Modeling climate change effects on air quality: Studies of allergenic tree pollen emission and transport

Yong Zhang, Leonard Bielory,
Lai-yung Ruby Leung and Panos G. Georgopoulos

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Computational Chemodynamics Laboratory
Environmental and Occupational Health Sciences Institute (EOHSI)
170 Frelinghuysen Road, Piscataway, NJ 08854

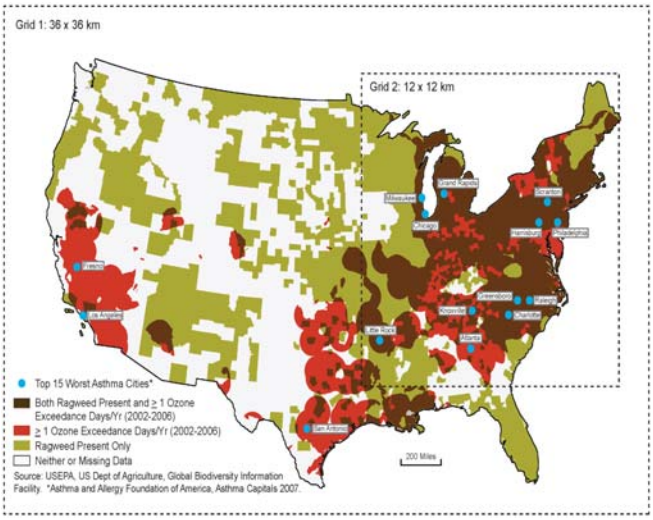
Outline

- Introduction to the modeling framework of WRF-SMOKE-CMAQ-Pollen*
- Pollen emission and transport models
- Spatiotemporal emission profiles of birch and oak pollen
- Spatiotemporal concentration profiles of birch and oak pollen
- Summary and ongoing work

* WRF: Weather Research and Forecasting model
SMOKE: Sparse Matrix Operator Kernel Emissions model
CMAQ: Community Multiscale Air Quality model

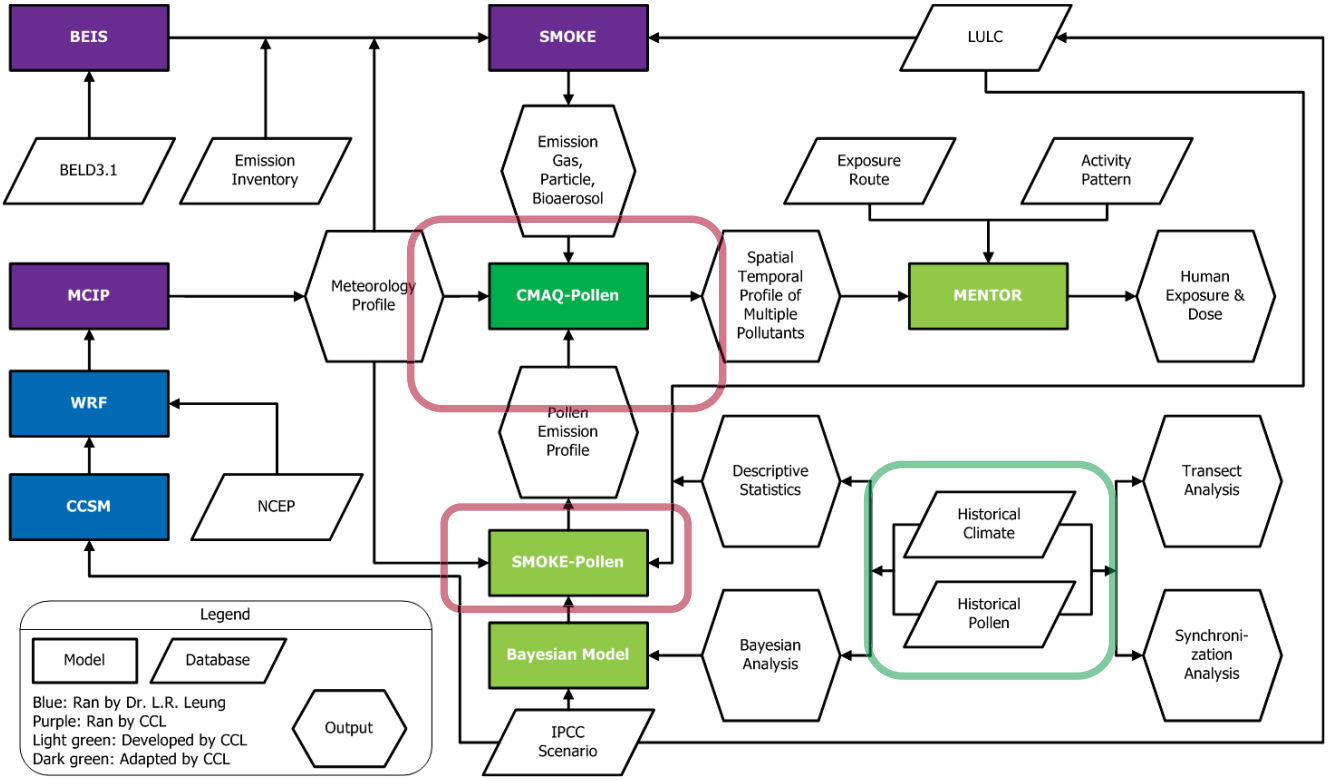
Motivation

- Allergenic pollen acts synergistically with common air pollutants, such as ozone, to cause Allergic Airway Disease (AAD)
  - In US, 55% of employees reported experiencing allergic rhinitis symptoms for an average of 52.5 days
    Lamb et al. (2006)
  - In US, the total direct medical cost of allergic rhinitis was estimated at $3.4 billion in 1996
    Law et al. (2003)
- Climatic change is expected to affect spatiotemporal dynamics of airborne pollen
  - Long range transport and larger quantity of pollen *Slavov et al. (2004); Martin, et al. (2010).*
  - Rapid shifting of flowering time
    Fitter et al. (2002)
  - Dramatic changes of ecologic dynamics in Arctic region *Post et al. (2009)*



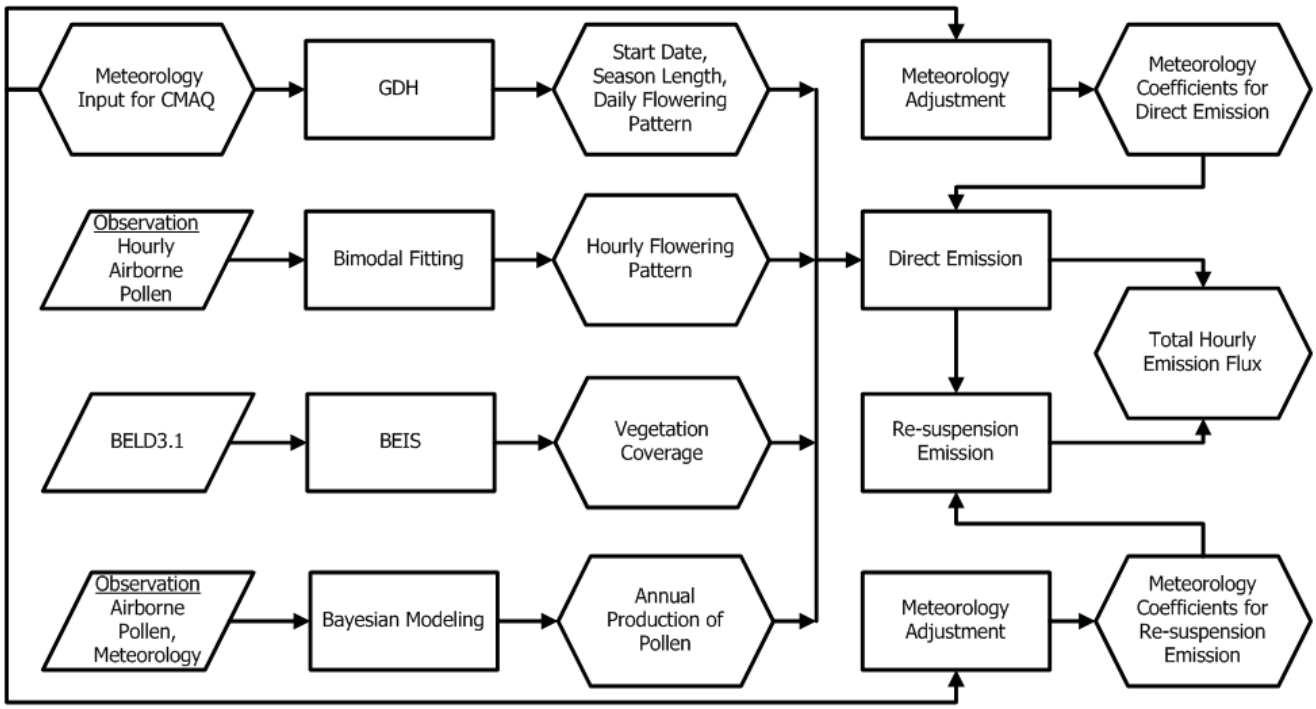
Ragweed and ozone co-occurrence in the continental United States (Adapted from a map published by NRDC, the Natural Resources Defense Council, www.nrdc.org)

A modeling system linking climate change and exposure



BEIS: Biogenic Emission Inventory System; BELD3.1: Biogenic Emissions Land use Database, version 3.1; CCSM: Community Climate System Model; CMAQ: Community Multiscale Air Quality model; IPCC: Intergovernmental Panel on Climate Change; LULC: Land Use and Land Coverage; MCIP: Meteorology-Chemistry Interface Processor; MENTOR: Modeling Environment for Total Risk studies; NCEP: National Center for Environmental Prediction; SMOKE: Sparse Matrix Operator Kernel Emissions model; WRF: Weather Research and Forecasting model.

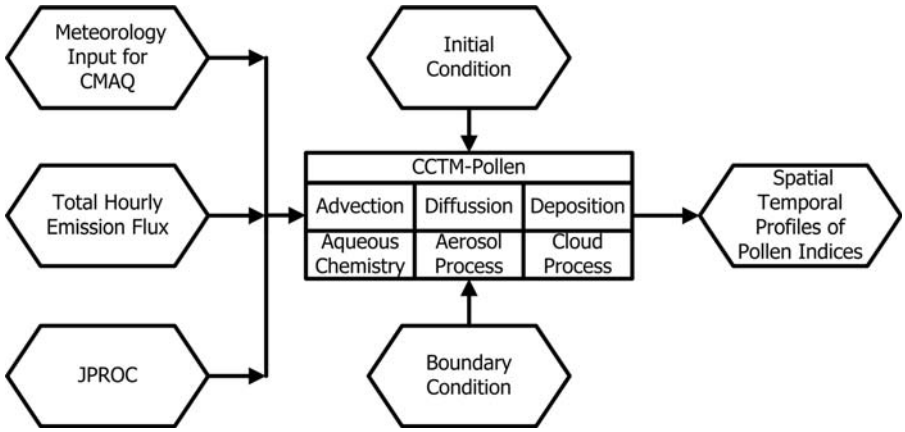
Pollen emission model



BEIS: Biogenic Emission Inventory System; BELD3.1: Biogenic Emissions Land use Database, version 3.1;
CMAQ: Community Multiscale Air Quality model; GDH: Growing Degree Hours

Transport model

- Treat pollen grain as coarse mode particle
- Adapt CMAQ4.7.1 by modifying relavant subroutines such as aero_depv.F, AERO_EMIS.F, AERO_INFO.f and aero_subs.f *etc.*
- Compile adapted CMAQ modules to incorporate different physicochemical process



Governing equations

Adapted from Byun and Schere (2006)

$$\underbrace{\frac{\partial \varphi_p^*}{\partial t}}_{(a)} + \overbrace{\nabla_s \cdot \left[\varphi_p^* \hat{\mathbf{V}}_s\right]}^{(b)} + \underbrace{\frac{\partial(\varphi_p^* \hat{v}^3)}{\partial \hat{x}^3}}_{(c)} + \overbrace{\nabla_s \cdot \left[\overline{\rho}\sqrt{\hat{\gamma}}\hat{\boldsymbol{F}}_{q_p}\right]}^{(d)} + \underbrace{\frac{\partial(\overline{\rho}\sqrt{\hat{\gamma}}\hat{F}^3_{q_p})}{\partial \hat{x}^3}}_{(e)}$$

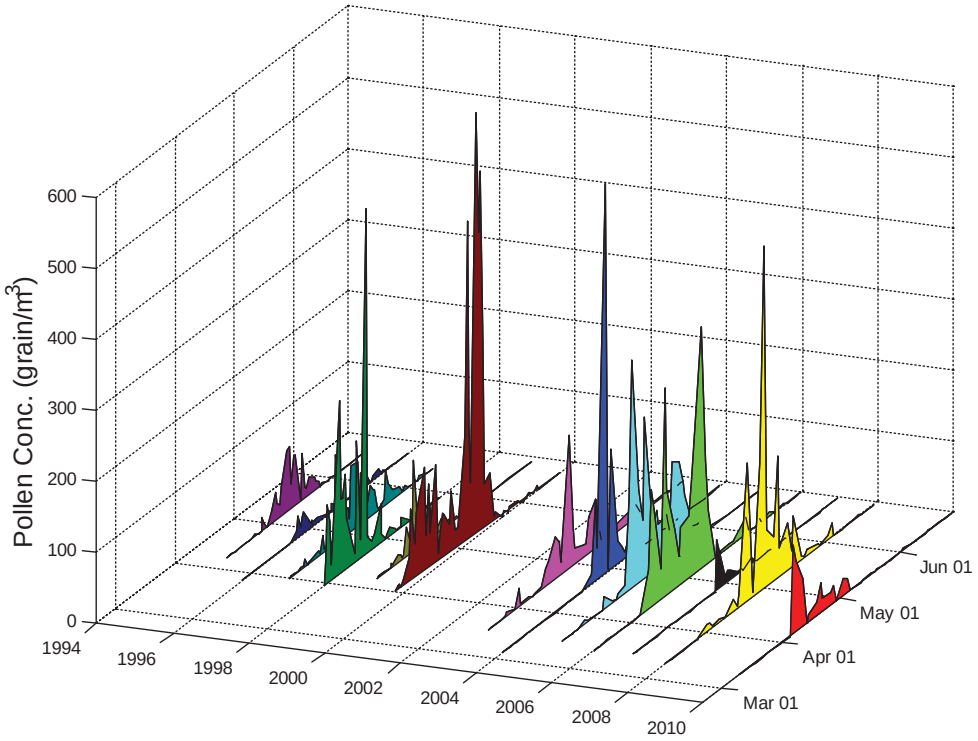
$$= \overbrace{\sqrt{\hat{\gamma}} S_{\varphi_p}}^{(f)} + \underbrace{\left.\frac{\partial \varphi_p^*}{\partial t}\right|_{cld}}_{(g)} + \overbrace{\left.\frac{\partial \varphi_p^*}{\partial t}\right|_{aero}}^{h}$$

(a) time rate of change of pollen concentration, (b) horizontal advection, (c) vertical advection, (d) horizontal eddy diffusion, (e) vertical eddy diffusion, (f) emissions, (g) cloud mixing and aqueous chemistry, (h) aerosol process

CCTM: CMAQ Chemical Transport Model; JPROC: Photolysis rate preprocessor

Variations of biogenic aeroallergens in NJ

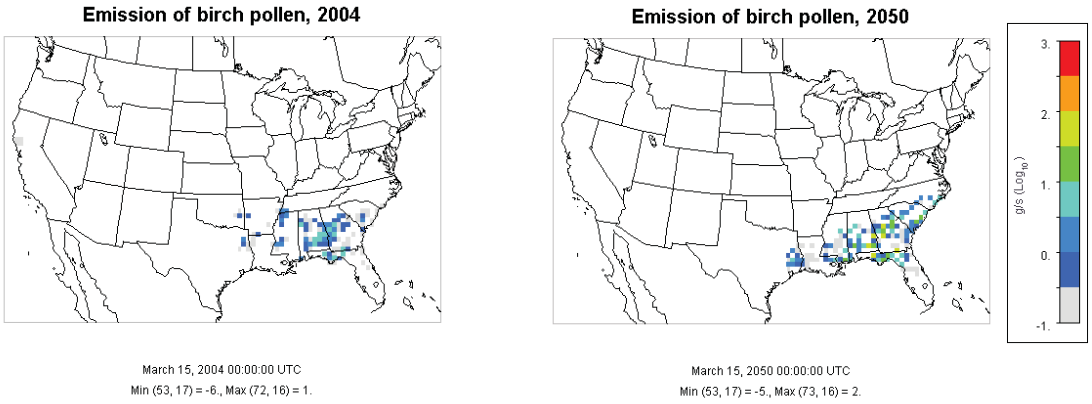
Birch



Variations of mean daily concentrations of birch pollen in New Jersey. Data of daily airborne pollen count is from the pollen monitoring station in Cherry Hill, NJ.

Spatiotemporal emission profiles of birch pollen

- Domain: Contiguous Continental US
- Period: March 15th 00:00 – April 25th 23:00
- Resolution: 50 x 50 km; Hourly; 1 Layer

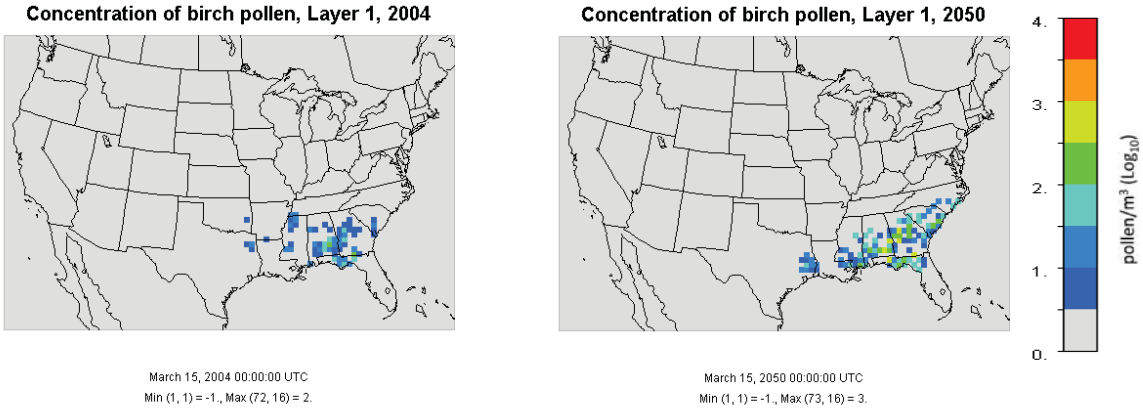


Six representative stations were selected to parameterize emission model

- Observed daily pollen counts should be available for birch, oak, ragweed, mugwort and grass in multiple years (e.g. 1994-2011)
- Representative geographical locations (e.g. East, West, North, South & Middle)

Spatiotemporal concentration profiles of birch pollen, Layer 1

- Domain: Contiguous Continental US
- Period: March 15th 00:00 – April 25th 23:00
- Resolution: 50 x 50 km; Hourly; 10 Layers

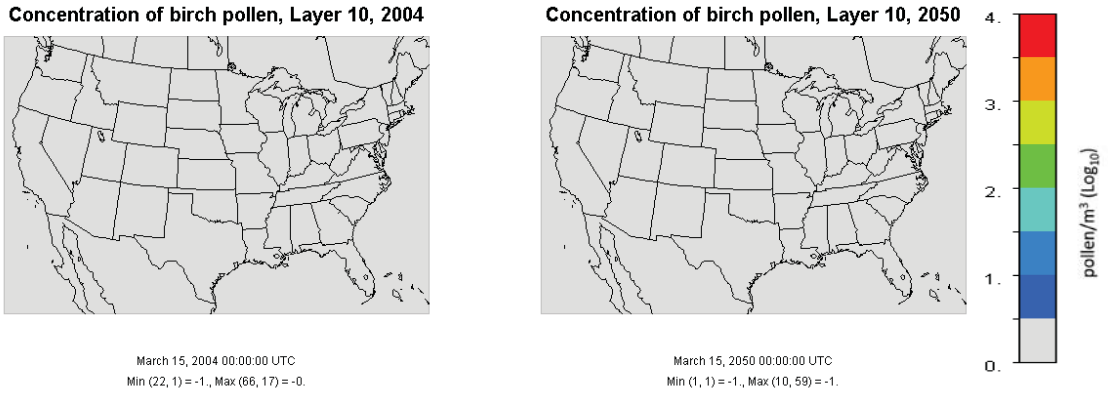


Layers are based on pressure

- Layer 1: 0-59m above the ground surface

Spatiotemporal concentration profiles of birch pollen, Layer 10

- Domain: Contiguous Continental US
- Period: March 15th 00:00 – April 25th 23:00
- Resolution: 50 x 50 km; Hourly; 10 Layers



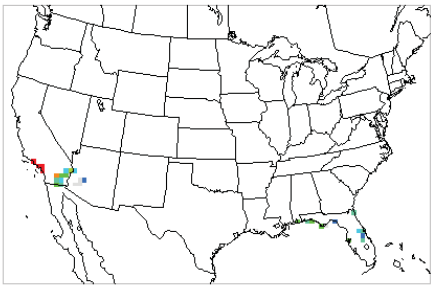
Layers are based on pressure

- Layer 10: 1800m and more above the ground surface

Spatiotemporal emission profiles of oak pollen

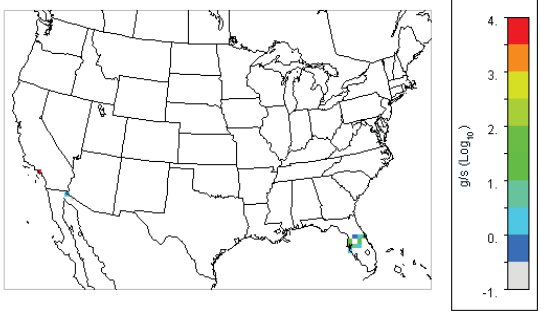
- Domain: Contiguous Continental US
- Period: March 15th 00:00 – April 30th 23:00
- Resolution: 50 x 50 km; Hourly; 1 Layer

Emission of oak pollen, 2004



March 15, 2004 00:00:00 UTC
Min (55, 12) = -2., Max (9, 26) = 6.

Emission of oak pollen, 2050

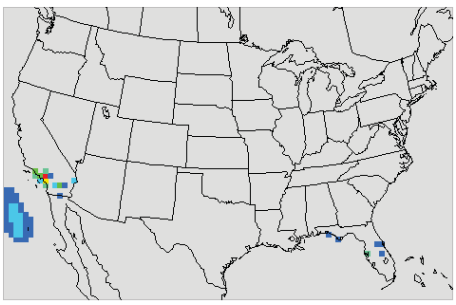


March 15, 2050 00:00:00 UTC
Min (77, 14) = -1., Max (8, 26) = 4.

Spatiotemporal concentration profiles of oak pollen, Layer 1

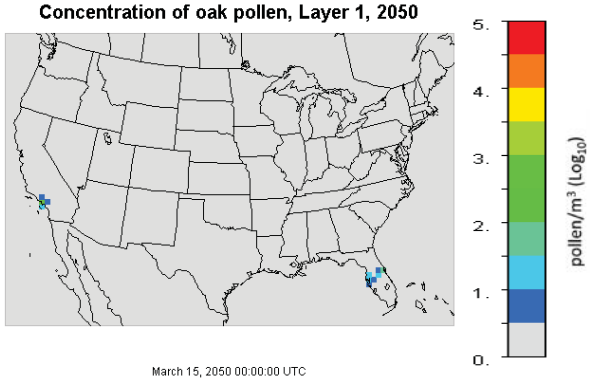
- Domain: Contiguous Continental US
- Period: March 15th 00:00 – April 25th 23:00
- Resolution: 50 x 50 km; Hourly; 10 Layers

Concentration of oak pollen, Layer 1, 2004



March 15, 2004 00:00:00 UTC
Min (17, 1) = -2., Max (9, 26) = 5.

Concentration of oak pollen, Layer 1, 2050



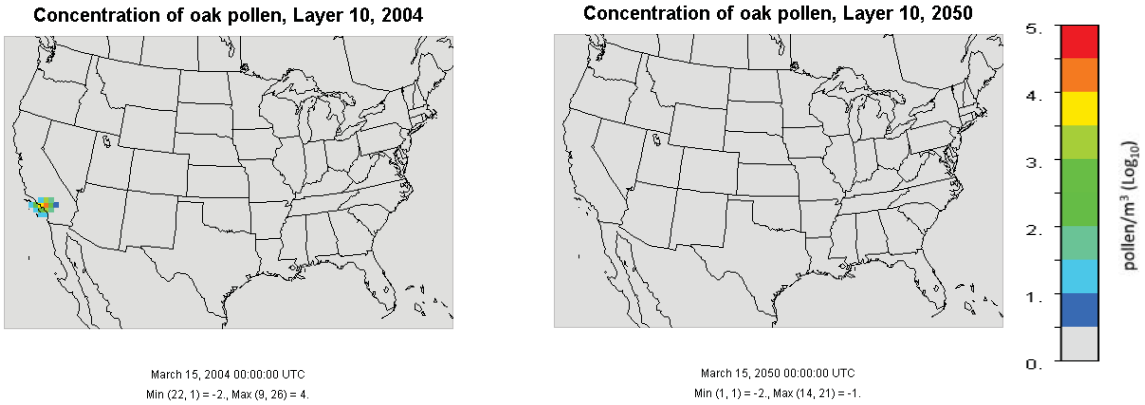
March 15, 2050 00:00:00 UTC
Min (1, 1) = -2., Max (8, 26) = 3.

Layers are based on pressure

- Layer 1: 0-59m above the ground surface

Spatiotemporal concentration profiles of oak pollen, Layer 10

- Domain: Contiguous Continental US
- Period: March 15th 00:00 – April 25th 23:00
- Resolution: 50 x 50 km; Hourly; 10 Layers



Layers are based on pressure

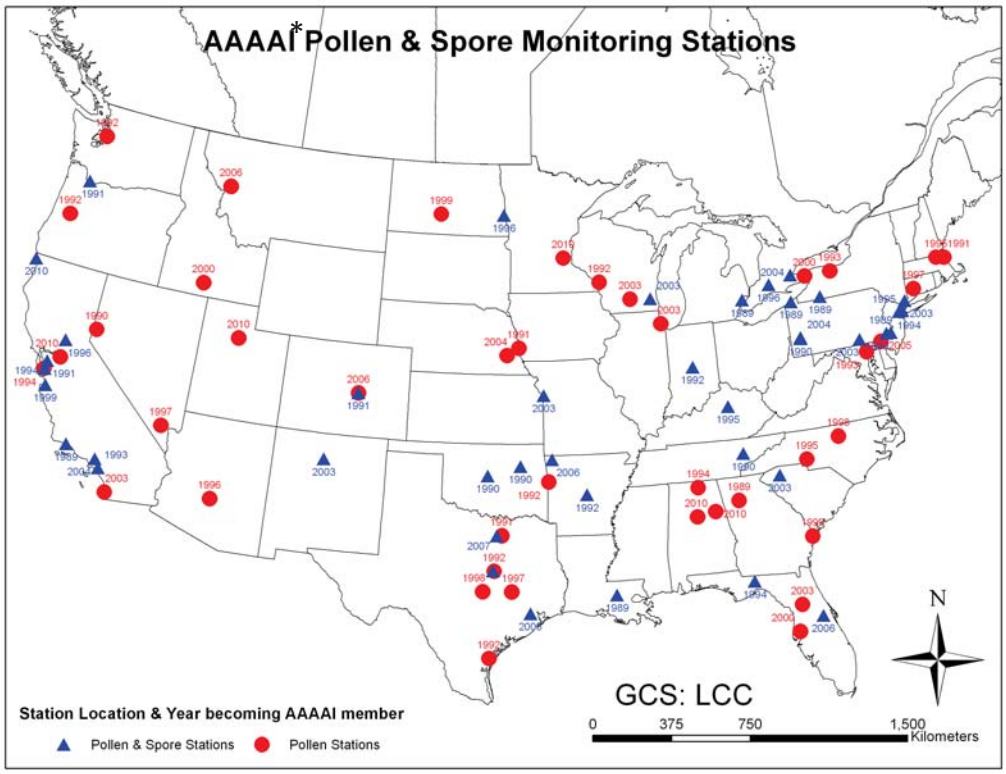
- Layer 10: 1800m and more above the ground surface

Evaluation of WRF-SMOKE-CMAQ-Pollen simulations

- Mean Square Error (MSE) of simulation and observation
- Quantile-Quantile plot of simulation and observation
- Skill Score (SS) of simulation using climatic mean as reference forecast

Warner (2011)

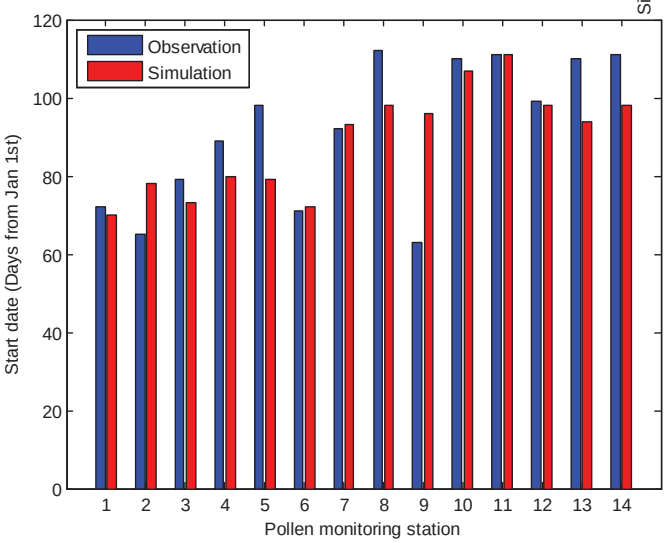
$$SS = \frac{MSE - MSE_{ref}}{0 - MSE_{ref}} = 1 - \frac{MSE}{MSE_{ref}}$$

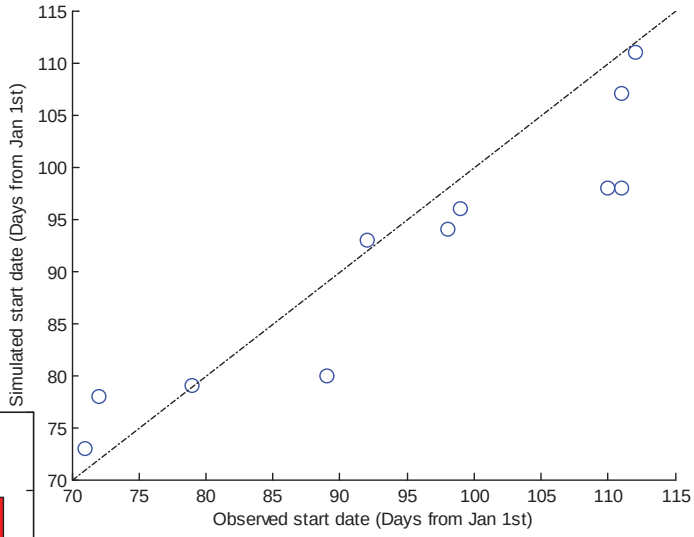


*American Academy of Allergy, Asthma & Immunology

Evaluation of start date estimates of birch pollen

- 14 representative stations with valid daily birch pollen count in 2004
- Observations are paired with simulation estimates in the corresponding grids

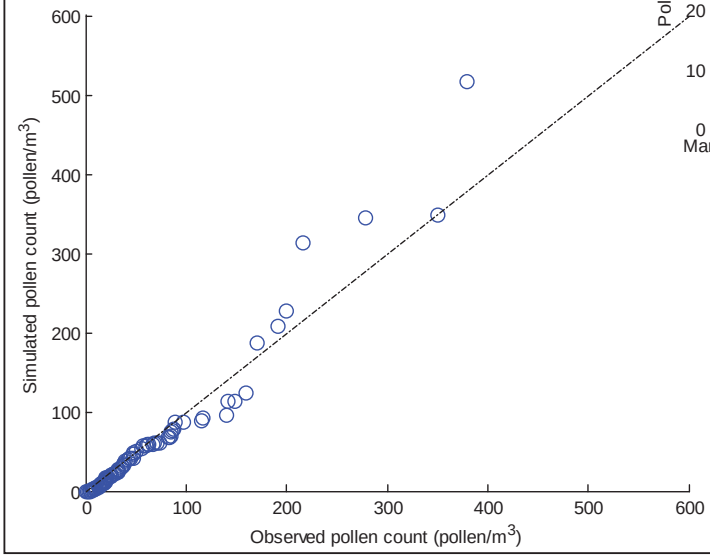


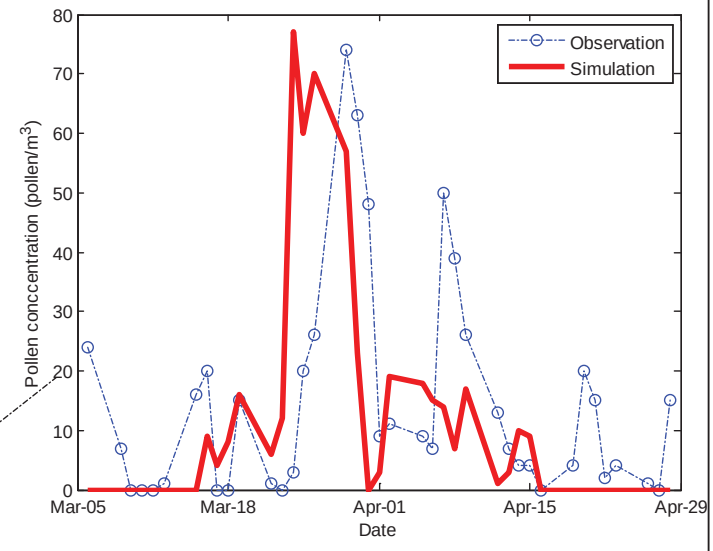


Comparison of simulated and observed start date of birch pollen at 14 monitoring stations which have available records of daily pollen count in 2004

Evaluation of daily birch pollen curve

Quantile-Quantile plot of simulated and observed birch pollen levels in 14 monitoring stations





Comparison of the simulated and observed daily concentrations of birch pollen at a monitoring station (Atlanta, GA); the simulated daily concentrations were obtained by averaging the simulated hourly concentrations at that station

Evaluation of daily birch pollen curve

Root Mean Square Errors (RMSE) and Skill Scores (SS) based on observation, simulation and climatologic mean of daily birch pollen levels

Station	RMSE	RRMSE[a]	RMSE-C[b]	SS
1, Austin (TX)	68	0.11	72	0.06
2, Atalanta (GA)	22	0.04	32	0.33
3, Little Rock (AR)	16	0.10	19	0.15
4, Knoxville (TN)	62	0.10	56	-0.11
5, Durham (NC)	78	0.11	87	0.11
6, Pleasanton (CA)	54	0.13	48	-0.14
7, Baltimore (MD)	24	0.17	27	0.12
8, Cherry Hill (NJ)	256	0.29	239	-0.07
9, York (PA)	27	0.14	30	0.09
10, Armonk (NY)	223	0.34	657	0.66
11, Waterbury (CT)	219	0.59	423	0.48
12, Chicago (IL)	11	0.07	14	0.22
13, Madison (WI)	136	0.20	120	-0.13
14, Onalaska (WI)	27	0.08	22	-0.21

a RRMSE: relative RMSE, percentage of RMSE to annual total pollen count;
b RMSE-C: RMSE based on climatologic mean of pollen levels (2003-2010);

Summary and ongoing work

Summary

- A novel pollen emission model was developed and parameterized based on principles and data of physics, phenology and meteorology
- The existing CMAQ4.7.1 modeling system was adapted to simulate pollen transport based on the new pollen emission module and WRF meteorology dataset established in North American Regional Climate Change Assessment Program
- The WRF-SMOKE-CMAQ-Pollen modeling system was applied to model spatiotemporal profiles of birch pollen emissions and concentrations. Simulation results showed a reasonable agreement with observations.

Ongoing work

- Apply the WRF-SMOKE-CMAQ-Pollen modeling system to ragweed, mugwort and grass pollen
- Evaluate climate change effects on spatiotemporal distributions of biogenic aeroallergens
- Estimate population exposures to biogenic aeroallergens under climate change scenarios

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