

# Warehousing and Particulate Matter Pollution in the Cumberland Valley, Pennsylvania

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[Graphical StoryMap Summary](#)

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## Executive Summary

Warehousing is a major industry in the Cumberland Valley (CV). This study evaluates the economic, environmental, and monetized public health impacts of warehousing in the CV. Key findings are summarized as follows:

- **Warehouse development:** 200 warehouses were identified in the CV. Of these, 66% were established before 2003. Average warehouse size increased from 9.71 acres in 2003 to 20.25 acres in 2022.
- **Truck traffic:** Truck traffic increased by 20.8% on I-76 and 43.5% on I-81 between 2001 and 2023.
- **Temporal and seasonal PM<sub>2.5</sub> patterns:** PM<sub>2.5</sub> concentrations are highest at night, with a secondary peak during the morning commute. Seasonally, PM<sub>2.5</sub> concentrations are highest in summer, followed by winter, and lowest in spring and fall. Annual PM<sub>2.5</sub> concentrations declined by 45-51% between 2001-2024, with the largest decrease occurring in summer.
- **CV vs. non-CV PM<sub>2.5</sub> (EPA data):** Average PM<sub>2.5</sub> concentrations are 14% higher inside the CV than outside, with a maximum difference of 31% in winter and minimum of 3% in summer. Reductions in PM<sub>2.5</sub> concentrations over time are greater inside the CV than outside.
- **CV vs. non-CV PM<sub>2.5</sub> (PurpleAir data):** PM<sub>2.5</sub> concentrations are 3.44-5.39 µg/m<sup>3</sup> higher inside the CV compared to outside the CV.
- **CV vs. non-CV AOD (Satellite data):** Annually, aerosol optical depth (AOD) is 5-10% higher in the CV compared to the non-CV areas with AOD hotspots at each exit along I-81. AOD has decreased 18-21% between 2001 and 2024.
- **Regional PM<sub>2.5</sub> drivers:** Mid Atlantic PM<sub>2.5</sub> concentrations are highest in summer, followed by spring, fall, and winter. High PM<sub>2.5</sub> days are associated with persistent high-pressure systems rather than passing cold fronts, characterized by higher sea-level pressure, lower wind speeds with more southerly flow, warmer temperatures, and higher humidity.
- **Warehousing PM<sub>2.5</sub> emissions:** PM<sub>2.5</sub> emissions from the warehousing industry in the CV declined by 45% between 2014 and 2020. The CV was expected to account for 0.06% of U.S. and 3% of Pennsylvania warehousing PM<sub>2.5</sub> emissions but actually contributed 1% and 16%, respectively, indicating a disproportionate regional impact.
- **Economic output and monetized health impacts:** In 2020, warehousing in Franklin County generated \$750 million in GDP and \$2.5 million in PM<sub>2.5</sub> related health costs. From 2014-2020, warehousing GDP increased 30% (\$170 million), while health costs declined by 66% (\$5.6 million). Health costs, as a share of warehousing GDP, fell by 76%, from 1.60% to 0.38%.

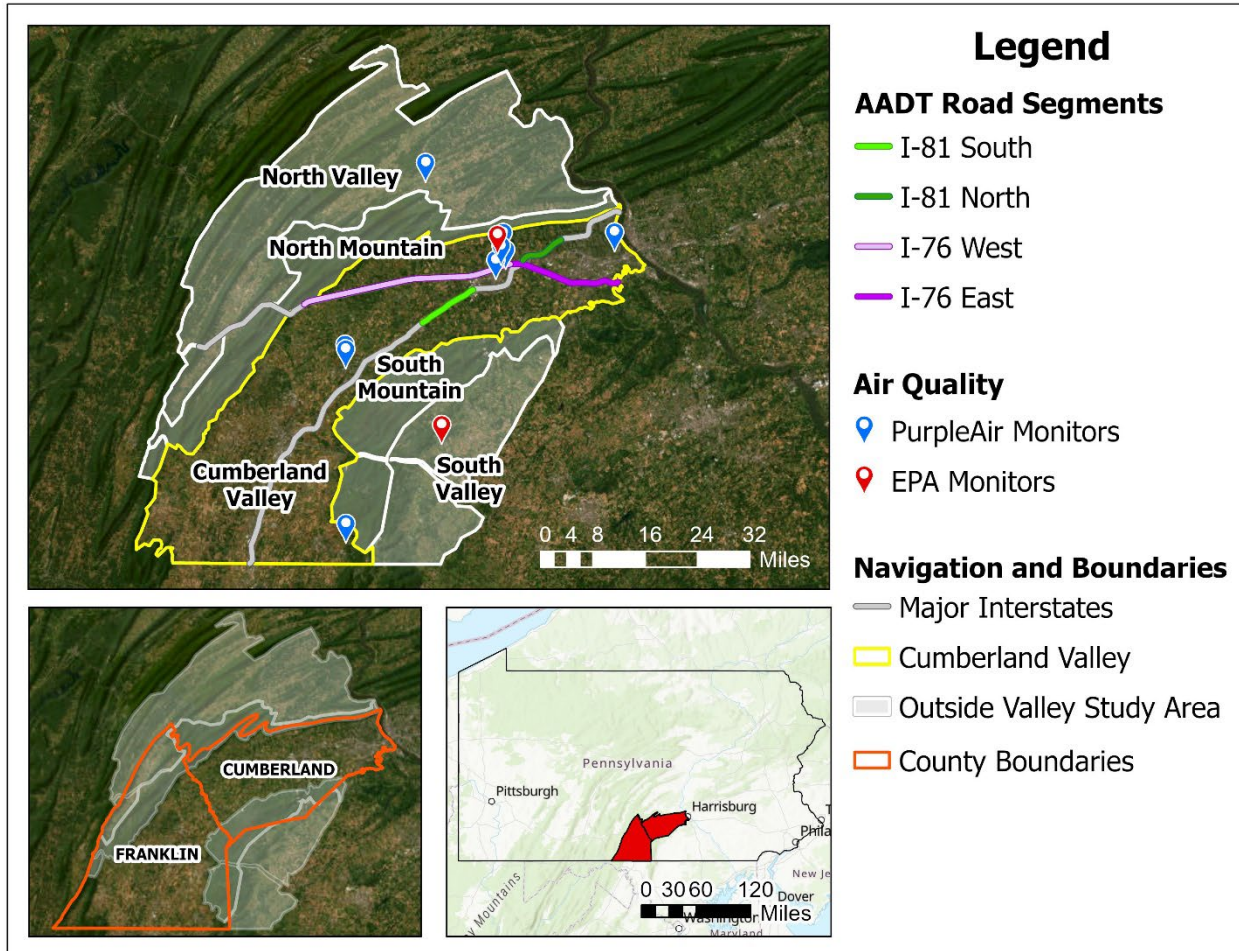
## Introduction and Background

The Cumberland Valley (CV) is in Cumberland and Franklin Counties in southcentral Pennsylvania (**Figure 1**). Together, these counties had a combined population of 434,801 in 2024 (Cumberland = 275,516, Franklin = 159,285) (United States Census Bureau, 2024a; United States Census Bureau, 2024b). Cumberland and Franklin Counties rank as the second and twelfth fastest growing counties in Pennsylvania, with population growth rates of 6.2% and 2.1%, respectively, between 2020 and 2024 (United States Census Bureau, 2024c).

In 2001, the leading industries in the CV were healthcare, manufacturing, and retail (Imagine West Shore, 2009). Since that time, warehouse development has increased substantially due to the CV's proximity to major transportation corridors (I-76, I-81, I-83) and the ability to reach one third of the US population in a day's drive (Marr et al., 2008). The CV is also attractive for warehouse development due to land availability. As of 2022, Cumberland and Franklin Counties contained approximately 411,000 acres of prime farmland, accounting for about 47% of the total land area of the two counties (United States Department of Agriculture, 2022a; United States Department of Agriculture, 2022b). Farmland, particularly on urban fringes, tends to generate relatively low economic output compared to other uses and locations (OCED, 2009). These economic conditions may incentivize farmers to sell land for development. Given the large land requirements associated with warehousing, farmland, especially on the urban fringe, often represents the most economically viable option for warehouse development. As a result, warehousing has emerged as a dominant industry in the CV.

In 2001, the warehousing and storage industry accounted for 3.9% and 1.8% total employment in Cumberland and Franklin Counties, respectively. By contrast, the industry now employs 9.3% of the workforce in Cumberland County and 10.6% in Franklin County (United States Bureau of Labor Statistics, 2025). Warehousing is the top industry in the CV, followed by restaurants and education (Pennsylvania Department of Labor and Industry, 2025a; Pennsylvania Department of Labor and Industry, 2025b).

The growth of warehousing in the CV has raised concerns about air quality. There are strong linkages between increased concentrations of particulate matter with a diameter of less than 2.5 micrometers (PM<sub>2.5</sub>) in areas with significant warehouse development. In particular, areas with high warehouse densities, greater loading dock sizes, and a large amount of parking spaces have increased pollutant levels (Yang et al., 2024; Kerr et al., 2024). Increased air pollution from warehousing is due to the increased accessibility of these areas to diesel-engine tractor trailers (deSouza et al., 2022).



**Figure 1.** Study area.

Sources: PEMA, NAIP, EPA, PurpleAir

Beyond warehouse development, the CV is also vulnerable to poor air quality due to its geography and road network. Several major thoroughfares run through the CV (I-76, I-81, I-83, US-11, US-15, and US-30) which contribute to high traffic volumes and  $PM_{2.5}$  emissions. In valley settings, the surrounding mountains effectively trap pollutants by limiting air circulation (Rendon et al., 2014; Lagmiri and Dahech 2024). Additionally, temperature inversions, which are typical in mountain-valley settings, also limit air circulation by pooling cold air (Rendon et al., 2014; Lagmiri and Dahech 2024; Codeiro et al., 2025). Valley regions often experience worse air quality in the winter due to these inversions (Whiteman et al., 1999; Wang et al., 2015). The CV has winter and summer peaks in  $PM_{2.5}$  concentration due to its geography and seasonal weather conditions (Hawkins and Holland, 2010).

$PM_{2.5}$  is classified as one of the EPA's six criteria pollutants (United States Environmental Protection Agency, 2016). Particulate matter is composed of tiny suspended solid particles and liquid droplets in the air that originate from a wide variety of sources, including construction activities and engine combustion. The relatively small size of  $PM_{2.5}$  allows it to enter the bloodstream and lungs and therefore, has been linked to premature death due to damages to

and complications with cardiovascular and respiratory systems (Pun et al., 2017; Apte et al., 2015; United States Environmental Protection Agency, 2016).

This study examines the environmental, economic, and monetized public health impacts of the warehousing industry in the CV. Impacts were determined through analyses of the relationships between warehouse development, traffic counts, meteorological factors, and economic development. The findings of this study provide an improved understanding of warehousing impacts and may assist with future land use and environmental regulation decisions.

## Methods

### ***Warehouse Inventory***

Aerial imagery of Cumberland and Franklin Counties from 2004-2022, in 3-year intervals, were obtained from the National Agricultural Imaging Program and Pennsylvania Emergency Management Agency via the Pennsylvania Spatial Data Access (PASDA) imagery navigator (<https://maps.psiee.psu.edu/imagerynavigator/>). To locate potential warehouse locations, a four-class (warehouse, forest, agriculture, and urban) supervised classification schema was developed and applied to 2022 aerial imagery. The classification model was trained by highlighting known warehouses, forests, agricultural, and urban areas on aerial imagery. Locations classified as potential warehouses were validated through aerial and Google Earth imagery inspection along with field inspection. Approximate creation date for each warehouse was also identified in this validation process. Boundaries of the warehouses positively identified in the imagery were digitized and the area calculated. As a final check, land use codes for each identified warehouse in Cumberland County were obtained from the Cumberland County’s Tax Parcel Viewer to ensure that the property was actually a warehouse. Equivalent tax data do not exist for Franklin County.

### ***Traffic***

Annual Average Daily Traffic (AADT) for tractor trailers and total traffic were obtained from the Pennsylvania Department of Transportation (PADOT) AADT maps for each year from 2001 to 2023. The selected study areas were I-81 and I-76 on either side of Carlisle (**Figure 1**). Traffic counts for each year and for each road segment were pulled from the maps to create a traffic time series for each segment. 2019 AADT maps were not available.

**Table 1.** Number and percentage of days for each data type for the two EPA PM monitors.

	Hourly	Daily	Missing
Imperial Court (inside)	5519 (63.6%)	2964 (34.2%)	193 (2.2%)
Arendtsville (outside)	5460 (62.9%)	2826 (32.6%)	390 (4.5%)

Notes: Hourly indicates the daily value was calculated from hourly data and an hour of maximum concentration is available. Daily indicates that only a single daily value was available.

Source: Author calculations on EPA data

### Measured Local PM

Daily PM<sub>2.5</sub> data for Imperial Court (Carlisle) and Arendtsville (**Figure 1**) were obtained from the EPA (<https://www.epa.gov/outdoor-air-quality-data>) for 2001-2024. Imperial Court was considered inside the CV and Arendtsville was considered outside the CV. Daily data were available in multiple formats. Days with hourly data and an hour of maximum concentration were first selected. Missing days were filled with a simple daily average value and no hour of maximum concentration. **Table 1** shows the makeup of each daily dataset. For days with maximum hour values, the number of days with a maximum concentration at each of 24 hours was counted. Monthly and seasonal average concentrations were also calculated as well as annual and seasonal averages for each year.

Hourly PM<sub>2.5</sub> data were also obtained from PurpleAir sensors located within the CV study area (<https://map.purpleair.com/>). PurpleAir sensors are lower price and quality than data from the EPA sensors. As such, there are many more PurpleAir sensors than EPA sensors and significant quality control must be performed on the PurpleAir sensors. Initially, 24 sensors were identified. This list was reduced to 9 sensors by selecting sensors containing a minimum of 24,000 hourly observations (~2.7 years) (**Figure 1** and **Table 2**). This process ensured reasonable overlap between the sensors for comparisons. Sensors have an A and B channel. In cases where data from one of the channels was degraded, the other channel was used. Otherwise, the A and B channels were averaged. A t-test was calculated on the average PM<sub>2.5</sub> difference between all pairs of sensors using only hours when each pair member recorded data. For each sensor, the average difference for all pairs of differences was calculated and mapped.

**Table 2.** PurpleAir sensor descriptive information.

#	PA ID	Name	# Hourly Obs.	Start Date	End Date	% Missing
1	19193	Middlesex Township	49,895	2018-11-15	2024-12-31	7.1
2	51971	Clean Air Board	38,792	2020-04-09	2024-12-31	6.4
3	56485	Meglio - Loysville	26,918	2020-05-26	2024-11-26	31.8
4	87705	Middlesex Twp., Meadowbrook	31,384	2020-11-02	2024-12-21	13.4
5	91311	Clean Air Board - CAMP HILL	35,341	2020-11-20	2024-12-31	2.0
6	95999	SU - Shearer Hall	28,268	2020-12-22	2024-12-31	19.8
7	123583	BASIN HILL	24,276	2022-03-21	2024-12-31	0.5
8	125305	SU - King Street	24,141	2022-01-14	2024-12-31	7.1
9	147418	Wayne Heights	41,449	2019-12-10	2024-12-31	6.6

Source: Author calculations on PurpleAir data

**Table 3.** Average number and (percentage) of missing days for each area for the MODIS satellite data.

	Winter	Spring	Summer	Fall
North Valley	48.5 (56)	37.3 (41)	22.9 (25)	26.5 (29)
North Mountain	50.0 (58)	38.4 (42)	25.8 (28)	27.7 (30)
Cumberland Valley	43.9 (51)	32.9 (36)	21.0 (23)	23.3 (26)
South Mountain	49.0 (57)	39.2 (43)	28.8 (31)	28.9 (32)
South Valley	49.5 (57)	39.1 (43)	28.7 (31)	28.7 (32)

Source: Author calculations on MODIS data

### **Satellite Local PM**

Gridded, level 2, daily Multi-angle Implementation of Atmospheric Correction (MAIAC) land aerosol optical depth (AOD; 0.55 $\mu$ m, green band) data with a 1 km resolution were obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) Terra and Aqua satellites (USGS, 2025), via Google Earth Engine (GEE), for the region contained by the CV/non-CV areas (**Figure 1**). AOD is a dimensionless value that indicates the degree to which aerosols prevent the transmission of light through the atmospheric column. Therefore, AOD is highly and positively correlated with surface atmospheric PM concentration (van Donkelaar et al., 2010). Due to cloud cover, the dataset has many missing days (**Table 3**). Individual MODIS granules (scenes) were averaged to create a single daily image. Daily images were used to calculate daily areal averages for the CV/non-CV areas. Daily areal values were used to calculate seasonal and annual areal average AOD values. Additionally, daily images were averaged to calculate annual average images.

### **Modeled Regional PM**

Gridded 3-hour surface PM<sub>2.5</sub> data with an approximate 45 km resolution were obtained from the Copernicus Atmosphere Monitoring Service (CAMS) Global Near-Real-Time data set (Benedetti et al., 2009; Morcrette et al., 2009) for the area, 38.8°-41.6°N and 75.0-80.2°W for July 2016 through December 2024. Data are provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) and were obtained from GEE. Daily, monthly, seasonal, and annual averages were calculated for each grid cell and for the entire region. The CAMS model was upgraded in July 2023, and a noticeable shift occurs in the data time series. To correct this feature in the daily time series, daily differences were calculated from the average value before and after July 2023. The difference time series was used for further analyses.

### **Weather Impacts on Regional PM**

To assess weather impacts on regional PM<sub>2.5</sub> concentration, gridded daily surface air temperature, specific humidity, u and v winds, and sea level pressure (SLP) were obtained from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data set (Kalnay et al., 1996)

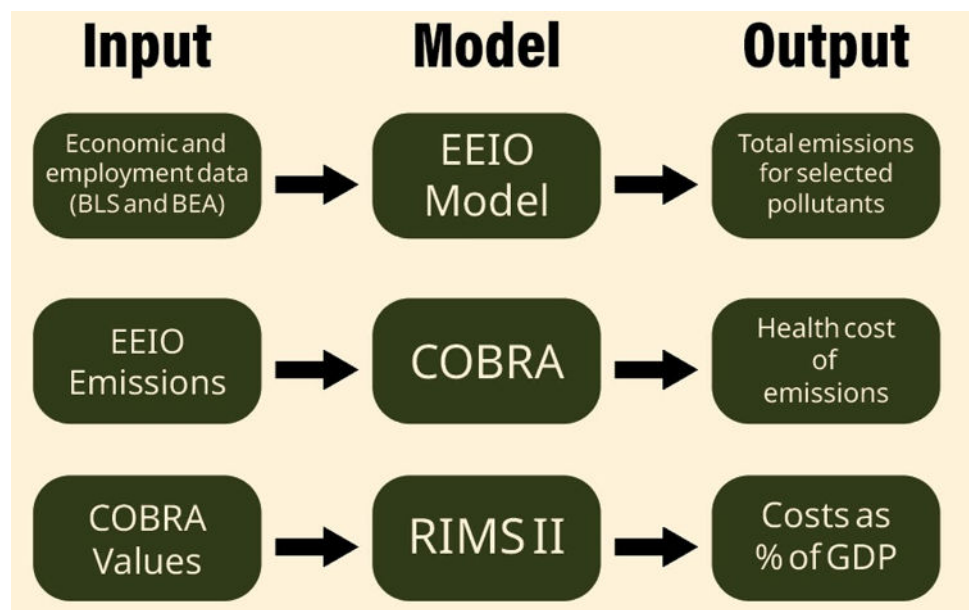
([https://downloads.psl.noaa.gov/Datasets/ncep\\_reanalysis\\_dailyavgs/](https://downloads.psl.noaa.gov/Datasets/ncep_reanalysis_dailyavgs/)). Composite maps of each

variable were created for the top and bottom 10% of regional CAMS PM<sub>2.5</sub> concentration days for each season. Difference maps were also created between the high and low PM<sub>2.5</sub> concentration maps.

**Economic Modeling**

Three economic models were used to assess PM<sub>2.5</sub> emissions and the monetized public health impacts of those emissions in the CV (**Figure 2**). The EPA’s Extended Environmental Input Output (EEIO) State Level v1 PA model for 2014-2020 was utilized to provide an estimated total yearly PM<sub>2.5</sub> emissions for the warehousing and storage industry (North American Industry Classification System, NAICS, id #: 493) nationally, state-wide, and within the CV. EEIO uses economic and environmental data to estimate emissions across industries defined by NAICS and their supply chains. Emissions multipliers were available for 2014, 2017, and 2020. Linear interpolation was used to determine multipliers between the known years. A variety of techniques were evaluated to determine multipliers before 2014 and after 2020. Each technique induced significant uncertainty. Therefore, only multipliers between 2014-2017 were used for this study.

To drive the EEIO model, total national economic output and total number of workers for the warehousing industry for 2014-2020 were obtained from the Bureau of Economic Analysis (BEA) and the Bureau of Labor Statistics (BLS) respectively and divided to get the average economic output per worker in the warehousing industry. The national output per worker was multiplied by the number of workers in the warehousing and storage industry in Pennsylvania and the CV to obtain the total annual economic output for each respective geography. Economic output values were multiplied by EEIO pollution-specific multipliers to calculate direct, indirect, and total PM<sub>2.5</sub> emissions from warehousing for the CV, Pennsylvania, and the Rest of the US (RoUS).



**Figure 2.** Schematic workflow of the EPA economic models.

Source: Authors

The EPA CO-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA) estimates the monetized public health impacts of air pollution. The Regional Input-Output Modeling System (RIMS II) estimates the economic impact of an industry within a region. Comparing COBRA and RIMS II outputs allows for a PM<sub>2.5</sub> air pollution cost vs. economic benefit analysis for the CV. This analysis was performed for 2014-2020 for only Franklin County due to data availability. Results are assumed to be similar for Cumberland County. The EEIO model estimates pollutant emissions which drive the COBRA model and produce monetized health costs associated with emissions. Several emissions scenarios to estimate the total yearly monetary health impact of the warehousing industry in Franklin County were created within the COBRA model using the PM<sub>2.5</sub>, NO<sub>x</sub>, and SO<sub>2</sub> emissions values derived from the EEIO model. Employment data were used to drive the RIMS II model to generate the local gross domestic product (GDP) for the warehousing industry in Franklin County.

## **Results**

### ***Warehouse Inventory***

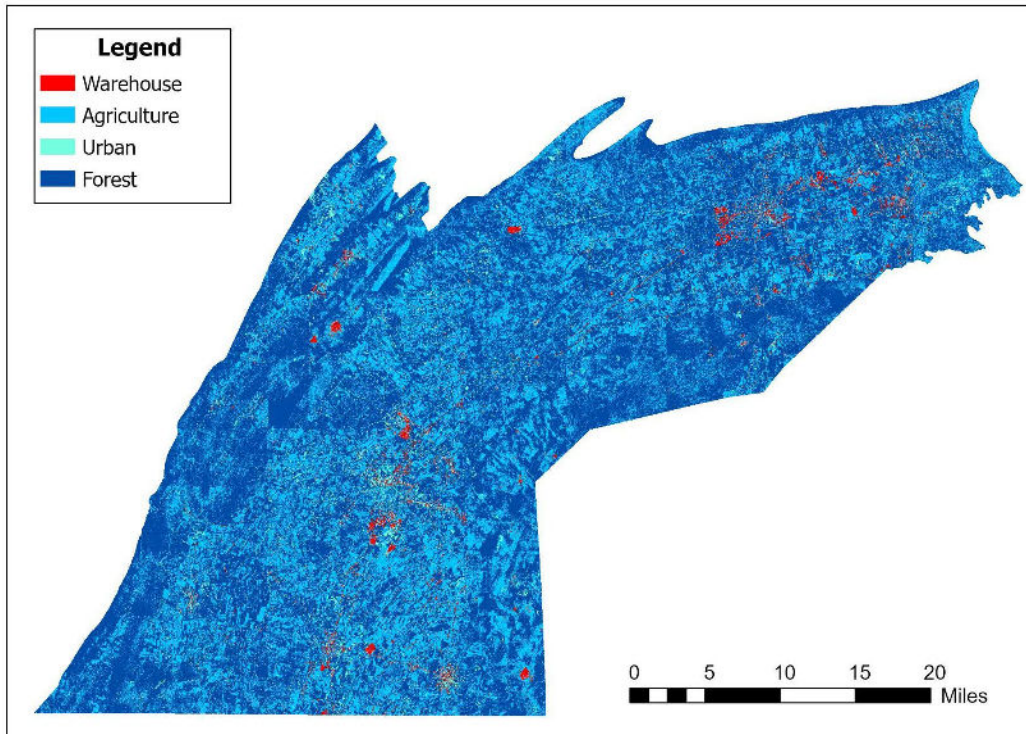
In total, 200 warehouses were identified in the CV, 140 in Cumberland County and 60 in Franklin County, constituting 1,921 total acres. Warehouses are heavily concentrated around major thoroughfares and urban areas, particularly near I-81 and Carlisle (**Figures 3, 4, and 5b**). The largest identified warehouse (41.6 acres) is in Franklin County and was built in 2022. 66% of observed warehouses were created before 2003, collectively accounting for 47% of the current total warehouse acreage (**Figure 5a**). From 1988 to 2003, the number of warehouses increased from 4 to 132, accompanied by a 905-acre increase in total warehouse area. Between 2003 and 2022, the warehouse count increased by 68. However, total warehouse acreage increased by 1,015 acres, suggesting a shift toward larger facilities. Furthermore, from 2021 to 2022 alone, only 14 facilities were created, yet the warehouse area increased by 268 acres. Although the rate of warehouse creation has decreased since the late 1980's, warehouse sizes have continued to increase, most notably in recent years. Average warehouse size grew from 9.7 acres per warehouse in 2003 to 20.3 acres per warehouse in 2022.

### ***Traffic***

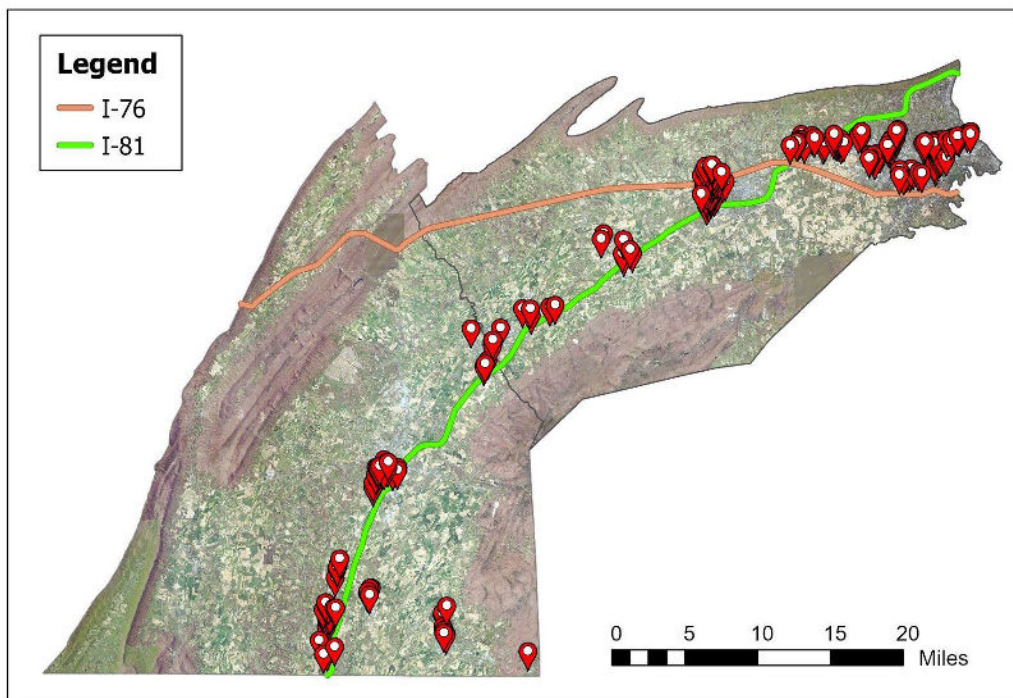
Truck traffic on I-76 and I-81 increased by 20.8% and 43.5% respectively between 2001 and 2023 (**Figure 6**). I-81 consistently experiences greater truck traffic volumes compared to I-76.

### ***Measured Local PM***

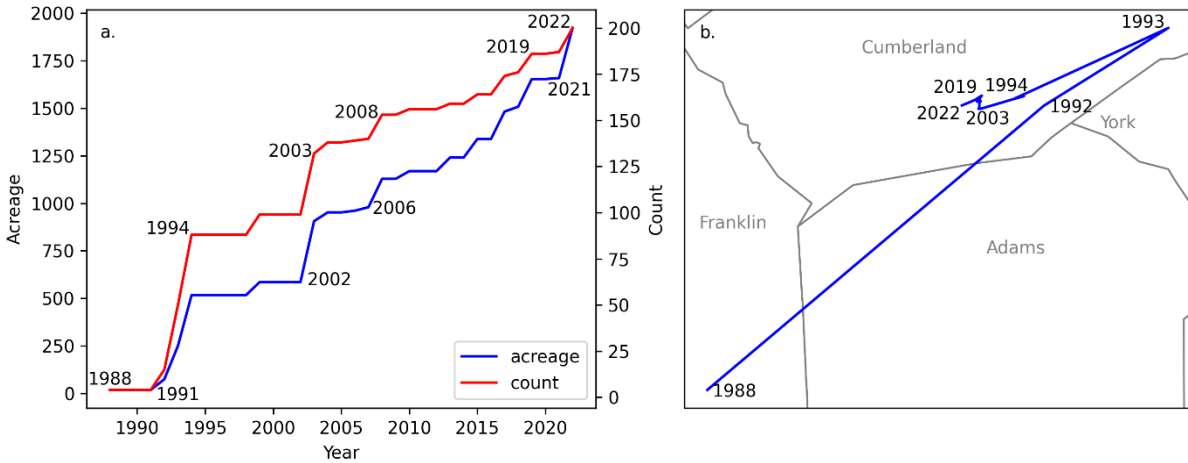
Counts of the number of days when the EPA sensors' daily maximum concentration occurred at each hour indicate a daily cycle to PM<sub>2.5</sub> concentration (**Figure 7**) for both locations. Hours of maximum concentration counts were higher at night and lower during the day. This is likely due to lower wind speeds and the potential for temperature inversions at night. While counts are lower during the daytime, there is an increase in counts around 8-11 AM that corresponds to increased traffic during the morning commute. During the evening commute, wind speeds are faster and depending on the time of year, darkness may occur, which muddies the potential to see a second commuter-related spike in counts in the evening.



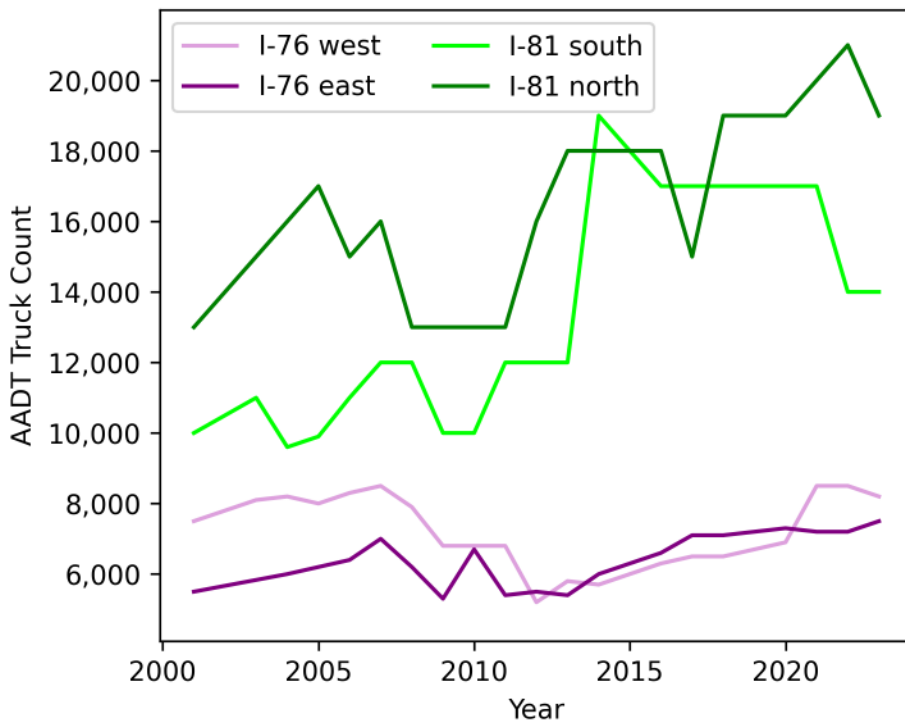
**Figure 3.** Supervised classification of 2022 aerial photographs for the CV counties.  
 Source: Author calculations on PASDA data



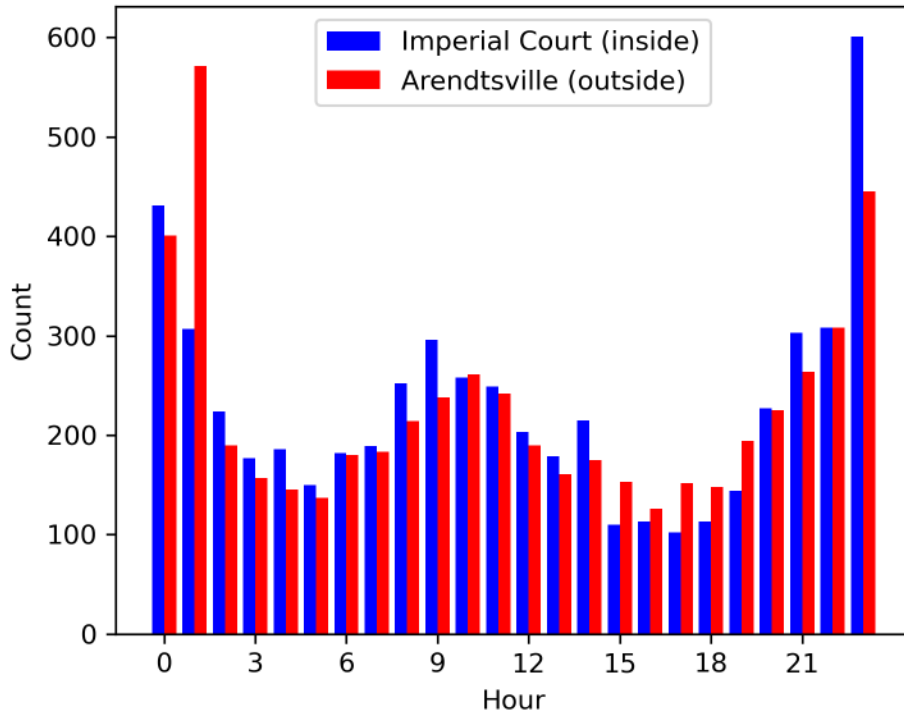
**Figure 4.** Warehouse locations in the CV.  
 Notes: Locations were identified through aerial photograph supervised classification and ground validation.  
 Source: Author calculations on PASDA data



**Figure 5.** Warehouse count and total acreage in the CV (a). Average location of warehouses by year (b). Counties are shown and labeled for reference.  
 Source: Author calculations on PASDA data

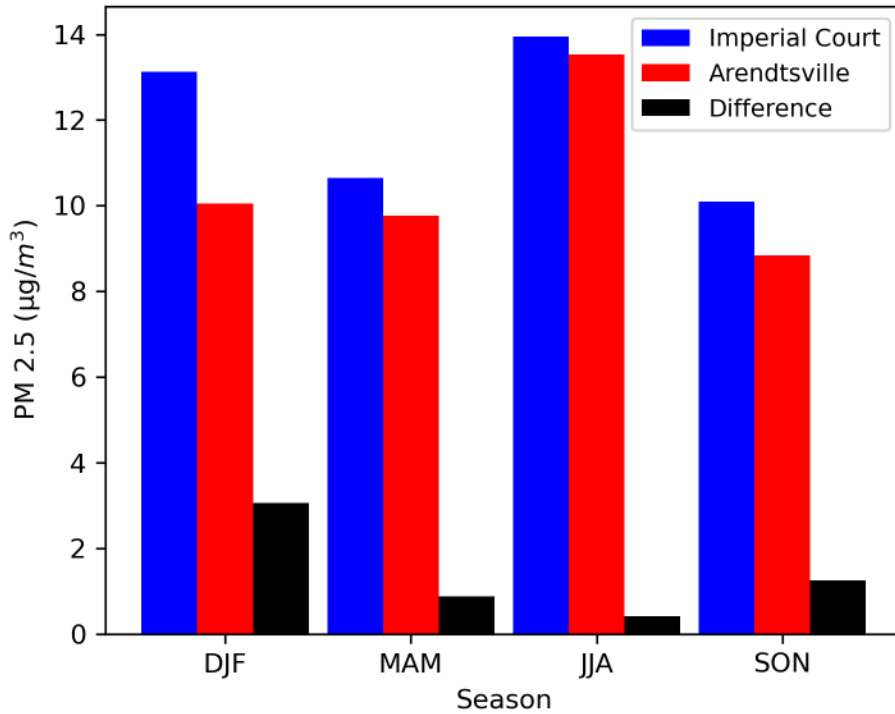


**Figure 6.** Annual total truck traffic counts for the segments of I-81 and I-76 in Figure 1. Directions refer to the location of the road segment relative to Carlisle and not the direction of travel.  
 Sources: PADOT AADT maps.



**Figure 7.** Hourly counts of the occurrence of the daily maximum PM<sub>2.5</sub> concentration for Imperial Court (inside the CV) and Arendtsville (outside the CV).

Source: Author calculations on EPA data



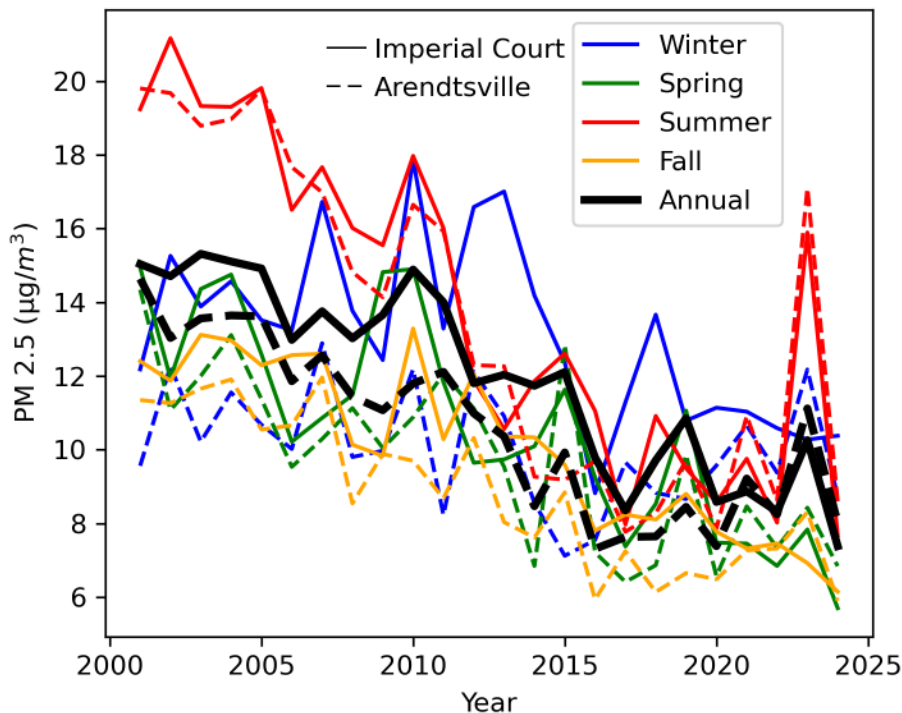
**Figure 8.** Seasonal average PM<sub>2.5</sub> concentration for Imperial Court (inside the CV) and Arendtsville (outside the CV) as well as the differences between the locations.

Notes: DJF=winter, MAM=spring, JJA=summer, SON=fall.

Source: Author calculations on EPA data

Seasonal average PM<sub>2.5</sub> concentrations for the EPA sensors are highest in summer and winter and lowest in spring and fall (**Figure 8**). Weather conditions during summer and winter (presented later) contribute to this result. For all seasons, concentrations at Imperial Court, inside the CV, are higher than Arendtsville, outside the CV. The average daily difference between locations is 1.4 µg/m<sup>3</sup> (14% greater) with a maximum single-day difference of 36.0 µg/m<sup>3</sup>. The average difference is greatest in winter at 3.1 µg/m<sup>3</sup> (31% greater) and smallest in summer at 0.4 µg/m<sup>3</sup> (3% greater).

Seasonal and annual average PM<sub>2.5</sub> concentrations for the EPA sensors for both locations decreased between 2001-2024 (**Figure 9, Table 4**). Decreases are likely due to technological improvements that reduce vehicular emissions. Natural events, like the Canadian wildfires during summer 2023 have a sizable impact. All trends are significant at the 95% confidence level except Arendtsville in winter. Annual trends (percent decrease) are -0.33 µg/m<sup>3</sup>/yr (51% decrease) and -0.30 µg/m<sup>3</sup>/yr (45% decrease) at Imperial Court and Arendtsville, respectively. Summer decreases are largest and winter decreases smallest, again likely due to weather influences (presented later). Decreases are greater at Imperial Court (inside the CV) than Arendtsville (outside the CV). Concentrations are generally higher at Imperial Court (inside the CV) than Arendtsville (outside the CV).



**Figure 9.** Seasonal and annual average PM<sub>2.5</sub> concentration time series for Imperial Court (inside the CV) and Arendtsville (outside the CV).

Source: Author calculations on EPA data

**Table 4.** Seasonal and annual trends and percent decreases in average PM<sub>2.5</sub> concentration time series for Imperial Court (inside the CV) and Arendtsville (outside the CV).

		Winter	Spring	Summer	Fall	Annual
Imperial Court (inside)	Trend	-0.19*	-0.33*	-0.54*	-0.29*	-0.33*
	% Decrease	15	62	60	50	51
Arendtsville (outside)	Trend	-0.08	-0.25*	-0.51*	-0.25*	-0.30*
	% Decrease	9	52	57	48	45

Notes: \*=significant at 95% confidence. Trend units are  $\mu\text{g}/\text{m}^3/\text{yr}$ . Percent decrease is based on 2001 and 2024 values.

Source: Author calculations on EPA data

For reference, the EPA PM<sub>2.5</sub> annual primary and secondary National Ambient Air Quality Standards (NAAQS) are 9 and 15  $\mu\text{g}/\text{m}^3$ , respectively and the World Health Organization (WHO) PM<sub>2.5</sub> annual Air Quality Guideline (AQG) is 5  $\mu\text{g}/\text{m}^3$ . Currently, both Imperial Court and Arendtsville exceed the WHO AQG, are well under the EPA secondary NAAQS, and are slightly above or below the EPA primary NAAQS depending on the year. This is an improvement from the early 2000's when both locations exceeded all standards and guidelines.

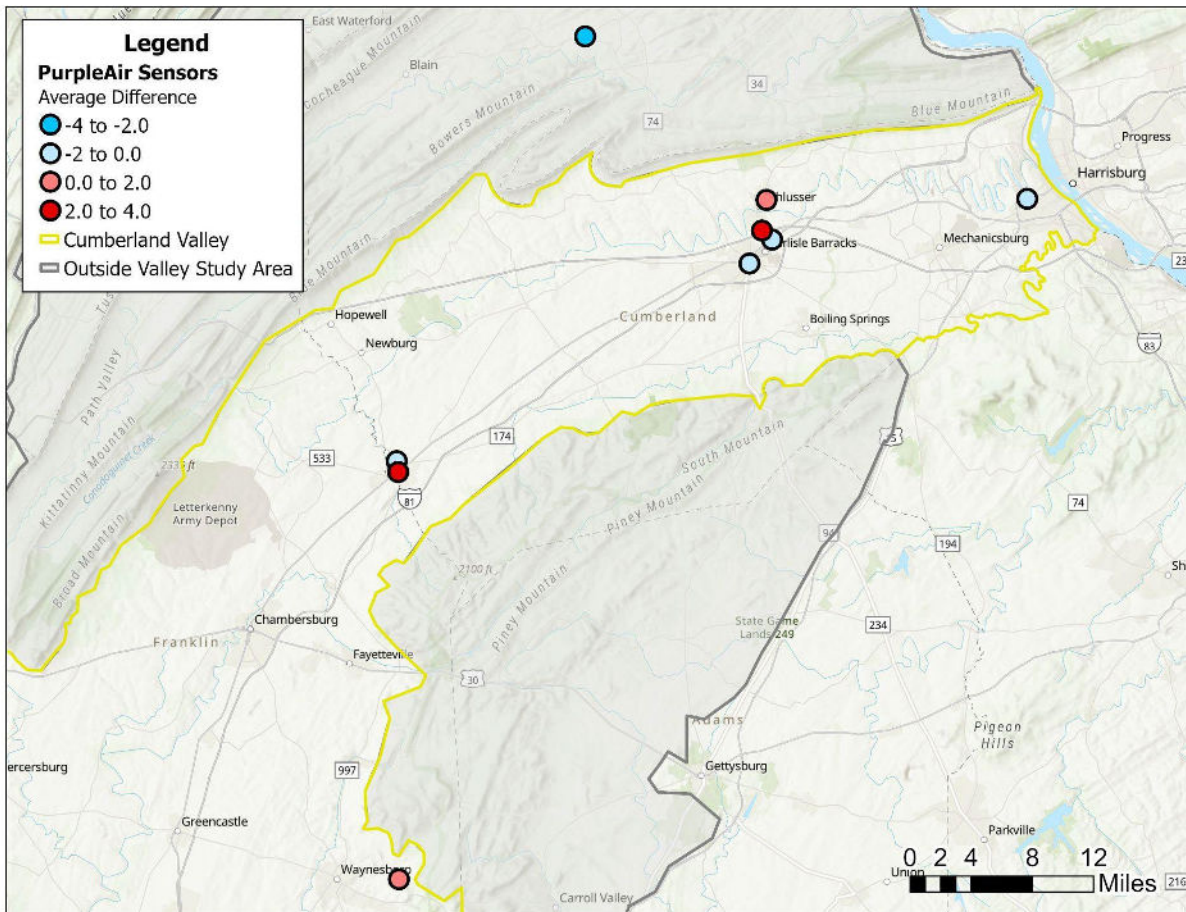
Average PM<sub>2.5</sub> concentration differences for all pairs of PurpleAir sensors indicate that sensor 7, BASIN HILL, located near I-76 in the middle of the CV had the highest PM<sub>2.5</sub> concentration when compared to all other sensors (**Table 5** and **Figure 10**). Sensor 3, Meglio - Loysville, the only sensor located outside the CV, had the lowest PM<sub>2.5</sub> concentration. Sensor 3 has a maximum and average difference of -5.39 and -3.44  $\mu\text{g}/\text{m}^3$ , respectively. Sensor 3's absolute differences are much larger than any other sensor. All other sensors are in the CV and thus, are more similar, and have a higher PM<sub>2.5</sub> concentration.

**Table 5.** Average difference in PM<sub>2.5</sub> concentration between each pair of PurpleAir sensors.

#	7	8	9	4	1	2	5	6	3
7	0.00	-0.52	-2.29	-1.25	-3.18	-3.20	-3.65	-4.33	-4.88
8	0.52	0.00	-1.77	-0.94	-2.83	-2.79	-3.29	-3.84	-4.87
9	2.29	1.77	0.00	-1.20	-3.09	-2.63	-3.27	-2.59	-5.39
4	1.25	0.94	1.20	0.00	-1.15	-1.26	-1.70	-2.68	-3.53
1	3.18	2.83	3.09	1.15	0.00	-0.10	-0.47	-1.14	-2.58
2	3.20	2.79	2.63	1.26	0.10	0.00	-0.39	-1.10	-2.42
5	3.65	3.29	3.27	1.70	0.47	0.39	0.00	-0.74	-2.26
6	4.33	3.84	2.59	2.68	1.14	1.10	0.74	0.00	-1.53
3	4.88	4.87	5.39	3.53	2.58	2.42	2.26	1.53	0.00
<b>Avg</b>	2.91	2.48	1.76	0.87	-0.75	-0.76	-1.22	-1.86	-3.44

Notes: Units are  $\mu\text{g}/\text{m}^3$ . Red indicates the column sensor average value is larger than the row sensor. Blue indicates the column sensor average value is smaller than the row sensor. All differences are significant at the 95% confidence level except for one light red cell. Sensors are ordered from most positive to most negative differences.

Source: Author calculations on PurpleAir data



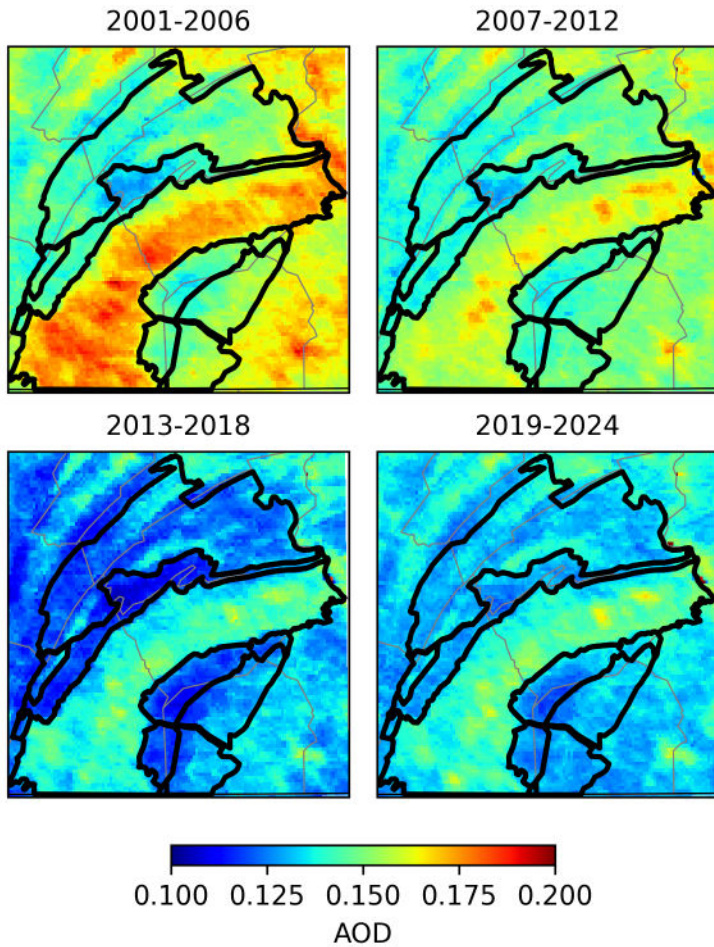
**Figure 10.** Average  $PM_{2.5}$  concentration difference between PurpleAir stations and all other stations.

Source: Author calculations on PurpleAir data

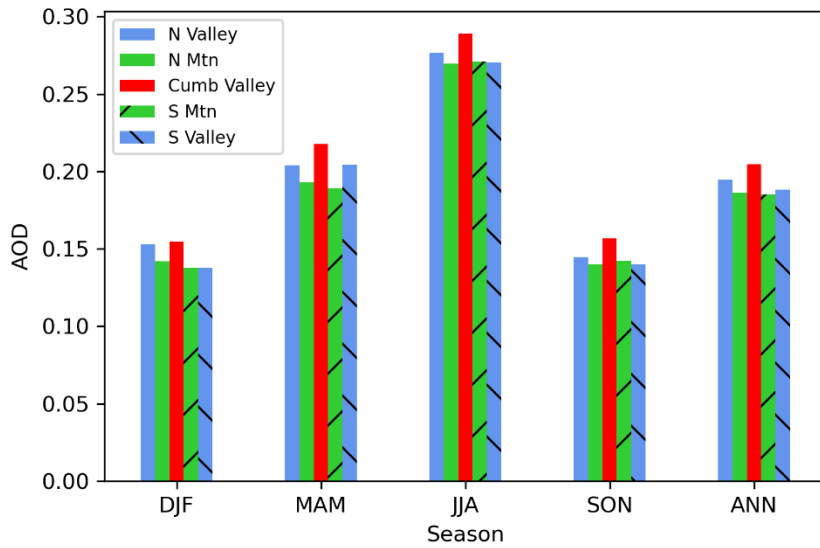
### **Satellite Local PM**

Annual average satellite images show distinctly higher AOD values in the CV compared to the surrounding areas (**Figure 11**). The images also show an overall decrease in AOD values between 2001-2024. Within the CV, AOD hotspots are apparent at each exit along I-81 as it runs the length of the CV from the Susquehanna River on the eastern edge to the Maryland border on the southern edge. Outside the CV and outside the study area in **Figure 1**, other AOD hotspots, not considered in this study, can be seen in developed areas such as the greater Harrisburg, PA area in the northeast corner of the images and Hanover, PA in the southeast corner.

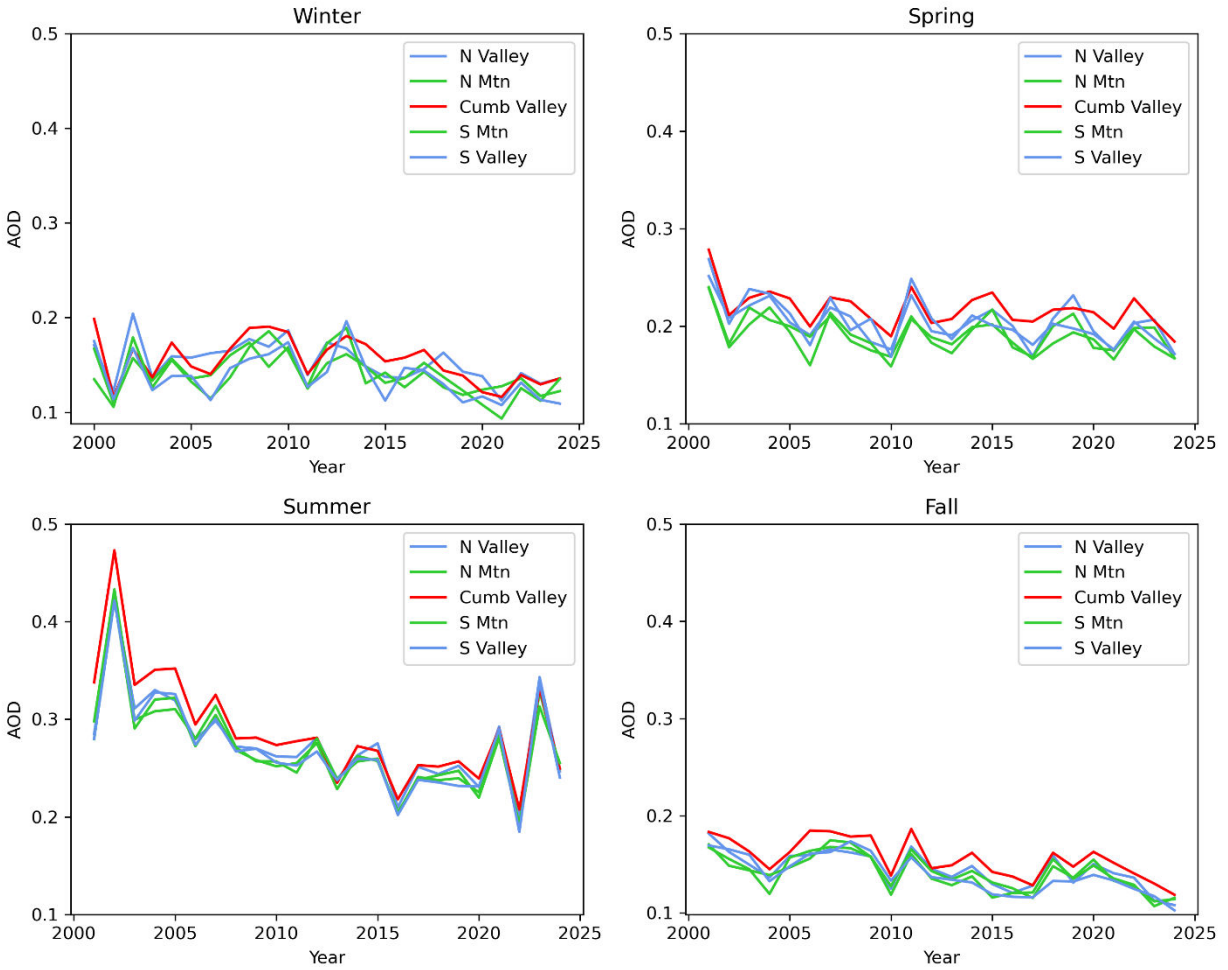
Averages for the areas in **Figures 1** and **11** allow for a more quantitative analysis. Seasonal average AOD is highest in summer and lowest in winter (**Figure 12**). For EPA measured  $PM$  concentration, summer was the highest concentration season, followed by winter. The ranking difference between winter  $PM$  and winter AOD may be due to the considerable number of missing days in the winter AOD data (**Table 3**) due to increased cloud cover. Across all seasons, AOD is higher in the CV than the north and south mountains and valleys. Annually, AOD is 5-10% higher in the CV compared to the non-CV areas.



**Figure 11.** Six-year annual average AOD.  
Source: Author calculations on MODIS data

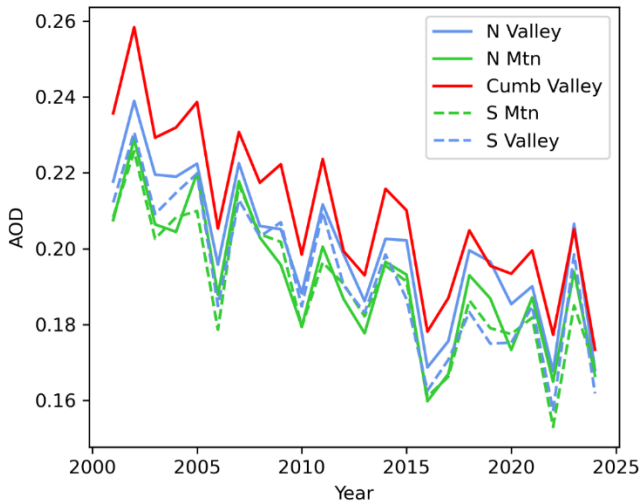


**Figure 12.** Seasonal average AOD for the areas in **Figure 1**.  
Notes: DJF=winter, MAM=spring, JJA=summer, SON=fall.  
Source: Author calculations on MODIS data



**Figure 13.** Seasonal average AOD time series for the areas in **Figure 1**.

Source: Author calculations on EPA data



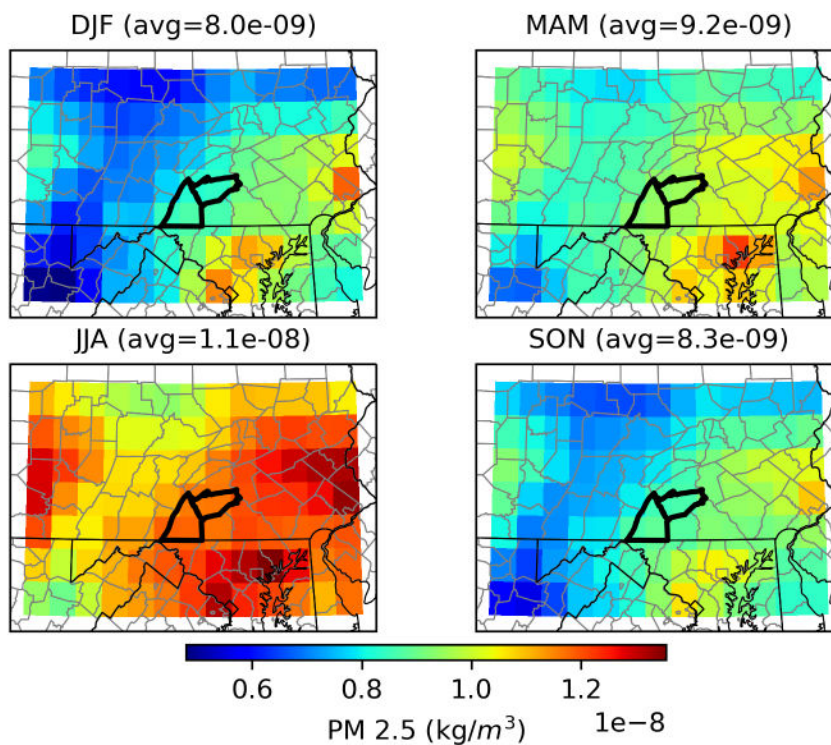
**Figure 14.** Annual average AOD time series for the areas in **Figure 1**.

Source: Author calculations on EPA data

Seasonal and annual AOD have all decreased between 2001-2024 for all areas (**Figures 13 and 14**). All trends are significant ( $p < 0.05$ ) except South Mountain in Winter ( $p = 0.13$ ) and North Mountain in spring ( $p = 0.07$ ). For most years, for all seasons and annually, CV values are higher than the north and south mountain and valley values. Comparing the first and last three years of the time series, AOD has decreased 4-13% in winter, 12-21% in spring, 23-31% in summer, 24-30% in winter, and 18-21% annually. Compared to the north and south mountain and valley areas, decreases in the CV in winter (3.5%) are smallest, in summer (31.2%) and annually (23.2%) are largest, and in spring and fall are in between the smallest and largest values for the other areas.

### Regional Modeled PM

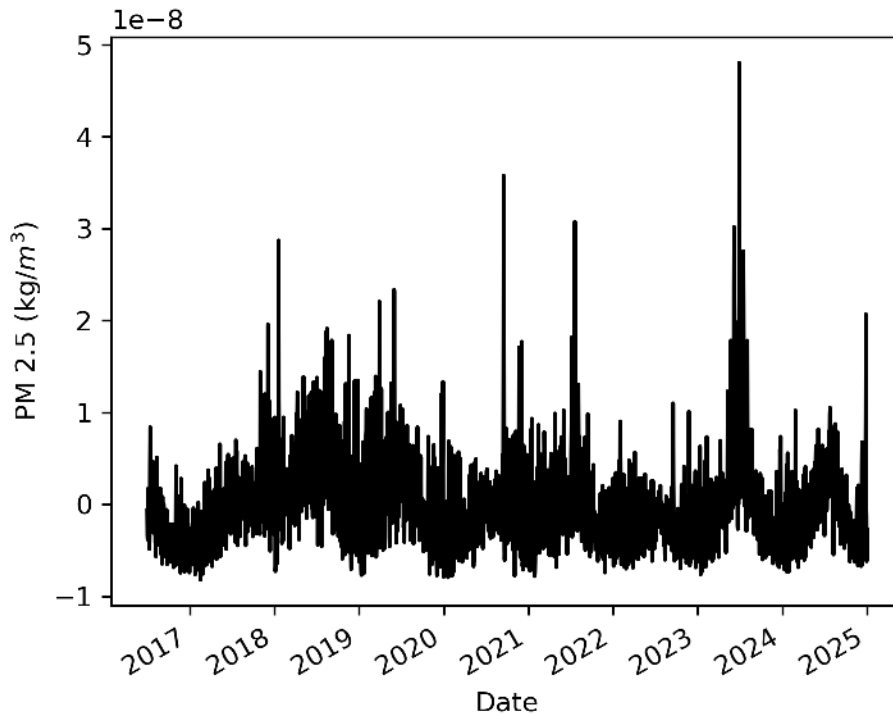
Regional CAMS PM<sub>2.5</sub> concentrations are highest in summer, followed by spring, fall, and winter (**Figure 15**). These seasonal rankings differ slightly from CV PM<sub>2.5</sub> concentrations where winter was the second highest. Significant spatial variability exists in the regional CAMS data. For each season, concentrations are generally highest along the I-95 corridor from eastern Pennsylvania to Washington DC, lower in the more rural and forested areas of west-central and northern Pennsylvania, western Maryland, and northeastern West Virginia, and higher again around Pittsburgh, Pennsylvania. The relatively low winter PM<sub>2.5</sub> concentrations in rural areas accounts for the overall low regional winter value. Gridded data are not as nuanced as the station data for the CV and thus some detail is lost. Gridded data are, however, useful for assessing regional patterns and the influences on those regional patterns.



**Figure 15.** Seasonal regional gridded CAMS PM<sub>2.5</sub> concentration.

Notes: DJF=winter, MAM=spring, JJA=summer, SON=fall. Values in ( ) are the means of all grid cells in the map.

Source: Author calculations on CAMS data



**Figure 16.** Daily average of gridded CAMS PM<sub>2.5</sub> concentration time series.

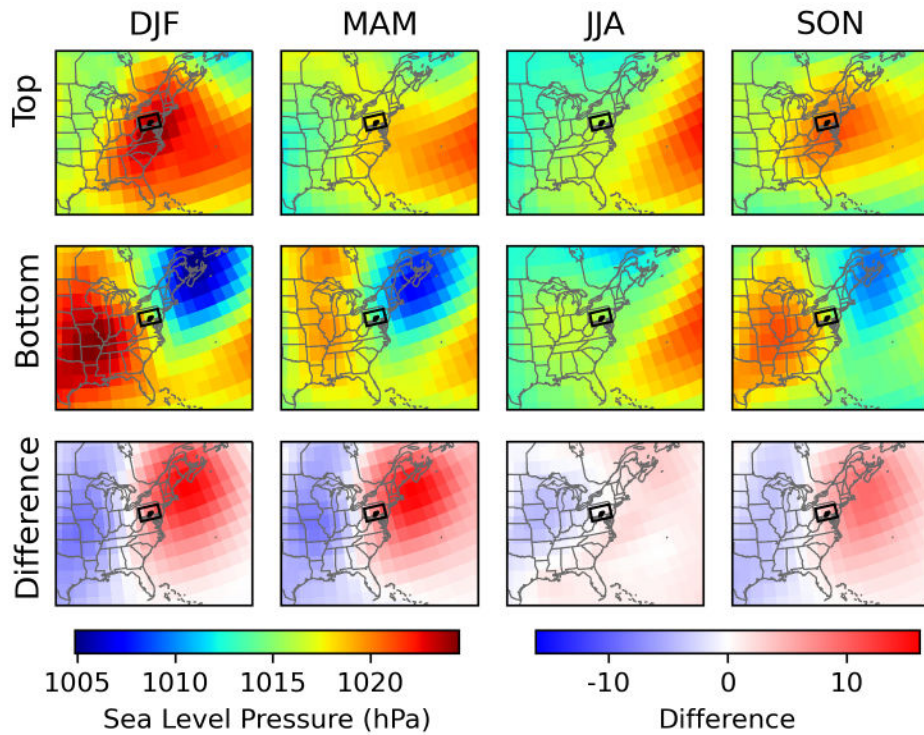
Notes: Values are presented as differences from the means before and after CAMS adjustment.

Source: Author calculations on CAMS data

The time series of the daily average of all CAMS grid cells shows this same seasonal cycle of higher summer PM<sub>2.5</sub> concentrations with noticeable spikes for events like the Canadian wildfires in summer 2023 (**Figure 16**). There is not a meaningful trend in regional PM<sub>2.5</sub> concentration due to the relatively short data record. CV PM<sub>2.5</sub> concentration station data do show significant decreases over a longer period but are relatively constant during 2017-2024, the period of the regional data.

### ***Weather Impacts on Regional PM***

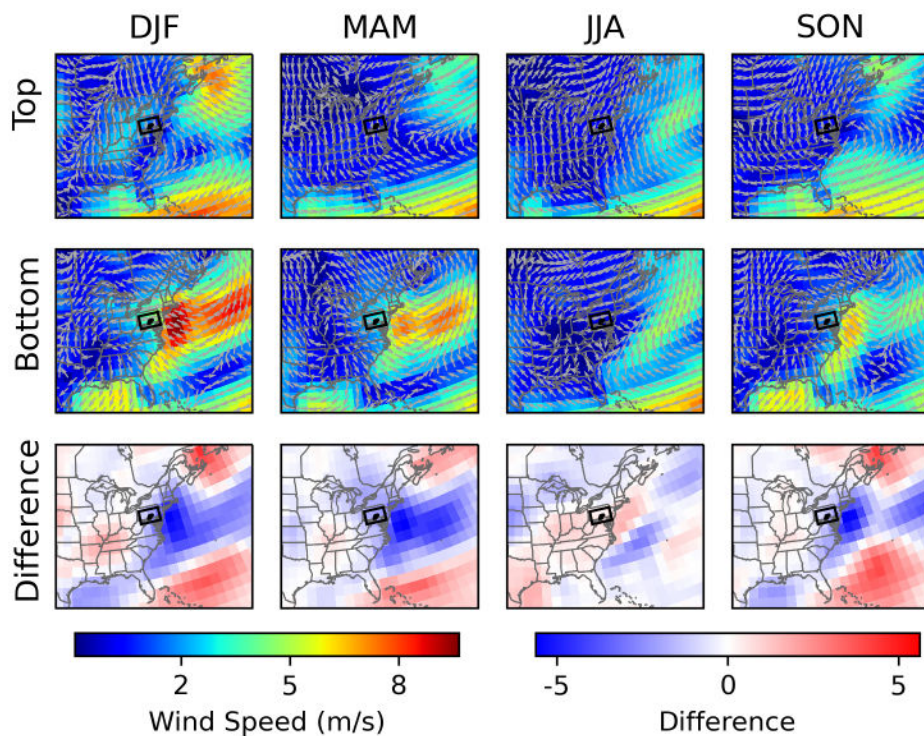
High CAMS PM<sub>2.5</sub> concentration days are characterized by high SLP in the CAMS region (**Figure 17**, top row). In winter and fall, the high pressure center is nearly on top of the CAM region, with higher pressure occurring in winter. In spring and summer, the high pressure is located more to the east of the CAMS region in the Atlantic Ocean. The seasonal high pressure movement is indicative of typical seasonal global pressure patterns where the Atlantic subtropical high becomes more dominant during the summer months. Low CAMS PM<sub>2.5</sub> concentration days are characterized in winter, spring, and fall by high pressure to the west of the CAMS study area and low pressure to the east of the CAMS study area, indicative of a frontal passage (**Figure 17**, middle row). The summer low PM<sub>2.5</sub> concentration map is similar to the high concentration map, but the high pressure center is shifted to the east for low PM<sub>2.5</sub> concentration days. The resulting seasonal differences between high and low PM<sub>2.5</sub> concentration days (**Figure 17**, bottom row) are higher SLP for high PM<sub>2.5</sub> concentration days centered over the Atlantic Ocean but encompassing the CAMS study area and lower SLP to the west of the CAMS study area.



**Figure 17.** Regional seasonal composite sea level pressure patterns.

Notes: The CAMS and CV areas are both highlighted in all maps. Columns are seasons. DJF=winter, MAM=spring, JJA=summer, SON=fall. The first row is average gridded values for the top 10% highest CAMS PM<sub>2.5</sub> pollution days. The second row is for the lowest 10% days. The third row is the difference between the first and second row.

Source: Author calculations on NCEP/NCAR data



**Figure 18.** Same as **Figure 17** but for wind speed and direction.

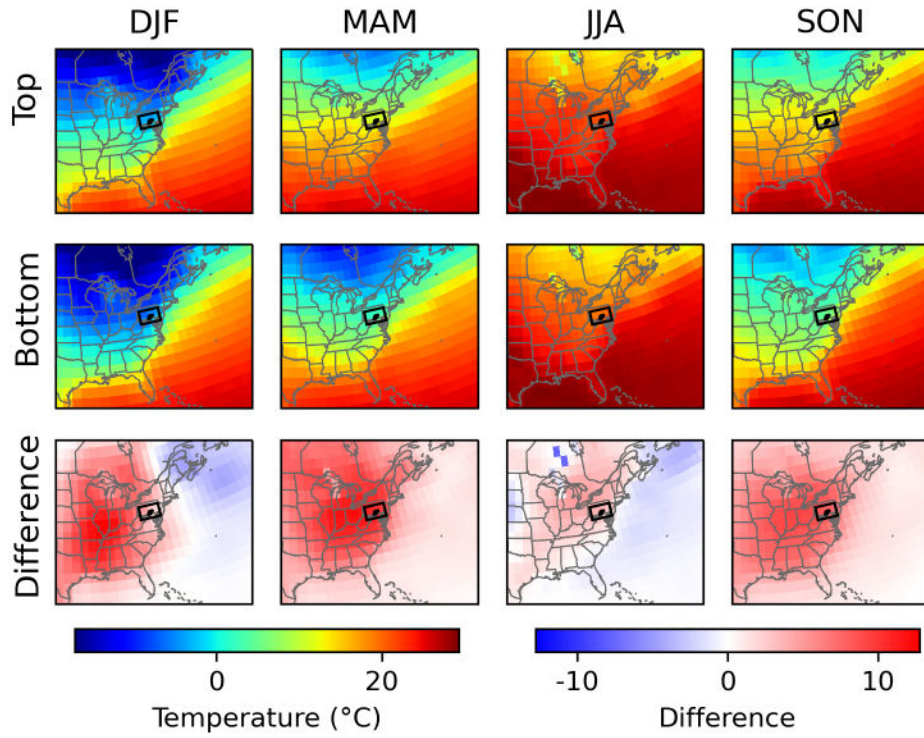


Figure 19. Same as Figure 17 but for temperature.

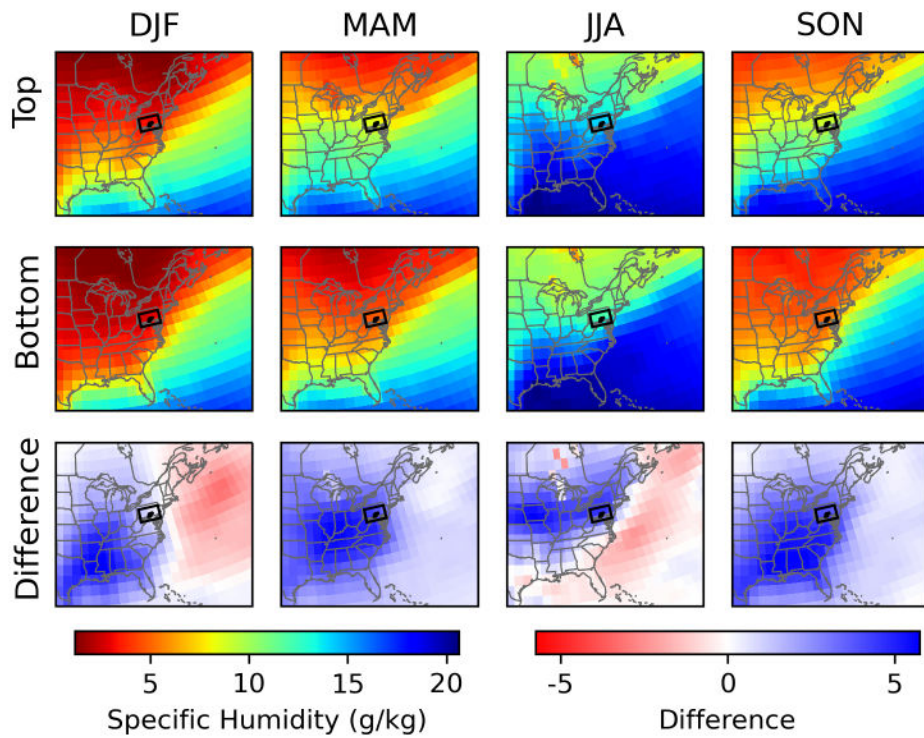


Figure 20. Same as Figure 17 but for specific humidity.

**Table 6.** Seasonal NCEP/NCAR reanalysis values for the grid cell closest to the CV for composite maps of the top and bottom 10% of CAMS PM<sub>2.5</sub> pollution days.

	Winter		Spring		Summer		Fall	
	Top	Bot	Top	Bot	Top	Bot	Top	Bot
SLP (mb)	1023.6	1016.6	1018.0	1013.8	1016.0	1015.9	1020.6	1016.7
Wind Speed (m/s)	2.1	4.4	1.0	3.2	1.0	0.9	1.3	2.7
Temp (°C)	-3.8	-5.4	10.9	2.6	21.4	19.6	12.8	5.2
Spec Hum (g/kg)	3.1	2.8	8.3	4.8	14.2	12.1	9.0	5.3

Source: Author calculations on NCEP/NCAR data

The surface winds that result from these SLP patterns are slower and more southerly during high PM<sub>2.5</sub> concentration days for all seasons (**Figure 18**). During the non-summer seasons, the frontal passage that is associated with low PM<sub>2.5</sub> concentration days produces stronger, and more westerly and northerly winds. During the summer on low PM<sub>2.5</sub> concentration days, the subtropical high is shifted eastward which also allows for faster winds.

The more southerly wind flow during high PM<sub>2.5</sub> concentration days serves to advect warmer and more humid air into the CAMS region (**Figures 19 and 20**). The relatively stagnant conditions serve to keep this warm, humid air in place. The non-summer frontal boundary during low PM<sub>2.5</sub> concentration days is apparent in the temperature and humidity maps as the gradients are more north-south oriented compared to the high PM<sub>2.5</sub> concentration days where the gradients are more east-west oriented along latitudinal lines.

For all variables, winter patterns and winter differences between high and low PM<sub>2.5</sub> concentration days are most pronounced as winter storm tracks shift south into the US. In summer, storm tracks shift northward, and the region is more under the influence of the subtropical high. Spring and fall are transition seasons.

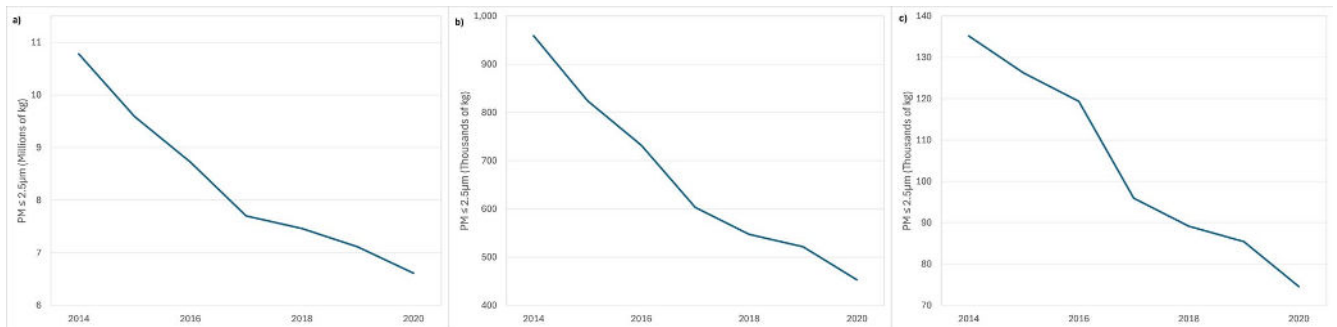
Map analyses are summarized by examining the NCEP/NCAR grid cell closest to the CV (**Table 6**). Across all seasons, high PM<sub>2.5</sub> concentration days, compared to low PM<sub>2.5</sub> concentration days, are characterized by higher SLP, slower wind speed, warmer temperature, and higher specific humidity. The only exception is summer wind speed where high PM<sub>2.5</sub> concentration days have slightly higher wind speed, but the difference is small and both values are slow.

### ***Economic Modeling***

Total emissions for PM<sub>2.5</sub> associated with the warehouse industry have decreased from 2014 to 2020 nationally (41%), statewide in Pennsylvania (53%), and locally in the CV (45%) (**Figure**

21). The decreases are likely due to efforts to reduce emissions, regulate industries, and technological advances. The comparatively slower decrease at the national level is likely due to varying state and local air quality regulations and implementation.

With 67 counties in Pennsylvania, the CV (two counties), would be expected to contribute 3% (2/67) of Pennsylvania’s total warehouse emissions. The CV, however, contributes 16% (Table 7). With 50 states in the U.S., Pennsylvania would be expected to contribute 2% (1/50) of the US’s total warehouse emissions. Pennsylvania contributes 5-9%. Finally, with approximately 3,142 counties in the US, the CV would be expected to contribute 0.06% (2/3,142) to the total US warehouse emissions. The CV, however, contributes 0.6-1.1%. Percentages suggest an outsized influence of the CV and PA to the nation’s warehouse-related PM<sub>2.5</sub> emissions.



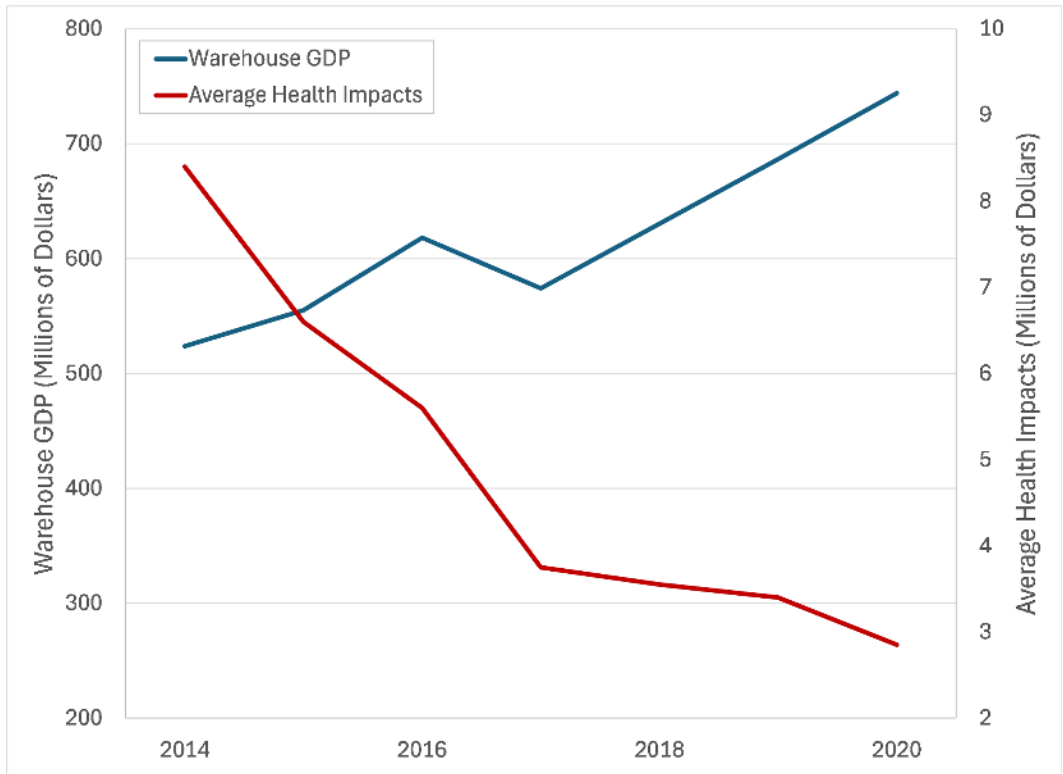
**Figure 21.** Total EEIO PM<sub>2.5</sub> emissions in (a) US, (b) Pennsylvania, and (c) CV.

Source: Author calculations on BEA, BLS, and EEIO data

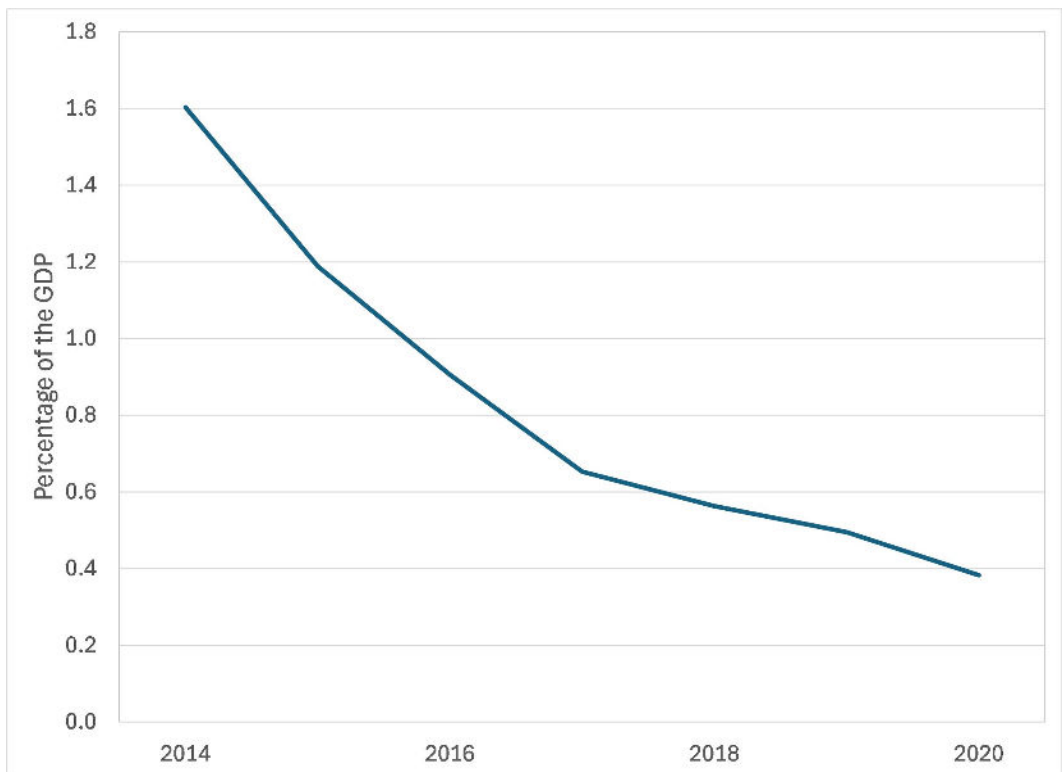
**Table 7.** 2020 warehouse PM<sub>2.5</sub> emissions, calculated as a percentage of emissions for different geographies.

Relationship	Emission Type	Percentage
CV as a percentage of PA	Direct	16
	Indirect	16
	Total	16
PA as a percentage of US	Direct	4
	Indirect	6
	Total	6
CV as a percentage of US	Direct	0.6
	Indirect	1.1
	Total	1.0

Source: Author calculations on BEA, BLS, and EEIO data



**Figure 22.** GDP and monetary health impacts of the warehousing industry in Franklin County.  
 Source: Author calculations on BEA, BLS, EEIO, COBRA, and RIMS II data



**Figure 23.** Monetized health impacts for Franklin County as a percentage of warehousing GDP.  
 Source: Author calculations on BEA, BLS, EEIO, COBRA, and RIMS II data

Monetized public health impacts associated with warehousing PM<sub>2.5</sub> emissions in Franklin County decreased by \$5,550,000 (66%) from 2014 to 2020 (**Figure 22**). Much of this reduction occurred between 2014 to 2017, when impacts decreased by \$4,650,000 (55%). In contrast, the decline between 2017 and 2020 was more modest at \$900,000 (24%), showing a deceleration to the rate of improvement. Comparatively, over this same 2017 to 2020 period, the warehousing GDP continued to grow sharply by \$169,979,861 (30%), likely due to increasing demand for goods and services. The observed reduction in monetized health impacts is attributable to the decreased emissions generated by EEIO. Consistent with these trends, monetized health impacts as a proportion of warehousing GDP fell by 76% from 2014 to 2020, decreasing from 1.60% to 0.38% (**Figure 23**). This trend suggests increased economic growth in the warehousing sector in Franklin County (and the entire CV) with decreasing health impacts. This statement is contingent upon the condition that technology continues to improve and therefore, emissions continue to fall.

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