Health Canada Santé Canada

Health Impacts of Air Pollution in Canada

An estimate of premature mortalities

Canada

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Summary

A large body of scientific evidence has accumulated over the last 25 years attributing air pollution to a wide range of significant adverse health effects, ranging from respiratory symptoms to development of disease and premature mortality. Advances in understanding over this period in both the health and atmospheric science have provided the ability to quantitatively estimate the impacts on human health of major air pollutants. In general, these estimates depend on an evaluation of population exposure (both short-term and long-term) to specific pollutants and evidence from scientific studies of the relationship between exposure and increased risk of adverse health effects, including mortality. In Canada and internationally, health impact estimates identify air pollution as one of the most important risk factors for premature mortality.

The approach for quantitatively estimating the population health impacts of air pollution is well recognized by health science organizations internationally. The objective of this analysis is to update and enhance an earlier Health Canada publication (Judek et al. 2004), based on recent scientific advancements. Compared with previous estimates, the new scientific information provides more specific analysis of cause of death associated with exposure to air pollution. In addition, updated air pollution data are also available for all of Canada, and the new estimates apply to the entire Canadian population instead of being limited to the larger urban centres. The analysis presented here makes use of these advances to provide an update of previous efforts by Health Canada to quantify air pollution health impacts.

Health Canada estimates the number of annual mortalities in Canada that can be attributed to air pollution from human sources in North America to be 14,400 deaths. This estimate is based on both acute and chronic exposure to air pollution, and covers all internal causes of mortality, with additional detail regarding some specific causes of death (cardiovascular, respiratory). The selected mortality endpoints were considered the most appropriate in generating an estimate of air pollution-related premature mortality for Canada.

Rationale

Air pollution is recognized globally as a major health risk. Exposure to ambient air pollution, for example, increases the risk of premature mortality from heart disease, stroke and lung cancer. Air pollution is currently considered the fourth-leading mortality health risk in the world and was responsible for one in ten deaths in 2013 (or 5.5 million premature mortalities worldwide) (World Bank and IHME, 2016). As the estimated number of mortalities attributable to air pollution has increased over the years, managing air pollution remains a priority.

This analysis is intended to provide a comprehensive estimate of mortality in Canada related to ambient levels of fine particulate matter (particulate matter with an aerodynamic diameter of less than 2.5 micrometres or $PM_{2.5}$), ozone (O_3) and nitrogen dioxide (NO_2). These pollutants were selected based on robust epidemiological evidence of adverse health impacts as well as our ability to accurately estimate their ambient levels and spatial distribution across Canada. This analysis is an update and an enhancement of Health Canada's earlier efforts for quantitatively estimating the population health impacts of air pollution in Canada (e.g. Judek et al. 2004).

Estimates of air pollution attributable mortality have been developed globally and for many countries in the world (Cohen et al. 2017; IHME and HEI, 2017; WHO, 2016). Such estimates have indicated that air pollution, especially $PM_{2.5}$, is the most important environmental risk factor known, and is among the most important general risk factors impacting human health. In Canada, estimates of air pollution attributable mortality have been developed by Health Canada in 2004 (Judek et al. 2004), by the Canadian Medical Association in 2008 (CMA, 2008), and by Stieb and co-authors in 2015 (Stieb et al. 2015). In general, all such estimates depend on an evaluation of population exposure (both short-term and long-term) to specific pollutants and evidence from scientific studies of the mathematical relationship between exposure and increased risk of mortality (referred to as concentration response functions or CRFs). Estimates of air pollution attributable mortality are expected to change over time, due to continuous improvements regarding data availability and methodology, both in terms of epidemiology and the spatial representations of air pollution exposure, as well as changes in population health and demographics. For example, new scientific information enhances specific analyses of causes of death associated with exposure to air pollution. In addition, new air pollution data and modelling tools provide better estimates of air pollution levels for all regions of Canada. Further, quantitative health impact estimates now apply to the entire Canadian population instead of being limited to the larger urban centres.

The objective of this analysis is to provide an updated estimate of air pollution attributable mortality in Canada based on the best available science and data. The method described here is considered to be comprehensive and appropriate for the Canadian context.

Methods

Pollutants included in the estimate

This analysis of air pollution health impacts in Canada focusses on $PM_{2.5}$, NO_2, and O_3. These three pollutants have been most consistently associated with mortality in epidemiological studies and exert the largest impact on adverse health outcomes. Further, ambient concentration maps covering all of Canada are available for $PM_{2.5}$, NO_2 and O_3. Carbon monoxide (CO) and sulphur dioxide (SO_2) were also examined in this analysis.

For each of these pollutants ($PM_{2.5}$, NO_2 and O_3), there is robust scientific evidence of health effects at very low concentrations, and no evidence of an exposure threshold: that is, any incremental increase in air pollutant concentration is associated with an increased risk of adverse health outcomes. The current analysis estimates the mortality that is associated with the incremental ambient air pollutant levels resulting from human source (anthropogenic) emissions in North America only. Health impacts associated with "background" pollutant concentrations (which include emissions from natural and non-North American sources) were not included. This approach was taken given that anthropogenic emissions are generally targeted for the purposes of air quality management.

Calculating the background concentrations of air pollution

Estimating background concentrations for $PM_{2.5}$, NO_2 and O_3 is complex and involves a combination of qualitative (i.e. expert judgment) and quantitative (i.e. evidence-based or data-driven) approaches based on concentration measurements at rural and remote monitoring sites. This results in a set of *monthly-average* background concentrations for O_3, which has a strong seasonal cycle in its ambient concentrations, and *annual-average* background concentrations for NO_2 and $PM_{2.5}$. Regional differences likely exist in the background concentrations, but for the purposes of this analysis, a single background concentration was chosen. Very low concentrations at rural and remote sites are used to establish the background concentrations based on one of the two following methods:

1. The data from rural and remote measurement sites are separated into sectors of different air mass origin and the background concentrations are selected as the monthly or annual average concentrations associated with the sectors containing no major anthropogenic sources; or

2. Many years of rural and remote measurement data are plotted in a time series that allows a qualitative selection of the lowest values that are, in turn, considered to be most representative of background air masses.

The estimated average background concentrations for Canada using the above methods are 1.8 $\mu g/m^3$ for $PM_{2.5}$ (annual), 0.2 ppb for NO_2 (annual), and 25.8 ppb (annual) and 28 ppb (May-September) for O_3.

Calculating the contribution from anthropogenic sources to air pollution

Quantifying the health impacts of air pollution for Canada requires measurements of air pollution in all areas. Air pollution monitoring in Canada, however, only occurs at a number of discrete monitoring stations across the country. Therefore national estimates of ambient air pollution levels (i.e. exposure surfaces including both anthropogenic and natural and non-North American contributions) are produced for $PM_{2.5}$, NO_2 and O_3 by combining a number of data sources as described below. Ambient concentrations are averaged over three years of data available to ensure that results are not influenced by annual variations in concentrations.

- Estimates of median annual $PM_{2.5}$ concentration for 2010–12 were derived from remote sensing observations from three satellite instruments: Multi-angle Imaging SpectroRadiometer (MISR), Moderate Resolution Imaging Spectroradiometer (MODIS), and Sea-viewing Wide Field-of-view Sensor (SeaWiFS) (Boys et al. 2014; Crouse et al. 2015; Stieb et al. 2015; van Donkelaar et al. 2010, 2013, 2015). The median annual $PM_{2.5}$ concentration estimates were available on a grid with a spatial resolution of approximately 10 km × 10 km.
- O_3 estimates of both (1) the annual average and (2) the average of the daily 8-hour maximum in the warm seasons for 2007–2009 were derived from an interpolation technique that weighs and combines modelled O_3 forecasts with measurements (observations) of O_3 (Robichaud and Ménard 2014; Kalnay 2003). The modelled O_3 forecast was provided by the Canadian and Hemispheric Regional Ozone and NOx System (CHRONOS) operational regional air quality forecast model (Pudykiewicz et al. 1997), while measurements came from the Canadian Air and Precipitation Monitoring Network (CAPMon) and the Canadian National Air Pollution Surveillance (NAPS) network. The combination of modelled and observed values (also termed objective analysis) improves estimates of ambient O_3 concentrations over areas lacking monitoring data compared to standard interpolation techniques. Estimates for Canada were available with 21 km horizontal resolution.
- NO_2 concentrations were estimated using a national land use regression model developed using data from the NAPS network, the Aura satellite (NASA 2011) and the Goddard Earth Observing System chemical transport model (GEOS-Chem 2011) (Hystad et al. 2011; Lamsal et al. 2008). Estimates were based on data for the period 2009-2011. The NO_2 estimates were available on a grid with a spatial resolution of approximately 10 km × 10 km.

Air pollution concentration estimates were provided as a surface of grid cells, which was then mapped to the Canadian population (using the 2006 census) by area weighting based on 478,780 dissemination blocks. From the area-weighted values for each dissemination block, population-weighted air pollution concentrations were estimated for all 288 census divisions of Canada. The national population-weighted average ambient concentrations were 6.5 µg/m^3 for $PM_{2.5}$, 38.8 ppb for annual O_3 , 43.6 ppb for summer O_3 (May-September), and 8.5 ppb for NO_2.

With respect to short-term exposures, changes in annual average exposure were assumed to equal the average change in daily exposure (Stieb et al. 2015). Air pollutant concentrations attributable to anthropogenic emissions (i.e. above-background pollutant concentrations) were then estimated by subtracting the average background concentrations from the ambient concentrations.

Calculating the mortality due to air pollution

The total mortality attributable to air pollution was estimated for ambient concentrations of $PM_{2.5}$, O_3 and NO_2 above background concentrations. The analysis was conducted using Health Canada's Air Quality Benefits Assessment Tool (AQBAT) (Judek et al. 2012). The AQBAT model produces an estimate of the number of premature deaths and other health outcomes in Canada. Health effect information for the three air pollutants is included in the form of CRFs. A CRF is a statistically derived estimate, from a single study or a meta-analysis of multiple studies, of the percentage of excess health risk for a given endpoint (in this case, mortality) associated with a unit increase in the ambient pollutant concentration (e.g. per 1 µg/m^3 of $PM_{2.5}$).

CRF values for $PM_{2.5}$ mortality from ischemic heart disease (IHD), cerebrovascular disease (CVD), lung cancer (LC) and chronic obstructive pulmonary disease (COPD), for adults 25 years and over, are included (Shin et al. 2013). This mirrors the approach employed in the Global Burden of Disease (GBD) analyses (Cohen et al. 2017; Lim et al. 2010; www.healthdata.org/gbd), led by the Institute for Health Metrics and Evaluation (IHME), and the World Health Organisation (WHO), which include estimates on air quality and health impacts across the world. However, IHD, CVD, LC and COPD are a subset of all internal cause (non-accidental) mortality. All internal cause mortality is also reported and is the main metric for the current report. CRFs were calculated for all internal cause mortality for $PM_{2.5}$ from a Canadian cohort (Crouse et al. 2012), for NO_2 from Canadian data (Burnett et al. 2004), and O_3 from an American cohort (Jerrett et al. 2009).[1] CRF values for the three pollutants are reported in Table 1. CRFs can be input as a distribution function in the calculations, accounting for inherent uncertainty in the CRF estimates. Monte Carlo simulations employing 10,000 iterations were used to propagate this uncertainty in the CRFs. The model generates a central estimate of the most likely health impacts equal to the mean of the output distribution, as well as low- and high-end estimates equal to the 2.5th and 97.5th percentiles of the output distribution.

Age-specific baseline incidence rates (of the mortality types in question) for the target population were included to estimate the number of excess health outcomes (i.e. mortalities) associated with the increased risk due to a change in air pollutant concentration. Health outcomes were considered to have no threshold for effect (i.e. effects were assumed to occur at all levels of exposure).

Baseline mortality rates are a key factor in estimating the count of premature mortalities for a pollutant concentration change. Baseline cause- and age-specific mortality rates were derived from counts of mortality obtained for each census division (CD) with the exception of Québec where these data were not available. Québec mortality counts for each CD were derived by applying national age- and cause-specific rates to the population age distribution of individual CDs. Rates are averaged over the three most recent years of available data to improve stability (Stieb et al. 2015).

In the context of this analysis, CRFs pertaining to acute exposure were derived from studies examining effects of air pollutants in the days before death, while CRFs pertaining to chronic exposure were derived from studies of air pollutants averaged over the years prior to death.

Results

Reducing ambient $PM_{2.5}$ concentrations in Canada from current to background levels would result in an 8.1% (95% confidence interval (CI) 2.5–19.3%) reduction in mortality from the four selected causes identified above. This is equivalent to 5,600 annual mortalities attributable to chronic exposure to $PM_{2.5}$ in Canada. Alternatively, 4.3% (95% CI 2.3–6.2%) of all internal causes of death are attributable to above-background concentrations of $PM_{2.5}$, representing 9,500 deaths per year.

It is estimated that 0.6% (95% CI 0.2–1.0%) of all internal causes of death in Canada can be attributed to acute exposure of the Canadian population to above-background concentrations of NO_2 (i.e. mortality that occurs a few days after an elevation in ambient NO_2). This represents 1,300 mortalities a year.

Acute exposure to above-background O_3 was associated with 1.1% (95% CI 0.7%-1.4%) of all internal cause mortality (2,400 deaths per year), whereas chronic exposure to above-background O_3 was linked with 5.7% of respiratory-related mortalities (95% CI 2.0–9.4%), equivalent to 1,200 respiratory mortalities per year.

The results for $PM_{2.5}$ appear in Stieb et al. (2015), whereas results for NO_2 and O_3 are based on supplementary analyses. Additional details are included in Table 1.

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[1] For $PM_{2.5}$, CRFs have been developed for all internal cause mortality, as well as for specific causes: IHD, LC, CVD, and COPD. For example, see Crouse et al. (2012) and (Stieb et al. 2015). The all cause internal mortality endpoint generally leads to higher mortality estimates than the four specific causes of death.

Overall, the total mortality attributable to anthropogenic air pollution in Canada is estimated to be 14,400 deaths per year, based on air pollutant concentrations from 2007 to 2012.[2] Specifically, this represents the estimated population health impacts of $PM_{2.5}$, O_3 and NO_2.

Because people are exposed concurrently to multiple air pollutants in ambient air, rather than to individual pollutants in isolation, it is difficult in epidemiological studies to separate the true independent effects of individual pollutants. Where possible, the CRFs employed in this analysis were derived from statistical models that included the other pollutants, providing a measure of adjustment for possible overlapping effects among pollutants. However, it is still possible that there is double counting of effects among pollutants, or that effects attributed to one pollutant are not fully disentangled from those attributed to other pollutants.

Discussion

This estimate of 14,400 deaths per year represents Health Canada's current estimate of the number of annual mortalities in Canada that can be attributed to air pollution from human sources in North America. Similar estimates have been produced in the past. In 2004, Health Canada provided an estimate of 5,900 deaths per year in 8 major Canadian census divisions, which included approximately a third of the national population (Judek et al. 2004). In 2008, the Canadian Medical Association extrapolated monitoring data to all of Canada, estimating that 21,000 deaths could be attributed to ambient $PM_{2.5}$ concentrations (including background and above-background concentrations). The most recent IHME GBD estimates for mortality attributable to air pollution in Canada are 7,100 for $PM_{2.5}$ and 690 for O_3 (IHME and HEI 2017). Although these numbers appear to diverge, the underlying science is consistent. Variations or discrepancies between estimates may occur owing to differences in the data and methods used to calculate air pollution health impacts, and especially in assignment of concentration levels to the population. For example, the use of different CRFs can influence estimates. As mentioned previously, CRFs for $PM_{2.5}$ exist for all internal causes or for specific causes of mortality (i.e. IHD, LC, COPD, and CVD). A CRF also depends on the population or cohort from which it is derived; Canadian data are more appropriate than European or even American data. The air pollution exposure estimates (i.e., the exposure surface for Canada) can also differ based on the chemical transport models and the monitoring data used to estimate ambient air pollution levels in Canada and in some cases the methods used to extrapolate monitored data to the entire population. Mortality estimates also depend on detailed demographic data, such as population count and distribution, as well as baseline rates of mortality in Canada. The data and method used in the current analysis are considered to be more comprehensive and appropriate for the Canadian context than previous estimates as they integrate new science and knowledge on the health effects of air pollution in Canada.

In this analysis, an estimated North American background concentration was applied as the reference for the calculation. This approach was taken given that anthropogenic emissions are generally targeted for the purposes of air quality management. Even if air pollution levels are low in Canada compared with those in other developed nations,[3] recent Canadian studies show attributable mortality even at quite low pollutant concentrations (Crouse et al. 2015).

The GBD estimates by the IHME are based on four specific causes of death for $PM_{2.5}$ (i.e. IHD, LC, COPD, and CVD) and one for O_3. (i.e. COPD). This is particularly appropriate for estimating air pollution impacts globally given the potentially wide variation throughout the world in underlying cause-specific mortality rates. However, the evidence that exposure to ambient $PM_{2.5}$ air pollution has impacts beyond these four diseases made the use of a CRF based on all internal causes of mortality the most appropriate choice in generating an estimate for Canada.

In this analysis, three different methods (Satellite observations coupled to a chemical transport model for $PM_{2.5}$, ground observations coupled to another chemical transport model for O_3, and a land use regression

[2] $PM_{2.5}$: 2010-2012; O_3: 2007-2009; NO_2: 2009-2011
[3] www.who.int/phe/health_topics/outdoorair/databases/cities/en/

model informed by various data sources for NO_2) were applied to calculate exposure of the Canadian population to each of the three pollutants; unfortunately the data periods are not exactly the same. These three estimation methods provide the best available national exposure estimates for each pollutant and despite the inconsistencies they provide the best exposure estimate available at this time. Health Canada and Environment and Climate Change Canada are currently collaborating on the evaluation of approaches to developing a more coherent integrated exposure estimate that can be updated annually or biannually.

It must be noted that variations in health impact estimates are to be expected in future updates by Health Canada. Variations or discrepancies between estimates may occur owing to, for example: different data or methods to assess population exposure to air pollutants; different exposure–response or concentration-response relationships; or differences in the baseline rates of mortality in Canada. Mortality estimates can be especially influenced by values used for exposure–response relationships, which are regularly updated as new data is produced, becomes available, and is integrated in the existing epidemiologic data sets. In addition, if annual trends are generated from the analyses, the health impact estimates will be recalculated for all years included in the analysis to ensure that trends are internally consistent.

Further, Health Canada estimates may differ from those published by international agencies, such as the IHME (GBD reports), the HEI and the WHO. However, estimates by Health Canada and others should converge and show similar trends.

Conclusions

Air pollution is recognized globally as a leading risk factor for premature mortality, based on the weight of evidence available in a robust database of international epidemiological studies and supporting evidence from toxicological investigations. As a result of extensive research and assessment, including comprehensive review by Health Canada, $PM_{2.5}$, NO_2, and O_3 have been found to exert the largest population health impacts.

Health Canada estimates that 14,400 deaths per year in Canada can be attributed to human sources of these three air pollutants. The current analysis estimates the mortality associated with the incremental ambient air pollutant levels resulting from human source emissions as air quality management measures generally target these emissions.

The data and method used in the current analysis (e.g. background concentrations, CRFs) integrate new science and knowledge on the health effects of air pollution in Canada compared with previous Canadian estimates. They are more comprehensive and appropriate, and provide the best exposure estimate available at this time.

Table 1. Estimate of premature mortalities attributable to above-background levels of air pollution: results, analysis parameters, and sources

Pollutant	**$PM_{2.5}$**	**NO_2**	**O_3**
Number of mortalities **(% of baseline mortality)**	**9,500** (4.3%) – all cause mortality; chronic exposure **5,600** (2.5%) – 4 specific causes of mortality; chronic exposure	**1,300** (0.6%) – acute exposure	**2,400** (1.1%) – acute exposure **1,200** (0.6%) – chronic exposure
Causes of death	All (excluding external causes, e.g. accidents, suicide) 4 causes: IHD, LC, CVD, COPD	All (excluding external causes, e.g. accidents, suicide)	Acute: All (excluding external causes, e.g. accidents, suicide) Chronic: Respiratory
CRF – % increase per Δx	All: 10% per 10 $\mu g/m^3$ IDH: 27.7% per 10 $\mu g/m^3$ LC: 16.9% per 10 $\mu g/m^3$ CVD: 17.9% per 10 $\mu g/m^3$ COPD: 9.2% per 10 $\mu g/m^3$	1.5% per 20 ppb	Acute: 1.7% per 20 ppb Chronic: 8.2% per 20 ppb
Source of CRF	All: Crouse et al. 2012 4 causes: Shin et al. 2013	Burnett et al. 2004 (supplementary analysis model including CO, NO_2, O_3, SO_2)	Acute: Burnett et al. 2004 (supplementary analysis model including CO, NO_2, O_3, SO_2) Chronic: Jerrett et al. 2009
Morbidity effects also estimated	Yes	No	Yes
Years of exposure data	2010–2012	2009–2011	2007–2009
Source of exposure data	Satellite observations; van Donkelaar et al. 2015	National model incorporating observations from NAPS monitors, satellite observations, land use patterns and distance from highways and major roads; Hystad et al. 2011	Combination of values from the CHRONOS air quality forecast model and observations from NAPS monitors; Robichaud and Ménard 2014

National population weighted average ambient concentration	**6.5 µg/m^3**	**8.5 ppb**	**38.8 ppb (annual)** **43.6 ppb (May-Sept)**
Estimated natural background concentration	**1.8 µg/m3**	**0.2 ppb**	**25.8 ppb (annual)** **28 ppb (May-Sept)**
Results previously published	Stieb et al. 2015	No	No

CHRONOS: Canadian and Hemispheric Regional Ozone and NOx System; COPD: chronic obstructive pulmonary disease; CRF: concentration-response function; CVD: cerebrovascular disease; IHD: ischemic heart disease; LC: lung cancer; µg/m^3: micrograms per cubic metre; NAPS: National Air Pollutant Surveillance network; ppb: parts per billion

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