AGU PUBLICATIONS

GeoHealth

Supporting Information for

Impacts of oak pollen on allergic asthma in the United States and potential influence of future climate change

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Introduction

This Supporting Information provides additional information on the pollen health effect literature review, pollen concentrations and season lengths, climate modeling, and other key elements of the analysis.

Text S1. Selection of pollen type associated with asthma emergency department visits

After we identified the health endpoint of concern, we conducted a systematic literature search to identify studies examining the relationship between pollen and asthma ED visits and to inform our selection of a single pollen type to include in this analysis (Table S1). Our literature search consisted of two steps. First, we identified relevant papers from the National Climate Assessment reference list as well as from PubMed and Google Scholar searches. Second, we examined the reference lists of these papers to identify additional studies of pollen and asthma ED visits. Throughout both steps, we limited the scope of this search to studies conducted in either the US or Canada. We further limited the scope to studies reporting an effect size (i.e., excluding studies that only undertook descriptive analysis).

Text S2. Conceptual diagrams

Conceptual diagrams are provided in Figures S1 through S3 for analysis of asthma emergency department visits associated with 1994-2010 average oak pollen concentrations and season lengths, simulation of future oak pollen season length, and analysis of asthma emergency department visits associated with future oak pollen under baseline (1994-2010 average) conditions and two climate scenarios.

Text S3. Baseline and future projected oak pollen season length and seasonal total concentration

Baseline (1994-2010 average) oak pollen season length and season total concentrations for 58 National Allergy Bureau (NAB) stations (56 in the U.S. and 2 in Canada) were taken from the compilation by Zhang et al. (2015, see their Supplemental Material) and are reproduced here in Table S2. We added data obtained directly from the NAB station in Dayton, OH, to derive oak pollen exposure estimates for Cincinnati, as it is closer than any of the 58 NAB stations included in the compilation by Zhang et al. (2015). Though this analysis focused on the continental U.S., we included the two NAB stations in Canada to more accurately interpolate season length and pollen concentrations for nearby gridcells.

To project from these baseline season length values to future years under the two representative concentration pathway (RCP) scenarios, we used future temperature and precipitation simulated by five general circulation models (GCMs) from the Fifth Phase of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012) listed in Table S3. Downscaled temperature and precipitation outputs from each of these models were obtained from the Localized Constructed Analogs dataset (LOCA; BuRec 2016), and regridded to 0.5°x0.5° resolution over the CONUS domain.[1] These five GCMs were chosen to capture a large range of the variability in climate outcomes observed across the entire CMIP5 ensemble, as shown in Figure S4 through Figure S13. These projections are used to estimate oak pollen season length for each RCP scenario in each of the future analytical years.

To generate average daily temperature, the widely-used and straightforward practice of taking an average of the daily tmax and tmin was used. This approach is commonly used for observational data, and therefore models which are calibrated against observed temperatures will often be based on the tmax/tmin average. However, the Zhang et al. (2015) pollen forecast model appears to be based on the average temperature weighted by time over the course of the day. The precise relationship between this weighted average over time, tmax, and tmin is a function of latitude, range of daily temperature, and other factors. The benefits of methodological simplicity from using the average of tmax and tmin, particularly for the climate forecasts outweigh the slight loss in accuracy for a model that depends on a weighted average over time, in particular because our application of pollen season estimation uses the average of tmax and tmin for both the baseline period and forecast period (to bias correct the results).

Though substantial variation can be seen across the model outputs, several consistent patterns emerge. The models consistently show temperature (January through March average) increases from 2030 to 2090, with greater warming simulated under RCP8.5 compared with RCP4.5. Temperature increases are more pronounced using output from the CanESM2, HadGEM2-ES, and MIROC5 models compared with the CCSM4 and GISS-E2-R models. The GISS-E2-R model shows the least warming for all scenarios and years, with some cooling projected in some areas even through 2090 for RCP4.5. The models also consistently show precipitation (September of the year before the forecast year through August of the forecast year) increasing in the Northeastern U.S. and decreasing in the Southwest U.S. from 2030 to 2090, though the CanESM2 model shows increasing precipitation in some parts of the West where other models show a decrease.

Since each GCM's output represents an equally plausible forecast based on current understanding, though not necessarily equal in likelihood, we projected oak pollen season length separately for each combination of GCM and RCP scenario to indicate a range of potential values. Figure S14 through Figure S18 show the ratios of future projected to baseline oak pollen season length (days) for each GCM, RCP, and forecast year.

As described in the Methods, simulated temperature and precipitation were used to project oak pollen season length for each monitor location to the future. Figure S19 and

[1] The LOCA projections are the primary dataset being used in the forthcoming Climate Science Special Report of the U.S. Global Change Research Program's Fourth National Climate Assessment.

Figure S20 show the oak pollen season length scalars used to project season length for each GCM, RCP scenario, and year separately. We observe wide variation in the scalars produced by the outputs from the five GCMs, driven by differences in simulated temperature and precipitation in the gridcells containing the monitor locations. There are no clear patterns among these results, indicating that there are no obvious outliers or biases among the GCMs. Despite the inter-model variation, the scalars are generally greater than 1, indicating that the oak pollen season lengthens in the future relative to the 1994-2010 average.

Text S4. City definitions

Geographic definitions for each of the cities included in the analysis are provided in Figures S21 through S23.

Text S5. City-specific health impact results

City-specific health impact results are given in Tables S4 and S5.

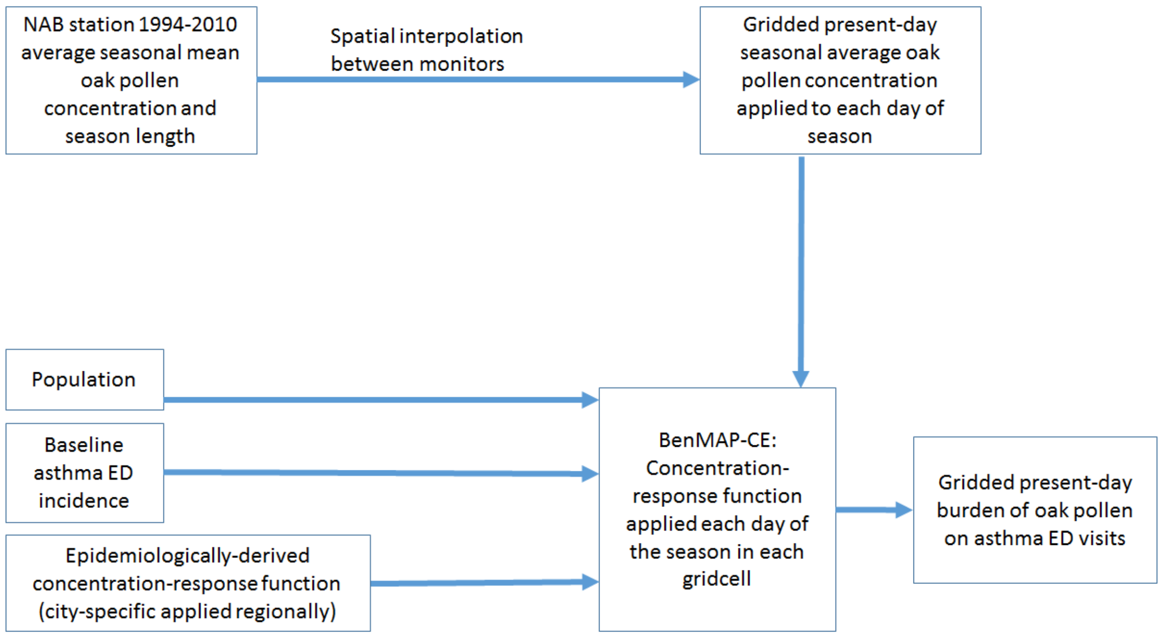

Figure S1. Conceptual diagram for analysis of asthma emergency department visits associated with 1994-2010 average oak pollen concentrations and season lengths.

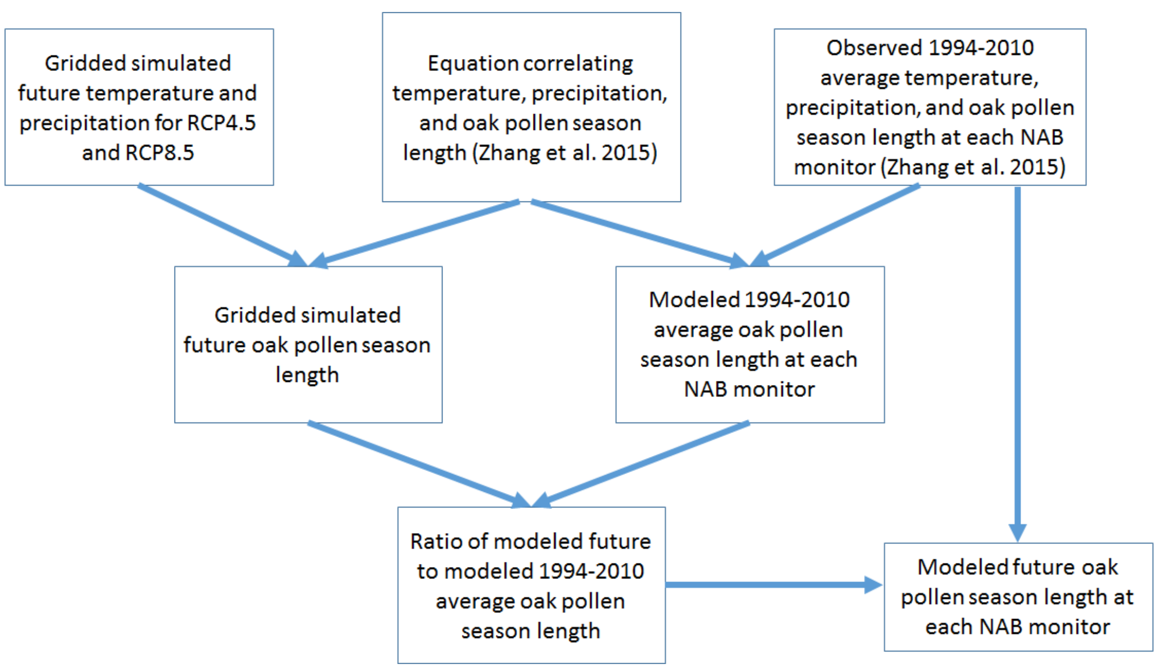

Figure S2. Conceptual diagram for simulation of future oak pollen season length.

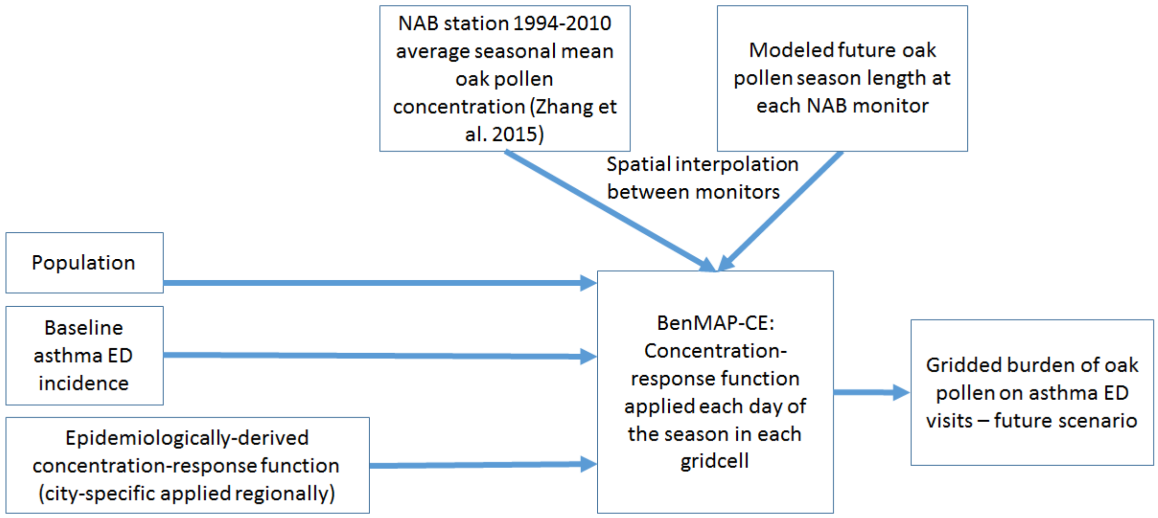

Figure S3. Conceptual diagram for analysis of asthma emergency department visits associated with future oak pollen under baseline (1994-2010 average) conditions and two climate scenarios.

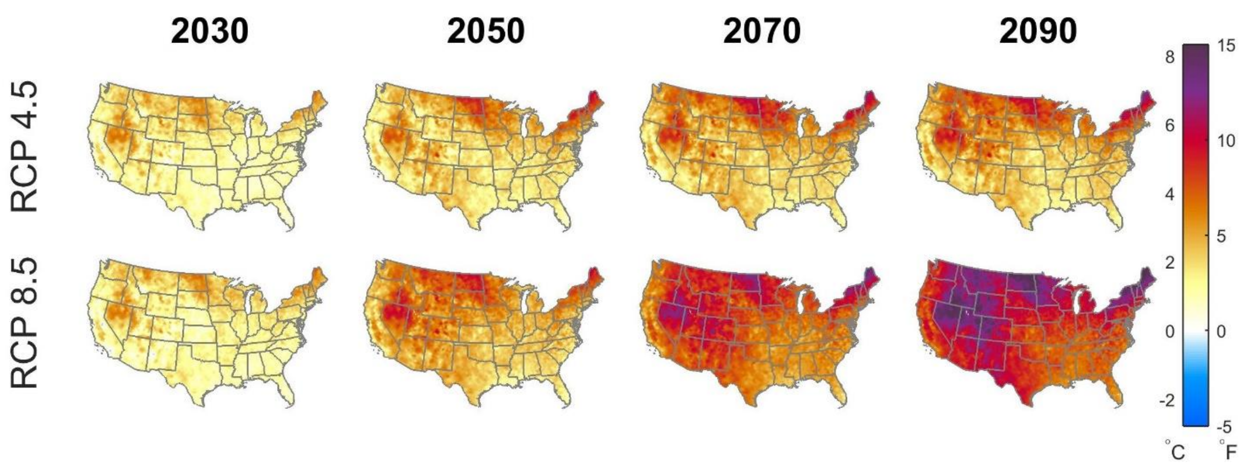

Figure S4. Absolute change in January through March average temperature (degrees C or F) for each RCP scenario in each of the forecast years using output from the CanESM2 model.

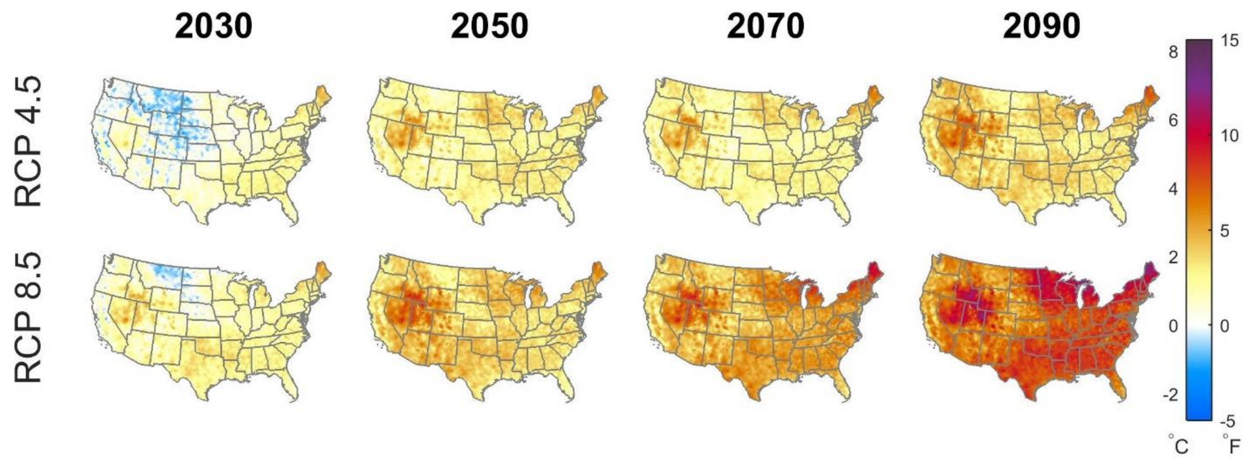

Figure S5. As for Figure S4, but using output from the CCSM4 model.

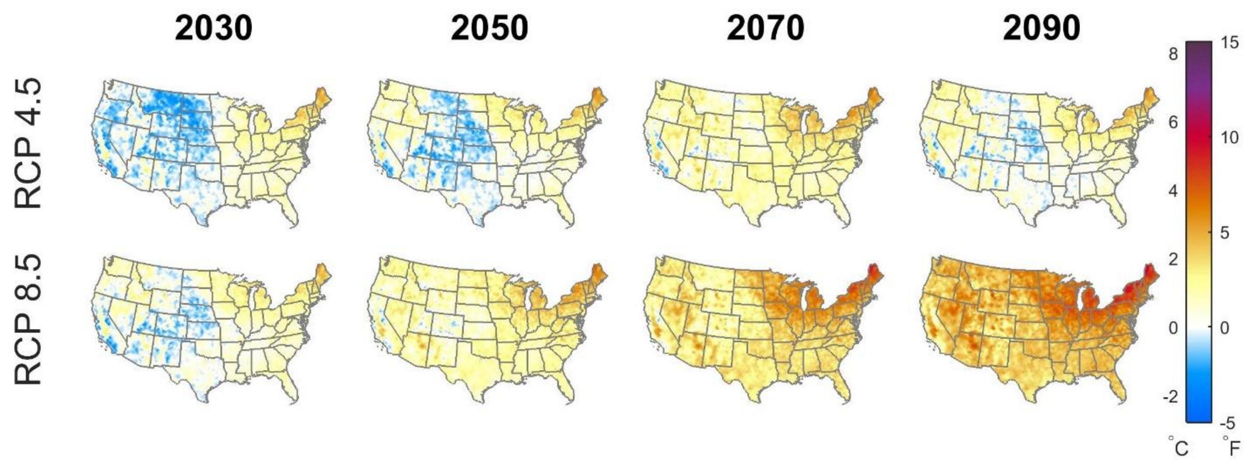

Figure S6. As for Figure S4, but using output from the GISS-E2-R model.

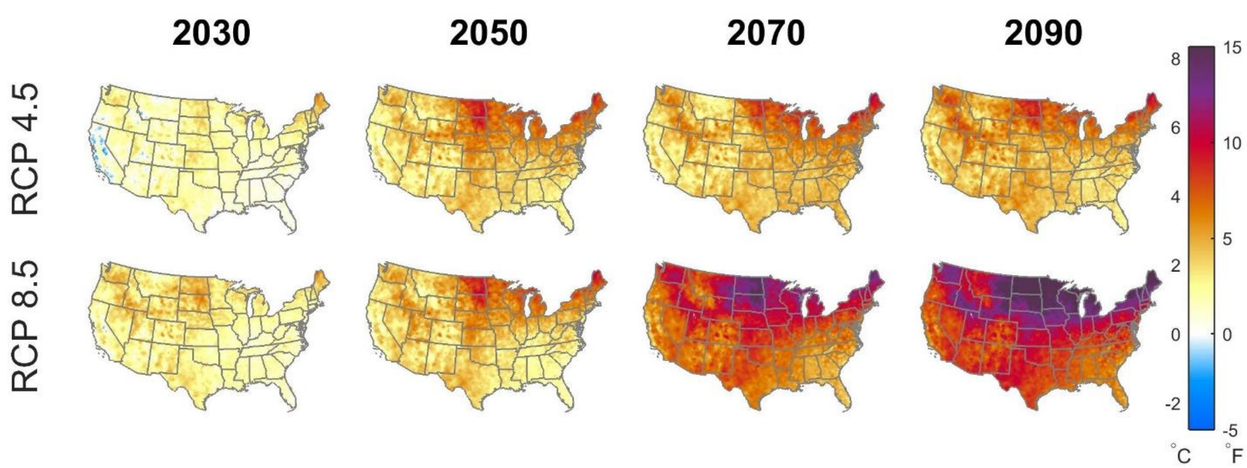

Figure S1. As for Figure S, but using output from the HadGEM2-ES model.

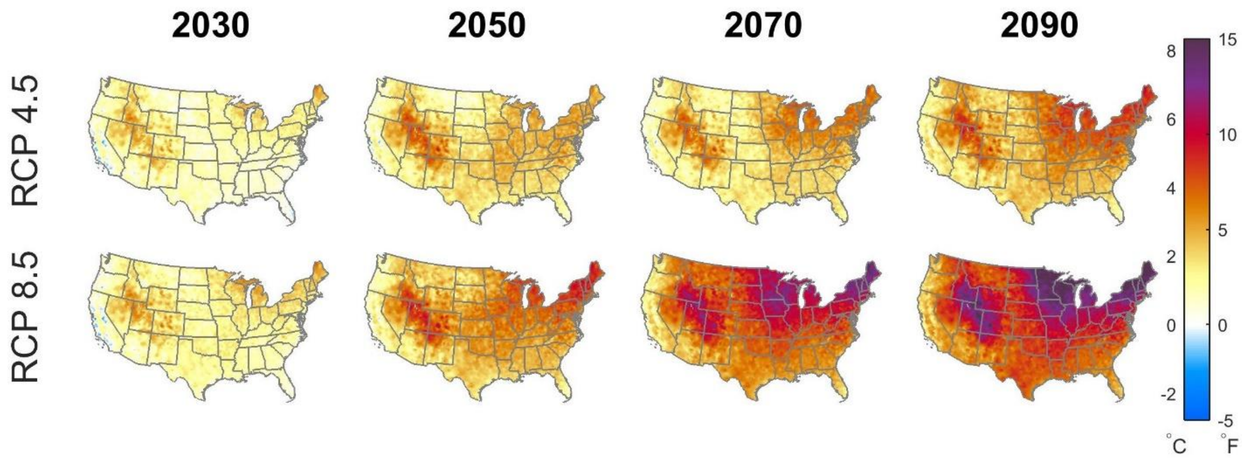

Figure S2. As for Figure S, but using output from the MIROC5 model.

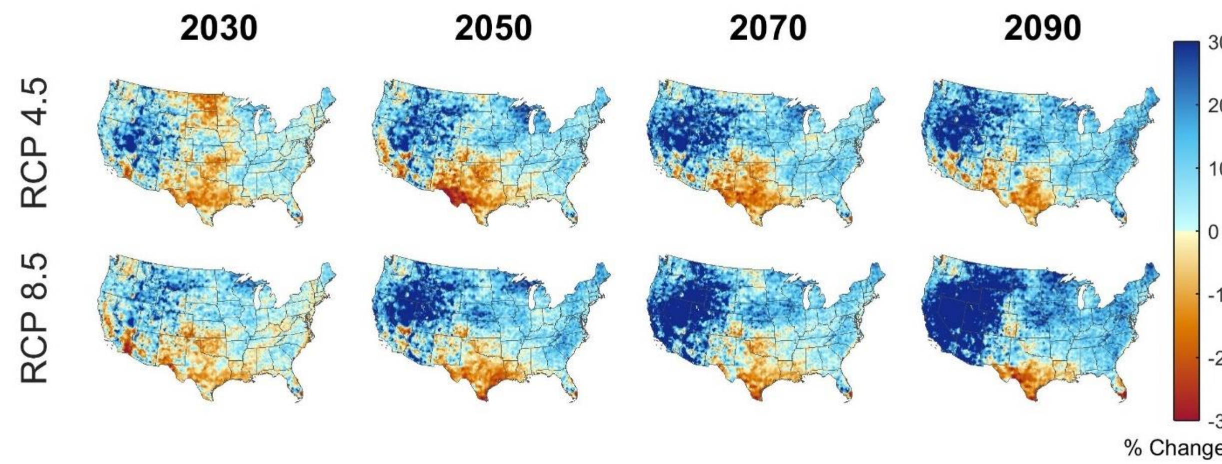

Figure S3. Percent change in cumulative annual precipitation (mm) for each RCP scenario for the period starting in September of the year before the forecast year shown through August of the forecast year using output from the CanESM2 model.

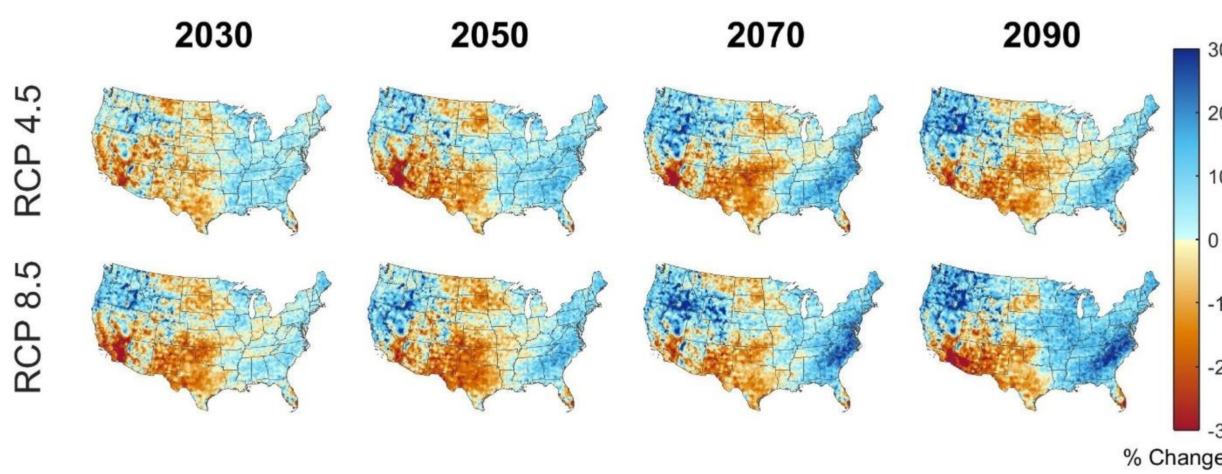

Figure S4. As for Figure S3, but using output from the CCSM4 model.

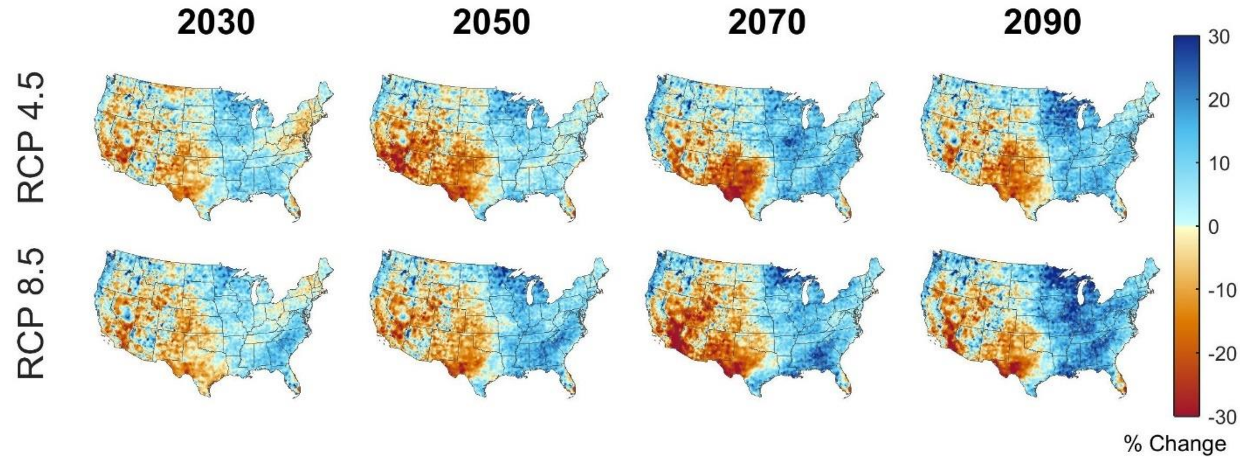

Figure S5. As for Figure S3, but using output from the GISS-E2-R model.

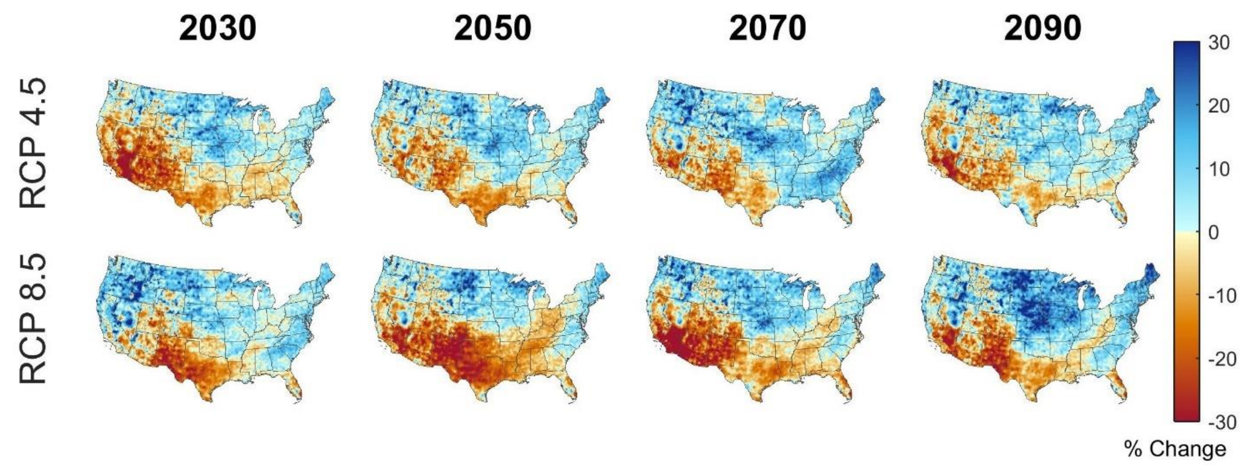

Figure S6. As for Figure S3, but using output from the HadGEM2-ES model.

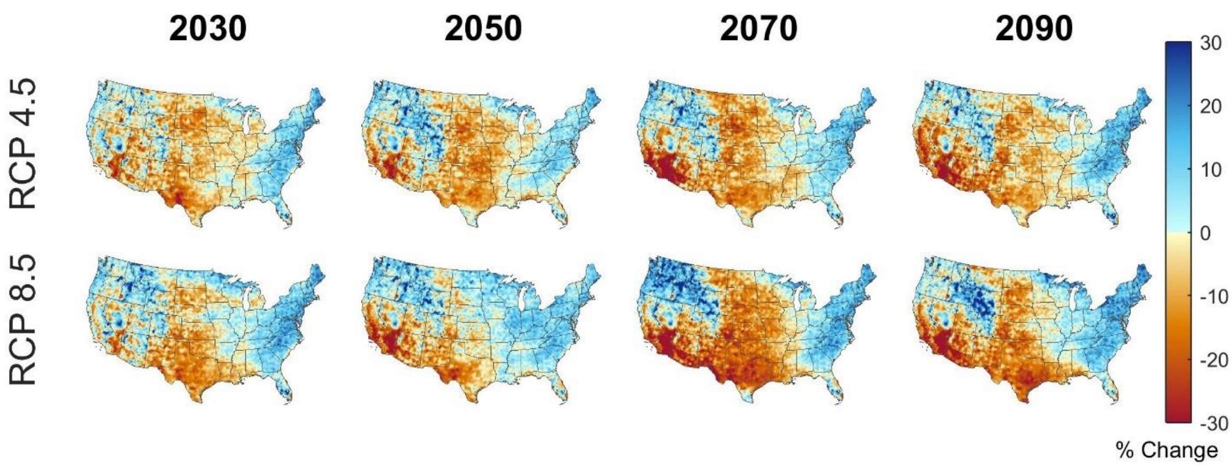

Figure S7. As for Figure S3, but using output from the MIROC5 model.

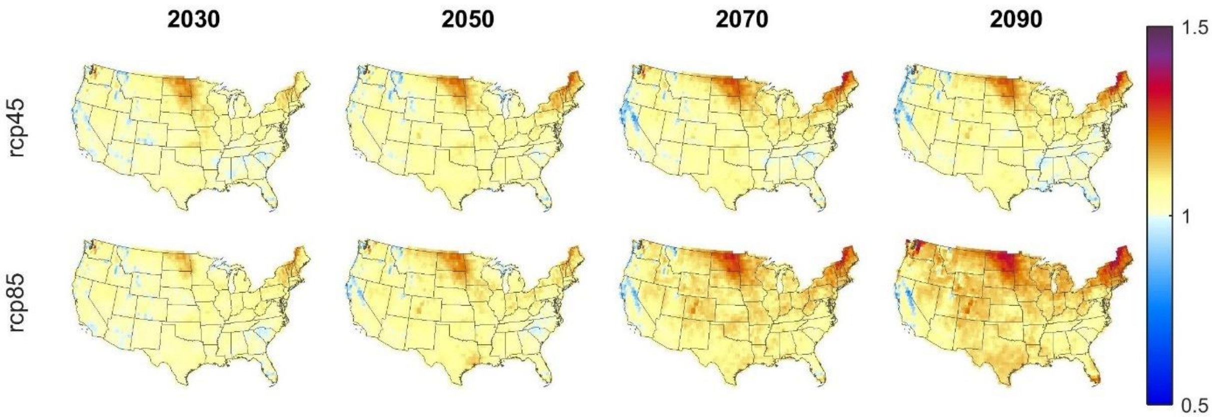

Figure S8. Ratio of future projected to baseline (mean 1994-2010) oak pollen season length (days), using temperature and precipitation output from the CanESM2 model.

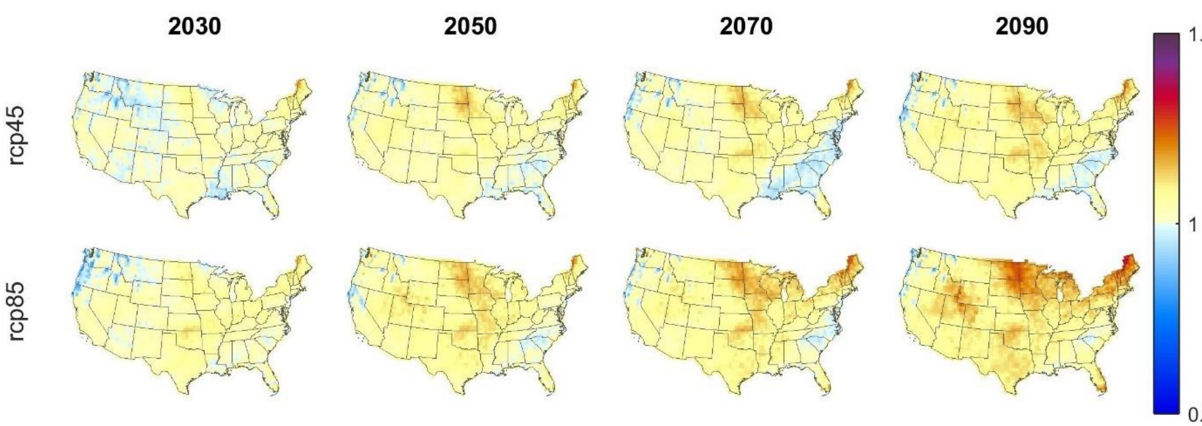

Figure S9. As for Figure S8, but using temperature and precipitation output from the CCSM4 model.

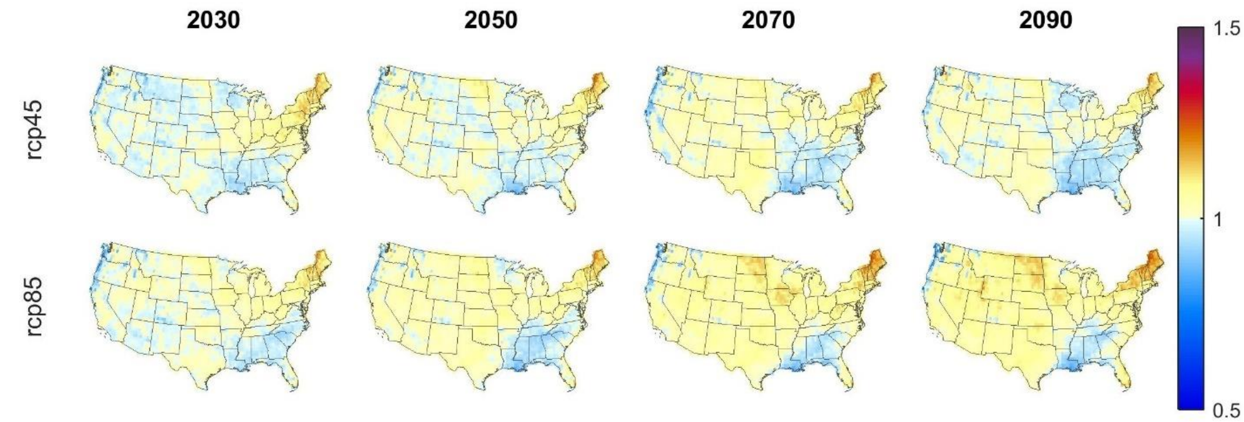

Figure S10. As for Figure S8, but using temperature and precipitation output from the GISS-E2-R model.

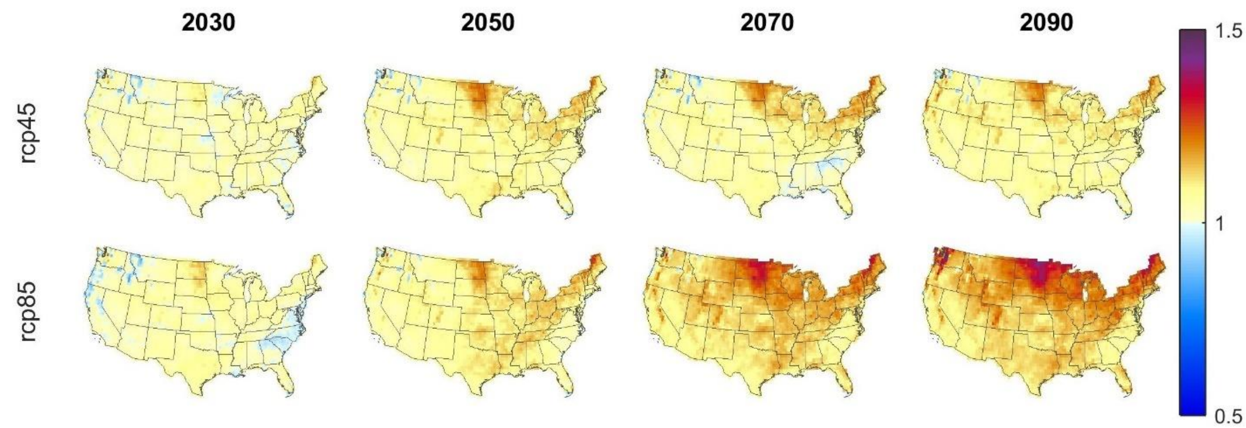

Figure S11. As for Figure S8, but using temperature and precipitation output from the HadGEM2-ES model.

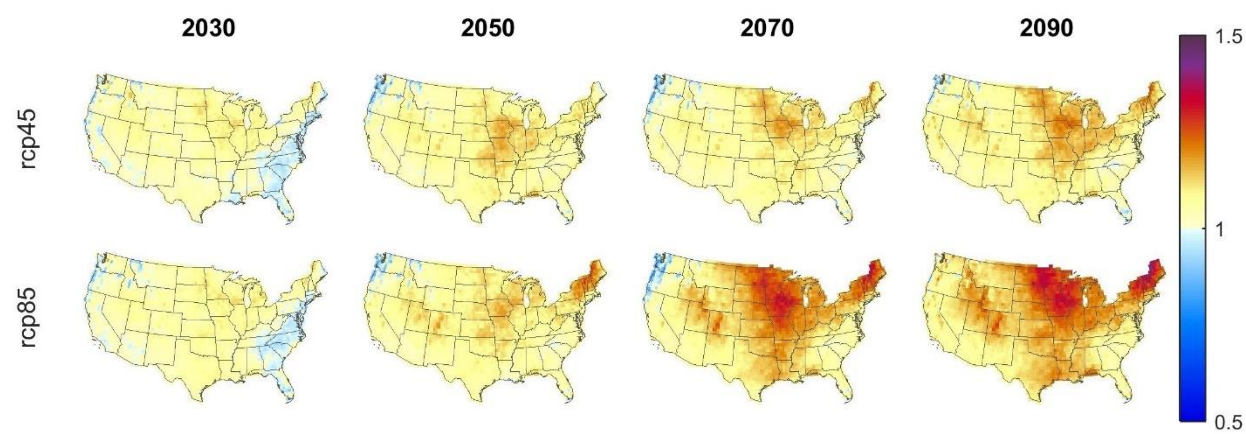

Figure S12. As for Figure S8 but using temperature and precipitation output from the MIROC5 model.

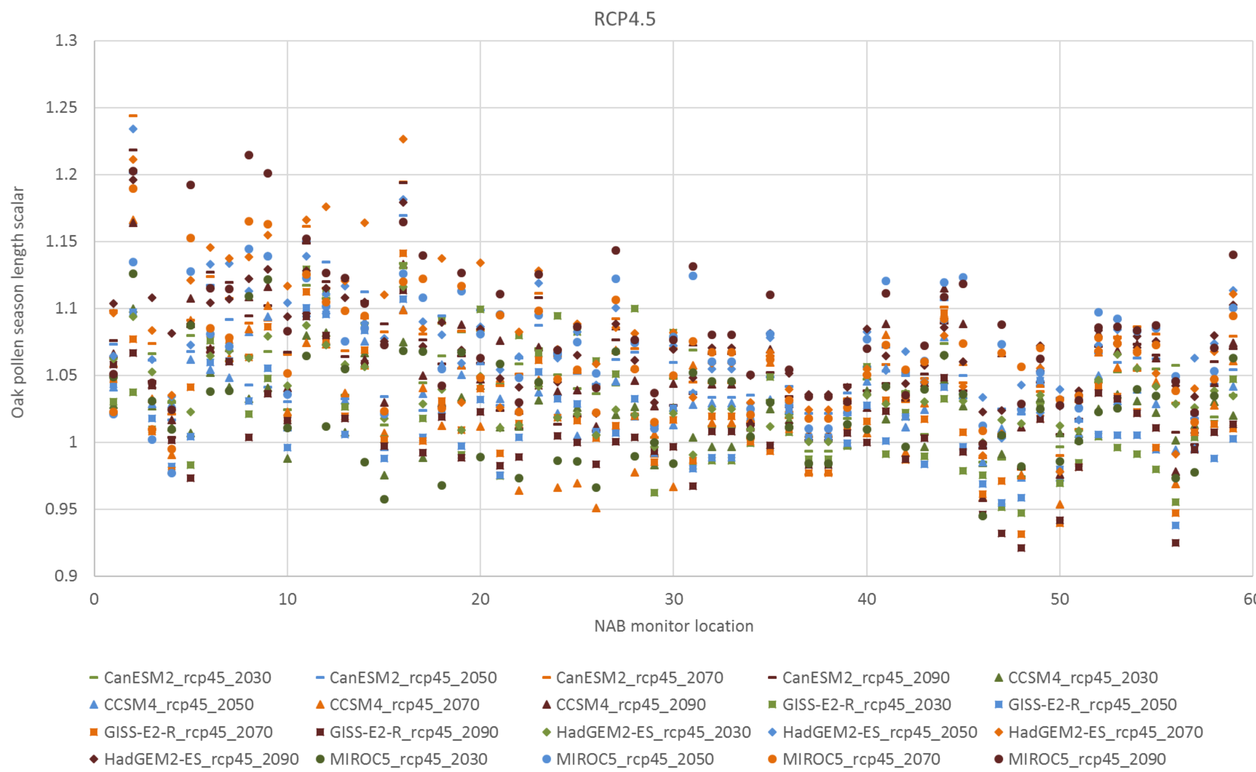

Figure S13. Oak pollen season length scalars (modeled future season length over modeled 1994-2010 average season length in days) for RCP4.5 for each monitor location, separately for each General Circulation Model and year.

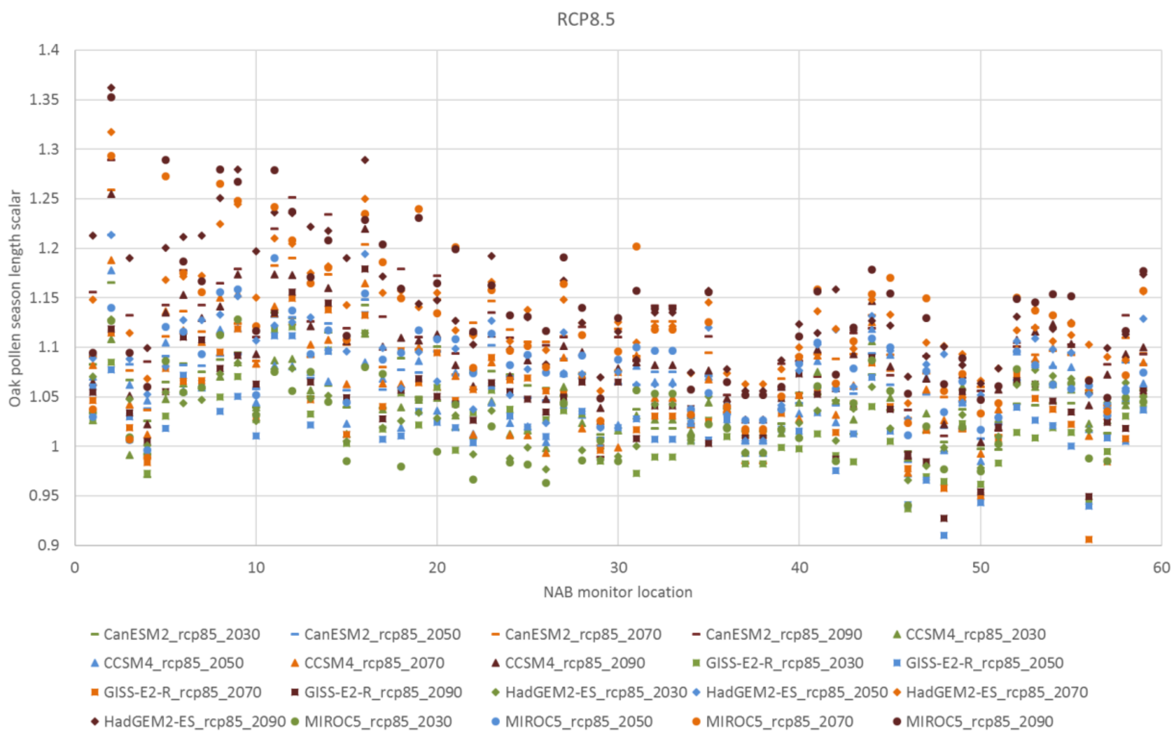

Figure S14. As for Figure S13 but for the RCP8.5 scenario.

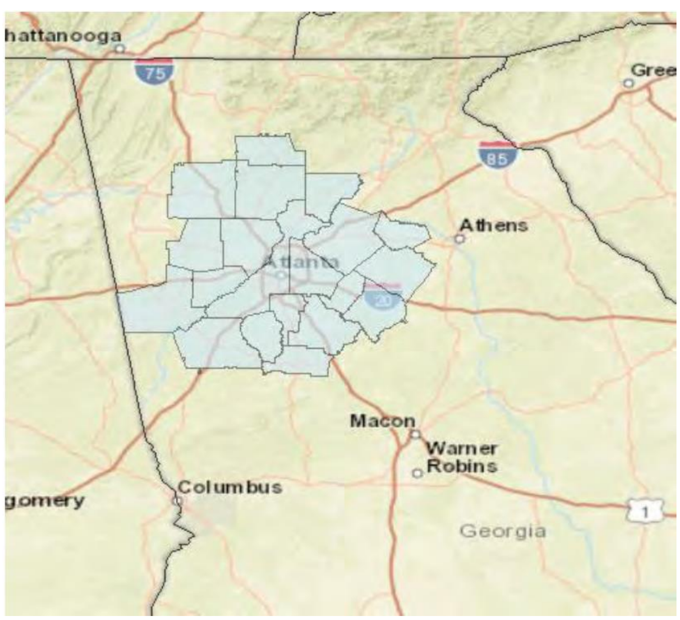

Figure S15. City definition for Atlanta, matching as closely as possible the geographical area included by Darrow et al. (2012).

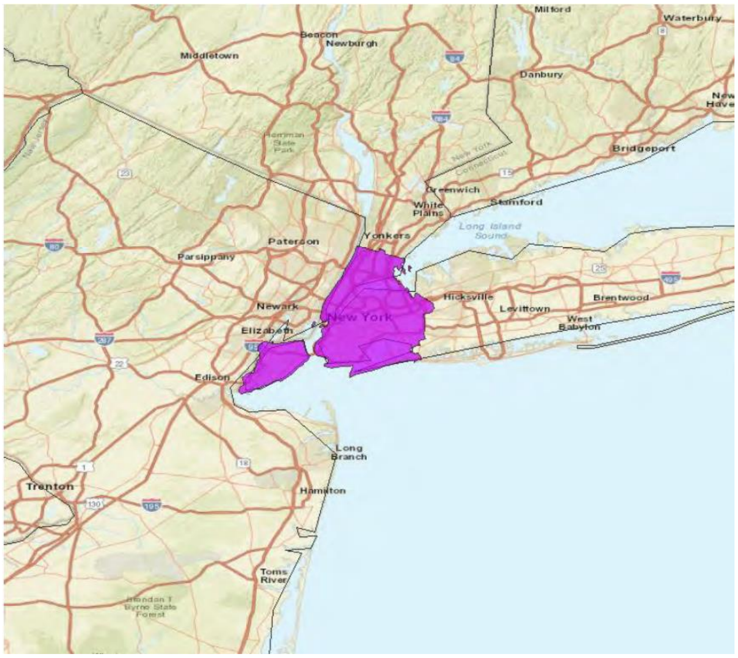

Figure S16. City definition for New York City, matching as closely as possible the geographical area included by Ito et al. (2015).

Figure S17. City definition for Cincinnati, matching as closely as possible the geographical area included by Zhong et al. (2006).

Study	Location	Years	Outcome Definition and Geographic Extent	Pollen type(s) significantly associated with outcome[2]	Consideration of air pollution as confounder
Babin et al. 2007	Washington, DC	2001-2004	Asthma ED visits (age 1-17) in Washington, DC	Tree,[3] grass[4]	No
Darrow et al. 2012	Atlanta, GA	1993-2004	Asthma ED visits (all ages) in the 20-county Atlanta metropolitan area	Oak, grass	Yes
Gleason et al. 2014	New Jersey	2004-2007	Asthma ED visits (age 3-17) in the state of New Jersey	Tree, weed[5]	No
Heguy et al. 2008	Montreal, QC, Canada	1994-2004	Asthma ED visits (age 0-8) in Montreal	Grass	Yes
Ito et al. 2015	New York, NY	2002-2012	Asthma ED visits (all ages) from 52 hospitals comprising 95% of all ED visits in NYC	Maple, birch, beech, ash, sycamore, oak, hickory	Yes
Lierl & Hornung 2003	Cincinnati, OH	1996-1997	Combined measure of asthma ED visits and inpatient hospitalizations (age 0-18) at the Cincinnati Children's Hospital[1]	Total pollen	Yes
Sun et al. 2016	Wake County, NC	2006-2012	Asthma ED visits (all ages) at 8 civilian hospital-affiliated EDs	Tree, grass, weed	Yes
Zhong et al. 2006	Cincinnati, OH	2002 only	Asthma visits (age 1-18), defined as either an ED visit or an outpatient clinic visit, at the Cincinnati Children's Hospital[6]	Oak/maple,[7] pine family	Yes

Table S1. Studies of the relationship between daily pollen concentrations and asthma emergency department (ED) visits in the US and Canada.

[2] In single-pollen type models.
[3] "Tree" refers to the sum of all observed tree pollen genera within a given study.
[4] "Grass" refers to the grass pollen family (Poaceae). Finer taxonomic classification of grass pollen taxa is typically not available in studies relying on NAB data, as different grass pollen genera and species are not distinguishable from each other under a standard microscope.
[5] "Weed" refers to the sum of all observed weed pollen genera within a given study.
[6] According to Lierl and Hornung (2003) the Cincinnati Children's Hospital "provides virtually all the emergency room and inpatient care for pediatric asthma patients residing in the urban Cincinnati area, as well as the majority of inpatient asthma care for children living in the surrounding suburban and rural areas"
[7] Refers to the sum of oak and maple pollen

Station ID	Station name	Station lat	Station lon	Observed baseline season length (days)	Modeled baseline season length (days)	Observed season total count (mean ± std, pollen/m^3)
1	Seattle, WA	47.66	-122.29	16	28.4	602 ± 261
2	Fargo, ND	46.84	-96.87	21	20.8	1993 ± 1130
3	Vancouver, WA	45.62	-122.5	54	25.7	168 ± 30
4	Eugene, OR	44.04	-123.09	28	26.6	539 ± 501
5	LaCrosse, WI	43.88	-91.19	25	21.8	2531 ± 760
6	Rochester, NY	43.1	-77.58	24	24.0	2411 ± 2259
7	Niagara Falls, ON, Canada	43.09	-79.09	33	23.6	1076 ± 169
8	Madison, WI	43.08	-89.43	19	21.9	3278 ± 1326
9	Waukesha, WI	43.02	-88.24	21	22.4	2329 ± 1186
10	London, ON, Canada	42.99	-81.25	40	22.5	1027 ± 609
11	Albany, NY	42.68	-73.77	20	21.1	7139 ± 4299
12	Chelmsford, MA	42.6	-71.35	20	20.2	5310 ± 1744
13	St. Clair Shores, MI	42.51	-82.9	26	24.2	1442 ± 965
14	Salem, MA	42.5	-70.92	17	20.7	3058 ± 1229
15	Erie, PA	42.1	-80.13	19	22.8	2953 ± 1484
16	Olean, NY	42.09	-78.43	34	19.8	1618 ± 676
17	Chicago, IL	41.91	-87.77	42	23.6	995 ± 720
18	Waterbury, CT	41.55	-73.07	30	19.4	5491 ± 5087
19	Omaha, NE	41.14	-95.97	25	24.5	1298 ± 642
20	Armonk, NY	41.13	-73.73	19	21.4	13695 ± 5761
21	Lincoln, NE	40.82	-96.64	26	26.0	4047 ± 3516
22	Springfield, NJ	40.74	-74.19	25	22.7	9271 ± 4074
23	Pittsburgh, PA	40.47	-79.95	21	24.0	3258 ± 1645
24	Philadelphia, PA	39.96	-75.16	35	24.5	4327 ± 2913
25	York, PA	39.94	-76.71	39	23.7	4301 ± 1553
26	Cherry Hill, NJ	39.94	-74.91	29	24.2	7133 ± 4859
27	Indianapolis, IN	39.91	-86.2	19	23.5	1860 ± 1476
28	New Castle, DE	39.66	-75.57	35	23.7	3794 ± 455
29	Reno, NV	39.56	-119.77	39	32.8	847 ± 1530
30	Baltimore, MD	39.37	-76.47	25	25.2	2714 ± 1654
31	Kansas City, MO	39.08	-94.58	23	25.6	7058 ± 5936
32	Colorado Springs 2, CO	38.87	-104.83	39	29.7	572 ± 498
33	Colorado Springs 1, CO	38.87	-104.82	52	29.7	617 ± 508
34	Roseville, CA	38.76	-121.27	36	36.4	642 ± 508
35	Lexington, KY	38.04	-84.5	26	24.4	1893 ± 2481
36	Pleasanton, CA	37.69	-121.91	43	37.1	2829 ± 2095

37	San Jose 1, CA	37.33	-121.94	50	35.2	1937 ± 1419
38	San Jose 2, CA	37.31	-121.97	47	35.2	2689 ± 1996
39	Las Vegas, NV	36.17	-115.15	52	39.5	263 ± 127
40	Durham, NC	36.05	-78.9	23	27.0	7504 ± 4964
41	Tulsa 1, OK	36.03	-95.87	24	27.6	15626 ± 8670
42	Knoxville, TN	35.95	-84.01	34	25.0	1635 ± 1309
43	Los Alamos, NM	35.88	-106.32	32	31.9	454 ± 162
44	Oklahoma City, OK	35.61	-97.6	30	29.8	2868 ± 1612
45	Fort Smith, AR	35.35	-94.39	23	27.1	4345 ± 2921
46	Charlotte, NC	35.3	-80.75	28	28.7	12233 ± 7994
47	Little Rock, AR	34.75	-92.39	24	27.6	6456 ± 4239
48	Huntsville, AL	34.73	-86.59	23	25.6	4172 ± 2397
49	Santa Barbara, CA	34.44	-119.76	63	37.8	1056 ± 552
50	Atlanta, GA	33.97	-84.55	25	26.9	11663 ± 4778
51	Orange, CA	33.78	-117.86	50	40.9	951 ± 583
52	Dallas, TX	33.04	-96.83	42	31.2	2344 ± 502
53	Waco, TX	31.51	-97.2	69	33.2	26968 ± 12960
54	Georgetown, TX	30.64	-97.76	25	34.2	36066 ± 6305
55	College Station, TX	30.64	-96.31	26	33.2	13474 ± 6355
56	Tallahassee, FL	30.44	-84.28	35	29.2	25830 ± 25080
57	Tampa, FL	28.06	-82.43	49	33.7	21989 ± 18927
58	Corpus Christi, TX	27.8	-97.4	30	38.2	11743 ± 3964
59	Dayton, OH	39.76	-84.19	27	24.0	5739 ± 1211

Table S2. National Allergy Bureau station ID, name, latitude, longitude, observed mean (1994-2010) oak pollen season length, modeled baseline (2015) oak pollen season length, and observed mean (1994-2010) season total oak pollen concentration, for the 59 stations used in this study. Station ID, name, latitude, longitude, observed baseline season length, and observed season total count are reproduced from Zhang et al. (2015) for 58 stations, and obtained directly from the NAB station for Dayton, OH. Stations are numbered by latitude North to South. Modelled baseline season length is calculated as described in the Methods.

Center (Modeling Group)	Model Acronym	References
National Center for Atmospheric Research	CCSM4	Gent et al. 2011; Neale et al. 2013
NASA Goddard Institute for Space Studies	GISS-E2-R	Schmidt et al. 2006
Canadian Centre for Climate Modeling and Analysis	CanESM2	Von Salzen et al. 2013
Met Office Hadley Centre	HadGEM2-ES	Collins et al., 2011; Davies et al. 2005
Atmosphere and Ocean Research Institute, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC5	Watanabe et al. 2010

Table S3. General Circulation Models used in the analyses.

Region	Age range (years)	Oak pollen-related asthma ED visits (x100)	Population (x100,000)
Total three cities	0-17[a]	29 (15 - 43)	54
	18-99	14 (7 - 23)	123
	Total	44 (22 - 66)	176
New York City	0-17	18 (11 - 27)	30
	18-64	14 (7 - 22)	77
	Total	32 (18 - 49)	107
Atlanta	0-17	1 (0 - 1)	15
	18-99	0 (0 - 1)	45
	Total	1 (1 - 1)	60
Cincinnati	0-18	10 (3 - 16)	9

Table S4. City-specific oak pollen-related asthma emergency department (ED) visits in 2010, using average 1994-2010 oak pollen concentrations and season length with city-specific concentration-response functions. Confidence intervals (95%, in parentheses) represent uncertainty in concentration-response function only.

		New York City	Atlanta	Cincinnati	Total
2030	**Baseline**	3,700 (2,100 – 5,600)	100 (100 - 200)	1,000 (300 - 1500)	4,900 (2,400 – 7,300)
	RCP4.5	300 (8%)	0 (-1%)	0 (4%)	300 (7%)
	RCP8.5	100 (3%)	0 (-2%)	0 (4%)	200 (3%)
2050	**Baseline**	4,400 (2,400 – 6,600)	100 (100 - 200)	1,000 (300 - 1500)	5,500 (2,800 – 8,200)
	RCP4.5	300 (6%)	0 (1%)	100 (6%)	300 (6%)
	RCP8.5	200 (5%)	0 (1%)	100 (7%)	300 (6%)
2070	**Baseline**	5,000 (2,800 – 7,500)	100 (100 - 200)	900 (300 – 1,400)	6,100 (3,200 – 9,100)
	RCP4.5	300 (5%)	0 (-2%)	100 (7%)	300 (5%)
	RCP8.5	500 (11%)	0 (3%)	100 (11%)	600 (10%)
2090	**Baseline**	5,400 (3,000 -8,100)	200 (100 - 200)	900 (300 – 1,400)	6,500 (3,400 – 9,700)
	RCP4.5	300 (5%)	0 (0%)	100 (8%)	300 (5%)
	RCP8.5	600 (12%)	0 (3%)	100 (12%)	800 (12%)

Table S5. Annual city-specific oak pollen-related asthma emergency department (ED) visits (all ages) for baseline (1994-2010 oak pollen season with future population) and change from baseline for each RCP scenario, averaged across all five General Circulation Models. Confidence intervals (95%, in parentheses) reflect uncertainty in concentration-response function only.