Isolating the Industrial Contribution of PM$_{2.5}$ in Hamilton and Burlington, Ontario

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ABSTRACT

Hourly measurements of particulate matter that is smaller than 2.5 $\mu$m in diameter (PM$_{2.5}$) have been made at air-monitoring sites in Hamilton and Burlington, Ontario, Canada, since 2003. These sites are separated by ~6 km; Burlington is right on Lake Ontario while Hamilton has, directly to the east, very heavy industry between it and Lake Ontario. Hence, by taking the difference between measurements at Hamilton and Burlington, it is possible to isolate, during east-wind conditions, PM$_{2.5}$ that result from emissions from the industrial sectors (primarily steel mills) located in Hamilton’s northeast end. After screening the data for east winds off Lake Ontario, it was found that median background values of PM$_{2.5}$, of 5–10 $\mu$g m$^{-3}$, are increased by an additional 5–10 $\mu$g m$^{-3}$ by emissions from local sources. On the contrary, however, industrial contributions to PM$_{2.5}$ in Burlington during south winds are much smaller at ~1 $\mu$g m$^{-3}$ (industrial sectors are due south of Burlington). This difference is likely due either to wind direction–dependent local circulation patterns or to alignment of sources that can concentrate PM$_{2.5}$ into Hamilton. It was also found that throughout much of 2009, but especially during spring and early summer, the industrial contribution of PM$_{2.5}$ at Hamilton was reduced relative to other years by amounts that are statistically significant at the 95% confidence level, even when measurements are augmented with large amounts of Gaussian noise. These reductions are consistent with documented reductions in steel production during the global economic crisis that peaked in the first half of 2009.

1. Introduction

There is widespread agreement that inhalation by humans of particulate matter that is smaller than 2.5 $\mu$m in diameter (PM$_{2.5}$) is detrimental to cardiopulmonary health and life expectancy (e.g., Brunekreef 1997; Coyle et al. 2003; Jerrett 2005; Pope et al. 2009). This is because small particles can travel deep inside lungs where they can get trapped and even diffuse into the bloodstream, thereby causing physical or chemical damage. While extreme exposures arising from events such as forest fires, dust storms, and volcanoes can be catastrophic, protracted exposure of millions of people to PM$_{2.5}$ produced by industrial activity is thought to be the greater, and financially most costly, threat to human health (e.g., Mokdad et al. 2004).

Results reported here stem from an investigation into PM$_{2.5}$ measurements made in the vicinity of Hamilton, Ontario, Canada, by sensors maintained by Ontario’s Ministry of the Environment (MoE). The motivation behind this study was the author’s perception that air in the west end of Hamilton seemed to be anomalously clean during the spring and early summer of 2009 while the region was experiencing east winds off Lake Ontario but that by midsummer the anomaly had ended. The first half of 2009 saw the depths of the “global economic crisis,” with associated reductions in industrial output in both Canada and the United States (see online at http://www.tradingeconomics.com/canada/industrial-production and http://www.oecd.org). Hence, the purpose of the study was twofold: 1) to isolate and quantify PM$_{2.5}$ output from the industrial sectors located in the northeast corner of Hamilton and 2) to quantify changes in industrial sector-produced PM$_{2.5}$ during the spring and early summer of 2009 relative to the same period in other years, thereby taking advantage of the fortuitous, large-scale experiment resulting from economic changes.

During east-wind conditions, air incident at the Burlington air-monitoring site (hereinafter referred to as B), which is located on the west shore of Lake
Ontario, has had an extended stretch across Lake Ontario, which lacks sources of PM$_{2.5}$. Conversely, the Hamilton-Downtown air-monitoring site (hereinafter referred to as HD) is ~5 km inland from Lake Ontario and ~6 km southwest of B. Land use between HD and Lake Ontario consists almost entirely of very heavy industry plus a major highway. If it can be demonstrated that contributions of PM$_{2.5}$ from a highway ~5 km away are negligible, differences between PM$_{2.5}$ at HD and B, during persistent east-wind conditions, should be a good approximation of the contribution of local heavy industry to HD’s PM$_{2.5}$. By the same token, reversing the difference and screening for persistent south winds should isolate the contribution of industrial-sector PM$_{2.5}$ to B.

The following section documents the PM$_{2.5}$ and meteorological data used. The third section addresses some issues about tests for statistically significance differences. The final two sections present results and a short summary.

2. Data

Ontario’s MoE maintains numerous air-monitoring stations across southern Ontario; many have recorded hourly PM$_{2.5}$ (µg m$^{-3}$, to the nearest whole number) since 2003. Quality controlled data are freely available online (http://www.airqualityontario.com/history/). Ontario uses Thermo Scientific (Thermo Fisher Scientific, Inc.) tapered-element oscillating-microbalance (TEOM 1400ab) sensors at all stations (Ontario Ministry of the Environment 2012). For this study, data were used from HD (43.26°N, 79.86°W; elevation = 79 m MSL), Hamilton-West (43.26°N, 79.91°W; elevation = 96 m MSL; hereinafter referred to as HW), and B (43.31°N, 79.80°W; elevation = 78 m MSL). Figure 1 shows their locations. Wind directions were obtained from hourly meteorological data reported at Environment Canada’s Burlington automated site (43.3°N, 79.8°W; elevation = 78 m). They are reported starting at 10° east of north and increasing clockwise in 10° increments; zero corresponds to calm conditions, and 360° corresponds to a north wind. To admit an hourly value of PM$_{2.5}$, wind had to be coming from a designated sector for the hours immediately before and after the central hour (i.e., a persistent wind for at least three consecutive hours) and the central hour had to have a valid measure of PM$_{2.5}$. Data for the period from 1 January 2003 to 31 December 2010 were considered.

3. Statistical tests and measurement uncertainty

One of the main intentions was to compare 2009 values of PM$_{2.5}$, grouped by month, with values in the collection of years from 2003 to 2008 plus 2010. The obvious approach is to define a null hypothesis $H_0$ and to proceed to apply an appropriate statistical test that guides one to either accept or reject $H_0$ at some confidence level (CL). An immediate question is whether measurements taken in a particular month for years from 2003 to 2008 plus 2010 can be considered to be

1 Hamilton’s airport also reports weather conditions, but it was deemed to be less representative than the Burlington site given that it is ~10 km south of HD at an elevation of 238 m MSL.
drawn from a single population? For this study, if a time series of monthly-mean PM$_{2.5}$ between 2003 and 2010 and omitting 2009 exhibited a linear trend that differed insignificantly from zero at the 95% CL, it was assumed that all measurements taken in a particular month for years from 2003 to 2008 plus 2010 can be considered to have been drawn from a single population and are therefore suitable for comparison with the sample drawn from the 2009 population. If, however, the trend was significant at the 95% CL then that month was omitted from further analyses.

Significant trends in monthly-mean PM$_{2.5}$ between 2003 and 2010 were identified by performing linear least squares regressions on monthly means, with the number of hourly samples per month as weights, using the bootstrap method with 1000 synthetic samples (e.g., Efron 1979; Press et al. 1992). Since our concern was whether 2009 values differed from other years, 2009 values were not used in the regressions. If 95% of the 1000 computed slopes were either all greater than or all less than zero, the trend was deemed to be significantly positive or negative, respectively. Those months that exhibited a significant trend were not analyzed further.

Another potential issue is that uncertainties associated with hourly measurements of PM$_{2.5}$ are notoriously difficult to quantify and can be large (J. Brook and E. Weick 2011, personal communication); reported estimates of random fractional uncertainty for hourly measurements of PM$_{2.5}$ are as large as ~30% (e.g., Hains et al. 2007), although Thermo Scientific maintains that for ideal conditions the TEOM 1400ab is accurate to 1.5 µg m$^{-3}$ for hourly averages (additional details pertaining to the TEOM 1400ab are available online at http://www.thermoscientific.com/ecomm/servlet/productsdetail_11152___11960558_-1). One would prefer to test $H_0$ for actual populations rather than with measurements that come with possibly substantial amounts of (unknown) uncertainty. The concern with measurement noise is that it may be fostering type-II errors: that is, failure to reject a false $H_0$ because of the experiment being flooded by measurement uncertainty or error. On the other hand, if $H_0$ can be rejected at some CL, then it is of little concern that measurement uncertainty is likely augmenting sampling noise, because reducing measurement uncertainty would allow one to reject $H_0$ with increasing confidence.

Nevertheless, assuming that $H_0$ can be rejected at some CL while using measured data, it is interesting to ask the question, How robust is the rejection of $H_0$? A procedure is offered here that should help to answer it. The idea is to augment hourly PM$_{2.5}$ measurements with unbiased noise until $H_0$ can no longer be rejected.

For those samples in which $H_0$ was rejected, we begin by generating mock samples by adding unbiased random noise $\varepsilon$ to each measurement, where

$$\varepsilon = \phi g(0, 1) x.$$  

(1)

Here, $g(0, 1)$ is a random sample from a Gaussian distribution with a mean of zero and unit variance, $\phi$ is a prefactor dictating relative uncertainty, and $x$ is the measurement. One is free to add noise whenever one wishes, with Eq. (1) being perhaps the simplest option. Repeating this process $N$ times, for a given $\phi$, produces $N$ mock datasets. For this study $N = 1000$. Using Student’s $t$ test as an example, for each of the $n = 1, \ldots, N$ datasets

$$t_n(\phi) = \frac{\hat{\mu}_1 - \hat{\mu}_2}{\hat{\sigma}_n(\phi)}$$  

(2)

is computed, where $\hat{\mu}_1$ and $\hat{\mu}_2$ are sample means and $\hat{\sigma}_n(\phi)$ is an appropriate pooled sample standard deviation. Sample means are independent of $\phi$ by virtue of Eq. (1). Computed next are $N$ values of

$$A_n(\phi) = \left[ \frac{1}{\sqrt{2\pi}} \right]^{-1} \int_{-t_n(\phi)}^{t_n(\phi)} \left( 1 + \frac{x^2}{\nu} \right)^{-(\nu+1)/2} dx,$$  

(3)

the area under Student’s distribution, which depends on the number of degrees of freedom $\nu$, which, like $\sigma$, depends on assumptions made about the underlying populations and sample sizes. Here, $B$ is the beta function. In a conventional test there is a single value of $A$, and if $A > 1 - \alpha$, one rejects $H_0$ at the 100(1 - $\alpha$)% CL (e.g., von Storch and Zwiers 1999). For our case, however, $A_n(\phi)$ are sorted from smallest to largest, and the median, $\tilde{A}(\phi)$, of $A_n(\phi)$ is selected. One then solves, preferably with an efficient root-finding routine such as Brent’s method (Brent 1973, chapter 4), for $\phi$ that satisfies

$$\tilde{A}(\phi^*) = 1 - \alpha,$$  

(4)

in which $\phi^*$ is interpreted as the relative noise level that has to be added to measured data before one cannot reject $H_0$.

The maximum value of $\phi$ considered here was 0.5. Hence, if $\phi^* = 0.5$, it means that $H_0$ was still able to be rejected at the 100(1 - $\alpha$)% CL even after adding 50% random Gaussian noise to the measurements. The larger $\phi^*$ is, the more robust is the rejection of $H_0$ using measured values. This procedure is not limited to the $t$ test. Results are presented here for the $t$ test and for the
Kolmogorov–Smirnov (KS) test for cumulative frequency distributions.

4. Method

The primary assertion made here is that differences between PM$_{2.5}$ values in HD and B during persistent east winds, as measured at the Burlington weather station, approximate closely the contribution of heavy industry, dominated by large steel mills, to downtown Hamilton’s PM$_{2.5}$. Hence, for persistent winds in the sector $45^\circ$–$135^\circ$, local industry’s contribution to HD’s PM$_{2.5}$ is defined simply as

$$\text{PM}_{2.5}^{\text{indust}} = \begin{cases} \text{PM}_{2.5}^{\text{HD}} - \text{PM}_{2.5}^{\text{B}}, & \text{if } \text{PM}_{2.5}^{\text{HD}} > \text{PM}_{2.5}^{\text{B}} \text{ and } \text{PM}_{2.5}^{\text{HD}} > \text{PM}_{2.5}^{\text{HW}} \\ 0, & \text{if } \text{PM}_{2.5}^{\text{HD}} \leq \text{PM}_{2.5}^{\text{B}} \text{ or } \text{PM}_{2.5}^{\text{HD}} \leq \text{PM}_{2.5}^{\text{HW}} \end{cases}$$

where PM$_{2.5}^{\text{HD}}$, PM$_{2.5}^{\text{B}}$, and PM$_{2.5}^{\text{HW}}$ are hourly values measured at HD, B, and HW, respectively. The secondary check on the value at HW was an attempt to eliminate cases with significant sources of PM$_{2.5}$ inside the city; it eliminated just 7% of the otherwise admissible samples. Note, however, that in addition to the steel mills the Queen Elizabeth Way highway (QEW) is situated $\sim 5$ km east of HD along the shore of Lake Ontario. It must, therefore, be established whether the QEW contributes significantly to PM$_{2.5}^{\text{HD}}$.

The influence of the QEW can be deduced by looking at HW data (see Fig. 1). During west-northwest winds (from $270^\circ$ to $300^\circ$) the upwind land usages, and thus PM$_{2.5}$ sources, are very similar for B and HW save for the fact that the QEW is now only $\sim 1$ km west of B and well downwind of HW. So if the QEW has a discernible impact on PM$_{2.5}$ it should show up at B during west-northwest winds.

Figure 2 shows that during west-northwest winds B and HW exhibited nearly identical monthly-mean PM$_{2.5}$ values for both 2009 and other years. On average, B exceeds HW by only $\sim 0.5$ $\mu$g m$^{-3}$. Moreover, for the $t$ test and KS test, months with differences between 2009 and other years that were insignificant at the 95% CL were almost common for the two sites. This suggests strongly that the QEW’s contribution of PM$_{2.5}$ to a site just 1 km downwind is minor. As such, values of PM$_{2.5}^{\text{indust}}$ from Eq. (5) during east winds...
should be governed overwhelmingly by PM$_{2.5}$ from heavy industry.

5. Results

First, before we discuss PM$_{indust}^{2.5}$, consider Fig. 3, which shows monthly-mean values of PM$_{2.5}$ for HD and B for 3-hourly persistent east winds (from 45° to 135°). Aside from HD’s monthly means exceeding B’s by typically 5–10 µg m$^{-3}$, the most notable feature is that the majority of the months during 2009 experienced reductions in mean PM$_{2.5}$ relative to other years that were significant at the 95% CL—even when $\phi^*_t = 0$. The other obvious point is that the prominent maximum usually seen at HD during spring and early summer was entirely absent during 2009. Although May and June saw downward trends over 2003–10, it is likely that the reductions in 2009 were significant (cf. B’s values). Although not shown, similar reductions during much of 2009 occurred for most stations in southern Ontario for south and west winds.

Application of Eq. (5) during east winds led to 429 values of PM$_{indust}^{2.5}$ for 2009 and 3355 for other years. Figure 4 shows results for PM$_{indust}^{2.5}$. In comparing Fig. 4 with Fig. 3, it is clear that Hamilton’s industrial component is a substantial fraction of the total PM$_{2.5}$. Note that, because of the screening involved in producing PM$_{indust}^{2.5}$, addition of the mean values of PM$_{indust}^{2.5}$ and PM$_B^{2.5}$ does not equal the means of PM$_{HD}^{2.5}$.

As indicated in Fig. 4, only April experienced a significant trend over the period 2003–10; Fig. 5 shows cumulative distributions of bootstrap linear regression slopes. Because April’s trend was upward, and 2009’s value was overly small, an exception was made and statistical tests were performed for April, the results of which indicate that reductions in 2009 were easily significant at the 95% CL. The other spring months of 2009 (March, May, and June) also saw sizable reductions in PM$_{indust}^{2.5}$, with large corresponding $\phi^*_t$. In fact, the pronounced peak usually witnessed in spring and early summer was essentially eliminated in 2009. The reason for a spring and early-summer peak is not obvious, although it might be due to temperature inversions and land–sea breezes that tend to set up in this area when Lake Ontario and adjacent land areas are relatively cold and warm, respectively. A full answer for this

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2 The reductions reported here for 2009 are in accord with a report from the government of Ontario (Ontario Ministry of the Environment 2012) that indicates that 94% of Ontario’s air quality sites registered their smallest annual-mean PM$_{2.5}$ in 2009.

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Fig. 3. As in Fig. 2, but shown are monthly-mean PM$_{2.5}$ values for the HD and B sites given east winds (45°–135°).

Fig. 4. As in Fig. 3, but for the contribution to HD’s PM$_{2.5}$ from the industrial sectors (see Fig. 1). PM$_{indust}^{2.5}$, as computed using Eq. (5), during east winds.
phenomenon would probably require high-resolution numerical modeling of the diurnal cycle of tracers and local circulation.

Figure 6 shows that underlying distributions of PM\textsubscript{indust}2.5 for April–June (AMJ) of 2009 differed much from those of other years, as indicated in Fig. 4, where the results of the KS tests implied that cumulative distributions of PM\textsubscript{2.5} for 2009 differed significantly from those of other years. To be specific, what was responsible for the large differences was a marked absence of very large values and a pronounced amount of small values. By July and August of 2009, distributions returned to resembling closely those for other years.

Let us assume that PM\textsubscript{indust}2.5 typically decreases with distance \(d\) from the industrial sectors as

\[
\text{PM}_{2.5}^{\text{indust}}(d) \approx \text{PM}_{2.5}^{0} \exp(-d/\delta),
\]

where \(\text{PM}_{2.5}^{0}\) is concentration at, or very close to, the source, and \(\delta\) is a length associated with the rates of particulate fallout, washout, and dispersion (Fioletov et al. 2011). With the help of data collected farther downwind at HW, median \(\delta\) was found to be \(\sim 4\) km, implying that for every 5 km removed from the industrial sector the contribution to local PM\textsubscript{2.5} from the industrial sectors decreases by a factor of \(\sim 0.3\). Likewise, median PM\textsubscript{2.5} for years other than 2009 was \(\sim 27\) \(\mu\text{g m}^{-3}\) during AMJ and \(\sim 15\) \(\mu\text{g m}^{-3}\) during other months as well as during almost all of 2009. These values meet or exceed air quality guidelines set by the World Health Organization (World Health Organization 2005).

Conversely, one might expect that for south winds PM\textsubscript{2.5} at B should show a notable increase over that of HD because, as Fig. 1 shows, the industrial sectors are south of B and northeast of HD and HW. To test this expectation, a very similar experiment was tried by screening for south winds, rather than east winds, and redefining PM\textsubscript{indust} as

\[
\text{PM}_{2.5}^{\text{indust}} = \begin{cases} 
\text{PM}_{2.5}^{B} - \text{PM}_{2.5}^{\text{HW}}; & \text{PM}_{2.5}^{B} > \text{PM}_{2.5}^{\text{HW}} \\
0; & \text{PM}_{2.5}^{B} \leq \text{PM}_{2.5}^{\text{HW}}
\end{cases}
\]

where PM\textsubscript{indust} now approximates the industrial-sector contributions to B. Application of Eq. (7) during south winds led to 76 values of PM\textsubscript{2.5} for 2009 and 638 for other years (for those months without significant trends over the study period). Figure 7 shows that monthly-mean values of PM\textsubscript{2.5} were \(\sim 4 \pm 2\) \(\mu\text{g m}^{-3}\) for all months, with almost no significant differences between 2009 and other years at the 95\% CL.

The small values of PM\textsubscript{2.5} for B, typically smaller by a factor of 2–3 than those for HD, are a bit perplexing given that both sites are approximately equidistant from Hamilton’s industrial sector and that there is no reason to assume that emission rates depend on wind direction. If Eq. (6) is adhered to, and PM\textsubscript{0} is assumed to be the same for both sites, it is implied that \(\delta\) is \(\sim 2.5\) km for south winds and \(\sim 4\) km for east winds. It is possible that local circulation patterns in and around the west end of Lake Ontario could concentrate pollutants into
Hamilton during east winds via a channeling effect of the Niagara Escarpment that runs east–west to both the north and south of downtown Hamilton (see Fig. 1).

On the other hand, it is possible that the major sources of PM$_{2.5}$ within the industrial sector are aligned in a narrow (i.e., <1 km wide) east–west band, resulting in heavy concentrations within a fairly narrow band through Hamilton during east winds. Conversely, assuming this is the case, during south winds the same sources would be aligned perpendicular to the wind and spread over 2–3 km, thereby resulting in lower concentrations with which to begin. In this scenario, it would then be that PM$_{2.5}$, rather than $d$, depends most on wind direction. In fact, if $d = 4$ km is used for B’s PM$_{indust}^{2.5}$, the effective PM$_{2.5}^{0}$ for AMJ would be $\sim 12 \mu g m^{-3}$ as compared with an effective PM$_{2.5}^{0} \approx 27 \mu g m^{-3}$ for the same period for HD’s PM$_{indust}^{2.5}$ for years other than 2009 and $\sim 13 \mu g m^{-3}$ for 2009. The reduction of HD’s PM$_{2.5}$ during 2009 might be due to the cessation of specific sources inside the industrial sector, but this suggestion leaves unanswered why B’s PM$_{2.5}^{0}$ appears to have changed so little during 2009.

As a final point, Fig. 8 shows mean values of PM$_{indust}^{2.5}$ for AMJ, collectively, for each year for both HD and B. Also plotted is total crude steel production for Canada for each year’s AMJ. Asterisks indicate that 2011 values of PM$_{indust}^{2.5}$ are preliminary because they have yet to be quality-control checked by Ontario’s MoE.

with the pronounced dips in 2009 being in accord with well-documented closures and cutbacks at Hamilton’s steel mills in response to the global economic crisis.

6. Conclusions

Because of the positioning of air quality monitoring stations in and around Hamilton, it is appears possible to extract estimates of PM$_{2.5}$ resulting from emissions from Hamilton’s north-end industrial sectors. Between Lake Ontario and air quality monitoring stations located within the city of Hamilton lie steel mills that are known to be dominant sources of air pollution. Nearby, on the west coast of Lake Ontario, lies the Burlington air quality site (see Fig. 1). Hence, by taking the difference of Hamilton and Burlington values of PM$_{2.5}$ during east winds, the remainders provide estimates of the industrial sectors’ contribution to Hamilton’s PM$_{2.5}$.

When winds at the west end of Lake Ontario have a strong easterly component, PM$_{2.5}$ values in downtown Hamilton are, on average, approximately 2 times those of nearby Burlington (see Fig. 3). Since the industrial sectors are almost all that lie between Hamilton’s downtown and Lake Ontario, the argument is that their emissions are largely responsible for Hamilton’s enhancement of PM$_{2.5}$ over those in Burlington. During spring and early summer, when land–sea breezes are common in this area, the contribution from the heavy industrial sectors to downtown Hamilton’s PM$_{2.5}$ was typically 7–10 $\mu g m^{-3}$ (see Figs. 3 and 4), roughly the same as that coming in off the lake and thus raising
PM$_{2.5}$ values in Hamilton’s downtown core to 2 times the regional background. During the global economic crisis of 2009, however, when steel production was attenuated greatly, the apparent contribution of heavy industry to Hamilton’s PM$_{2.5}$ was much reduced and, on average, only exceeded Burlington’s values by about 3–5 $\mu$g m$^{-3}$.

In turn, by screening for south winds rather than east winds, it should be possible to identify the industrial sectors’ contribution to Burlington’s PM$_{2.5}$. Despite Burlington’s and downtown Hamilton’s air quality stations being approximately equidistant from the industrial sectors, however, Burlington receives approximately a factor of 2–3 less PM$_{2.5}$ from the industrial sectors than does downtown Hamilton. This could be due to complicated circulation patterns in and around the west end of Lake Ontario. It might also stem from an east–west alignment of sources within the industrial sectors that leads to an accumulation of pollutants during (parallel) east winds yet during (perpendicular) south winds gives pollutant dispersion, effectively, a jump-start.

With an assumption that industrial activity is independent of wind direction, it might be possible to carefully extrapolate the results of this cursory study to estimate annual contributions of PM$_{2.5}$ from Hamilton’s industrial sectors. It might then be possible to correlate local industrial contributions of PM$_{2.5}$ with hospitalization records and thus arrive at, with the aid of the 2009 anomaly, an estimate of the public-health cost of respiratory-related treatments as a direct result of local sources of PM$_{2.5}$ (and other collateral chemicals). Going a step further, it might also be possible to deduce whether specific industrial contributions of PM$_{2.5}$ play a role in modulating local stratiform and cumuliform precipitation patterns (Li et al. 2011).

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REFERENCES


