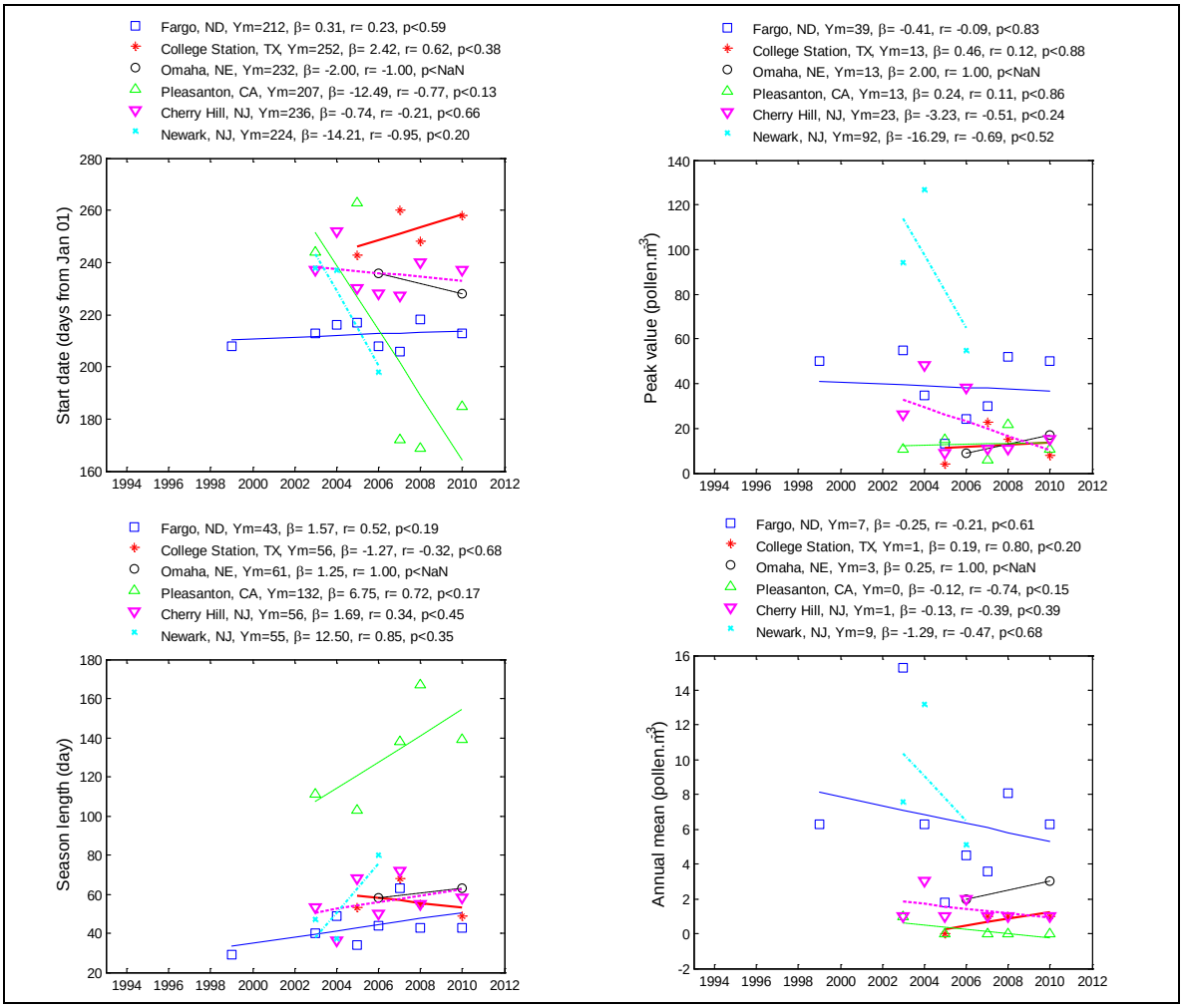


Figure 3 depicts trend analyses results of mugwort pollen indices between 1994 and 2010. Mugwort pollen seasons tended to start earlier at Omaha, Pleasanton, Cherry Hill and Newark, but occurred later at Fargo and College Station. Season lengths for mugwot pollen tended to be longer except for that at College Station. Season lengths at Pleasanton are extremely longer than those observed at other stations. This may be due to the poor identification of mugwort pollen grains in the counting process; pollen grains of other species may have been unintentionally counted as mugwort pollen at Pleasanton. Annual mean and peak values are found to decrease at Fargo, Cherry Hill and Newark, while increasing at College Station and Omaha.

Figure 3. Mugwort pollen indices and calculated trends from 1994 to 2010 for six stations in the US. Ym is the mean value, β the annual trend, r the correlation coefficient and p the significance of the trend. NaN indicates there are not sufficient data to calculate p value.



The observed trends of longer pollen seasons and earlier start dates are consistent with the literature, and most likely due to the recent warming climate [23, 24]. Although ragweed pollen production has also been reported to increase in environment with warming climate and higher CO_2 levels [18, 24], half of our studied stations showed decreasing trends in annual mean and peak

value of pollen concentrations. Similar decreasing trends of ragweed pollen counts have also been reported by Frei and Gassner in Switzerland [17]. The inconsistent variations in annual mean and peak values may be caused by the changes in ragweed and mugwort area coverage due to urbanization. It should be noted that because there are not sufficient pollen counts recorded for a longer period at most of the studied stations, only a few of the observed trends of ragweed and mugwort pollen indices are statistically significant.

Pollen Season

Natural variability exists in both climate [25] and plant growth [26, 27]. In order to reduce the effects of the natural climate and plant-growth variability on pollen indices, mean ragweed and mugwort pollen indices were calculated for periods of 1994-2000 and 2001-2010. Pollen indices in these two periods were also compared using the Student Test to check the significance of the corresponding difference. Table 1 lists the average pollen indices in periods of 1994-2000 and 2001-2010. Also listed are the corresponding differences between these two periods.

Table 1. Comparisons of mean Start Date (SD, day of year), Season Length (SL, day), Peak Value (PV, pollen/m^{-3}) and Annual Mean (AM, pollen/m^{-3}) between periods of 1994-2000 and 2001-2010 at the six stations. The * indicates the difference is statistically significant at 5% level.

Station		Mean in 1994-2000				Mean in 2001-2010				Difference			
		SD	SL	PV	AM	SD	SL	PV	AM	SD	SL	PV	AM
Fargo	Ragweed	229	23	814	196	222	30	391	84	-6	7	-423	-112
	Mugwort	208	29	50	7	213	45	37	7	5	16	-13	0
College Station	Ragweed	262	35	485	137	259	36	791	189	-2	1	307	52
	Mugwort	-	-	-	-	252	56	13	1	-	-	-	-
Omaha	Ragweed	234	42	435	120	231	44	359	85	-3	2	-76	-35
	Mugwort	-	-	-	-	232	61	13	3	-	-	-	-
Pleasanton	Ragweed	-	-	-	-	251	76	1	0	-	-	-	-
	Mugwort	-	-	-	-	207	**132**	13	0	-	-	-	-
Cherry Hill	Ragweed	232	47	81	21	228	55	72	10	-5	8	-9	-11*
	Mugwort	-	-	-	-	236	56	23	1	-	-	-	-
Newark	Ragweed	-	-	-	-	230	42	93	20	-	-	-	-
	Mugwort	-	-	-	-	224	55	92	9	-	-	-	-

Comparisons of mean ragweed pollen indices in Table 1 indicate that ragweed pollen season in period of 2001-2010 started 2 to 6 days earlier than in period of 1994-2000. The season length of ragweed pollen in period of 2001-2010 tended to be 1 to 8 days longer than in period of 1994-2000. Annual mean and peak values of ragweed pollen decreased at Fargo, Omaha and Cherry Hill, but increased at College Station. The overall earlier start dates and longer season lengths of

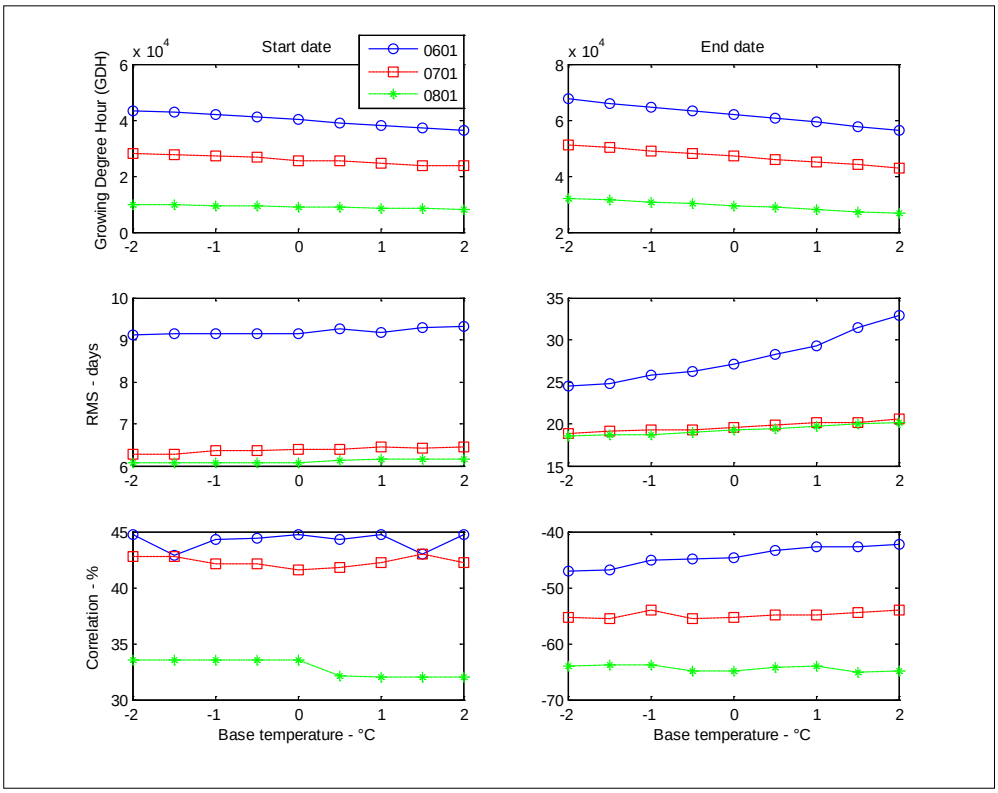
ragweed pollen are in good agreement with the reported observations from multiple monitoring stations [28], wild and urbanized areas [5].

Since only one year mugwort pollen count was registered during the period of 1994-2000 at Fargo, valid comparisons of mean mugwort pollen indices could not be made for both time periods. Furthermore, the derived mugwort pollen indices, especially season length at Pleasanton, seems to be an outlier compared to those at other stations. The average start dates of mugwort pollen season in period of 2001-2010 varied from July 31 at Fargo to September 8 at College Station. The mean season lengths of mugwort pollen in period 2001-2010 were different across the studied stations, ranging from 45 days at Fargo to 61 days at Omaha.

Parameterization of The GDH Model

Figure 4 depicts the station-specific optimum GDHs, initial dates and base temperatures for ragweed pollen at Cherry Hill. The top panel illustrates the optimum GDHs of start and end dates. The middle and bottom panels show corresponding root mean square errors and correlation coefficients utilizing the GDH values from the top panels.

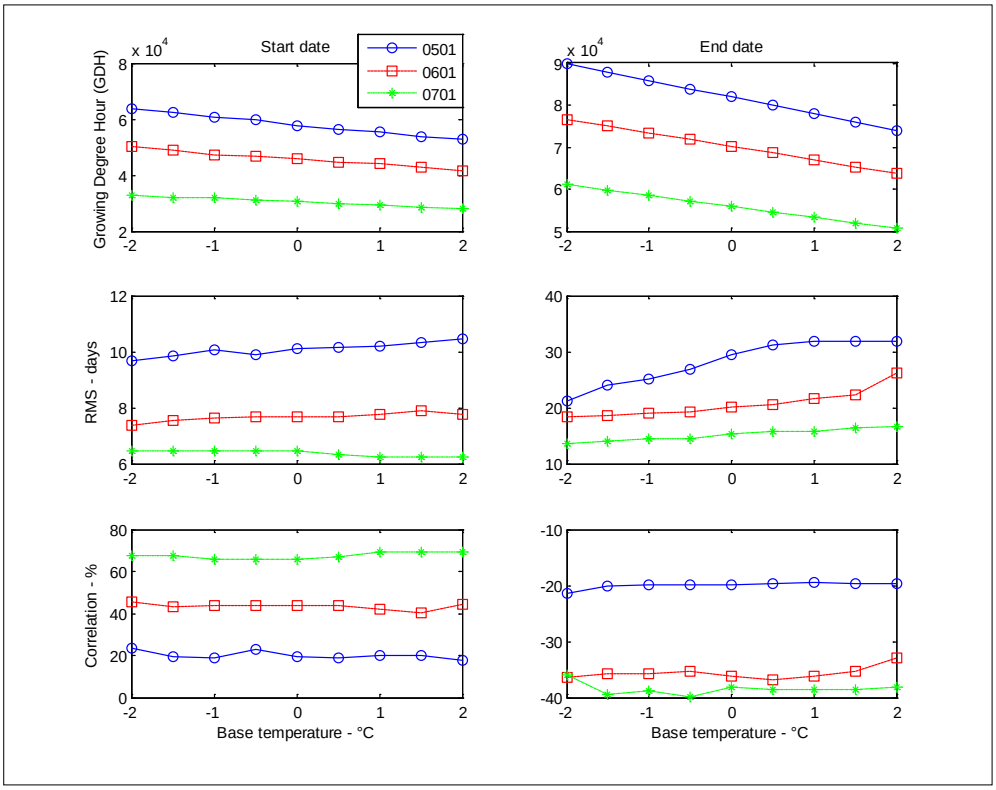
Figure 4. Optimum GDHs (top panel) of start and end dates with different initial dates and base temperatures for ragweed pollen at the Cherry Hill, New Jersey station. Also plotted are the corresponding Root Mean Square (RMS) errors (middle panel) and correlation coefficients (bottom panel) for the observed pollen data.



As demonstrated by the RMSs in Figure 4, August 1 is the optimum *ID*. Also shown in Figure 4 is that the GDH model is not sensitive to base temperature. 0 °C is assumed as the base temperature in the current study. Under the optimum *ID* and base temperature, the RMS for start date is about 6 days while for end date is about 19 days; the correlation coefficient for start date approximates 34% while for end date is -64%. RMSs and correlation coefficients showed that the GDH model may not be suitable to predict the end dates of ragweed pollen. The GDH model reported by Kasprzyk [29] based on accumulation of daily mean temperature, daily maximum temperature, and difference between daily maximum and minimum temperatures were also tested to predict the start dates at the studied stations. In terms of both RMSs and correlation coefficients, the results are not as good as the GDH model presented here based on accumulation of the difference between hourly temperature and base temperature.

Figure 5 illustrates the station specific optimum GDH, *ID*, and base temperatures for mugwort pollen at Cherry Hill. Similar phenomena as for ragweed pollen shown in Figure 4 can also be identified for mugwort pollen in Figure 5. For mugwort pollen at Cherry Hill, the optimum GDHs for start date is 30,610 with *ID* being July 1 and base temperature being 0 °C.

Figure 5. Optimum GDHs (Top Panel) of start and end dates with different initial dates and base temperatures for mugwort pollen at the Cherry Hill, New Jersey station. Also plotted are the corresponding Root Mean Square (RMS) errors (Middle Panel) and correlation coefficients (Bottom Panel) for the observed pollen data.



Similarly, station specific optimum GDH, *ID,* and base temperature were generated through analysis of airborne ragweed and mugwort pollen data and corresponding observed hourly temperatures for monitoring stations at Fargo, College Station, Omaha, Pleasanton, and Newark. For a valid parameterization of GDH model, pollen data are required to be available for at least five years at a monitoring station. The corresponding station-specific optimum GDHs, *IDs* and base temperatures for all six stations, if available, are listed in Table 2. Also listed are the corresponding RMSs, correlation coefficients and *p* values.

It is shown in Table 2 that, the optimum threshold GDH values of start dates range from 5571 to 31,605 for ragweed; and from 14,925 to 30,610 for mugwort. The optimum initial date and base temperature for GDH model of start date were found to be August 1 and 0°C for ragweed; July 1st and 0°C for mugwort. The optimum initial date being June 1st for mugwort pollen at Pleasanton is an exception in that unusually long season lengths were recorded at this station. These GDH model parameters are crucial information to drive the dynamic pollen emission and dispersion models, which will generate spatiotemporal concentration profiles of allergenic pollen.

Table 2. Station specific Growing Degree Hour (GDH, Degree Hour) of start date under optimum base temperature (T_b) and initial date (ID). Also listed are the corresponding Root Mean Square error (RMS), correlation coefficient r, p value and number of years (N) with valid data.

Station		**N**	**GDH** (°C.h)	**RMS** (day)	**r**	**p**	**T_b** (°C)	**ID** (mmdd)
Fargo	Ragweed	12	5571	6	0.11	0.74	0	0801
	Mugwort	8	14925	6	-0.07	0.86	0	0701
College Station	Ragweed	10	31605	5	0.21	0.56	0	0801
	Mugwort	4	-	-	-	-	-	-
Omaha	Ragweed	10	7531	9	-0.38	0.28	0	0801
	Mugwort	2	-	-	-	-	-	-
Pleasanton	Ragweed	1	-	-	-	-	-	-
	Mugwort	5	24605	39	0.24	0.70	0	0601
Cherry Hill	Ragweed	14	9020	6	0.34	0.24	0	0801
	Mugwort	7	30610	6	0.66	0.11	0	0701
Newark	Ragweed	6	10804	3	0.38	0.46	0	0801
	Mugwort	3	-	-	-	-	-	-

CONCLUSIONS

Observed airborne ragweed and mugwort pollen data from six stations at locations representing a wide range of geographic and climatic conditions across CONUS, were analyzed statistically to identify their trends of start date, season length, annual mean and peak value of daily

concentrations. Ragweed and mugwort pollen seasons were found to start earlier and last for a longer duration from 1994 to 2010. The trends for observed annual means and peak values of daily concentrations appeared to be different for ragweed and mugwort pollen across the different stations.
GDH models were used to investigate the relationships between start and end dates of pollen seasons, and hourly temperatures. The station-specific optimum GDH values, initial date and base temperatures were generated for start dates, but not suitable for end dates.

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KEYWORDS

Climate change, Airborne allergenic pollen, Ragweed, Mugwort, Growing degree hours