Association of weather and air pollution interactions on daily mortality in 12 Canadian cities

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Abstract

The overall composition of the troposphere, including meteorological attributes and air pollution concentrations, affect human health outcomes. Our objectives were first to determine the likelihood of extreme air pollution events in select weather types within 12 Canadian cities, and second to examine the association between daily mortality and daily concentrations of air pollutants, assessing both single- and two-pollutant interactions. Each pollutant is examined to determine the likelihood of an extreme air pollution episode occurring in a given weather type and city. Next, we use a distributed lag nonlinear model (DLNM) to estimate city-specific relative risks of mortality (RR) due to the single and two-way-interactive effects of nitrogen dioxide (NO_2), ozone (O_3), sulphur dioxide (SO_2), and particulate matter <2.5 μm ($PM_{2.5}$) from 1981–2008.We control for exposure timeframe and time lag in days, as well as synoptic weather type, day-of-week, and mean air temperature. In dry tropical (DT) or moist tropical plus (MT+) weather, an extreme pollution event (top 5% of pollution levels) is found to be on average, four-fold and two-fold more likely to occur, respectively. We found significant RR effects of single-pollutant exposure on mortality for all four air pollutants examined. In the DM, MM, and MT weather types, moderate increases in average risk estimates for all pollutants are found, with increases of 4.5%, 4.1%, and 5.1%, respectively. However, for the DT or MT+ weather types, the overall average increases due to pollutant exposure are higher, at 14.9% and 11.9%, respectively. The two-way interactive effects have weaker effect estimates. Adjusting for O_3 lowers the effect estimates and variability of the

WIT Transactions on Ecology and The Environment, Vol 174, © 2013 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/AIR130021

remaining pollutants, with 67% of the cases becoming significantly lower, and 40% of the cases becoming insignificant. Our findings suggest that the health effects of air pollution exposure differ under specific synoptic weather patterns. The forecasting of such weather can provide more accurate estimates of mortality risk due to air pollution for the overall population across Canada.
Keywords: distributed nonlinear lag model, spatial synoptic classification, mortality, air pollution, heat stress, Canada, human health, relative risk.

1 Introduction

Recent studies pertaining to weather and atmospheric effects on humans have established associations between human health outcomes and meteorological conditions (e.g., [1, 2]). There is a complex relationship between climate, air pollution, and health outcomes. Air pollution has been shown to be a contributing factor to human morbidity and mortality, and is also related to synoptic weather [3, 4]. Although temperature alone has been shown to be a satisfactory predictor of health outcomes [5–7], it is known that human physiology responds to the complex synergistic effects of all external elements of ambient air. This is holistically expressed at the synoptic level by using weather type classification [3].

Models based simply on one or two variables do not take into account all aspects of a full weather situation. However, time-series models have become more prevalent in the literature as a means to measure the effects of weather and air pollution together on human health outcomes, such as mortality or morbidity (e.g., [8–11]). The health impacts of heat have been observed to be closer to the heat event itself (0–3 days) [1], and in some recent studies have been found to be even closer (0- or 1-day lag) [6, 12]. However, less is known about the correct time lags to use for the effects of air pollution on human health during hot weather.

There remains a considerable amount to discover concerning the delayed and modifying effects of air pollution and meteorological variables on human health [7]. Given the variety of weather elements affecting pollution levels, a synoptic approach is well-suited to study city-specific pollution variations [3, 13]. Inconsistencies in results also necessitate further research into air pollution and interactive effects relating synoptic climatology to mortality [13]. Accordingly, the goal of this study is to conduct a large-scale investigative analysis, using 28-years of data, and examining the short-term effects of the air pollutants NO_2, O_3, SO_2, and $PM_{2.5}$ on the relative risk of mortality (RR). We examine the modifying effects of single pollutant and two-pollutant interactions on RR, while controlling for weather type using a daily spatial synoptic classification (Sheridan [14]). We also assess urban variations of extreme pollution levels in 12 large Canadian cities using the SSC, along with city-specific and pooled RR, focusing our analyses on the summer season.

2 Methods

2.1 Mortality data

Daily non-accidental-related mortality data from 1981–2008 were obtained from the Canadian Vital Statistics databases at Statistics Canada (via the Public Health Agency of Canada) for Vancouver, CB; Calgary, AB; Edmonton, AB; Regina, SK; Winnipeg, MB; Toronto, ON; Windsor, ON; Ottawa, ON; Montreal, QC; Quebec City, QC; Halifax, NS; and St. John's, NF. Data availability for Quebec City and Montreal extended only to the year 2000; hence, we completed the analysis for these cities for 20 rather than 28 years. Causes of death were categorized using the International Classification of Diseases (ICD) 9th revision (codes < 800) and ICD 10th revision (codes A00 to R99).

2.2 Spatial synoptic classification data

A suite of routinely monitored meteorological parameters (air temperature, dew point temperature, wind velocity, atmospheric pressure, and cloud cover) is used to identify each weather situation as one of six weather-type categories (dry moderate (DM), dry polar (DP), dry tropical (DT), moist moderate (MM), moist polar (MP), moist tropical (MT; and its extreme subset, MT+) plus a transition category (TR), where one weather type yields to another. The current study focuses on the four moderate and hot weather types. Descriptions can be found in [13] and [14].

Developed by Sheridan [14], the SSC is a semi-automated classification system. It derives from an algorithm comparing listed surface observations to days that are most representative of the various weather types at each monitoring station. Meteorological data used to classify weather types into SSC categories for each of the 12 cities are obtained from airport weather stations maintained by the Meteorological Service of Canada.

2.3 Air pollution data

Air pollution data from the National Air Pollution Surveillance Network (NAPS) database were collected for the period of 1981–2008. Measurements of average hourly concentrations of ozone (O_3, ppb), nitrogen dioxide (NO_2, ppb), particulate matter < 2.5 μm in diameter ($PM_{2.5}$, μg m^3), and daily sulphur dioxide (SO_2, ppb) were utilized in these analyses. Hourly measurements were averaged to obtain daily concentrations of these pollutants. For $PM_{2.5}$, the earliest year for which data were available was 1998. For both SO_2 and O_3, complete datasets were available for the 1981–2008 period for all cities except St. John's (data from 1989–2008). NO_2 data were complete for all cities in the given years except for Calgary and St. John's (available data beginning in 1990 and 1989, respectively). Days with no recorded data were considered as missing and treated as such in the model.

2.4 Data analysis

2.4.1 Extreme pollution episodes

A detailed evaluation of the synoptic conditions associated with extreme air pollution levels for each city was completed using a method by Green *et al.* [3], whereby the top 5% of pollution days (classified as ‘extreme’) for each pollutant is examined by air mass (or weather type). To do so, we determine the relative ratio representing the relationship between the percent of days in the top 5%of pollution levels, to the percent frequency of the select weather type. Therefore, a ratio >1.0 indicates that an extreme pollution episode is more likely to occur in the given weather type. A ratio > 2.0 indicates statistical significance of this likelihood [3].

2.4.2 Distributed lag nonlinear modelling

For each city and weather type, the RR due to exposure to each pollutant is modelled. In addition, the effects of exposure to two pollutants are modelled to determine the modifying effect on mortality using a DLNM [15]. We apply lags of 0–6 days for each pollutant examined to estimate the RR due to exposure in a single day (lag 0), and multiple lag days.

We adjust for various time confounders using natural splines, accounting for serial autocorrelation. To do so, we use a categorical variable for day of week, and apply a natural cubic spline of time with one knot at each of 28, 56, 112, and 336 days of observation for annual, biannual, seasonal, and monthly time effects; therefore, the degrees of freedom (df) is 4. The DLNM is adjusted for mean air temperature, rather than minimum or maximum, as preliminary analysis demonstrated enhanced model strength based on model prediction values (or AIC). This was also found to be true based on AIC testing by Curriero *et al.* [5] in 11 U.S. cities, with further studies [9, 11] also using mean air temperature based on extensive work, and thereby better accounting for what people experience throughout the full day, rather than at one time (e.g., minimum or maximum temperature).

Separate model runs are completed for exposure to single air pollutants, as well as adjustments for the single pollutant due to simultaneous exposure to the remaining three pollutants. Therefore, in total, for each weather type assessed for a city, we complete 28 regressions (4 knots, 7 lags) for single-pollutant exposure analysis to reflect independent contributions to raw mortality. An additional 84 regressions per pollutant, weather type, and city, are assessed based on all possible two-way pollutant interactions. From this, we select the optimal single or lagged model with the number of knots that either minimize the AIC, or maximize the evidence that the residuals do not display any type of structure. Finally, a pooled estimate for all 12 cities is generated across each synoptic weather type using a random-effects model, with 95% CI.

3 Results

Across Canada, the prevalence of the mild and benign DM weather type in the summer season is the most prevalent (Table 1), with DT being the least common weather type. The DT weather type has the highest mean air temperature coinciding with the highest air pollution concentrations of NO_2, O_3, and SO_2. Moist tropical plus presents the second highest air temperatures, with the highest concentrations of $PM_{2.5}$ in all cities experiencing this weather type. MT+ overnight temperatures are generally the highest of all the summer air masses.

The extreme ambient conditions in the MT (and its extreme subset, MT+) weather type, and the associated high overnight temperatures, are responsible for its association with consistently elevated relative mortality, which was highest in 10 of the 12 cities. In addition, MT+ has the highest overall mean standardized mortality for all cities (1.92). The DT and MT weather types have an average mortality rate of 1.75 deaths per 100,000 people. The most benign weather types studied here are found to be DM and MM, which display the lowest standardized mortality and air temperatures, and have the lowest and comparable concentrations of all pollutants.

Table 1: Descriptive summertime statistics reporting the average[a] for 12 Canadian urban areas in each of the five studied weather types (DM, DT, MM, MT, MT+).

Weather Type	Freq (%)	Relative Mortality[b]	±SD	T_a (°C)	Windspeed (km hr^{-1})	Dew Point (°C)	Cloud Cover (10^{ths})
DM	29.8	1.68	±0.49	24.38	8.1	12.3	5.0
DT	2.5	1.75	±0.6	30.89	6.0	14	3.8
MM	19.1	1.67	±0.46	20.6	7.5	16.5	8.0
MT	11.5	1.75	±0.47	27.12	7.4	18.4	6.5
MT+	2.3	1.92	±0.41	29.51	7.0	20.1	7.0

[a]4:00pm averages for each variable.
[b]Mortality rate per 100,000 people, calculated based on yearly population.

3.1 Extreme air pollution

We have identified the synoptic conditions that when present, have a higher likelihood of being associated with extreme pollution episodes that have been shown to harm human health [3] (Table 2). Results for all cities combined demonstrate that on average, extreme air pollution episodes (defined as elevated levels of NO_2, O_3, SO_2 and $PM_{2.5}$) are most likely to occur in the DT weather type, with relative likelihood ratios of 2.1, 6.0, 2.2, and 4.2, respectively. Significant combined city results are also prevalent in hot, humid weather. For MT, extreme pollution episodes due to O_3 or $PM_{2.5}$ are almost three times more likely than normal. For MT+, the resulting in ratios are 3.8 for O_3 and 2.8 for $PM_{2.5}$. Overall, 75% and 67% of the cities studied experience a statistically significant likelihood of extreme episodes of O_3 and $PM_{2.5}$ pollution, respectively, under the DT weather type.

www.witpress.com, ISSN 1743-3541 (on-line)

Table 2: Summertime (JJA) synoptic weather types per city reported based on frequency (%), and likelihood ratio to result in extreme pollution episodes. Select weather types chosen based on high ratios and weather type presence.

City	Category	Freq		Pollutant Ratio[a]		
		(%)	NO_2	O_3	SO_2	$PM_{2.5}$
Calgary[b]	**DT**	3.2	1.93	2.17	2.21	5.56
	MT	0.5	1.54	1.54	3.13	3.95
Edmonton[b]	**DT**	1.1	1.43	8.57	1.47	5.48
	MT	0.7	0.00	2.35	0.00	6.01
Halifax	**DT**	0.6	1.82	1.66	1.74	5.73
	MT+	1.2	1.29	0.74	1.54	2.55
Montreal	**DT**	1.3	1.82	10.91	2.43	8.49
	MT+	4.4	0.89	2.83	0.53	3.97
Ottawa	**DT**	3.7	2.37	5.47	2.32	1.13
	MT+	2.4	0.68	1.67	0.33	1.79
Quebec City	**DT**	0.7	2.88	5.23	2.82	NA
	MT	16.1	1.07	2.3	0.58	2.95
	MT+	2.9	0.3	3.04	0	3.19
Regina	**DT**	4.0	3.04	4.84	1.11	2.07
	MT+	1.4	1.47	4.27	0.00	2.0
St. John's[c]	**MT**	6.9	0.5	2.01	0.56	2.86
	MT+	1.3	0.00	0.98	0.00	3.09
Toronto	**DT**	6.2	1.63	7.52	2.76	5.43
	MT+	3.5	0.66	1.32	0.66	3.93
Vancouver[b,c]	**MT**	0.7	3.15	13.64	2.1	5.88
Windsor	**DT**	4.7	2.4	6.18	3.12	3.73
	MT+	7.3	0.22	0.65	0.11	1.82
Winnipeg	**DT**	1.9	1.63	7.86	1.88	0.0
	MT+	2.9	0.00	2.35	0.00	2.5

[a]Ratio = (% of days within the top 5% level of pollution):(overall \% of occurrence of the weather type in JJA). A ratio > 2.0 (bolded) identifies those synoptic categories where the occurrence of an extreme pollution episode is statistically significantly more likely to occur, being greater than expected [3]. [b]MT+ weather type not present. [c]DT weather type not present.

3.2 DLNM modelling results

The pooled single- and two-pollutant adjusted models (95% CI) for each weather type are presented in Figure 1. Single-pollutant model results (Table 3) suggest a substantial health burden due to air pollution for all combinations of pollutants and weather types tested. We found the strongest risk for pollution-related mortality to be, on average, 1–3 days after exposure during warm-hot weather

Table 3: Relative risk of mortality (RR) and 95% CI associated with single pollutant models, calculated at pooled population weighted means (PWM), with standard error and average time-lag of all cities.

Weather Type	Pollutant	PWM	Lag (d)	SE	RR	95% CI
DM	NO_2	13.25	2	0.000	1.041†	(1.032-1.051)
	O_3	12.58	2	0.000	1.032†	(1.023-1.041)
	$PM_{2.5}$	12.99	1	0.001	1.050†	(1.035-1.065)
	SO_2	12.05	2	0.001	1.059†	(1.042-1.076)
DT	NO_2	12.01	2	0.001	1.067†	(1.035-1.100)
	O_3	12.14	2	0.001	1.064†	(1.033-1.096)
	$PM_{2.5}$	13.00	2	0.004	1.191†	(1.076-1.319)
	SO_2	12.42	3	0.008	1.272†	(1.057-1.531)
MM	NO_2	12.59	1	0.000	1.036†	(1.024-1.049)
	O_3	11.99	3	0.000	1.036†	(1.026-1.045)
	$PM_{2.5}$	12.80	3	0.001	1.050†	(1.034-1.065)
	SO2	13.11	2	0.001	1.041†	(1.027-1.055)
MT	NO_2	14.22	2	0.001	1.038†	(1.019-1.057)
	O_3	12.89	3	0.001	1.038†	(1.024-1.053)
	$PM_{2.5}$	14.46	3	0.001	1.051†	(1.008-1.097)
	SO_2	13.33	3	0.001	1.077†	(1.041-1.114)
MT+	NO_2	13.44	3	0.002	1.117†	(1.053-1.186)
	O_3	12.52	3	0.002	1.065†	(1.024-1.108)
	$PM_{2.5}$	13.04	3	0.004	1.117†	(1.018-1.225)
	SO_2	12.75	1	0.005	1.176†	(1.030-1.342)

†Indicates statistical significance of the estimate ($p< 0.05$).

types in the summer, thus displaying the cumulative delayed effects of air pollution. On average, the delayed effect of air pollution in the ‘hot’ weather types (DT, MT, MT+) occurs one day later than in the ‘mild’ weather types (DM, MM).

In all weather types, adjusting each pollutant with O_3 resulted in a lower RR estimate, with 67% significantly less, and 40% causing the significant effect to disappear (Figure 1). Additionally, by adjusting for O_3, the variability of the estimate decreases in all but one of the adjustments, suggesting better accuracy. In general, when the RR increases subsequent to an adjustment with another pollutant, the variability also increases. Within this study, this commonly results in an insignificant risk estimate due to the interaction.

In the dry moderate (DM) weather type, RR estimates remain significant after adjusting each air pollutant with the remaining three; hence, exposure to all pollutants has individual effects on mortality that are not significantly changed by adjustment for another pollutant. For the second moderate weather type – moist moderate (MM) – all single pollutant exposure effects are statistically significant, each with a magnitude similar to that in the DM weather type. The significant effect of O_3 individually, i.e., 1.036 (95% CI 1.026–1.045), is not independent, as it disappears and becomes insignificant after adjusting for $PM_{2.5}$ (1.015 (95% CI 0.990–1.032)). These two pollutants have a significant and moderately positive correlation ($r = 0.44$) in the MM weather type; hence, we are evaluating a similar signal in the model, and the single-model O_3 RR value is an overestimate.

Within the MT weather type, all individual effects of air pollutant exposure on mortality are statistically significant, with magnitudes similar to those of MM and DM. The NO_2 and O_3 individual effects disappear after adjustment for SO_2 and $PM_{2.5}$, with a significant reduction of 3.5% in RR found when adjusting NO_2 by O_3. The significant mortality effect due to $PM_{2.5}$ (RR = 1.051 (95% CI 1.008–1.097)), becomes less variable and insignificant after adjusting for O_3 (RR = 1.018 (95% CI 0.996–1.041)).

In the DT and MT+ weather types, exposure to all air pollutants has a larger effect on mortality than in DM, MM, and MT weather; yet, due to the lower number of studied cities experiencing DT and MT+ days (n=5 and n=4, respectively), and the low frequency of these days in those cities, we see increased variability in the model output, or no model results. The single-exposure effects of all pollutants in the extreme DT weather type are significant. The O_3 and $PM_{2.5}$ effects on mortality are independent, remaining statistically significant after adjustment, even with significant declines in RR when $PM_{2.5}$ is adjusted for by NO_2 and O_3.

For MT+, all single models are significant predictors of mortality, with only the SO_2 single effect being independent. The NO_2 effect significantly decreases and disappears when adjusted for both O_3 and SO_2. SO_2 shows the largest association with mortality, yet high variability (RR = 1.176, 95% CI 1.030–1.342), with O_3 adjustment also resulting in a significant effect-size reduction, and an overall insignificant effect.

The current study displayed overall relationships combining the 12 Canadian cities, however city specific differences are present due to factors such as varying sources of pollution (industrial, vehicle, nearby areas), climate, topography, demography, human behavior, and socioeconomic factors. In the current study, inter-city differences were present, with Vancouver displaying a significantly greater frequency of extreme pollution episodes for all pollutants studied (ratio = 4.17 on average) when the MT weather type is present. The MT+ weather type yields similar results wherever it is present, but occurs very infrequently in many areas of Canada. In Toronto, Winnipeg, Ottawa, Montreal, and Quebec City, the greatest extreme episode frequencies are associated with DT (ratio = 4.20 on average). Overall, 75% and 67% of the cities studied experience a statistically significant likelihood of extreme episodes of O_3 and $PM_{2.5}$ pollution, respectively, under the DT weather type. The three remaining cities (Vancouver, Halifax and St. John's) experience little to no DT air; rather, in these coastal cities, it is the more humid MT weather type that raises the likelihood of O_3 and $PM_{2.5}$ extreme pollution events. Therefore, one large-scale model with general criteria will not accurately estimate health outcomes in all cities, and the use of city-specific models is strongly suggested.

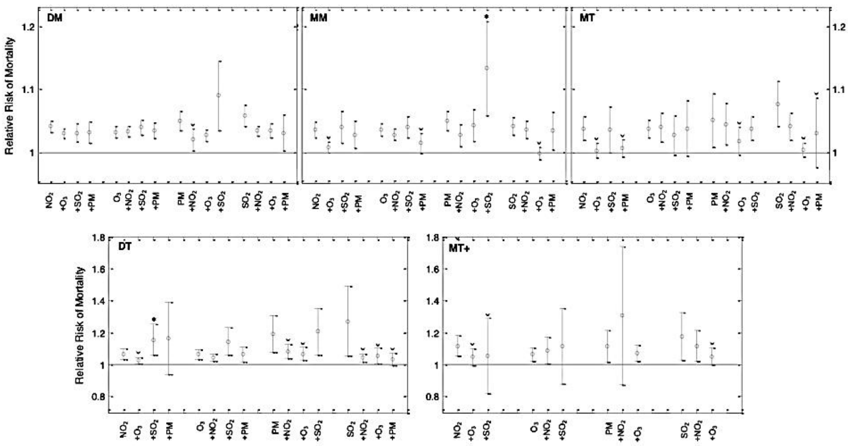

Figure 1: RR of mortality (95% CI) for single-pollutant (NO_2, O_3, $PM_{2.5}$, SO_2), and adjusted RR for remaining air pollutants, within 5 weather types.

4 Discussion

Our findings complement the substantial evidence for negative health outcomes attributable to exposure to air pollution. Through accurate forecasting of synoptic weather types, the detrimental effects of not only heat, but also air pollution, could be mitigated. For example, knowledge that high O_3 and $PM_{2.5}$ levels in MT (and MT+) weather are 2.0 to 4.0 times more likely, respectively, provides better warning potential and justification for intervention. This is also true for the DT weather type, i.e., extreme episodes are 6.0 times more likely (all-pollutant average), a finding that agrees with the results of Greene *et al.* [3], and also with the relatively higher pollutant concentrations in DT found by Rainham *et al.* [13] in Toronto, ON. Overall, the findings from the DLNM were robust, with consistent evidence observed for each single marker of air pollution exposure and its effect on human mortality. Clear trends among the various pollutants and weather types are difficult to distinguish. Conflicting evidence for confounding and effect modification by air pollution exposure may be due to the strong correlations between pollutants, thus making it difficult to isolate the causal signals (to the model) of one pollutant from those of another. Additionally, the magnitude of the interactions varies with weather type, as shown by the different effect modifications in the DT air, even with strong correlations between pollutants.

An evident trend in the results involves the overestimation of mortality risk by the single-pollutants NO_2, SO_2, and $PM_{2.5}$, as an adjustment for O_3 resulted in insignificance of the former three single effects. The lone exception to this pattern occurred in the MM weather type for $PM_{2.5}$ adjustment for O_3, where a similar signal in the model may be coming from each of these pollutants due to their significant correlation in MM air ($r = 0.44$); hence, ozone may be acting as a proxy for $PM_{2.5}$. This also helps to explain the only instance of a significant reduction of the RR due to O_3 when adjusted for $PM_{2.5}$, also within the MM weather type. Interactions between $PM_{2.5}$, O_3, and air temperature can increase the RR due to air pollution, more so under DT conditions, as found by Rainham *et al.* [13] and in the current study. For example, the DT weather type has a 4.0% higher risk of mortality than does DM ($p<0.05$) when $PM_{2.5}$ is adjusted for O_3, with attenuation and decreased variability from O_3 adjustment in both weather types. This attenuation of the RR is also found by Burnett *et al.* [16] when particulate matter is adjusted for by gaseous pollutants. Consequently, in the hot weather types $PM_{2.5}$ alone is a less accurate indicator of RR and should be adjusted for O_3 or other gaseous pollutants for more accurate mortality risk estimates.

The hot weather types – DT, MT, and MT+ – have frequently been shown to be associated with higher human mortality and morbidity due to heat exposure [12]; however, the combined effects of heat and air pollution exposure are potentially synergistic. In these weather types, we have a greater negative effect modification of the impact on human physiology due to the weather. Anderson and Bell [6] found hot-weather effect estimates to be reduced when ozone was controlled for, demonstrating that ozone partly controls the mortality signal from the model. We control for both temperature effects and weather-type, where ozone exposure estimates are much greater in the two extreme weather types (DT and MT+). Improved knowledge of the combined effects of temperature and air pollution on human mortality is vital for the medical community, policy makers, and community leaders to implement proper intervention strategies [6].

5 Conclusions

Our findings suggest that the health effects of air pollution exposure differ under specific synoptic weather patterns. Forecasting of such weather can provide more accurate estimates of the risk of mortality due to air pollution in the overall Canadian population. Using a DLNM, we are able to determine the optimal time and pollutant interactions for the delayed effects of air pollution exposure on human mortality. By looking at both individual- and two-pollutant models, we found statistically significant associations and modifications between air pollutant exposure and mortality, as well as significant modifications thereof. This builds upon and complements existing SSC studies, which are more prevalent for U.S. cities. Extreme air pollution episodes are more likely within the oppressive and hot synoptic categories of MT, MT+, and DT. As synoptic categories can be forecast several days in advance, then city-specific air pollution estimates can then be made for extreme pollution episodes and for issuing heat/health warnings.

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