Connections between summer air pollution and stagnation

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Abstract

The body of literature on ambient air pollution suggests that atmospheric stagnation events trigger high levels of air pollution. In this paper we use fifteen years (2000–2014) of summertime in situ air quality measurements together with meteorological reanalysis data to examine the temporal correlation of pollutants with the Air Stagnation Index (ASI) on daily timescales. We find that while the direction of the relationship between the ASI and summertime PM$_{2.5}$ and O$_3$ ranges from near-zero to positive throughout regions comprising the contiguous United States (US), the strength of the relationship is very weak (e.g. in the Northeast the correlation coefficient between the ASI and PM$_{2.5}$ is 0.09). Moreover, similar to our analysis of the correlation of day-to-day variations of the ASI and pollutants, the percentage of co-occurring extreme pollution and stagnation events is small (e.g. days with a high coverage of stagnation only co-occur with extreme pollution events about one-third of the time in the Northeast). The southern US is an exception to our overall findings as the strength of the relationship between the ASI and pollution is stronger and the percentage of co-occurring events is higher compared with other regions. The results of this study suggest a reevaluation of the ASI as an index to assess meteorological and climatic impacts to air quality.

1. Introduction

There is a widely-accepted paradigm that air stagnation events are a major cause of elevated surface concentrations of air pollutants such as ozone (O$_3$) and particulate matter with a diameter of 2.5 μm or less (PM$_{2.5}$) (e.g. review articles Jacob and Winner 2009, Fiore et al 2012, Fiore et al 2015). Recently there has been an increased focus on possible increases in the frequency of stagnation events due to climate change (Leung and Gustafson 2005, Horton et al 2012, 2014). The study of stagnation as a possible cause of extreme surface-level PM$_{2.5}$ and O$_3$ concentrations is scientifically and societally relevant due to their public health risks. These two pollutants lead to a myriad of adverse health impacts, particularly affecting human respiratory function (Ebi and McGregor 2008).

Stagnation is characterized by the trapping of air within the planetary boundary layer due to lack of ventilation or the presence of an inversion under clear sky conditions, often occurring in the presence of slow-moving high pressure systems (Wang and Angell 1999, Jacob and Winner 2009). These conditions lead to elevated pollutant concentrations on daily to interannual timescales (e.g. Logan 1989, Vukovich 1995, Wang and Angell 1999, Vautard et al 2005, Leibensperger et al 2008, Tai et al 2010, He et al 2013b, Dawson et al 2014, Oswald et al 2015, Hou and Wu 2016, Schnell and Prather 2017, Sun et al 2017); however, the change in pollutant concentrations due to stagnant conditions is small and the connections between stagnation and pollution are weak in some of these studies. Thus, there remains uncertainty in the exact impact of stagnation on air pollution.

We examine the daily variability of, and occurrence of, extreme events in PM$_{2.5}$, O$_3$, surface temperature and stagnation in the contiguous US by performing a systematic study that quantifies the connection between pollutants and stagnation on daily timescales and with individual pollution events. Using the common
Air Stagnation Index (henceforth ‘ASI’, described in section 2), we diagnose stagnation events and show only a weak correspondence between the ASI and pollution with regard to day-to-day variations as well as the co-occurrence of events.

2. Data and methods

2.1. Data

We use station-based measurements of PM$_{2.5}$ and O$_3$ from the US Environmental Protection Agency air quality system (AQS). For PM$_{2.5}$ we analyze the maximum value for each 24 hour period at each station, while for O$_3$ we analyze the maximum daily 8 hour average concentrations at each station.

We focus on Northern Hemisphere summer (1 June–31 August; JJA) as high O$_3$ concentrations (Vukovich 1995, Dawson et al. 2007b, Jacob and Winner 2009, Rieder et al. 2013), high PM$_{2.5}$ concentrations (Dawson et al. 2007a, Hand et al. 2012), or both high O$_3$ and PM$_{2.5}$ concentrations (Schnell and Prather 2017) have been shown to occur during this season. We use all available AQS measurements from summers between 2000 and 2014, including rural, suburban, and urban stations (figure 1). O$_3$ measurements are typically taken every day at a particular station whereas observations of PM$_{2.5}$ concentrations display more heterogeneity in time. A majority of PM$_{2.5}$ stations sample every 3 days, although some stations sample at a daily frequency while others sample every 6 days (Tai et al. 2010, Saunders and Waugh 2015, Liu et al. 2017). We assess meteorology with the Modern Era Retrospective-Analysis for Research and Applications (MERRA) reanalysis (Rienecker et al. 2011). The MERRA data have resolution 1° latitude ×2°/3° longitude, and we use daily mean values of 2 meter temperature ($T_{2m}$), 10 meter wind ($U_{10m}$), 500 hPa wind ($U_{500hPa}$), and total surface precipitation flux (pr). Each field is sampled only at MERRA grid cells containing AQS stations on days with PM$_{2.5}$ and O$_3$ observations. If there are > 1 AQS stations within the bounds of a particular MERRA grid cell, this cell is counted proportionally to the number of AQS stations contained within when we calculate regionally-averaged $T_{2m}$ and the percentage of stagnant grid cells in a region.

2.2. Methods

The daily variations of PM$_{2.5}$, O$_3$, $T_{2m}$, and the ASI are examined; the first two derived from AQS and latter two from MERRA. The ASI is described in detail in Horton et al. (2012, 2014), and the use of the ASI for air quality applications is ubiquitous in the literature (e.g. Leung and Gustafson Jr 2005, Horton et al. 2012, 2014, Oswald et al. 2015, Strode et al. 2015, Hou and Wu 2016, Schnell and Prather 2017, Sun et al. 2017). The ASI is a binary index based on absolute thresholds. Here we consider a MERRA grid cell as stagnant when daily mean $U_{500hPa} < 13$ m s$^{-1}$, daily mean $U_{10m} < 3.2$ m s$^{-1}$, and total daily pr < 1 mm.

The definition of the ASI used in this study and described in Horton et al. (2012, 2014) slightly differs from the definition used by the National Centers for Environmental Information (NCEI, formerly the National Climatic Data Center), detailed in Wang and Angell (1999) and Korshover and Angell (1982). To this end, we compared the spatial distribution of stagnant days determined after Horton et al. (2012, 2014) with maps of the number of stagnant days in a given month from the NCEI website (www.ncdc.noaa.gov/societal-impacts/air-stagnation/), and we found similar results regardless of the precise definition of the ASI.

Concerns may be raised that our results are an artifact of our choice of the MERRA reanalysis to calculate the ASI. To counter this, we have compared the ASI derived from MERRA to that from the coarser NCEP reanalysis as well as using gauge-based precipitation from the Climate Prediction Center (CPC) Unified Precipitation Project. The results of this (not shown) indicate similar ASI distributions using MERRA, NCEP, and CPC datasets, and our broad conclusions do not change; however, specific results could change if other reanalyses are used.

These findings are reinforced by a sensitivity analysis through which we examined the sensitivity of the pollutant - ASI correlations to each of the three thresholds used to define the ASI (figure S1 available at stacks.iop.org/ERL/13/084001/mmedia). By varying the $U_{10m}$, $U_{500hPa}$, and pr thresholds by values ranging from 25%–175% of the standard threshold we found only small changes in the correlations between PM$_{2.5}$ and O$_3$ with the ASI that did not change our overall results. Thus, we have confidence that our results are robust to both data and methods used and that the conclusions of our study are not sensitive to the precise definition of stagnant conditions.

We calculate daily regionally- or state-averaged values for all four quantities used in this study (PM$_{2.5}$, O$_3$, $T_{2m}$, and ASI) by computing the arithmetic mean using all available daily values for each region or state (figure 1 and figure S2). Since the ASI is a binary field, we use a different approach to form spatially-averaged values: for a given day we calculate the percentage of AQS stations within a region that is classified as stagnant (ASI = true). Therefore, the regional ASI varies between 0 and 100%.

We use two approaches to quantify the relationship between the four different quantities. First, we calculate the Pearson product-moment correlation coefficient, r, between the daily time series of pairs of quantities. Second, we consider days which are ‘events’ in one quantity (i.e. days with high regional ASI) and calculate the distribution of the other quantities to see how often they are concurrently extreme events. We consider an event as a day in which regionally-averaged quantities equal or
exceed their 80th percentile ($P_{80}$) of daily JJA values for a particular summer. The use of a quantity’s percentile as a threshold for events allows for a consistent number of events each summer (by definition, 19 events per summer) because focusing on exceedences over an absolute value would preferentially group PM$_{2.5}$ and O$_3$ events towards the beginning of the measuring period due to the decreasing trend in ambient pollutant concentrations between 2000 and 2014. This approach is similar to that of Schnell and Prather (2017) and Sun et al (2017), although the exact percentile we have chosen ($P_{80}$) differs. For both approaches we also consider how lag might affect the correspondence since temporal offsets between PM$_{2.5}$, O$_3$, and temperature events exist (Schnell and Prather 2017).

### 3. Northeast United States

We first consider stagnation and pollution in the Northeast US (figure 1) and examine the variability of, and relationships among, Northeast-averaged pollutants, the percentage of stagnation coverage, and surface temperature. As an example, figure 2(a)–(c) shows the daily variation of these quantities during the summer of 2011. All quantities display large daily variability, but figures 2(a)–(c) shows that the variabilities of these quantities are not always correlated. In particular, days or periods with a high percentage of stagnation coverage do not generally correspond to days or periods with high pollutant concentrations (compare figures 2(a) and (b)), and $r$ between the ASI and PM$_{2.5}$ or O$_3$, as indicated in figure 2(d), are near zero. We note that there are some hints that the ASI might precede pollution in some cases, and the role of lag will be further explored in this section; but, overall, the correlation between PM$_{2.5}$ - ASI and O$_3$ - ASI is weak. In contrast, PM$_{2.5}$ and O$_3$ are highly correlated during the summer of 2011 and are generally accompanied by similar temperature variations (figures 2(b)–(c)).

Although we primarily use regionally-averaged quantities in our present work, evaluating the spatial overlap of stagnant regions with the regions of highest pollutant concentrations leads to similar results. For example, in the case study shown in figure S3, representing the highest Northeast-averaged pollutant concentrations during the summer of 2011, stagnant regions show little cohesive structure and are mostly confined to the southern US, not the region with the highest PM$_{2.5}$ and O$_3$ concentrations (in this case, the Eastern Seaboard). On the other hand, we observe that the pollutants display much of the same spatial and temporal progression and the highest temperatures closely coincide with the region of maximum pollutant concentrations observed in the Northeast.

The results from summer 2011 hold for most years between 2000 and 2014. This is shown in figure 2(d), which shows $r$ between each pair of variables for each summer and multi-year average correlation coefficients. Of the pairs examined, PM$_{2.5}$ and O$_3$ consistently have the strongest positive relationship followed by T$_{2m}$ - PM$_{2.5}$ and T$_{2m}$ - O$_3$. The correlation between the pollutants and ASI is weak and, for the case of PM$_{2.5}$ - ASI, near-zero indicating almost no degree of a linear relationship. The average correlation coefficient of O$_3$ - ASI is higher than PM$_{2.5}$ - ASI (i.e. 0.28 versus 0.09) and is strongly influenced by the high $r$ values in 2003 and 2010 (for these two summers the relationship between the ASI and O$_3$ was approximately as strong as the relationship of O$_3$ and T$_{2m}$). The cause of this strong O$_3$ - ASI correlation for these two summers requires further examination; but, in general, the correlation is weak.

The correlation between T$_{2m}$ and ASI in the Northeast is the weakest of all the pairs analyzed, and several years indicate that the correlation coefficients between surface temperature and the ASI are slightly negative. These results are inconsistent with the commonly-made statements linking stagnant conditions with high ambient temperatures (Tai et al 2010, Austin et al 2014, Fiore et al 2015, Shen et al 2016b, Zhang et al 2017).
Figure 2. Daily percentage of stagnant stations in the Northeast is shown in (a), and regionally-averaged pollutant concentrations from stations in the Northeast are depicted and labeled with consistent colors in (b). Here PM$_{2.5}$ and O$_3$ represent daily regionally-averaged concentrations from all available monitoring stations in the Northeast. (c) shows average 2 meter temperatures averaged colocated with stations in the Northeast. Pearson product-moment correlation coefficients ($r$) between each pair of variables for each summer in the measuring period were calculated for the Northeast (d), and the multi-year average $r$ values are noted in boldface in the table’s final column.

Given the size of the Northeast region, pollutant concentrations and colocated meteorology could substantially differ from station to station; however, we find similar correlations for individual states comprising the Northeast region compared with the regionally-averaged Northeast correlation (figure S2). For example, $r$ between Northeast-averaged PM$_{2.5}$ and the regional percentage of stagnant cells is 0.09. Upon considering the correlation coefficients for the 14 individual states in the Northeast, we find that $r$ varies from $-0.01$ to 0.28. Thus, although stationary (or quasi-stationary) anticyclones could migrate within a particular region and affect the relationship between pollutants and the ASI within, we find that our methodology is spatially-insensitive up to a region that is roughly the size of a typical anticyclone.

We also repeated the correlation analysis between the ASI and pollutants (figure 2(d)) for AQS stations in rural, suburban, or urban environments, and the details of this analysis are shown in table S1. Considering pollutant concentrations in different environments could lead to different relationships between the ASI and pollutants due to, for example, NO$_x$ titration, but we find that comparing only rural-, urban-, or suburban-averaged PM$_{2.5}$ (O$_3$) with the percentage of stagnant cells calculated for each environment leads to correlation coefficients ranging from 0.05 to 0.13 (0.24 to 0.31) compared to an correlation of 0.09 (0.28) using an average of all rural, urban, and suburban AQS stations.

We have shown that there are weak correlations between the daily time series of the spatial extent of the ASI and pollutants or temperature, but this does not necessarily mean that this lack of relationship applies for extreme events. We now examine whether pollution events show preferential co-occurrence with ASI events. As described in section 2, an event is defined as a day in which pollutant concentrations, surface temperature, or the percentage of stagnant cells fall into the top 20th percentile of days for a particular summer. Given the dates of pollutant and ASI events, we calculate the same-day percentile distributions of other variables (grey histograms in figure 3) and the maximum percentile of the other variables on the day before the event and the day following the event (lag = ± 1 day; black outlined histograms). Our results are not sensitive to the use of $P_{80}$ as the threshold for events, and we observe similar relative differences between the combinations of different quantities.

We first consider the relationship between PM$_{2.5}$ and O$_3$ events. Given the high correlation in the daily time series of these quantities, a high co-occurrence of events is expected. This is indeed the case, and nearly two-thirds of PM$_{2.5}$ and O$_3$ events co-occur, while the frequency of co-occurring events increases to over 80% if we consider that PM$_{2.5}$ or O$_3$ could also precede or proceed each other by a day (figures 3(a)–(b)). The picture is, however, different for co-occurrence between pollution and ASI events, and there is only a small percentage of co-occurring pollutant and ASI events (figures 3(d)–(e)). Allowing for
Figure 3. Percentile distributions of Northeast-averaged quantities are plotted in grey five percentile bins on days with PM$_{2.5}$, O$_3$, and ASI events (a), (d) and (g), O$_3$ (b), (e) and (h), and ASI events (c), (f) and (i). White vertical lines superimposed on the grey histograms indicate the 80th percentile ($P_{80}$), and the corresponding white-colored text states the percentage of events occurring above this threshold and are therefore also pollution, temperature, or ASI events by definition. The same distributions but for the given quantity preceding or proceeding the other quantities by a day (lag = ±1 day) is shown in black outlined histograms. Text above these outlined histograms is the percentage of lagged events that are also events in the other quantity.

the ASI to lag pollutant events by ±1 day leads to a higher frequency of co-occurring events (46% for both PM$_{2.5}$ and O$_3$, black outlined histograms in figures 3(d)–(e)). Although this indicates that nearly half of pollution events tend to occur within a day of ASI events, over 50% of pollution events do occur under non-stagnant conditions, presenting a possible gap in the community’s understanding of the drivers of these events.

The percentile distributions of temperature for pollutant events (figures 3(g)–(h)) are negatively skewed and indicate that polluted days are likely to also be hot days in the Northeast. Comparing the percentage of same day or lagged co-occurring events in figures 3(g)–(h) versus figures 3(d)–(e) suggests that a metric as simple as surface temperature is a much better predictor than the ASI; for instance, 2.5 times as many same-day temperature and PM$_{2.5}$ events co-occur than same-day ASI and PM$_{2.5}$ events (55% versus 22%).

The lack of co-occurrence of ASI events with pollution and temperature events is highlighted in the third column of figure 3, which shows the percentile distributions of pollutants and temperature for ASI events. Days with ASI events are characterized by relatively flat, uniform distributions of same-day PM$_{2.5}$, O$_3$, and $T_{2m}$; therefore, regional ASI events in the Northeast are generally neither polluted nor hot days; however, allowing for lag increases the percentage of co-occurrence for ASI events, although these lagged distributions are not as negatively skewed as the lagged temperature-pollutant distributions.

Sun et al (2017) have recently shown the impact of meteorological persistence on O$_3$. Using different data and methods than us, they drew similar conclusions to our study: a single stagnation day is not a good predictor of high O$_3$, while the best single day predictor of high O$_3$ concentrations is high temperature (Sun et al 2017). Their results also suggested that successive (multi-day) ASI events have the potential to enhance pollutant concentrations. We evaluate this possibility by calculating the average percentiles of Northeast-averaged PM$_{2.5}$ and O$_3$ for ASI events of different lengths (i.e. single-day ASI event, two successive ASI events, etc). This analysis shows a small increase in the percentile of PM$_{2.5}$ and O$_3$ on the event’s final day with increasing event length (figure S4), but overall, even three or four consecutive days with ASI events fail to enhance PM$_{2.5}$ or O$_3$ to levels that would classify their average concentrations as events (i.e. $\geq P_{80}$). This is consistent with Sun et al (2017) who showed that four consecutive ASI days could only increase the conditional probability of a high O$_3$ day to $\sim$0.60.
4. Contiguous United States

The analysis in the previous section showed a weak correspondence between the ASI and pollution, both with respect to daily variability and the co-occurrence of extreme events, in the Northeast US. We next turn our focus to the other regions shown in figure 1 and highlight the correspondence of pollution and the ASI in these regions. We use the correlation coefficient ($r$) averaged over all summers (figure 4(a)) and the percentage of co-occurring events (figure 4(b)) to analyze the correspondence of pollution, surface temperature, and the ASI for each region.

The relationships between the variables in the Midwest are qualitatively similar to the Northeast. High PM$_{2.5}$ concentrations are often accompanied by high O$_3$ concentrations and high temperatures and vice versa, but same-day pollution and temperature events co-occur with ASI events with greater frequency in the Midwest compared to the Northeast (i.e. 32% for PM$_{2.5}$ - ASI, 45% for O$_3$ - ASI, and 18% for T$_2$ - ASI; figure S5(e), (f), (i)); however, the ASI cannot explicitly explain a majority of pollution events, even when allowing for the ASI to precede pollution by 1 day (dashed outlined bars in figure 4). Again, as in the Northeast, there is not a strong relationship between the ASI and temperature ($r = 0.05$, 18% of events co-occur).

We repeat the analysis shown in figure 3 for the other regions defined in figure 1 and present these findings in the supporting information (figures S5–S8). The South stands out as the region with the highest correlation and event co-occurrence between the ASI and pollution. Allowing for ±1 day lag between the ASI and pollutants increases the event co-occurrence in the South; however, an interesting aspect of the lag analysis in this region is that allowing the ASI to lag O$_3$ events by ±1 day (figure S6(e)) increases the probability of co-occurring O$_3$ events (71%) whereas only allowing the ASI to precede O$_3$ by 1 day (figure 4(b)) decreases the likelihood (52%). This implies stagnant conditions occur the day following O$_3$ events in the South. This result is counterintuitive, and further work is needed beyond this study to understand the timing of event onset. Unlike in the Northeast, PM$_{2.5}$ and O$_3$ events are less likely to co-occur in the South by ∼20% (figures 3(a)–(b) versus figure S6(a)–(b)). In the South stagnation events preferentially occur on days with more moderate to cooler temperatures (figure S5(i)).

In the Intermountainous West and West the relationship between PM$_{2.5}$ and O$_3$ is weaker than in other regions and could reflect compositional differences of PM$_{2.5}$ in these regions (Hand et al 2012) and the role of PM$_{2.5}$ composition on the chemical coupling between PM$_{2.5}$ and O$_3$ (Meng et al 1997, Brown and Jin 2013). Of all the regions examined, same-day temperature and ASI events occur with the greatest frequency in the Intermountainous West and West (35% and 42%, respectively) (figure 4(b)). Correlations between the ASI and pollutants in the Intermountainous West and West are intermediate between the South and the Midwest/Northeast. However, allowing for the ASI to precede pollutants by 1 day in the Intermountainous West and West does not increase the likelihood of co-occurring events or strengthen correlation coefficients by the same margin as for other regions. Similar to the South, this 1 day lag decreases the coincidence of co-occurring ASI and pollutant events (29 to 27% for PM$_{2.5}$, 43 to 38% for O$_3$) and weakens correlation coefficients (0.31 to 0.27 for PM$_{2.5}$, 0.51 to 0.37 for O$_3$) in the West (figure 4).

Understanding the regional heterogeneity of stagnation’s correspondence with pollutants requires further examination, but the increased frequency of concurrent stagnation and pollution events in the South and West (figures 4(b) and 5) could stem from the increased persistence of pollution events in these regions compared to the northern regions (e.g. Lehman et al 2004) as lengthened pollution events could allow for a preferential coincidence with stagnant regions. Similarly, Zhang et al 2018 found the highest coincidence of stagnation with O$_3$ occurred in the South, Southeast, and along the West Coast. Thus, the increased frequency of co-occurrence in these regions might also arise from the strong correlation between pollutants and U$_{10m}$, one of the three variables used to calculate the ASI.

As done for the Northeast, we also considered the ASI - pollutant correlations from different environments and observed only small differences using only rural, urban, or suburban stations (table S1). The correlation between rural PM$_{2.5}$ and the ASI in the West is a peculiar case: here, the rural correlation is $r = 0.11$ whereas the correlations for urban, suburban, or all locations are ∼0.30; we speculate that this could arise from the paucity of AQS stations in this region or if rural stations in this region are located at higher altitudes than the urban and suburban stations and therefore sample the lower free troposphere.

5. Reconciliation with previous studies

As discussed in the introduction (section 1), it is widely-accepted that atmospheric stagnation is one of main causes of extreme air pollution. However, we reveal that stagnant conditions, as characterized by the ASI, cannot explain a majority of pollutant events and are not well-correlated with pollutant concentrations. This appears to contradict some previous studies. For example, Tai et al 2010 and Dawson et al 2014 have shown high PM$_{2.5}$ during stagnant compared to non-stagnant days or periods. The apparent contradiction is because the increase in PM$_{2.5}$ between stagnant and non-stagnant days is much smaller than daily variability in these studies (for example, Tai et al 2010 report an increase in PM$_{2.5}$ of 2.6 μg m$^{-3}$ on stagnant days across the contiguous US). If we calculate the difference...
Figure 4. Spatially-averaged daily pollutant concentrations, surface temperatures, and the percentage of stagnant cells over each region defined in figure 1. (a) 2000–2014 average correlation coefficients between the variables. The grey bars show correlations with no time lag, while dashed, outlined bars show the correlation coefficient for PM$_{2.5}$ - ASI and O$_3$ - ASI when ASI precedes the pollutants by 1 day. (b) The frequency of event co-occurrence for each region. Again, the dashed lines correspond to the frequency of event co-occurrence when the ASI precedes PM$_{2.5}$ or O$_3$ events by 1 day.

in PM$_{2.5}$ and O$_3$ concentrations between summertime stagnant and non-stagnant days (figure 5), we also find a small increase (for instance, 2.34 $\mu$g m$^{-3}$ for PM$_{2.5}$ and 7.94 ppbv for O$_3$ in the Northeast). This is consistent with our correlation analysis: although the strength of the correlation between the ASI and PM$_{2.5}$ or O$_3$ is weak, there is, in general, a positive association, indicating increased PM$_{2.5}$ or O$_3$ with increased stagnation coverage. Thus, on average, days with a high percentage of stagnation coverage have higher pollutant concentrations than days with a low percentage. However, the difference is small, and we have shown that there are many days when the percentage of stagnant cells and pollutants are not both high (or both low).

The fact that there is on average a small increase in pollutant concentrations on stagnant days (figure 5) also reconciles our analysis with previous studies showing the interannual relationship between stagnation and pollution (Leibensperger et al 2008, Schnell and Prather 2017). Repeating our analysis for mean JJA values we also find moderate positive correlations between pollutants and the ASI in the Northeast (i.e. $r_{ASI-PM_{2.5}}$ and $r_{ASI-O_3}$; figure S9), but the difference in pollutants between years is small (i.e. interannual standard deviation of mean JJA values for PM$_{2.5}$ (O$_3$) is only 1.89 $\mu$g m$^{-3}$ (4.11 ppbv) in the Northeast).

In summary, there are differences in average PM$_{2.5}$ or O$_3$ concentrations between stagnant and non-stagnant days or between summers with different frequencies of stagnation events, but these differences are very small and there is far from a one-to-one correspondence between stagnation and pollutants on daily timescales or for the co-occurrence of extreme events.

Our findings of a weak relationships between pollution and the ASI is consistent with Wang et al (2018) and Huang et al (2018) who showed that the ASI was not well-correlated with PM$_{2.5}$ and O$_3$, respectively, in China. Furthermore, Oswald et al (2015) determined
that various statistical methods did not find stagnation to be the strongest predictor of surface-level \( \text{O}_3 \). Finally, while Schnell and Prather (2017) showed interannual correlations between \( \text{PM}_{2.5} \), \( \text{O}_3 \), and the ASI, maps depicting the day-to-day spatial correspondence of pollutants and the ASI yielded similar findings to our results in figure S3; that is, ASI coverage shows erratic overlap with pollutant extremes.

This study serves to document the correspondence between common criteria pollutants, temperature, and stagnation during the summer, and its purpose is not to propose an alternative metric beyond the ASI for understanding pollution. However, we offer the following commentary to address the weak correspondence between the ASI and pollutants: the meteorological variables which define the ASI may not be the best predictor variables for diagnosing polluted areas or periods. Camalier et al (2007) examined the effects of meteorology on \( \text{O}_3 \) trends in urban areas and found that, for much of the Northeast and South, temperature, humidity, and transport direction were the best meteorological parameters to predict \( \text{O}_3 \); none of these variables are included in the ASI. Shen et al (2015) uncovered that the largest fraction of the total variance in \( \text{O}_3 \) can be explained by the north-south movement of the mid-latitude jet. Since the jet is often confined to more northerly latitudes, the increased correspondence of stagnation with pollutants in the South (figures 4, S6) could result from weaker mid-tropospheric wind speeds at 500 hPa. Regardless, the exact position of the jet is not taken into account by the ASI, nor can the ASI characterize all of the known microscale patterns (e.g. Jacob and Winner 2009, and references therein), synoptic patterns (e.g. Barnes and Fiore 2013, Shen et al 2015, Otero et al 2016), teleconnection patterns (e.g. Shen and Mickley 2017), and distribution of anthropogenic precursor emissions (e.g. He et al 2013a) which have been shown to influence surface-level pollution. Another possibility is that stagnant flow and limited ventilation simply are not the dominant factors causing pollution events. We plan further research to answer this question.

6. Conclusions

There are good mechanistic reasons to suspect that stagnation would (via pollutant trapping by weak winds and no scavenging by precipitation) lead to increased surface-level pollution. However, we fail to find a widespread correspondence. In most regions of the US there is only a weak correspondence between stagnation and summertime \( \text{PM}_{2.5} \) and \( \text{O}_3 \), both with regard to day-to-day variations as well as the co-occurrence of events. For example, in the Northeast, 78% (66%) of same-day \( \text{PM}_{2.5} \) and \( \text{O}_3 \) events occur when the percentage of stagnant cells is such that it is not classified as a stagnation event. Similarly, days with a high coverage of stagnation only co-occur with pollution events about one-third of the time in the Northeast. This signal is relatively consistent across the contiguous US; although the South is an exception as pollution and ASI events co-occur with greater likelihood and correlations are strongest compared with other regions, but even in the South same-day correlations do not exceed 0.38 for

![Figure 5](image_url)

Figure 5. For the five regions defined in figure 1, the regionally-averaged distributions of summer \( \text{PM}_{2.5} \) (top) and \( \text{O}_3 \) (bottom) concentrations are determined for the top 20th percentile of days with ASI coverage (‘Stagnant’) and the bottom 20th percentile (‘Non-Stagnant’). Text above the pairs of boxplots corresponds to the relative enhancement in mean pollutant concentrations between stagnant and non-stagnant days.
PM$_{2.5}$ - ASI and 0.64 for O$_3$ - ASI, and there are many pollution events not associated with stagnation events. Our results also indicate a lack of consensus between stagnation and high temperature across the US. In the South, the region with the strongest correlation between stagnation and pollution, the correlation between stagnation and temperature is near-zero. Thus, we cannot make any definitive statements on the relationship between hot and stagnant days. In contrast to the general lack of relationship between stagnation and pollution concentrations or surface temperature, there is generally a strong correlation between temperature and PM$_{2.5}$ and O$_3$ concentrations ($r = 0.46$ and 0.38 averaged over the contiguous US, respectively). Jacob and Winner (2009) found that no significant correlations of PM$_{2.5}$ with temperature had been reported in the literature. While the PM$_{2.5}$ - temperature relationship is complicated and varies between summer and winter (e.g. Dawson et al 2014), our findings uncover consistently positive correlations between PM$_{2.5}$ - temperature for the summer season and are an important update to Jacob and Winner (2009).

The findings from this study suggest that the community shy away from using the ASI as a metric to understand pollution events and instead test different pollution-related indices using meteorological predictors such as temperature or boundary layer height as correlations and event co-occurrence between pollution and these other indices could differ from the ones shown here. Furthermore, our results suggest caution is required when inferring changes in air pollution from projected changes of stagnation under climate change.

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