

# Documentation for Estimation of PM<sub>2.5</sub> in western US: Total and Attributed to Wildfires and Prescribed Fires

C.E. Reid<sup>1</sup>, M.M. Maestas<sup>1</sup>, E. Considine<sup>1</sup>, G. Li<sup>1</sup>,  
N.H.F. French<sup>2</sup>, M. Billmire<sup>2</sup>, M. Jerrett<sup>3</sup>

<sup>1</sup>University of Colorado Boulder and <sup>2</sup>Michigan Technological University  
and <sup>3</sup>University of California, Los Angeles

December 17, 2018

## Abstract

The purpose of this document is to provide detailed information about the estimation of PM<sub>2.5</sub> (total and attributed to prescribed fires and wildfires) that our work could be reproduced. Figure 1 shows the study area of interest.

## Contents

<b>1</b>	<b>Phase 1: Data Sources and Points of Interest for Machine Learning</b>	<b>3</b>
1.1	PM <sub>2.5</sub> data	4
1.1.1	Processing PM <sub>2.5</sub> data	4
1.1.2	Notes about very high data points	5
1.2	Compare 88101 to 88502 PM <sub>2.5</sub>	6
1.3	PM <sub>2.5</sub> Monitor data from US EPA AQS Air Data Query Tool	11
1.4	EPA PM <sub>2.5</sub> Plots	14
1.5	PM <sub>2.5</sub> data from the Federal Land Manager Environmental Database	15
1.6	PM <sub>2.5</sub> data from the Fire Cache Smoke Monitor Archive	16
1.7	Fire Cache Smoke Monitor (DRI) Plots	19
1.8	California State Air Quality and Meteorological Information System (AQMIS)	21
1.9	CARB Plots	22
1.10	PM <sub>2.5</sub> Monitor data from Uintah Basin	23
1.11	PM <sub>2.5</sub> data from PCAPS in the Salt Lake Valley	25
1.12	Utah Department of Environmental Quality	26
1.13	Utah DEQ Plots	27
1.14	MODIS AOD	28
1.15	GASP-West AOD	30
1.16	MERRA-2	32
1.17	MAIAC	33
1.18	MODIS Thermal Anomalies/Fire Daily L3 Global 1km (MCD14DL)	34

1.19	Landsat-derived burned area essential climate variable (BAECV) fire activity data .	35
1.20	MODIS/Terra and Aqua Burned Area Monthly L3 Global 500 m SIN Grid V006 (MCD64A1) . . . . .	36
1.21	Visible Infrared Imaging Radiometer Suite (VIIRS) (VNP14IMGTDL_NRT) . . .	37
1.22	Classified land cover information from the Landsat-derived NLCD 2011 . . . . .	39
1.23	MODIS Snow Cover Daily L3 Global 500m Grid, Version 6 (MOD10A1 and MYD10A1) . . . . .	40
1.24	Elevation . . . . .	41
1.25	Meteorological Data . . . . .	42
1.26	Dust Storms . . . . .	45
1.27	Locations of Interest . . . . .	46
1.27.1	County Centroids . . . . .	46
1.27.2	Population-weighted county centroids . . . . .	46
1.27.3	Geometric Centroids of Counties Images . . . . .	46
<b>2</b>	<b>Phase 2: Extraction to Observation Locations and Points of Interest</b>	<b>48</b>
<b>3</b>	<b>Phase 3: Merge extracted data</b>	<b>49</b>
3.1	Predictor input files for points of interest . . . . .	50
<b>4</b>	<b>Phase 4: Machine Learning Methods</b>	<b>51</b>
4.1	ML Scripts . . . . .	52
<b>5</b>	<b>Phase 5: Predictions to Points of Interest</b>	<b>53</b>
<b>6</b>	<b>Ideas, To Do, Resources, etc</b>	<b>54</b>
<b>7</b>	<b>PM2.5 Surface Paper Notes</b>	<b>55</b>
7.1	Papers published in Atmospheric Environment - use as style example . . . . .	55
<b>8</b>	<b>Papers to cite/discuss in Introduction and/or Discussion</b>	<b>55</b>
8.1	Notes on Papers . . . . .	55
<b>9</b>	<b>Fire attribution paper</b>	<b>56</b>
9.1	text written for the COPD paper - variation of this may be useful . . . . .	56
	<b>References</b>	<b>57</b>

# 1 Phase 1: Data Sources and Points of Interest for Machine Learning

For the creation of the spatiotemporal daily exposure surface via machine learning, a large number of data sets will be collected as discussed below. The dependent variable will be daily 24-hour  $PM_{2.5}$  from monitoring data.

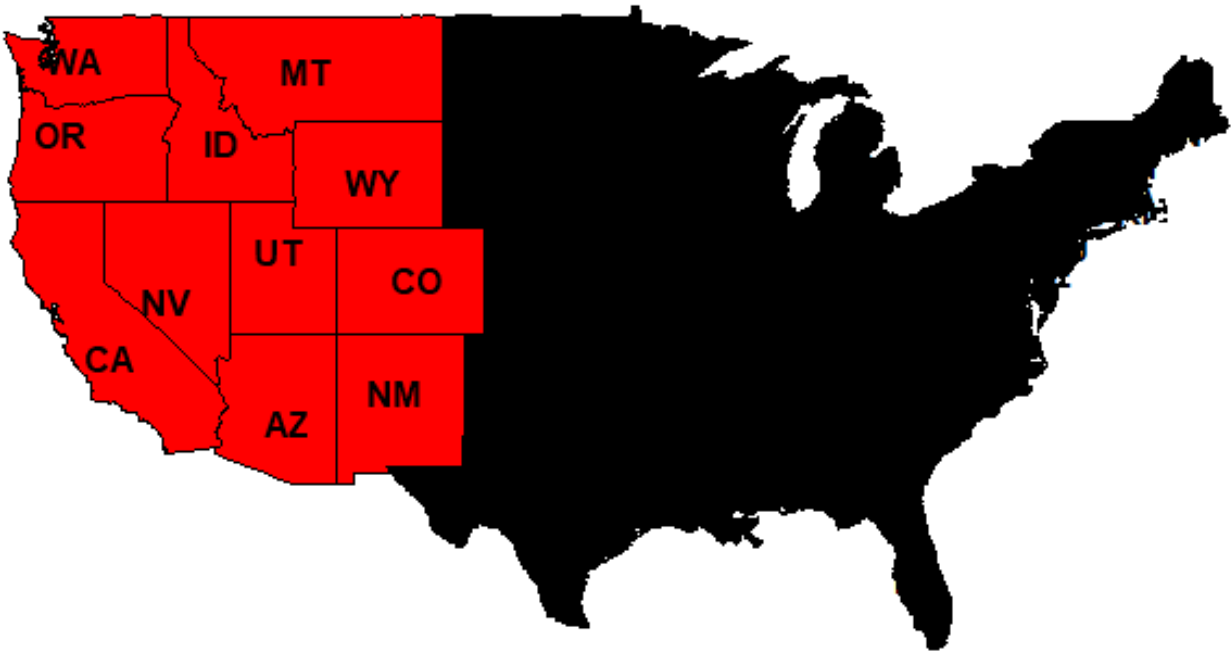


Figure 1: Map of 11-state study area.

## 1.1 PM2.5 data

### 1.1.1 Processing PM2.5 data

These are the scripts that process and compile the PM2.5 data:

1. Script1\_Install\_Pkgs.R » install packages
2. Define\_directories.R » clears all variables and defines directories. Needs to be ran between each of the following scripts. (Want to automate this eventually.) When processing a new batch of data, iterate “processed\_data\_version” by one letter and create a new subfolder in /home/Processed\_Data/ named PM25\_data\_part\_\* where \* is the new processed\_data\_version.
3. Process\_PM25\_data\_step1.R » compiles the various PM2.5 data sources into a single data frame. The only eliminations of data are geographic, to remove states that are neither in our study area. Update time frame of study if necessary. The output from this script is a csv file and sink .txt for each PM<sub>2.5</sub> data source as well as a file with all of the PM2.5 data sources merged together (“PM25\_Step1\_part\_\*.csv”).
  - (a) For DRI data, put in flags for voltage data outside the range 11-17 V. (These thresholds are somewhat arbitrary, but it was noticed that when the voltage was outside this range, the PM<sub>2.5</sub> concentrations were often absurdly high, e.g., greater than 24,000 ug/m<sup>3</sup>.)
4. Process\_PM25\_data\_step2.R » cleans the data. The following is a list of the quality cuts and changes made to the data:
  - (a) Replace “UNKNOWN” datum in EPA data with “NAD27” per Colleen’s advice.
  - (b) Remove negative and NA PM<sub>2.5</sub> concentrations. This includes removing all data for a monitor on a given day if any of the hourly observations were negative.
  - (c) For the hourly data, remove monitor-days that do not have at least 18/24 observations.
  - (d) For DRI data, remove data with voltage flags (which includes flags that came with the data and flags that were put in because the battery voltage was outside the range 11-17 V.
  - (e) For DRI data, remove data at or below 0 L/min for flow. Think about whether a minimum value of flow should be set (higher than zero).
  - (f) June 6, 2014 24-hr average PM<sub>2.5</sub> concentration from monitor “Smoke NCFS E-BAM #1” (Fire\_Cache\_Smoke\_DRI\_Smoke\_NCFS\_E\_BAM\_N1.csv) is 24,203 ug/m<sup>3</sup>. There’s nothing apparent wrong with the hourly data, however, this is the only day of data that made it through the other quality checks from this data file. This suggests that this monitor is suspect, and will be removed.
  - (g) Remove data points with lat/lon outside this box: (50,-126) to (25,-101)
  - (h) **To Do** think about making cuts on any unrealistic air temperatures for DRI data
  - (i) **To Do** need to convert missing values that have a -9999 etc to NA value
  - (j) **To Do** merge "24-HR BLK AVG" and "24 HOUR" data together in Sample Duration variable
  - (k) **To Do** figure out why Observation percent has a max value of 200%
  - (l) **To Do** figure out if max AQI value of 546 is reasonable
  - (m) **To Do** Some DRI files looked like they had hour 20:00 data shifted a couple of columns - look into this and fix it.
  - (n) **To Do** Finish filling in Year, month, day information based on date

- (o) **To Do** look over summary() output and plots of every variable and determine if any other cuts are necessary
- Process\_PM25\_data\_step3.R » convert all PM2.5 data to the same datum (NAD83) and project coordinates. Take the reprojected location info and put it into the data frame with the daily PM<sub>2.5</sub> data.
- Process\_PM25\_data\_step4.R » combine locations and location/date files for parts b and c. (Part a should be disregarded.) **To Do** write code to take difference between parts bc and d to get a list of just the dates/locations that are new in part d. **To Do** process part d in this file
- 5. Process\_PM25\_data\_step5.R » composite replicate data - in process. **To Do** finish colocated version of code to go with aves version of code. Calls these functions:
  - (a) Combine\_true\_replicates\_R\_function.R
  - (b) fill\_in\_aves\_coloc\_unique\_PC\_POC\_MN\_function.R
    - i. concatenate\_within\_column\_function.R
  - (c) set\_data\_types\_by\_column\_R\_function.R
- 6. Plot\_ML\_Input\_File.R » create plots, maps, and statistical summary - needs to be changed to take input from De-duplicate code instead of file from Create\_ML\_Input\_File.R
- 7. **to be written** » merge with satellite and other data

### 1.1.2 Notes about very high data points

June 15, 2012 24-hr average PM<sub>2.5</sub> concentration from monitor “Smoke #22” (Fire\_Cache\_Smoke\_DRI\_Smok is 5,638 ug/m<sup>3</sup> - can’t find any reason, so far, to remove this data point, though it’s very odd that the concentrations were low single-digits except for two hours which were extremely high (123,000 and 1000 ug/m<sup>3</sup>).

## 88101 and 88502 Time Series

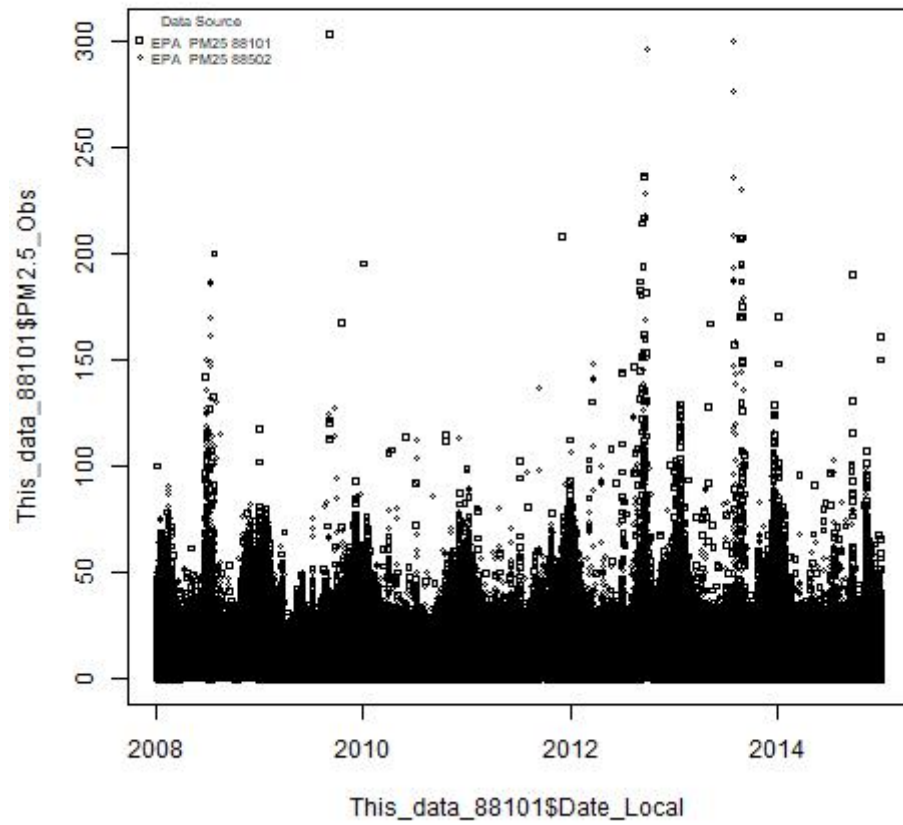


Figure 2: Time series of 88101 and 88502 PM2.5 data.

## 1.2 Compare 88101 to 88502 PM2.5

### All PM2.5 Monitor Locations

## All PM2.5 Observation Locations



Figure 3: Map of locations of PM2.5 observations for entire study period, 2008 to 2014.

## PM2.5 Observation Locations, 2008

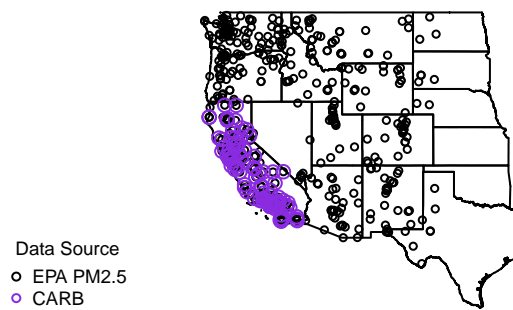


Figure 4: Map of locations of PM2.5 observations during 2008.

## PM2.5 Observation Locations, 2009



Figure 5: Map of locations of PM2.5 observations during 2009.

## PM2.5 Observation Locations, 2010



Figure 6: Map of locations of PM2.5 observations during 2010.



## PM2.5 Observation Locations, 2011

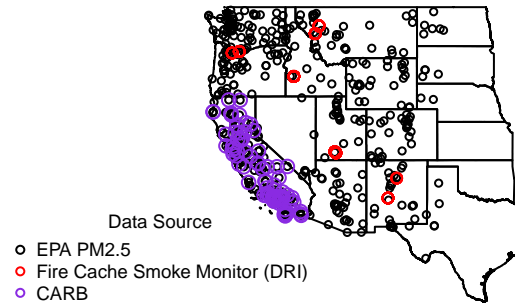


Figure 7: Map of locations of PM2.5 observations during 2011.

## PM2.5 Observation Locations, 2012

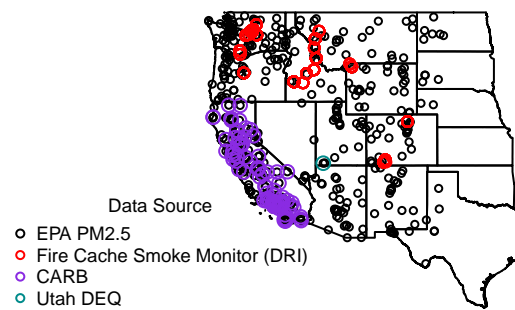


Figure 8: Map of locations of PM2.5 observations during 2012.

## PM2.5 Observation Locations, 2013

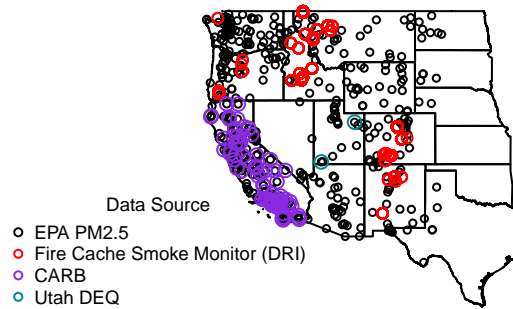


Figure 9: Map of locations of PM2.5 observations during 2013.

## PM2.5 Observation Locations, 2014

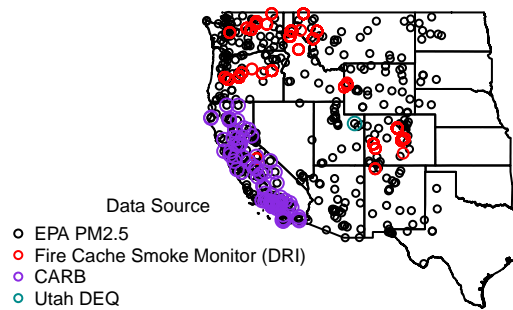


Figure 10: Map of locations of PM2.5 observations during 2014.

## 1.3 PM2.5 Monitor data from US EPA AQS Air Data Query Tool

### Data Source

- **Contact**

Can email the Air Quality Analysis Group (U.S. EPA Office of Air Quality Planning and Standards) on their website at <https://www.epa.gov/outdoor-air-quality-data/forms/contact-us-about-outdoor-air-quality>

- **Citation/Link**

United States Environmental Protection Agency. *Pre-Generated Data Files: Daily Summary Files, PM2.5 FRM/FEM Mass (88101) and PM2.5 non FRM/FEM Mass (88502), 2008-2014*. [https://aqs.epa.gov/aqsweb/airdata/download\\_files.html#Daily](https://aqs.epa.gov/aqsweb/airdata/download_files.html#Daily)

- **Data (local)**

- **Geographic Extent**

- **Temporal Extent** 2008 through 2014

- **Acknowledgment**

Download spreadsheet listing all AQS monitors with datums ([https://aqs.epa.gov/aqsweb/airdata/aqs\\_monitors.zip](https://aqs.epa.gov/aqsweb/airdata/aqs_monitors.zip)) from “Monitor Listing” at [https://aqs.epa.gov/aqsweb/airdata/download\\_files.html#Meta](https://aqs.epa.gov/aqsweb/airdata/download_files.html#Meta). The file name is aqs\_monitors.csv in the AQS\_Daily\_Summaries folder in the S3 data.

### Brief Description

We will download PM<sub>2.5</sub> data from both the US EPA AQS Air Data Query Tool (US EPA, 2017c) and the IMPROVE monitors that capture air quality information in more rural areas (US EPA, 2017e) for the 11-state region (Figure 1) including any of the following parameter codes: 88101, 88500, 88502, 81104 (US EPA, 2017a,d,f).

### Notes

#### File Format

#### Data Filtering and Processing

#### Final Variable(s)

#### Methods

- 1.
- 2.

### Quality Control

#### Script Names

- 1.

#### Data File Names

1. daily\_88101\_2008.csv
2. daily\_88101\_2009.csv
3. daily\_88101\_2010.csv
4. daily\_88101\_2011.csv
5. daily\_88101\_2012.csv

6. daily\_88101\_2013.csv
7. daily\_88101\_2014.csv
8. daily\_88502\_2008.csv
9. daily\_88502\_2009.csv
10. daily\_88502\_2010.csv
11. daily\_88502\_2011.csv
12. daily\_88502\_2012.csv
13. daily\_88502\_2013.csv
14. daily\_88502\_2014.csv



Figure 11: Map of 88101 and 88502 PM<sub>2.5</sub> Monitors.



Figure 12: EPA PM2.5 time series.

## 1.4 EPA PM2.5 Plots

## 1.5 PM<sub>2.5</sub> data from the Federal Land Manager Environmental Database

### Data Source

- **Citation/Link** <http://views.cira.colostate.edu/fed/DataWizard/Default.aspx>
- **Download Date** March 15, 2018
- **Data (local)** PM<sub>2.5</sub> data from the Federal Land Manager Environmental Database
- **Geographic Extent** Nationwide
- **Temporal Extent** January 1, 2008 - December 31, 2014
- **Acknowledgment** - need to fill in

Downloading IMPROVE Aerosol, RHR II (New Equation) data (one parameter at a time):

1. Reports: Raw data
2. Datasets: "IMPROVE Aerosol, RHR II (New Equation)"
3. Sites: select all
4. Parameters:
  - (a) Mass, PM<sub>2.5</sub> (Fine): Code MF, Type PM<sub>2.5</sub>, Units ug/m<sup>3</sup> LC AQS ID 88101
  - (b) Mass, PM<sub>2.5</sub> Reconstructed (Fine): Code RCFM, Type PM<sub>2.5</sub> Units ug/m<sup>3</sup> LC, AQS ID 88401
5. Select Dates: By Years and Months: 2008-2014; select all months
6. Aggregations: Non-aggregated
7. Fields: Select All
8. Options: Text File; Generate one file containing all the data; Comma delimited, Standard ("wide" format); Data & Metadata, Display Column Headers, Don't Display Section Titles, String Quotes: Double Quotes, Missing Values (blank); Date Format: 3/14/2002; Display Results: In a separate browser window; Show Report Log
9. Submit

Repeat the downloading steps above, except replace step #2 with these Datasets and parameters:

1. IMPROVE Aerosol, RHR III (DRAFT - Preliminary Most Impaired Days dataset)
  - (a) Mass, PM<sub>2.5</sub> (Fine) is listed twice - these turned out to be the same data

### File Formats

csv

### Original Data File Names

1. Federal\_Land\_Manager\_IMPROVE\_RHR\_II\_88101\_20183151757452922Mvw0s.csv
2. Federal\_Land\_Manager\_IMPROVE\_RHR\_II\_88401\_20185113533660420xLwJ.csv
3. Federal\_Land\_Manager\_RHR\_III\_88101\_first\_param\_201851152033932P22My0.csv

## 1.6 PM<sub>2.5</sub> data from the Fire Cache Smoke Monitor Archive

### Data Source

- **Contact** Josh Walston at 775-673-7624; Amber Ortega directed us to the website and Scott Landis suggested that a good person to contact about the page would be Mike Broughton from the US Forest Service ([michaelbroughton@fs.fed.us](mailto:michaelbroughton@fs.fed.us))
- **Citation/Link** <https://wrcc.dri.edu/cgi-bin/smoke.pl>
- **Data (local)** PM<sub>2.5</sub> data from the Fire Cache Smoke Monitor Archive
- **Geographic Extent**
- **Temporal Extent**
- **Acknowledgment**

### Brief Description

#### Notes

Several of the files were password protected, so we contacted Josh and they were able to unlock most of them. As of March 20, 2018, only "Smoke NCFS E-BAM # 3 is still password protected. (Need to try calling Josh again.) Here are some comments that the system administrator passed along to us (via Josh): the data does not get quality controlled, so we should do our own qa/qc. The monitors/data were designed for the fire community to see data in real time, not for research purposes. If we want to speak with the people who ran the monitors, we should contact Josh and the director can probably put us in contact.

Update 2018-05-2018: sent email to Josh requesting the "Smoke NCFS E-BAM # 3" data with flags and with the other formatting settings we used on the other files. Also asked how to determine which datum is associated with the latitude/longitude data.

These monitors were not included because the website indicated that it did not have data during our study period (January 1, 2008 - December 31, 2014):

1. Smoke E-BAM 418
2. Smoke E-BAM 591
3. Smoke E-BAM 592
4. Smoke E-BAM 882
5. Smoke E-BAM 969
6. Smoke USFS R2-922
7. Smoke USFS R2-923
8. Smoke USFS R2-924
9. Smoke USFS R8-34
10. Smoke USFS R8-35
11. Smoke USFS R8-55
12. Smoke USFS R8-56
13. Smoke USFS 3015
14. Smoke USFS 3016
15. Smoke USFS R9-3017
16. Smoke USFS R9-3018
17. RSF Smoke Monitor 1
18. Lolo NF Smoke Monitor #1
19. Lolo NF Smoke Monitor #2



## **File Formats**

.CSV

## **Data Filtering and Processing**

### **Final Variable(s)**

### **Methods**

- 1.
- 2.

## **Quality Control**

### **Script Names**

- 1.

### **Original Data File Names**

1. Fire\_Cache\_Smoke\_DRI\_Cache-NCFS-EBAM#3-with-flags.csv
2. Fire\_Cache\_Smoke\_DRI\_FWS\_Smoke\_N1.csv
3. Fire\_Cache\_Smoke\_DRI\_Smoke\_N11.csv
4. Fire\_Cache\_Smoke\_DRI\_Smoke\_N13.csv
5. Fire\_Cache\_Smoke\_DRI\_Smoke\_N15.csv
6. Fire\_Cache\_Smoke\_DRI\_Smoke\_N16.csv
7. Fire\_Cache\_Smoke\_DRI\_Smoke\_N17.csv
8. Fire\_Cache\_Smoke\_DRI\_Smoke\_N19.csv
9. Fire\_Cache\_Smoke\_DRI\_Smoke\_N20.csv
10. Fire\_Cache\_Smoke\_DRI\_Smoke\_N21.csv
11. Fire\_Cache\_Smoke\_DRI\_Smoke\_N22.csv
12. Fire\_Cache\_Smoke\_DRI\_Smoke\_N23.csv
13. Fire\_Cache\_Smoke\_DRI\_Smoke\_N24.csv
14. Fire\_Cache\_Smoke\_DRI\_Smoke\_N25.csv
15. Fire\_Cache\_Smoke\_DRI\_Smoke\_N65.csv
16. Fire\_Cache\_Smoke\_DRI\_Smoke\_N66.csv
17. Fire\_Cache\_Smoke\_DRI\_Smoke\_N67.csv
18. Fire\_Cache\_Smoke\_DRI\_Smoke\_N68.csv
19. Fire\_Cache\_Smoke\_DRI\_Smoke\_N69.csv
20. Fire\_Cache\_Smoke\_DRI\_Smoke\_N84.csv
21. Fire\_Cache\_Smoke\_DRI\_Smoke\_N86.csv
22. Fire\_Cache\_Smoke\_DRI\_Smoke\_N215.csv
23. Fire\_Cache\_Smoke\_DRI\_Smoke\_N216.csv
24. Fire\_Cache\_Smoke\_DRI\_Smoke\_N217.csv
25. Fire\_Cache\_Smoke\_DRI\_Smoke\_E\_BAM\_52.csv
26. Fire\_Cache\_Smoke\_DRI\_Smoke\_E\_BAM\_65.csv
27. Fire\_Cache\_Smoke\_DRI\_Smoke\_E-BAM\_231.csv
28. Fire\_Cache\_Smoke\_DRI\_Smoke\_E-BAM\_840.csv
29. Fire\_Cache\_Smoke\_DRI\_Smoke\_E-BAM\_866.csv
30. Fire\_Cache\_Smoke\_DRI\_Smoke\_E-BAM\_925.csv
31. Fire\_Cache\_Smoke\_DRI\_Smoke\_NCFS\_E-BAM\_N1.csv

32. Fire\_Cache\_Smoke\_DRI\_Smoke\_NCFS\_E-BAM\_N2.csv
33. Fire\_Cache\_Smoke\_DRI\_Smoke\_USFS\_R1-39.csv
34. Fire\_Cache\_Smoke\_DRI\_Smoke\_USFS\_R1-52.csv
35. Fire\_Cache\_Smoke\_DRI\_Smoke\_USFS\_R1-53.csv
36. Fire\_Cache\_Smoke\_DRI\_Smoke\_USFS\_R1-306.csv
37. Fire\_Cache\_Smoke\_DRI\_Smoke\_USFS\_R1-307.csv
38. Fire\_Cache\_Smoke\_DRI\_Smoke\_USFS\_R2-69.csv
39. Fire\_Cache\_Smoke\_DRI\_Smoke\_USFS\_R2-78.csv
40. Fire\_Cache\_Smoke\_DRI\_Smoke\_USFS\_R2-264.csv
41. Fire\_Cache\_Smoke\_DRI\_Smoke\_USFS\_R2-265.csv
42. Fire\_Cache\_Smoke\_DRI\_Smoke\_USFS\_R3-28.csv
43. Fire\_Cache\_Smoke\_DRI\_Smoke\_USFS\_R3-86.csv
44. Fire\_Cache\_Smoke\_DRI\_Smoke\_USFS\_R5-39.csv
45. Fire\_Cache\_Smoke\_DRI\_Smoke\_USFS\_R5-49.csv
46. Fire\_Cache\_Smoke\_DRI\_Smoke\_USFS\_R8-33.csv
47. Fire\_Cache\_Smoke\_DRI\_Smoke\_USFS\_R9-15.csv
48. Fire\_Cache\_Smoke\_DRI\_Smoke\_USFS\_R9-16.csv
49. Fire\_Cache\_Smoke\_DRI\_Smoke\_USFS\_R9-17.csv
50. Fire\_Cache\_Smoke\_DRI\_Smoke\_USFS\_R9-60.csv
51. Fire\_Cache\_Smoke\_DRI\_Smoke\_NPS\_Yosemite\_01\_California.csv

#### **Processed/Cleaned Data File Names**

- 1.
- 2.

#### **Download instructions**

1. <https://wrcc.dri.edu/cgi-bin/smoke.pl>
2. Hover over the appropriate drop-down menu and click on the monitor you want to download e.g., “Cache Monitors” then “Smoke #11”
3. On the left-side menu, click on “Data Details”
4. Set the starting date: January 1, 2008 (or as far back as it goes if it doesn’t go back to 2008)
5. Set the ending date: December 31, 2014 (or the last date possible if it ends before 2014)
6. Elements (ignore - default is to include all elements)
7. Options
8. Excel (.xls) (It had html code in the file if I chose other options.)
9. Data Source: Original
10. Represent missing data as: -9999.
11. Include data flags: Yes
12. Date format: MM/DD/YYYY hh:mm
13. Time format: LST 0-23
14. Table Header: Column header short descriptions
15. Field Delimiter: comma (,)
16. Select the Units: Metric
17. Leave Sub interval windows set to: January 01, December 31, Hours: 00 and 24
18. Submit Info



Figure 13: Fire Cache Smoke Monitor (DRI) time series.

19. Open in excel
20. Save as: Fire\_Cache\_Smoke\_DRI\_\*.csv Where \* is the monitor name with spaces replaced with underscore and # symbols replaced with the letter N, e.g., the file name for monitor “Smoke #11” is “Fire\_Cache\_Smoke\_DRI\_Smoke\_N11.csv”
21. Upload file to S3 bucket: <https://732215511434.signin.aws.amazon.com/console>
22. Click on S3
23. Earthlab-reid-group
24. Fire\_Cache\_Smoke\_DRI (folder)
25. Check the following:
26. The name of the monitor is in cell A1
27. The header is spread across rows 2-4
28. There are 34 columns of data (goes through columns “AH” in excel)
29. Concentration in the 11th (“K”) columns
30. List the file names in the overleaf documentation (PM25\_Fire\_Cache\_Smoke\_Monitor\_Archive.tex)

## 1.7 Fire Cache Smoke Monitor (DRI) Plots



Figure 14: Fire Cache Smoke Monitor (DRI) time series without data above 1000 ug/m3 so that the majority of data can be seen.

## 1.8 California State Air Quality and Meteorological Information System (AQMIS)

### Data Source

- **Contact** Denise Odenwalder, Denise.Odenwalder@arb.ca.gov
- **Citation/Link To AQMIS:** <https://www.arb.ca.gov/aqmis2/aqmis2.php>
- **Data (local)**
- **Geographic Extent** Whole state of California, wherever there are monitors
- **Temporal Extent** 2008-2014, daily averages
- **Acknowledgment** California Air Resources Board was very helpful in gathering and sending us this data.

### Brief Description

- PM2.5 measurements at all monitoring stations in CA
- Some entries are 24-hour measurements while others are the average of hourly measurements
- One entry per 3 days

### Notes

Reached out to [aqmis@arb.ca.gov](mailto:aqmis@arb.ca.gov) after determining that there was data being collected in CA that is not published on the EPA AQS website. They emailed us within a week, with a file of the data we requested.

### File Formats

xlsx spreadsheet

### Data Filtering and Processing

#### Final Variable(s)

#### Methods

- 1.
- 2.

### Quality Control

#### Script Names

- 1.

#### Original Data File Names

- 1.
- 2.

#### Processed/Cleaned Data File Names

- 1.
- 2.



Figure 15: CARB time series.

## 1.9 CARB Plots

## 1.10 PM<sub>2.5</sub> Monitor data from Uintah Basin

### Data Source

- **Contact** Seth Lyman
- **Citation/Link** seth.lyman@usu.edu
- **Data (local)** PM<sub>2.5</sub> measurements from 10 sites in Uintah Basin, Utah
- **Geographic Extent** Uintah Basin, Utah
- **Temporal Extent** October 2009 - March 2017
- **Acknowledgment** PM<sub>2.5</sub> data from the Uintah Basin were provided by Seth Lyman at Utah State University.

### Brief Description

PM<sub>2.5</sub> data were provided by Seth Lyman at Utah State University via email on January 16, 2018. The .xlsx file has PM<sub>2.5</sub> data from 10 stations during 2009-2017. The .png file has the longitude and latitude of each site.

### Notes

Additional information from Seth's email:

"I've attached most of the PM<sub>2.5</sub> observations that have ever been collected in the Uintah Basin. What are in the Excel file are 24-hr average data. Data from Roosevelt, Vernal, Ouray, Red Wash, Myton, and Rangely are from the EPA AQS database.

Data from Horsepool are from a BAM 1020 monitor that we operate every winter. Data in Ft. Duchesne and Randlett are 24-hr filter samples that were analyzed gravimetrically. Data from Rabbit Mountain are from a BAM 1020, and data through mid-2013 are in the AQS database.

I have hourly data from Horsepool and Rabbit Mountain if you'd rather have that.

Site locations are given in the list of monitoring stations for the Basin below."

The .png file is easier to read in some programs than others, e.g., it looks fine in "Paint," but not "Photos."

### File Formats

Excel and png

### Data Filtering and Processing

FinalPM2.5\_multiyear\_thruwint2017\_sheet1.csv is the first sheet of FinalPM2.5\_multiyear\_thruwint2017.xlsx converted to .csv, and the second row of the header was merged into the first (24hr avg PM<sub>2.5</sub>).

FinalPM2.5\_multiyear\_thruwint2017\_GISsheet.csv is the third sheet of FinalPM2.5\_multiyear\_thruwint2017.xlsx converted to .csv and gives the latitude and longitude of each site. This sheet originally did not have location information from the Rangely site, so this was filled in by hand with the numbers from UintahBasinSiteLocations.png.

### Final Variable(s)

### Methods

- 1.

2.

## **Quality Control**

### **Script Names**

1.

### **Original Data File Names**

1. FinalPM2.5\_multiyear\_thruwint2017.xlsx
2. UintahBasinSiteLocations.png

### **Processed/Cleaned Data File Names**

1. FinalPM2.5\_multiyear\_thruwint2017\_sheet1.csv
2. UintahBasinSiteLocations.png



## 1.11 PM<sub>2.5</sub> data from PCAPS in the Salt Lake Valley

### Data Source

- **Contact** Dr. Geoff Silcox in Chemical Engineering at the University of Utah ([geoff@chemeng.utah.edu](mailto:geoff@chemeng.utah.edu))
- **Citation/Link** Publication: <https://www.sciencedirect.com/science/article/pii/S1352231011011204>  
(Data was received from Dr. Silcox via email on February 6, 2018.)
- **Data (local)** PM<sub>2.5</sub> data from the Persistent Cold Air Pool Study (PCAPS)
- **Geographic Extent** Salt Lake Valley
- **Temporal Extent** January - February, 2011
- **Acknowledgment** Dr. Geoff Silcox

### Brief Description

#### Notes

#### File Formats

.xlsx

### Data Filtering and Processing

PCAPS\_Site\_Locations.csv is the same data as Table 1 of final\_publication.pdf, and has the site locations and elevation.

### Final Variable(s)

#### Methods

- 1.
- 2.

### Quality Control

#### Script Names

- 1.

### Original Data File Names

1. final\_publication.pdf (Publication of paper)
2. MiniVol\_data.xlsx

### Processed/Cleaned Data File Names

1. MiniVol\_data.csv
2. PCAPS\_Site\_Locations.csv

## 1.12 Utah Department of Environmental Quality

### Data Source

- **Contact**
- **Citation/Link** <http://www.airmonitoring.utah.gov/dataarchive/archpm25.htm>
- **Data (local)**
- **Geographic Extent** Varies...
- **Temporal Extent** Hourly Value CSVs
- **Acknowledgment**

### Brief Description

PM2.5 data from all monitoring stations in Utah

### Notes

There was a lot of overlap with the EPA AQS data, so we took data only from the PM2.5 stations not reported by the EPA. This ended up being one or more of three stations (NP, HC, and RS) for 2009, 2010, 2012, and 2013.

Information about the monitoring stations: <http://www.airmonitoring.utah.gov/network/Counties.htm>

Meta information about monitors obtained from <http://www.airmonitoring.utah.gov/dataarchive/2016DailyMaxPM25.pdf>

### File Formats

### Data Filtering and Processing

### Final Variable(s)

### Methods

- 1.
- 2.

### Quality Control

### Script Names

- 1.

### Original Data File Names

- 1.
- 2.

### Processed/Cleaned Data File Names

- 1.
- 2.



Figure 16: Utah DEQ time series.

### 1.13 Utah DEQ Plots

## 1.14 MODIS AOD

### Data Source

- **Contact**
- **Citation/Link**
- **Data (local)**
- **Geographic Extent**
- **Temporal Extent**
- **Acknowledgment**

### Brief Description

We will use AOD estimates from the Deep Blue retrieval algorithm for AOD from the MODIS instrument on the NASA Terra and Aqua satellites (MOD04\_L2 and MYD04\_L2) ([Sayer et al., 2013](#)). The MODIS product is available twice daily at a 10 km spatial resolution for cloud-free scenes and is available longer than our 2008-2014 study period ([NASA LAADS DAAC, 2017a,b](#)).

AOD products use cloud filtering algorithms that often remove pixels in the center of the smoke plumes because they are assumed to be clouds due to high reflectivity ([Kondragunta and Seybold, 2009](#)). Given that these can be in the middle of smoke plumes, often the locations most heavily impacted by smoke have missing data for a key variable, AOD. In our previous work in summer in California when rain clouds are incredibly rare, we could be confident that missing values not along the coast were not clouds. However, for this larger study region and time period, this will be a bigger challenge. We will attempt to isolate smoke plumes from true clouds using satellite imagery and smoke plume polygons from NOAA's Hazard Mapping System Fire Smoke Product ([NOAA OSPO, 2017](#)). We will then estimate missing values within validated smoke plumes, but not within clouds, using radial basis functions as was done in our previous work ([Reid et al., 2015](#)). Radial basis functions are exact interpolation functions that will return observed AOD values where they exist but can interpolate higher values than nearby observations in missing locations, which is needed since the missing values were removed due to their high reflectivity ([Reid et al., 2015](#)).

### Notes

### File Format

.hdf

### Data Filtering and Processing

### Final Variable(s)

### Methods

1. Step 1: Download the MODIS AOD data sets from both Terra and Aqua sensors:

Using the [NASA EarthData online search tool](#), search for the 'MOD04' (Terra) data set. Set temporal extent by drawing polygon and set spatial extent by adjusting the appropriate filter on the web interface. Select the collection and proceed to download data. For data download options, specify "Stage for Delivery" through the "FTPPull" distribution option. Specify the email address for orders to be sent to. Orders will be sent to your email with instructions on how to connect to the FTP server and pull the ordered data into your local workspace through the command line. Because the amount of data being requested is large, the orders will come through several separate emails. Repeat this step for the 'MYD04'

(Aqua) data set. All of the raw downloaded data from this step will be in .hdf file format.

2. Step 2: Set up file system for data processing:

Create a directory locally named 'collected\_data'. In this directory, make two child directories named "MOD04\_terra" and "MYD04\_aqua". Follow instructions in email to download data through FTP into the appropriate MODIS directory ('MOD04\_terra' or 'MYD04\_aqua') depending on whether the order is from the Terra or Aqua sensor.

3. Step 3: Extract lat, long, and aod values from .hdf files and save into .csv files

Run script 'modis\_aod\_create\_csv\_file.py'. This script will take all the .hdf files that you have downloaded and store the lat, long and aod value for non-null pixels from the 'Deep\_Blue\_Aerosol\_Optical\_Depth\_550\_Mid\_Resolution' SDS. A .csv file will be created for each corresponding .hdf file.

4. Step 4: Create .shp file for each .csv file

Run 'modis\_aod\_convert\_csv\_to\_shapefile.py'. This script will read in the .csv files and convert them to .shp files using multiprocessing, which speeds up the process.

5. Step 5: Project .shp files to US Albers Equal Area Conic

Run 'modis\_aod\_project\_to\_albers.py'. This script will reproject the .shp files to be US Albers Equal Area Conic (ESRI:102003).

6. Step 6: Combine .shp files for same date and convert to raster with 10km resolution

Run 'modis\_aod\_create\_daily\_averages.py'. This will combine all .shp files from the same date and then produce a raster for each with a 10km resolution. Then, the interpolated grids are clipped to the 11 western states (our study area) with a 100km buffer.

7. Step 7: Extract MODIS AOD value at EPA monitor locations

Using ExtractValuesToPoints tool in ArcGIS.

## **Quality Control**

### **Script Names**

1. modis\_aod\_create\_csv\_file.py
2. modis\_aod\_convert\_csv\_to\_shapefile.py
3. modis\_aod\_project\_to\_albers.py
4. modis\_aod\_create\_daily\_averages.py

### **Data File Names**

1. western\_states\_merge.shp

## 1.15 GASP-West AOD

### Data Source

- **Contact**
- **Citation/Link**
- **Data (local)**
- **Geographic Extent**
- **Temporal Extent**
- **Acknowledgment**

### Brief Description

We will use AOD estimates from the Geostationary Operational Environmental Satellite West (GOES-West) Aerosol Smoke Product (GASP-West AOD). The GASP product is available at a 4 km resolution at nadir with retrievals every 30 minutes during daylight hours and is available from 2006 onward ([NOAA NCEI, 2017](#)).

AOD products use cloud filtering algorithms that often remove pixels in the center of the smoke plumes because they are assumed to be clouds due to high reflectivity ([Kondragunta and Seybold, 2009](#)). Given that these can be in the middle of smoke plumes, often the locations most heavily impacted by smoke have missing data for a key variable, AOD. In our previous work in summer in California when rain clouds are incredibly rare, we could be confident that missing values not along the coast were not clouds. However, for this larger study region and time period, this will be a bigger challenge. We will attempt to isolate smoke plumes from true clouds using satellite imagery and smoke plume polygons from NOAA's Hazard Mapping System Fire Smoke Product ([NOAA OSPO, 2017](#)). We will then estimate missing values within validated smoke plumes, but not within clouds, using radial basis functions as was done in our previous work ([Reid et al., 2015](#)). Radial basis functions are exact interpolation functions that will return observed AOD values where they exist but can interpolate higher values than nearby observations in missing locations, which is needed since the missing values were removed due to their high reflectivity ([Reid et al., 2015](#)).

### Notes

websites: <https://www.ncdc.noaa.gov/data-access/satellite-data/satellite-data-access-datasets>  
<https://www.ncdc.noaa.gov/data-access/satellite-data/satellite-data-access-datasets>

Order form for data: <https://www.ncdc.noaa.gov/has/has.dsselect>

<https://www.ncdc.noaa.gov/doclib/index.php?choice=dsi&searchstring=3635&submitted=1&submitted=Search>

### File Format

### Data Filtering and Processing

### Final Variable(s)

### Methods

#### 1. Download Data

Navigate to NCEI's [Archive Information Request System \(AIRS\)](#). Scroll down and click on 'Satellite' to expand menu. Click on 'Goes Products' to expand menu. Click on 'Order Data'. Select GOES-West for satellite ID, GASP-AOD-GZ for data type, and appropriate start and end date. Select "Yes" for Submit Batch. Enter email address and submit order. You

will get emails later on with FTP links to your data. Run ‘Generic\_FTP\_download\_to\_S3.py’ on an EC2 instance passing in the FTP url as the argument. This will download the data and upload it to S3 (and then delete it off the EC2 instance).

## **Quality Control**

### **Script Names**

1. Generic\_FTP\_download\_to\_S3.py

### **Data File Names**

- 1.

## **1.16 MERRA-2**

### **Data Source**

- **Contact**
- **Citation/Link**
- **Data (local)**
- **Geographic Extent**
- **Temporal Extent**
- **Acknowledgment**

### **Brief Description**

### **Notes**

### **File Formats**

### **Data Filtering and Processing**

### **Final Variable(s)**

### **Methods**

- 1.
- 2.

### **Quality Control**

### **Script Names**

- 1.

### **Original Data File Names**

- 1.
- 2.

### **Processed/Cleaned Data File Names**

- 1.
- 2.



## **1.17 MAIAC**

### **Data Source**

- **Contact**
- **Citation/Link**
- **Data (local)**
- **Geographic Extent**
- **Temporal Extent**
- **Acknowledgment**

### **Brief Description**

### **Notes**

### **File Format**

### **Data Filtering and Processing**

### **Final Variable(s)**

### **Methods**

- 1.

### **Quality Control**

### **Script Names**

1. Contacted NASA DeepBlue team via email and was given the [FTP](#) site for their research data output. Public data set not yet available. But should be in several months under the name 'MCD19'.

### **Data File Names**

1. n/a

## 1.18 MODIS Thermal Anomalies/Fire Daily L3 Global 1km (MCD14DL)

### Data Source

- Contact
- Citation/Link
- Data (local)
- Geographic Extent
- Temporal Extent
- Acknowledgment

### Brief Description

We will collect data about fire detection locations, size, and fire radiative power from the MODIS Thermal Anomalies/Fire Daily L3 Global 1km (MOD14 and MYD14) ([Giglio et al., 2006](#); [Hawbaker et al., 2017](#)). Using GIS techniques, we will create daily clusters of fire points and use these to calculate: (1) the distance to the nearest fire cluster by day and (2) the sum of Fire Radiative Power (FRP) of the nearest clusters of fires by day as it is likely that smoke levels are higher closer to fires. The MODIS product spans longer than our study period (2008-2014) at daily temporal resolution and has a spatial resolution of 1 km.

### Notes

### File Format

.shp

### Data Filtering and Processing

### Final Variable(s)

### Methods

1. Navigate to the [NASA EarthData FIRMS Archive Download site](#)
2. Select "Create new Request"
3. In the dropdown for region, select "Custom Region" and draw a bounding box around study area
4. In the dropdown for fire data source, select "MODIS C6"
5. Select dates for study time period
6. In the dropdown for file type, select "Shapefile (.shp)"
7. Enter your email address
8. You will get an email with a download link containing a zipfile with the data

### Quality Control

### Script Names

1. n/a

### Data File Names

1. n/a

## **1.19 Landsat-derived burned area essential climate variable (BAECV) fire activity data**

### **Data Source**

- **Contact**
- **Citation/Link**
- **Data (local)**
- **Geographic Extent**
- **Temporal Extent**
- **Acknowledgment**

### **Brief Description**

We will collect data about fire detection locations, size, and fire radiative power from the Landsat-derived burned area essential climate variable (BAECV) fire activity data, ([LP DAAC, 2017](#)). Using GIS techniques, we will create daily clusters of fire points and use these to calculate: (1) the distance to the nearest fire cluster by day and (2) the sum of Fire Radiative Power (FRP) of the nearest clusters of fires by day as it is likely that smoke levels are higher closer to fires. The BAECV can detect fires larger than 4 km<sup>2</sup> and provides an estimate of the date of the fire and is available from 1984-2015.

### **Notes**

#### **File Format**

.shp

### **Data Filtering and Processing**

#### **Final Variable(s)**

#### **Methods**

1. BAECV data set already downloaded by EarthLab fire group. Navigate to the ‘earthlab-ls-fire’ S3 bucket, then the v1.1 subdirectory. Here you will find yearly .tar.gz files. Have not spent time decompressing files and exploring data yet but my guess is that within each yearly file, we will find more detailed, daily burn data.

### **Quality Control**

#### **Script Names**

1. n/a

#### **Data File Names**

1. n/a

## 1.20 MODIS/Terra and Aqua Burned Area Monthly L3 Global 500 m SIN Grid V006 (MCD64A1)

### Data Source

- **Contact**
- **Citation/Link**
- **Data (local)**
- **Geographic Extent**
- **Temporal Extent**
- **Acknowledgment**

### Brief Description

We will collect data about fire detection locations, size, and fire radiative power from MODIS/Terra and Aqua Burned Area Monthly L3 Global 500 m SIN Grid V006 (MCD64A1) ([Schroeder et al., 2014](#)). Using GIS techniques, we will create daily clusters of fire points and use these to calculate: (1) the distance to the nearest fire cluster by day and (2) the sum of Fire Radiative Power (FRP) of the nearest clusters of fires by day as it is likely that smoke levels are higher closer to fires.

### Notes

#### File Format

.hdf

### Data Filtering and Processing

#### Final Variable(s)

#### Methods

1. Run script 'MODIS\_FTP\_download.py' and pass two arguments: the first is the data set name and the second is the local directory path to save files to (i.e. "MCD64A1" "C:/Users/User/MCD64A1\_"). Update: 'MODIS\_FTP\_download.py' is obsolete because NASA LAADS decommissioned their FTP site in favor of HTTPS. So, a new all-purpose script will need to be written to do this download that does HTTPS retrievals instead.

### Quality Control

#### Script Names

1. MODIS\_FTP\_Download.py

#### Data File Names

- 1.

## 1.21 Visible Infrared Imaging Radiometer Suite (VIIRS) (VNP14IMGTDL\_NRT)

### Data Source

- **Contact**
- **Citation/Link**
- **Data (local)**
- **Geographic Extent**
- **Temporal Extent**
- **Acknowledgment**

### Brief Description

We will collect data about fire detection locations, size, and fire radiative power from the Visible Infrared Imaging Radiometer Suite (VIIRS) (VNP14IMGTDL\_NRT) ([Schroeder et al., 2014](#)). Using GIS techniques, we will create daily clusters of fire points and use these to calculate: (1) the distance to the nearest fire cluster by day and (2) the sum of Fire Radiative Power (FRP) of the nearest clusters of fires by day as it is likely that smoke levels are higher closer to fires. The MODIS product spans longer than our study period (2008-2014) at daily temporal resolution and has a spatial resolution of 1 km. VIIRS was launched in 2011 and has 12 h temporal resolution with 750 m resolution. The BAECV can detect fires larger than 4 km<sup>2</sup> and provides an estimate of the date of the fire and is available from 1984-2015.

### Notes

### File Format

.csv

### Data Filtering and Processing

### Final Variable(s)

### Methods

1. Navigate to the [NASA EarthData FIRMS Archive Download site](#)
2. Select "Create new Request"
3. In the dropdown for region, select "Custom Region" and draw a bounding box around study area
4. In the dropdown for fire data source, select "VIIRS"
5. Select dates for study time period
6. In the dropdown for file type, select "Shapefile (.shp)"
7. Enter your email address
8. You will get an email with a download link containing a zipfile with the data

### Quality Control

### Script Names

1. n/a

**Data File Names**

1. fire\_archive\_V1\_2770.csv

## 1.22 Classified land cover information from the Landsat-derived NLCD 2011

### Data Source

- **Contact**
- **Citation/Link**
- **Data (local)**
- **Geographic Extent**
- **Temporal Extent**
- **Acknowledgment**

### Brief Description

Classified land cover information from the Landsat-derived NLCD 2011 ([Homer et al., 2017](#)) will be used to calculate estimates of the percentage of urban development (codes 22, 23, and 24), agriculture (codes 81 and 82), and vegetated area other than agricultural land (codes 21, 41, 42, 43, 52, and 71) within buffer radii of 100 m, 250 m, 500 m, and 1000 m around each monitor. The buffer distance that is most highly correlated with  $PM_{2.5}$  will be entered into each model. NLCD 2011 has a spatial resolution of 30 m and uses circa 2011 Landsat satellite data.

### Notes

### File Format

.shp

### Data Filtering and Processing

### Final Variable(s)

### Methods

1. Navigate to the [National Map Viewer](#) and find products for "National Land Cover Database (NLCD)" at the National extent. From the search results, download "NLCD 2011 Land Cover (2011 Edition, amended 2014)". This will download a zipfile with the data.

### Quality Control

### Script Names

1. n/a

### Data File Names

- 1.

## 1.23 MODIS Snow Cover Daily L3 Global 500m Grid, Version 6 (MOD10A1 and MYD10A1)

### Data Source

- **Contact**
- **Citation/Link**
- **Data (local)**
- **Geographic Extent**
- **Temporal Extent**
- **Acknowledgment**

### Brief Description

We will use snow cover data from the MODIS Snow Cover Daily L3 Global 500m Grid, Version 6 (MOD10A1 and MYD10A1) ([Hall and Riggs, 2016](#)) because snow coverage is a known contributor to wintertime PM<sub>2.5</sub> concentrations in mountain valleys ([Whiteman et al., 2014](#)). Daily MOD10A1 and MYD10A1 data are available since 2002 and have 500 m spatial resolution.

### Notes

### File Format

### Data Filtering and Processing

### Final Variable(s)

### Methods

1. Step 1: Download the MODIS AOD data sets from both Terra and Aqua sensors:

Using the [NASA EarthData online search tool](#), search for the 'MOD10A1' (Terra) data set. Set temporal extent by drawing polygon and set spatial extent by adjusting the appropriate filter on the web interface. Select the collection and proceed to download data. For data download options, specify "Stage for Delivery" through the "FTPPull" distribution option. Specify the email address for orders to be sent to. Orders will be sent to your email with instructions on how to connect to the FTP server and pull the ordered data into your local workspace through the command line. Because the amount of data being requested is large, the orders will come through several separate emails. Repeat this step for the 'MYD10A1' (Aqua) data set. All of the raw downloaded data from this step will be in .hdf file format.

### Quality Control

### Script Names

- 1.

### Data File Names

- 1.



## 1.24 Elevation

### Data Source

- **Contact**
- **Citation/Link**
- **Data (local)**
- **Geographic Extent**
- **Temporal Extent**
- **Acknowledgment**

### Brief Description

Elevation can influence  $PM_{2.5}$  concentrations; for example,  $PM_{2.5}$  can accumulate in mountain valleys during persistent cold air pools (commonly referred to as inversions) during winter (Whiteman et al., 2014). We will get elevation data from the 3D Elevation Program, which has resolution of 1 arc-second. This resolution is approximately 10 m north/south and varies east/west with latitude (USGS, 2017).

### Notes

### File Format

### Data Filtering and Processing

### Final Variable(s)

### Methods

1. Navigate to the [National Map Viewer](#) site and find products for Elevation Products (3DEP), 1 arc-second DEM, IMG file format. Once results are returned, select "Save as Text", which will download a text file containing server links to each NED tile.
2. Download the data using the [download\\_tiles.py](#) script, which will access the text file that you just downloaded.
3. Extract the elevation values using the [extract\\_values\\_to\\_points.py](#) script.

### Quality Control

### Script Names

1. `download_tiles.py`
2. `extract_values_to_points.py`

### Data File Names

1. n/a

## 1.25 Meteorological Data

### Data Source

North American Mesoscale, Analysis (NAM)

- **Contact**
- **Citation/Link** <https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/north-american-mesoscale-analysis>  
<https://nomads.ncdc.noaa.gov/data/namanl/>
- **Geographic Extent** North America
- **Temporal Extent** Available March, 2004 - present with slight delay
- **Acknowledgment**

### Brief Description

We will obtain meteorological data from the North American Mesoscale, Analysis (NAM) because it includes all of the standard meteorological variables, including planetary boundary layer height, which has proved to be an important variable for converting AOD to PM<sub>2.5</sub> (Liu et al., 2005). We will calculate 24-hour averages from 6-hourly data for temperature, relative humidity, sea level pressure, surface pressure, planetary boundary layer height, dew point temperature, precipitation, snow coverage, and the U and V components of wind speed. NAM has 12 km resolution and is available 2004 onward.

### Notes

#### File Format

Prior to 2018, the files are in \*.grb (“grib1”) format, while 2018 data is in \*.grb2 (“grib2”) format.

Resources about this file type:

- rNOMADS is an R package for accessing grb\* files. It is mostly geared for grib2 files. <https://cran.r-project.org/web/packages/rNOMADS/rNOMADS.pdf>
- Explanation of what grib files are: [http://www.cpc.ncep.noaa.gov/products/wesley/reading\\_grib.html](http://www.cpc.ncep.noaa.gov/products/wesley/reading_grib.html),
- wgrib program information: <http://www.cpc.ncep.noaa.gov/products/wesley/wgrib.html>

### Data Filtering and Processing

1. Use the earthlab/r-reidgroup docker image, which has wgrib and wgrib2 <http://www.cpc.ncep.noaa.gov/products/wesley/wgrib.html> and wgrib2 <http://www.cpc.ncep.noaa.gov/products/wesley/wgrib2/> installed on it.
2. Run “Define\_directories.R” before running each of the steps below. (Need to figure out how to automate this.)
3. Process\_NAM\_data\_step1.R reads in Locations\_Dates\_of\_PM25\_Obs\_DeDuplicate.csv and outputs Locations\_Dates\_of\_PM25\_Obs\_DeDuplicate\_wNextDay.csv, which includes the next day for each location/day listed in the first file. The purpose of this is so all of the necessary NAM files can be processed. UTC dates can go into the next day for western US time zones. This step uses these input files and R packages and functions:

- (a) `Locations_Dates_of_PM25_Obs_DeDuplicate.csv`
  - (b) `add_next_day_date_loc_function.R`.
4. `Process_NAM_data_step2_parallel.R` downloads each NAM file, extracts relevant data, and deletes the original NAM data. (All of the NAM files together would be about 1.6 Tb.) This file operates in parallel, and will use  $n-1$  cores, where  $n$  is the number of cores on the computer. The output is 1 csv with all locations of interest for a given date and time step. The time steps for the NAM are 0Z, 6Z, 12Z, and 18Z. The output files have the format `Locations_Dates_of_PM25_Obs_DeDuplicate_YYYY_MM_DD_XXUTC.csv` where XX refers to the timestep. Change the study start and stop dates for the dates to be processed. This step uses these input files and R packages and functions:
- (a) `Locations_Dates_of_PM25_Obs_DeDuplicate.csv` - Data file with dates (local) and locations where you want the NAM data
  - (b) `MeteoVariablesNAM.csv` - listing of meteorological variables to be extracted from NAM data
  - (c) `rNOMADS` R package (which calls `wgrib` and `wgrib2`) <https://cran.r-project.org/web/packages/rNOMADS/rNOMADS.pdf>
  - (d) `parallel` R package
  - (e) `grb1to2_conversion_prep_function.R` - This script downloads the files that will be necessary to run `grb1to2.pl`, created by the Climate Prediction Center <http://www.cpc.ncep.noaa.gov/products/wesley/grb1to2.html>
  - (f) `loop_NAM_run_times_parallel_function.R` - this function loops through the time steps on a given day and calls function (listed below) to extract meteo data at locations of interest
  - (g) `define_project_bounds_function.R` - the bounding box for the study area is defined in this function. The scripts can run faster if the entire NAM domain does not need to be loaded into memory.
  - (h) `extract_NAM_data_parallel_function.R` - this function extracts the NAM data at points of interest
  - (i) `which_type_of_grib_file_function.R` - this function determines whether the data for a given time step are grib1 or grib2 format
  - (j) `convert_grib1to2_function.R` - convert file type from grib1 to grib2, unless it's already a grib2 file. This is essentially a wrapper for `grb1to2.pl` created by the Climate Prediction Center <http://www.cpc.ncep.noaa.gov/products/wesley/grb1to2.html>
5. `Process_NAM_data_step3.R` merges all of the files from step 2 into a single file and adds a column at the beginning giving the UTC time stamp.
6. `Process_NAM_data_step4.R` To Do: deal with time zones and compiling 24-hr summaries
7. To Do: `Merge_NAM_times.R` will merge the 4 time steps to give a 24-hr summary. Min, max, mean, etc. is set in `MeteoVariablesNAM.csv`.

**Final Variable(s)**

See MeteoVariablesNAM.csv

**Quality Control**

## **1.26 Dust Storms**

### **Data Source**

- **Contact**
- **Citation/Link**
- **Data (local)**
- **Geographic Extent**
- **Temporal Extent**
- **Acknowledgment**

### **Brief Description**

Dust storm records will be included in the machine learning algorithm because they can be a significant indicator of airborne particulate matter from sources other than fires. Dust storm records are available from 1993-2017. The spatial resolution varies, but includes either forecast zone or county ([US National Weather Service, 2017b,c,a](#)).

### **Notes**

### **File Format**

### **Data Filtering and Processing**

### **Final Variable(s)**

### **Methods**

- 1.
- 2.

### **Quality Control**

### **Script Names**

- 1.

### **Data File Names**

- 1.

## 1.27 Locations of Interest

This section describes the code for identifying and compiling the predictor variables for locations of interest, such as county centroids.

### 1.27.1 County Centroids

1. CountyCentroid\_CreateLatLonDateFiles.R » Create two csv files in the /home/Processed\_Data/CountyCentroid/ folder. This script takes approximately 6 minutes to run on a laptop.
  - (a) Locations of county centroids for the study area: CountyCentroid\_Locations.csv (~ 30 KB)
  - (b) Locations of county centroids for study area expanded across all dates in study period: CountyCentroid\_Locations\_Dates\_[Study Start Date]to[Study End Date].csv (~ 140 MB)
2. CountyCentroid\_PlotLocations.R » Plot centroid locations and create summaries of the locations-only and dates-locations centroids files in CountyCentroid\_Locations\_File\_Summary.txt, which is stored in the same folder as the data. This script takes a few seconds to run on a laptop.

### 1.27.2 Population-weighted county centroids

1. Extract\_county\_pop\_centroids.R **To Do:** update this code to have a similar process as the geographic county centroid codes listed above.

### 1.27.3 Geometric Centroids of Counties Images

### Geometric Centroids of Counties

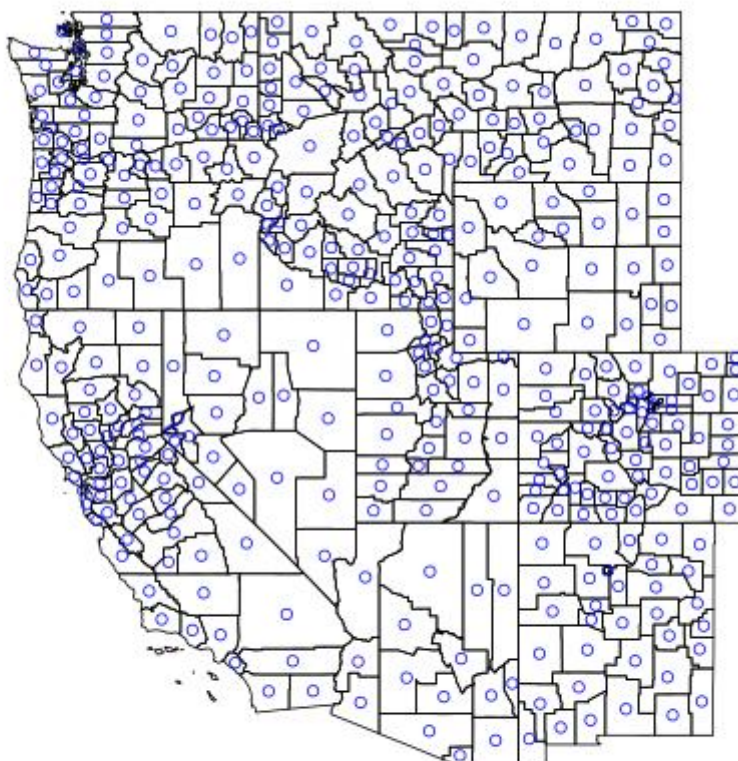


Figure 17: Geometric Centroids of Counties

## **2 Phase 2: Extraction to Observation Locations and Points of Interest**



### **3 Phase 3: Merge extracted data**

This phase both the input file for the ML training and the input file for the predictions to points of interest.

### 3.1 Predictor input files for points of interest

Once the predictor variables have been extracted to the points of interest, these need to be merged into a single input file for each type of point of interest (e.g., geometric county centroid, population-weighted county centroid, etc.).

1. Merge\_predictors\_to\_points\_of\_interest.R » Merge the predictor variables to the locations of interest for each set of points of interest. The file names for the source files will need to be updated as more predictor data is processed. This script takes about 2 minutes on a laptop. This script calls this function:
  - (a) Merge\_predictors\_to\_points\_of\_interest\_parallel\_wrapper\_function.R
2. Plot\_Predictor\_Inputs.R » Plot prediction input files that were created with above script. This script takes several minutes to run on laptop.

## **4 Phase 4: Machine Learning Methods**

setting aside a portion of the PM2.5 data set and then doing 10-fold cross validation on the rest of the data

see <http://www.cvent.com/events/nasa-aist-machine-learning-workshop/event-summary-1f5144a5d1734ca.aspx> and particularly the very end of <https://global.gotomeeting.com/public/recording-player.html?id=owZDmUustOjaW9sJGQ5u9cUG2pBa4D> for list of resources and papers to read.

#### 4.1 ML Scripts

1. ML\_PM25\_estimation\_step0.R » Merge the various predictor variables together with the monitor data or dates/locations of interest
2. ML\_PM25\_estimation\_step0a.R » Plot the training input file
  - (a) predictor variables vs date
  - (b) predictor variables vs PM<sub>2.5</sub>
3. ML\_PM25\_estimation\_step1.R » ML training algorithms
4. ML\_PM25\_estimation\_step1.R » create data frame of the dates/locations for which we want to predict PM2.5

## **5 Phase 5: Predictions to Points of Interest**

## 6 Ideas, To Do, Resources, etc

code up fires by type of land coverage

Consider using the work of Westerling et al for a comprehensive fire history (up through 2012) <http://science.sciencemag.org/content/313/5789/940>, <http://www.pnas.org/content/108/32/13165>, <http://rstb.royalsocietypublishing.org/content/371/1696/20150178> Westerling (2016b,a) Also look into the fire histories referenced in Westerling Westerling (2016b,a): [http://fam.nwcg.gov/fam-web/weatherfirecd/fire\\_files.htm](http://fam.nwcg.gov/fam-web/weatherfirecd/fire_files.htm) and <http://fam.nwcg.gov/fam-web/kcfast/mnmenu.htm> See also <http://www.nifc.gov>

look into the Fire and Smoke Model Evaluation Experiment (FASMEE) <http://www.fasmee.net>

Compare our results with EPA Downscaler <https://www.epa.gov/air-research/downscaler-model-predicting->

Look at Kollanus et al. (2016) again for references for PM2.5 paper, especially the introduction.

Consider using NAAPS in our study.

read ?

read ?

see also <https://www.5280.com/2018/09/can-colorado-burn-its-way-out-of-a-wildfire-crisis/>

Could we use inciweb to distinguish prescribed fires?

look up Global Fire Emissions Database (GFED3) - maybe it would be useful for our study as an input to the machine learning? see Liu et al. (2016)

see ? for potential data sources for ML project

emissions vary by temperature <https://cires.colorado.edu/news/wildfire-temperatures-key-better-understand> and <https://www.atmos-chem-phys.net/18/9263/2018/>

read Monitoring Trends in Burn Severity MTBS, 2014. Data Access: Fire Level Geospatial Data. US Department of Agriculture, Forest Service and US Department of Interior, Geological Survey. <http://mtbs.gov/data/individualfiredata.html/>.

Idea: look at ambulance calls and PM2.5, similar to what Salimi et al. (2016) did in Australia.

read ?

Database of planned/proposed prescribed burns: WRAP's Fire Emissions Tracking System: <http://wrapfets.org/index.cfm>

See Di et al., 2016 and Johnston et al., 2012, Rappold et al., 2014 in ? - combine modelled and monitored/satellite data to estimate PM2.5

See page 11 of ? for discussion of discrepancies related to burned area estimates

<http://www.ptep-online.com/ctan/symbols-a4.pdf>

US National Atlas [http://nationalmap.gov/small\\_scale/atlasftp.html](http://nationalmap.gov/small_scale/atlasftp.html)

Thought: Using DigitalGlobe for fire data compared to NASA: would have higher spatial resolution, but not consistently viewing all areas (no cost to CU people)

Look up Openair R package

Papers/resources to look into: [https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds\\_id=1293](https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1293)

[https://www.fs.fed.us/psw/publications/4451/psw\\_2009\\_4451-001.pdf](https://www.fs.fed.us/psw/publications/4451/psw_2009_4451-001.pdf)

<https://labcit.ligo.caltech.edu/~ethrane/Resources/UNIX/>

<https://community.tableau.com/thread/141548>

According to ?, GEOS-Chem “can be classified according to emission source”, that implies that we could tag the emissions as wildfire vs prescribed fire vs urban. Would there be any advantages of this model over CAMx?

could analyze data with NAAQS and WHO PM2.5 standards

projection/datum info: <https://gis.stackexchange.com/questions/664/whats-the-difference-between-a-projection-and-a-datum>  
<http://resources.esri.com/help/9.3/arcgisengine/dotnet/89b720a5-7339-44b0-8b58-0f5bf2843393.htm>  
<http://grindgis.com/blog/wgs84-vs-nad83>

Monitoring Trends in Burn Severity (MTBS) MTBS, 2016: Data Access: Fire Level Geospatial Data. USDA Forest Service/U.S. Geological Survey, accessed 8 October 2016, <https://mtbs.gov/direct-download>. Eidenshink, J., B. Schwind, K. Brewer, Z.-L. Zhu, B. Quayle, and S. Howard, 2007: A project for monitoring trends in burn severity. *Fire Ecol.*, 3, 3–21, <https://doi.org/10.4996/fireecology.0301003>.

Idea: Maybe instead of just distance to closest fire, we should follow the example of [Baek2016] and do distributed lags with concentric circles with information about fires in each concentric circle... also, instead of just distance to fire, maybe we could come up with a variable that is something like [distance\*size of fire] since both are important.

Fire stats/records: [https://www.nifc.gov/fireInfo/fireInfo\\_statistics.html](https://www.nifc.gov/fireInfo/fireInfo_statistics.html)

See ? for description of fire perimeter data that perhaps we could use (CA only)

See ? for info about MTBS and Active Fire Mapping Program and NWS smoke products. See also Lassman et al ? cited therein.

Read these papers cited in ? : Yao and Henderson, 2014; Henderson et al 2011; Liu et al 2015; Gan et al 2017; and look at their sources of PM2.5 data to see if we could add any of those to our project.

## 7 PM2.5 Surface Paper Notes

Discussion of trends in anthro PM2.5: ?

### 7.1 Papers published in Atmospheric Environment - use as style example

Need to go through these papers

- [Brokamp et al. \(2017\)](#) (partially done, done through intro)
- [Sampson et al. \(2013\)](#)
- [Anyenda et al. \(2016\)](#)
- [Torvela et al. \(2014\)](#)
- [Whiteman et al. \(2014\)](#)

Put in [Brokamp et al. \(2017\)](#); [Larsen et al. \(2017\)](#)

## 8 Papers to cite/discuss in Introduction and/or Discussion

[Westerling \(2016b,a\)](#)

try to find English version <http://80.24.165.149/webproduccion/PDFs/15CAP03.PDF>

For fire identification, consider using NOAA's Hazard Mapping System and BlueSky

### 8.1 Notes on Papers

See [J. et al. \(2016\)](#) for statistics about wildfires in western US, e.g., % started by humans, number of fires, etc.

## 9 Fire attribution paper

revisit ?

include ? - does a good job of summarizing the debate about more vs less prescribed burns  
sources of fire data ?, ?

will need to compare our work to ?

include [Westerling \(2016b,a\)](#) and [Abatzoglou and Williams \(2016\)](#)

See ? for an alternative method of attributing PM2.5 to wildfire smoke (instead of CAMx)

See Le et al 2014 ?

See Huff et al ?

### 9.1 text written for the COPD paper - variation of this may be useful

Larsen et al., 2017 [Larsen et al. \(2017\)](#) found that, on average, ground-level PM<sub>2.5</sub> concentrations increased by  $2.9 \mu\text{g}\cdot\text{m}^{-3}$  (2.8, 3.0) when there was a visible wildfire smoke plume overhead (from satellite imagery), as well as a 2.6 ppb (2.5-2.7) increase in O<sub>3</sub>. Satellite data provides a wealth of data and can provide information about air quality where monitors are not present. However, satellite imagery inherently comes with a substantial uncertainty in that satellite data describes the entire atmospheric column and not specifically just air pollution at the ground level, where people are breathing.



## References

- Abatzoglou, J. T. and Williams, A. P. (2016). Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences*, 113(42):11770–11775.
- Anyenda, E. O., Higashi, T., Kambayashi, Y., Thao, N. T. T., Michigami, Y., Fujimura, M., Hara, J., Tsujiguchi, H., Kitaoka, M., Asakura, H., Hori, D., Yamada, Y., Hayashi, K., Hayakawa, K., and Nakamura, H. (2016). Exposure to daily ambient particulate polycyclic aromatic hydrocarbons and cough occurrence in adult chronic cough patients: A longitudinal study. *Atmospheric Environment*, 140(Supplement C):34 – 41.
- Brokamp, C., Jandarov, R., Rao, M. B., LeMasters, G., and Ryan, P. (2017). Exposure assessment models for elemental components of particulate matter in an urban environment: A comparison of regression and random forest approaches. *Atmospheric Environment*, 151:1–11.
- French, N. H. F., McKenzie, D., Erickson, T., Koziol, B., Billmire, M., Endsley, K. A., Scheinerman, N. K. Y., Jenkins, L., Miller, M. E., Ottmar, R., and Prichard, S. (2014). Modeling Regional-Scale Wildland Fire Emissions with the Wildland Fire Emissions Information System. *Earth Interactions*, 18(16):1–26.
- Giglio, L., Csiszar, I., and Justice, C. O. (2006). Global distribution and seasonality of active fires as observed with the Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) sensors. *Journal of Geophysical Research: Biogeosciences*, 111(G2). G02016; <https://modis.gsfc.nasa.gov/data/dataproduct/mod14.php>.
- Hall, D. K. and Riggs, G. A. (2016). MODIS/Aqua Snow Cover Daily L3 Global 500m Grid, Version 6. *NASA National Snow and Ice Data Center Distributed Active Archive Center*. <http://dx.doi.org/10.5067/MODIS/MYD10A1.006>.
- Hawbaker, T. J., Vanderhoof, M. K., Beal, Y.-J., Takacs, J. D., Schmidt, G. L., Falgout, J. T., Williams, B., Fairaux, N. M., Caldwell, M. K., Picotte, J. J., Howard, S. M., Stitt, S., and Dwyer, J. L. (2017). Mapping burned areas using dense time-series of Landsat data. *Remote Sensing of Environment*, 198(Supplement C):504 – 522.
- Homer, C., Dewitz, J., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N., Wickham, J., and Megown, K. (2017). Completion of the 2011 National Land Cover Database for the Conterminous United States – Representing a Decade of Land Cover Change Information. *Photogrammetric Engineering & Remote Sensing*, 81(5):345 – 354. <https://www.mrlc.gov/nlcd2011.php>.
- J., F. E., T., A. J., K., B. J., T., F. J., and A., B. B. (2016). Quantifying the human influence on fire ignition across the western usa. *Ecological Applications*, 26(8):2390–2401.
- Kollanus, V., Tiittanen, P., Niemi, J. V., and Lanki, T. (2016). Effects of long-range transported air pollution from vegetation fires on daily mortality and hospital admissions in the Helsinki metropolitan area, Finland. *Environ Res*, 151:351–358.

- Kondragunta, S. and Seybold, M. (2009). Revisions to GOES Aerosol and Smoke Product (GASP) Algorithm. <http://www.ssd.noaa.gov/PS/FIRE/GASP/gasp.html>.
- Larsen, A. E., Reich, B. J., Ruminiski, M., and Rappold, A. G. (2017). Impacts of fire smoke plumes on regional air quality, 2006-2013. *Journal of Exposure Science & Environmental Epidemiology*.
- Liu, J. C., Wilson, A., Mickley, L. J., Dominici, F., Ebisu, K., Wang, Y., Sulprizio, M. P., Peng, R. D., Yue, X., Anderson, G. B., and Bell, M. L. (2016). Wildfire-specific Fine Particulate Matter and Risk of Hospital Admissions in Urban and Rural Counties. *Epidemiology*, 28:77–85.
- Liu, Y., Sarnat, J. A., Kilaru, V., Jacob, D. J., and Koutrakis, P. (2005). Estimating ground-level PM<sub>2.5</sub> in the eastern United States using satellite remote sensing. *Environ Sci Technol*, 39(9):3269–78.
- LP DAAC (2017, accessed November 12, 2017). MCD64A1: MODIS/Terra and Aqua Burned Area Monthly L3 Global 500 m SIN Grid V006. [https://lpdaac.usgs.gov/dataset\\_discovery/modis/modis\\_products\\_table/mcd64a1\\_v006](https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mcd64a1_v006).
- MTRI (2017 accessed November 7, 2017). *Wildland Fire Emissions Information System*. <http://wfeis.mtri.org/>.
- NASA LAADS DAAC (2017, accessed November 2, 2017a). MOD04\_L2 - MODIS/Terra Aerosol 5-Min L2 Swath 10km. [https://ladsweb.modaps.eosdis.nasa.gov/api/v1/productPage/product=MOD04\\_L2](https://ladsweb.modaps.eosdis.nasa.gov/api/v1/productPage/product=MOD04_L2).
- NASA LAADS DAAC (2017, accessed November 2, 2017b). MYD04\_L2 - MODIS/Aqua Aerosol 5-Min L2 Swath 10km. [https://ladsweb.modaps.eosdis.nasa.gov/api/v1/productPage/product=MYD04\\_L2](https://ladsweb.modaps.eosdis.nasa.gov/api/v1/productPage/product=MYD04_L2).
- NOAA NCEI (2017, accessed November 2, 2017). *Satellite Data Access by Datasets*. <https://www.ncdc.noaa.gov/data-access/satellite-data/satellite-data-access-datasets>.
- NOAA OSPO (2017, accessed November 3, 2017). *Hazard Mapping System Fire and Smoke Product*. <http://www.ospo.noaa.gov/Products/land/hms.html>.
- Ottmar, R. D., Sandberg, D. V., Riccardi, C. L., and Prichard, S. J. (2007). An overview of the Fuel Characteristic Classification System — Quantifying, classifying, and creating fuelbeds for resource planning. *Canadian Journal of Forest Research*, 37(12):2383–2393.
- Prichard, S. J., Ottmar, R. D., and Anderson, G. A. (2009). Consume 3.0 user's guide. *USDA Forest Service Pacific Wildland Fire Sciences Laboratory Rep.*, page 239.
- Reid, C. E., Jerrett, M., Petersen, M. L., Pfister, G. G., Morefield, P. E., Tager, I. B., Raffuse, S. M., and Balmes, J. R. (2015). Spatiotemporal prediction of fine particulate matter during the 2008 northern California wildfires using machine learning. *Environ Sci Technol*, 49(6):3887–96.
- Rolph, G., Stein, A., and Stunder, B. (2017). Real-time Environmental Applications and Display sYstem: READY. *Environmental Modelling & Software*, 95(Supplement C):210 – 228.

- Salimi, F., Henderson, S. B., Morgan, G. G., Jalaludin, B., and Johnston, F. H. (2016). Ambient particulate matter, landscape fire smoke, and emergency ambulance dispatches in Sydney, Australia. *Environ Int.*
- Sampson, P. D., Richards, M., Szpiro, A. A., Bergen, S., Sheppard, L., Larson, T. V., and Kaufman, J. D. (2013). A regionalized national universal kriging model using partial least squares regression for estimating annual pm2.5 concentrations in epidemiology. *Atmospheric Environment*, 75:383 – 392.
- Sayer, A. M., Hsu, N. C., Bettenhausen, C., and Jeong, M.-J. (2013). Validation and uncertainty estimates for MODIS Collection 6 “Deep Blue” aerosol data. *Journal of Geophysical Research: Atmospheres*, 118(14):7864–7872.
- Schroeder, W., Oliva, P., Giglio, L., and Csiszar, I. A. (2014). The New VIIRS 375m active fire detection data product: Algorithm description and initial assessment. *Remote Sensing of Environment*, 143(Supplement C):85 – 96.
- Torvela, T., Tissari, J., Sippula, O., Kaivosoja, T., Leskinen, J., Virén, A., Lähde, A., and Jokiniemi, J. (2014). Effect of wood combustion conditions on the morphology of freshly emitted fine particles. *Atmospheric Environment*, 87(Supplement C):65 – 76.
- US EPA (2017, accessed November 2, 2017a). *AQS Memos - Technical Note on Reporting PM2.5 Continuous Monitoring and Speciation Data to the Air Quality System (AQS)*. <https://www.epa.gov/aqs/aqs-memos-technical-note-reporting-pm25-continuous-monitoring-and-speciation-data-air-quality>.
- US EPA (2017, accessed November 2, 2017c). *Outdoor Air Quality Data Download Daily Data*. <https://www.epa.gov/outdoor-air-quality-data/download-daily-data>.
- US EPA (2017, accessed November 2, 2017d). *Parameters*. <https://aqs.epa.gov/aqsweb/documents/codetables/parameters.html>.
- US EPA (2017, accessed November 2, 2017e). *PM 2.5 - Visibility (IMPROVE)*. <https://www3.epa.gov/ttnamti1/visdata.html>.
- US EPA (2017, accessed November 2, 2017f). *Sampling Methods for All Parameters*. [https://aqs.epa.gov/aqsweb/documents/codetables/methods\\_all.html](https://aqs.epa.gov/aqsweb/documents/codetables/methods_all.html).
- US EPA (2017, accessed October 23, 2017b). *National Emissions Inventory (NEI)*. <https://www.epa.gov/air-emissions-inventories/national-emissions-inventory-nei>.
- US National Weather Service (2016, accessed November 2, 2017a). *National Weather Service Instruction 10-1605*. <https://www.ncdc.noaa.gov/stormevents/pd01016005curr.pdf>.
- US National Weather Service (2017, accessed November 2, 2017b). *Storm Events Database*. <https://www.ncdc.noaa.gov/stormevents/>.
- US National Weather Service (2017, accessed November 2, 2017c). *Storm Events Database: Database Details*. <https://www.ncdc.noaa.gov/stormevents/details.jsp>.

- USGS (2017, accessed November 6, 2017). *About 3DEP Products and Services*. [https://nationalmap.gov/3DEP/3dep\\_prodserv.html](https://nationalmap.gov/3DEP/3dep_prodserv.html).
- Wang, W., Barker, D., Bray, J., Bruyere, C., Duda, M., Dudhia, J., Gill, D., and Michalakes, J. (2007). User's Guide for Advanced Research WRF (ARW) Modeling System Version 3. *Mesoscale and Microscale Meteorology Division–National Center for Atmospheric Research (MMM-NCAR)*.
- Westerling, A. L. (2016a). Correction to 'increasing western us forest wildfire activity: sensitivity to changes in the timing of spring'. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, 371(1707).
- Westerling, A. L. (2016b). Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. *Philos Trans R Soc Lond B Biol Sci*, 371(1696). bibtex: westerling\_increasing\_2016.
- Whiteman, C. D., Hoch, S. W., Horel, J. D., and Charland, A. (2014). Relationship between particulate air pollution and meteorological variables in Utah's Salt Lake Valley. *Atmospheric Environment*, 94(Supplement C):742 – 753.