Environment Canada Environnement Canada

AMBIENT PARTICULATE MATTER

AN OVERVIEW

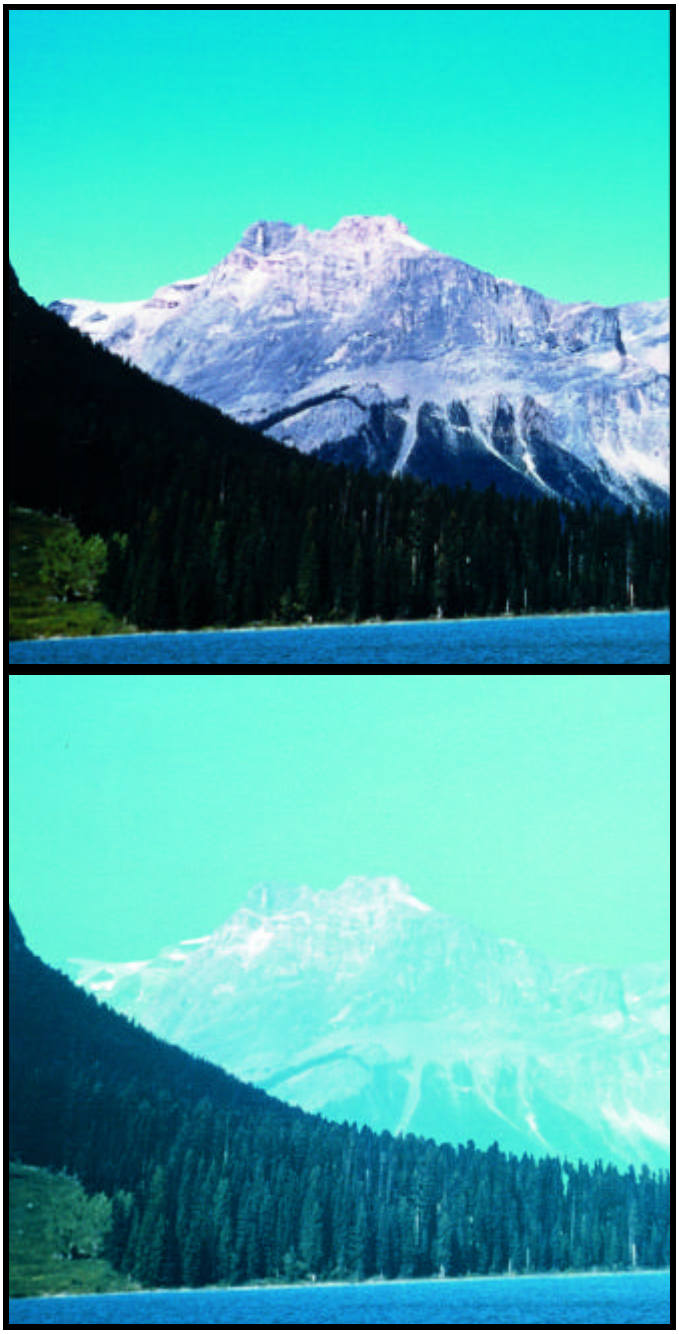
Ambient Particulate Matter (PM) is emerging as a critical environmental health issue. It has long been known that high concentrations of very small particles in the air, such as those experienced during the famous "killer" fog of London, England in December 1952, can severely affect susceptible people such as the sick and the elderly, even causing or contributing to death. What has emerged more recently is an understanding that even at low concentrations of PM, such as those experienced currently across Canada, human health is adversely affected. The challenge of responding to this concern is great, for PM is everywhere, and its sources are diverse and intimately linked to the industrialization of our society.

What is Particulate Matter?

The physical and chemical characteristics of PM are complex, reflecting a multitude of sources and the fact that particles are continually evolving as they interact with other components of the atmosphere. Given this complexity, it is useful to categorize PM on the basis of three key features: i) particle size, ii) sources and iii) composition.

Box 1: What is Particulate Matter?

Particulate Matter refers to all airborne liquid and solid particles, except pure water, that are microscopic in size. Coarse PM (of diameters <10µm and >2.5 µm) and fine PM (of diameters <2.5 µm) are of greatest concern to human health and also cause reduced visibility. Coarse PM contains primarily materials derived from the earth's crust, such as soil and minerals. Fine PM, usually the result of anthropogenic activities, contains sulphate, nitrate, ammonium, metals and hundreds of different organic compounds.



i) Particle Size

Particle size may vary from approximately .005 micrometres (µm) to 100 µm in diameter. For comparison, a human hair is approximately 70 µm wide. The largest of the particles are heavy enough to settle out rapidly from the air. Scientists are most concerned with the "suspended" portion of PM in the ambient air, which generally covers a size range up to about 40 µm. These particles are known as **Total Suspended Particulate (TSP)**. The smaller ambient particles have a characteristic mass distribution which results in their being considered as two major classes: **Coarse PM** (<10µm and >2.5 µm) and **Fine PM** (<2.5 µm). Figure 1 illustrates the major components of each. ***Common terminology uses PM10 to refer to all particles less than 10µm in diameter, and PM2.5 to refer to particles less than 2.5µm in diameter.***

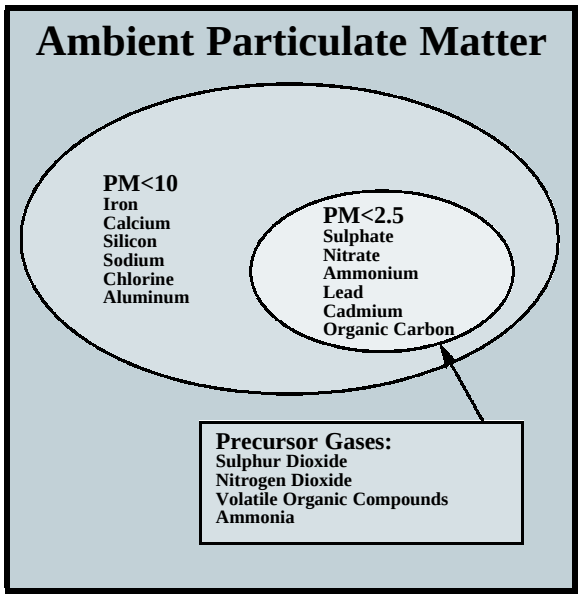


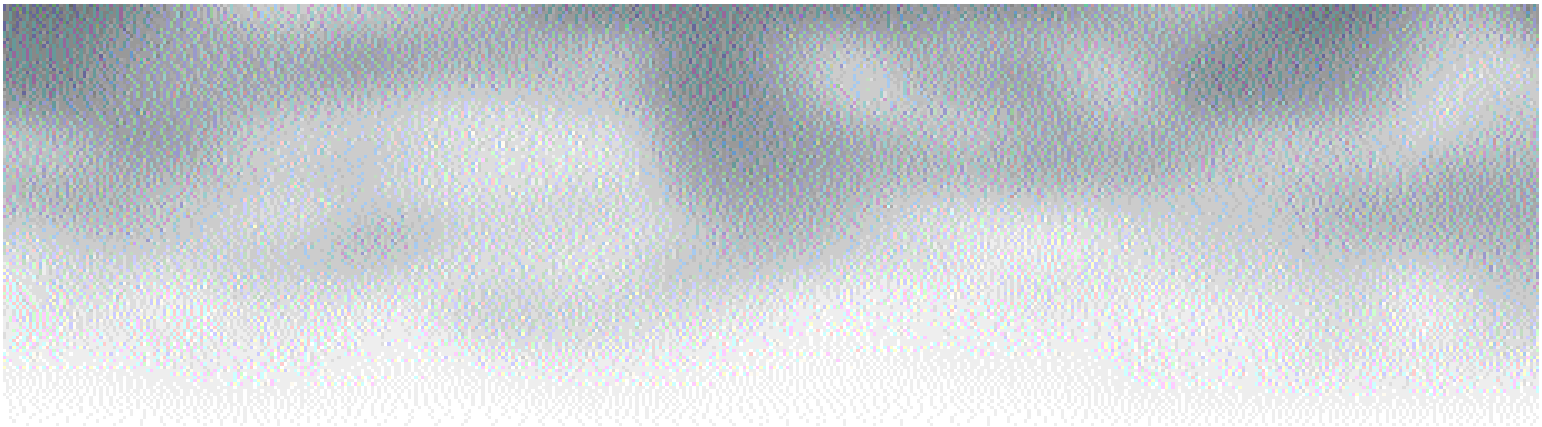
Figure 1: Composition of Particulate Matter according to size, illustrating the contribution of precursor gases to PM2.5.

As scientists have learned more about the health effects of PM, attention has focused on increasingly smaller particles. Smaller particles may remain in the air for days or even weeks, and can also penetrate far deeper into the lungs. Thus the strong interest in particles with an upper size limit of 10 µm. More recently the class of **ultrafine** particles measuring less than 0.1 µm in diameter has become an active area of research.

ii) Sources

Particulate matter is a ubiquitous pollutant, reflecting the fact that it has both **natural** and **anthropogenic** (arising from human activity) sources. **Natural sources** of PM include windblown soil and mineral particles, volcanic dust, sea salt spray, and biological material such as pollen, spores, bacteria, and debris from forest fires. By and large these natural sources produce coarse particles, although some high temperature sources such as wildfires will generate fine PM. **Anthropogenic sources** produce both coarse and fine particles. Windblown agricultural soil and dust from roads and construction sites produce primarily coarse anthropogenic PM. Smaller particles of more complex chemical composition are generated through fossil fuel combustion in electrical power plants, automobiles, industrial boilers, residential heating etc.

Another distinction of importance is between those particles that are emitted directly into the atmosphere (**primary particles**) versus those that are formed **in** the atmosphere from gaseous emissions (**secondary particles**). **Primary particles** are formed as a result of physical processes/forces, such as crushing, grinding and erosion, that lead to the physical breakdown of larger particles into smaller ones. As expected, particles formed in this manner are primarily coarse. Primary particles are also directly emitted from combustion sources (e.g. elemental carbon and organic carbons). In this case, the particles produced are fine particles.



Secondary particles are formed through chemical reactions involving gases and other particles in the atmosphere. Particles formed in this manner are fine particles (< 2.5 µm). The most common precursor gases involved in these reactions are nitrogen oxides (NO_x), sulphur dioxide (SO_2), volatile organic carbons (VOC) and ammonia (NH_3), which form particle sulphate and nitrate (often in the form of ammonium sulphate and nitrate) and numerous organic carbon compounds (Figure 1). All of the precursor gases are emitted during the combustion of fossil fuels and as a result of numerous other industrial processes. Volatile heavy metals are also emitted in vapour form during combustion and other high temperature processes. These can condense in the atmosphere to form fine particles.

There are a wide variety of natural and anthropogenic sources of PM (Table 1). Current estimates of the magnitude of actual emission sources in Canada are restricted to primary particulate matter and are thus incomplete. These data reveal that open sources such as roads and construction sites are major sources of both fine and coarse primary anthropogenic PM in Canada, a situation which poses a challenge in terms of control strategies. Estimates of the magnitude of secondary particulate sources are required to complement the data on primary emissions, however, these can only be derived using mathematical models which take into account precursor gas emissions and the complex atmospheric chemistry involved in the formation of secondary PM. Such models are still in the developmental stage.

U.S. emissions of precursor gases (NO_x, VOC and SO_2) can also contribute to Canadian particle levels, especially in Ontario, Québec and the Maritimes where prevailing winds favour the transport of air masses from the Eastern U.S. Secondary PM2.5, also may persist in the atmosphere for days or weeks, allowing it to be transported over long distances. This renders PM2.5 more of a regional problem than PM10, since the latter (which encompasses coarse particles) is more closely linked to local sources.

iii) Particle Composition

Coarse and fine particles have markedly different physical and chemical properties - differences that reflect the parent materials and mechanisms by which coarse and fine particles are generated. Coarse particles consist primarily of materials derived from the earth's crust, and are therefore rich in oxides of iron, calcium, silicon and aluminum (Figure 1). Sea salt spray is another major source of coarse particles

Table 1: Sources of Particulate Matter

	Natural		Anthropogenic	
	Primary	Secondary	Primary	Secondary
PM<2.5µm	• wildfires	• from biogenic VOCs • nitrates from natural NO_x emissions (predominantly from soil processes)	• fossil fuel combustion (industrial, residential, automobile) • roads and construction sites (tire and brake wear, dust) • metal smelting	• from anthropogenic sources of VOCs (autos, industrial processes, solvents) • sulphates and nitrates from anthropogenic sources of SO_2, NO_x and NH_3 (vehicles, power plants etc.)
PM<10µm	• windblown dust • sea salt spray • pollen, spores		• mineral dust from mining and extraction industries • windblown agricultural soil • road and construction dust	

in coastal regions, and these particles are typically enriched with sodium chloride. Fine particles are composed mainly of sulphate, nitrate, ammonium, inorganic and organic carbon compounds, and heavy metals such as lead and cadmium, all of which are indicators of anthropogenic activities. Sulphate (SO_4^{2-}) has repeatedly been shown to be the single most abundant component of fine particles. However, only a few of the numerous organic carbon compounds (which are potentially toxic) have been identified in fine PM and together these many organic compounds account for approximately 50% of the fine particle mass.

There are marked differences in PM2.5 composition across Canada reflecting the contributions of major emission sources. For example (Figure 2), in the Lower Fraser Valley of British Columbia at Abbotsford, nitrate and sulphate contribute equally to PM2.5 and the organic carbon component is large. On the east coast, in St. Andrews, New Brunswick, nitrate contributes much less to overall mass compared to sulphate, and the organic carbon fraction is much reduced relative to the site in B.C.

These chemical differences also impart differences in physical properties. For example, the "hygroscopic" or water attracting nature of particles is influenced by chemical composition, and in turn is a key factor in particle size, shape, pH (acidity), reactivity etc. Also, the more complex the chemical composition of fine particles, the more physically complex the particle structure, resulting in large rough surface areas relative to the mass. Both of these factors increase the particle reactivity and cause fine particles to be considered more toxic than coarse particles.

PM Linkages to Other Air Issues

An understanding of secondary particle formation and the role of precursor gases reveals that there are direct links between the PM air quality issue and a number of other critical air quality issues (Figure 3). Emissions of SO_2 and NO_x link the PM issue to **Acid Deposition**, since these are the pollutants involved in the formation of acid rain. **Ground Level Ozone**, the major component of photochemical smog, is linked to PM through the commonality of the precursor gases NO_x and VOC. PM is connected also to the issue of **Hazardous Air Pollutants (HAPs)** through organic carbon particles and metals, many of which are themselves toxic. Ambient particles may also act as "carriers" of other toxic contaminants (such as pesticides). An

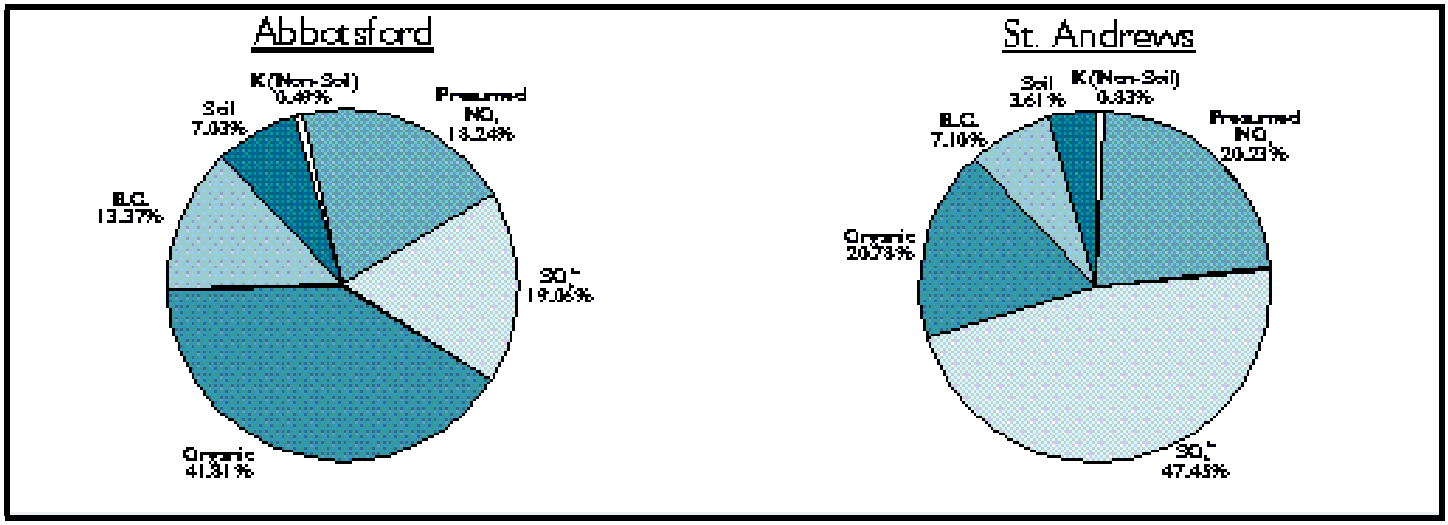


Figure 2: Relative composition of PM2.5 in Abbotsford, British Columbia and St. Andrews, New Brunswick. (Where B.C. refers to black carbon)

understanding of these linkages provides both for greater understanding of the atmospheric processes involved in air pollution, and an opportunity for management strategies to address multiple issues simultaneously.

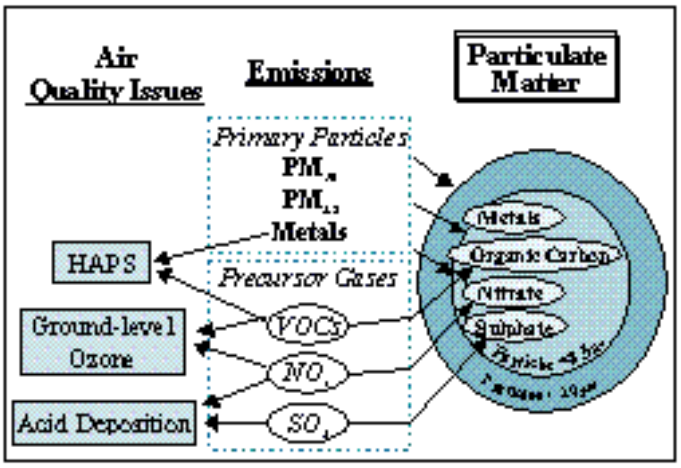


Figure 3: Linkages among air quality issues, emissions and particulate matter.

Ambient PM Levels in Canada

Ambient levels of PM at sites across Canada are affected by a number of factors, including, local sources of PM, long range transport, meteorological conditions and topographical and other physical features, such as the proximity of mountains, lakes and oceans. Consequently, PM levels vary with the season, with the time of day, and from site to site. Even within a city there can be marked differences in PM concentrations. Although PM is a problem in urban areas, it is not exclusively so. In general, where local sources are significant (e.g. small industrial towns), where long range transport is significant and/or where topographical and meteorological conditions hinder the dispersion of pollutants, elevated levels of PM can be expected.

The National Air Pollution Surveillance (NAPS) network is a co-operative federal/provincial/municipal program responsible for air quality monitoring in Canada. This monitoring network provides information on the ambient levels of particulate matter for Canadian cities and some rural locations. This information is used to assess trends in urban and regional air quality across the country. Particulate matter is measured as total particle mass, and in some locations particle composition is also monitored. Typically it is the mass measurements that are used for long term trend analysis and assessment of the success of air quality management programs. The particles are collected on filters which are then weighed to determine their mass. The air inlets on the particle monitors can be modified to collect particles of specific sizes. TSP monitoring began in 1974. PM10 and PM2.5 monitoring began in 1984. Currently, there are approximately 70 PM10 sites and 40 PM2.5 sites in operation across Canada.

Typically, particle samples have been collected over a 24 hour period on a one-in-six-day schedule. Thus, over a long enough time period, each day of the week is equally well represented. PM data are reported as daily (24 hr.) average concentrations. More recently, technology has become available that is capable of providing continuous, hourly measurements of ambient concentrations of PM10 and PM2.5. Detection limits for these instruments are typically 1 µg/m^3. The number of these continuous samplers being added to the Canadian network is growing.

General Characteristics of PM Data

PM data from most sampling sites share some common features (Figure 4). The concentration distribution is typically very skewed, with the majority of samples yielding low concentrations of PM while a few samples yield very high concentrations. This pattern may reflect the nature of PM emissions, with high pollution events being episodic or infrequent. Meteorological factors such as temperature and wind speed which affect the dispersion of pollutants over larger areas also play a role. In current assessments of PM

levels in Canada, it is estimated that maximum concentrations of PM10 and PM2.5 are underrepresented by 20-30% as a result of the sampling schedule which records ambient levels at a site only once every six days. At such a rate, the infrequent, high pollution events may be missed.

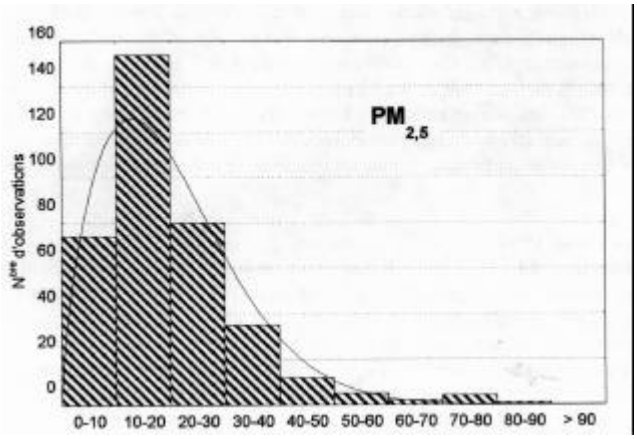
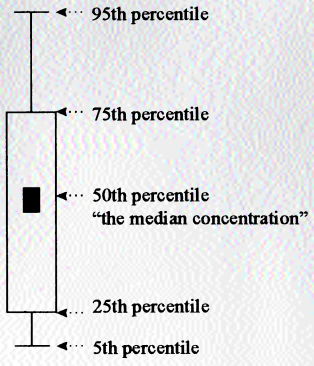


Figure 4: Typical distribution of 24 hr PM2.5 concentrations (µg/m^3) (Montreal Site #50109)

Box 2: Plotting Conventions:

Box plots are often used to present PM data. These are a common means of depicting air quality data since they capture both average values and the range of variation at each site in terms of percentiles of the concentration distribution. Box plots typically indicate the median (or 50th percentile), 5th and 95th, and 25th and 75th percentiles (e.g., the 95th percentile shows the concentration limit within which 95% of the data fell).



Background Concentrations of PM

Natural sources contribute to both fine and coarse particles in the atmosphere. "Background PM" is therefore defined as the natural concentration of particles that would be observed in the absence of anthropogenic sources. Background levels of PM vary with the season (i. e: changes in the concentration of pollen and spores, and relative humidity) and with geography (i.e.: significance of local sources - oceans, forest fires etc.). Due to the contributions of long range transport of fine particles and precursor gases to local PM concentrations, it is difficult to ascertain the exact magnitude of background concentrations, since even remote areas can be impacted by anthropogenic sources of particles. Background concentrations of PM have been estimated to fall in the range of 4-12 µg/m^3 for PM10 and 1-5 µg/m^3 for PM2.5 (annual averages) for remote regions of North America. However, over shorter periods of time, background PM concentrations can be much higher, reflecting the episodic nature of many natural sources of particles, such as dust storms or wildfires.

Total Suspended Particulate (TSP)

Based upon the 1984-1993 data from the NAPS network, median concentrations of TSP range from about 30 µg/m^3 in Halifax, 35 µg/m^3 in Ottawa and the B.C. sites, to higher values of 60-70 µg/m^3 in Montréal, Edmonton and Calgary. High concentrations of TSP can exceed 100 µg/m^3, and maximum values have even reached several hundred µg/m^3 under episode conditions. As a region, the Prairies tend to have higher and more variable TSP concentrations. Analyses of TSP data collected over the period 1981-1990 have shown that TSP concentrations in Canada have decreased by 34%.

PM10

The PM10 information includes all ambient particles less than 10 µm, including PM2.5. Data from the NAPS network have shown that mean 24 hr. PM10 concentrations range from 9-42 µg/m^3 across Canada, with most sites in the range of 20-30 µg/m^3 (Figure 5). The sites that generally experience the highest concentrations are in Montréal, Windsor, Hamilton, Walpole Island (a non-urban site near Detroit) and Calgary. Toronto, Winnipeg, Regina and Edmonton also have relatively high PM10 concentrations. Maximum values, which are episodic, are even higher with many sites experiencing values greater than 100 µg/m^3 and a few sites nearing 180 µg/m^3 .

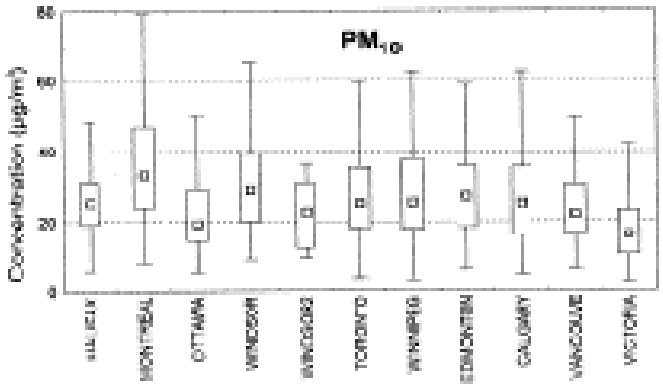


Figure 5: PM10 concentration (µg/m^3) distributions at 11 urban sites (1984 - 1993)

Analyses of the PM10 concentrations have shown that the seasonal pattern is not the same across Canada. Atlantic provinces show a variable pattern, with Saint John and Kejimkujik National Park showing their highest values in the summer, while Halifax has a wintertime maximum. Ontario sites experience their highest values during the summer months, which may reflect the peaks observed in precursor gases such as NO_x and SO_2 at this time in southern Ontario. Prairie sites, on the other hand, experience springtime maxima, a trend that is thought to reflect factors such as the lack of snow and vegetation cover that would otherwise prevent soil particles from becoming airborne, and the prevalence of street sanding debris. Sites in B.C. also tend towards an early spring or wintertime maximum. The seasonal variations in PM10 concentrations can be the result of both natural and anthropogenic factors.

In contrast, a consistent weekday pattern in PM10 concentrations has been observed at urban sites which is thought to be solely an anthropogenic effect. Most urban sites show minimum PM10 concentrations on Sundays and maximum values mid-week, a pattern attributed to transportation and industrial sources. At monitoring sites near roadways, the midweek vs. Sunday differences can be even larger (up to a 50% increase in PM10 midweek), clearly indicating the influence of transportation related emissions.

Over the period 1984-1993, annual average PM10 concentrations have decreased by an average of 2% per year on a national basis.

PM2.5

PM2.5 information from the NAPS network has shown that mean 24 hr PM2.5 concentrations across Canada range from 7 to 20 µg/m^3 . Sites that generally experience the highest concentrations are located in the Windsor-Québec City Corridor and in Vancouver, regions where there are high precursor gas emissions of NO_x and SO_2 (Figure 6). Here values are frequently well above 20 µg/m^3 and maximum values can exceed 100 µg/m^3 . Prairie sites have notably lower and less variable PM2.5 levels (Figure 6).

The seasonal variability of PM2.5 is more pronounced than that of PM10, but again there is no discernible geographic pattern to this variability. For example, maritime sites show both summertime and wintertime maxima.

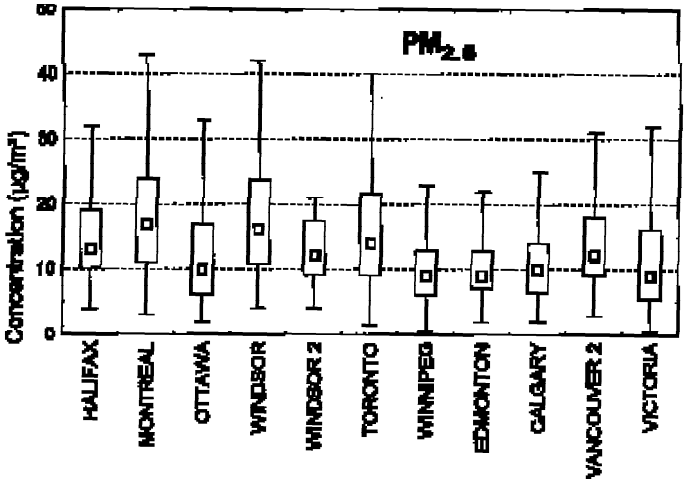


Figure 6: PM2.5 concentration (µg/m^3) distributions at 11 urban sites (1984 - 1993)

Most southern Ontario sites experience the highest PM2.5 concentrations in the summer months, reflecting high concentrations of SO_2 and NO_x there in the summer, however, Ottawa shows a wintertime maximum. Other sites with wintertime maxima (Jan/Feb) include Montréal, Edmonton, Calgary, Vancouver and Victoria. A strong weekly cycle in PM2.5 concentrations is also observed. Mean midweek concentrations of PM2.5 are on average 23% higher than Sunday means. For monitoring sites near roadways, the difference increased to up to 60%. Again a major role for transportation related emission sources is indicated.

Analysis of the PM2.5 data over the period 1984-1993 showed a significant decrease in PM2.5 concentrations on a national basis averaging 3.3% per year.

Relationships Among TSP, PM10, PM2.5 and Sulphate

As the sources and chemical characteristics of particles vary with their size, it is useful to know what proportion of TSP is PM10 or PM2.5, or what proportion of PM2.5 is particulate sulphate, and how these proportions vary across the country. The answers to these questions can help design effective control strategies, targeting different size particles in different regions of the country as required.

On average across Canada, PM10 accounts for approximately 50% of TSP, while PM2.5 accounts for approximately 25% of TSP. Consequently, the average ratio of PM2.5 / PM10 is also about 50%. There is considerable variation within and among sites in these ratios. The proportion of PM2.5 that is sulphate is much lower in Western Canada versus Eastern Canada (Figure 7). This is a pattern that has been repeatedly observed and is directly attributable to

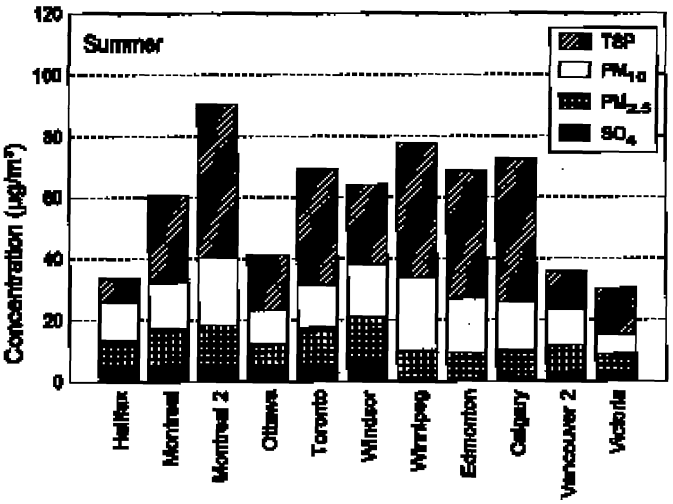
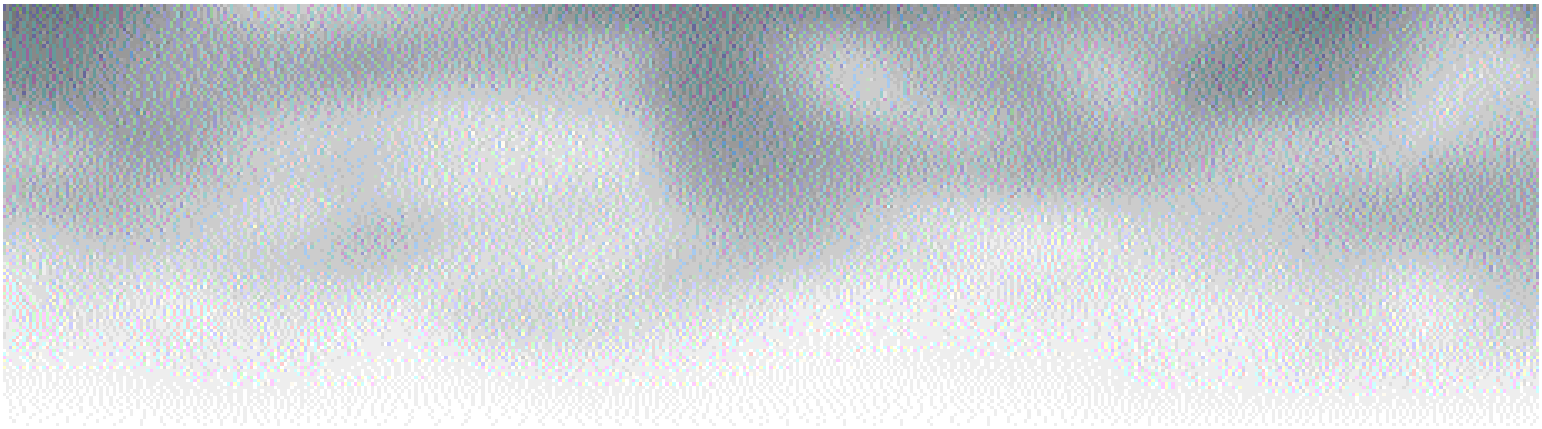


Figure 7: Relationships between mean TSP, PM10, PM2.5 and sulphate at 11 urban sites (1984 - 1993) during the summer period. The top of each individual box indicates the mean 24 hour concentration (i.e.: in Halifax the mean TSP, PM10, PM2.5 and sulphate concentrations were 33, 27, 16 and 4 µg/m^3).

the spatial pattern of SO_2 emissions within eastern N. America. One of the striking features of Figure 7 is the low PM2.5 levels relative to PM10 at Prairie sites, indicating a greater than average contribution of coarse particles to total PM10

Box 3: PM Differences within Cities

Figure 7 illustrates the potential for very different PM levels within the same city, in this case, Montreal. The site noted as Montreal 2 is located very near a busy traffic area, and this has resulted in proportionately higher TSP and PM10 levels than a nearby site located in an industrial area. This highlights the challenge in managing PM air quality, in that the diversity of sources within relatively small areas has a significant impact on the levels and characteristics of the ambient particles.



mass. This corroborates what is generally known about the prairie environment, that a significant portion of the ambient particles is derived from local crustal material (i.e. airborne soil particles).

Human Health Effects of Particulate Matter

The adverse health effects that result from exposure to particulate matter are specific to the cardio-respiratory (heart - lung) system. The smaller the particle, the deeper into the lungs it can penetrate, and the greater the risk of inducing a negative reaction. Most particles greater than about 10 µm will be caught in the nose and throat, never reaching the lungs. Particles smaller than 10 µm (PM10) can be breathed into the lungs and are therefore sometimes referred to as **inhalable particles**. The largest of these particles will be caught by cilia lining the walls of the bronchial tubes, which move the particles up and out. PM2.5 penetrates deeper into the lungs, into regions where there are no cilia, therefore particles are removed by other, slower mechanisms. PM 2.5 is sometimes referred to as **respirable** PM. The effects of small particles on the heart are not yet fully understood, but the lungs and heart are closely connected which means that a disturbance in one organ can affect the functioning of the other. The cardio-respiratory problems examined in studies of the effects of PM on human health include lung function, lung infections, asthma, chronic bronchitis and emphysema (the latter two are known as chronic obstructive lung disease) and various forms of heart disease.

There are three major approaches used by scientists to study the relationships between human health effects and air pollutants: 1) epidemiological studies, 2) controlled human exposure studies (also called "clinical studies"), and 3) toxicological studies. Epidemiological studies of the effects of particulate matter explore statistical associations between changes in ambient levels and changes in the prevalence of cardiorespiratory health problems in the general population. The analysis and interpretation of epidemiological data can be challenging given that other "confounding factors" (e.g., temperature, other pollutants, health status of individuals) may be contributing to the observed health effects. Clinical studies seek to further investigate the relationships uncovered by epidemiological studies, by exposing subjects to controlled amounts of pollutants in a laboratory setting. Clearly, for ethical reasons, only short term, reversible health effects can be induced. Toxicology studies involve exposing animals, or tissue samples (human or animal) to known amounts of pollutants. In toxicology studies, a much wider range of pollutants and concentrations can be tested. However, these types of experiments are highly artificial and it is difficult to extrapolate the results from tests animals to humans. All three types of studies have strengths and weaknesses. From a public health perspective, epidemiological studies provide the best means of examining population-wide effects resulting from exposure to real-world levels and mixes of atmospheric pollutants. Clinical and toxicological studies are largely used to support the epidemiological evidence and help elucidate the mechanisms by which exposures to particulate matter can induce disease.

Evidence from Epidemiological Studies

In evaluating the health impact of particulate air pollution, the results of a large number of studies have been considered, encompassing all three approaches described above. However, epidemiological studies provide by far the best evidence for cardiorespiratory effects to be causally related to airborne particulate matter at levels that are currently experienced (Table 2). These studies, conducted under a broad range of environmental conditions, in many different cities on three continents, and by a number of different investigators, have shown that the following health impacts are linked to ambient PM levels:

- increases in mortality due to cardiorespiratory diseases;
- increases in hospitalization due to cardiorespiratory diseases;
- decreases in lung function in children and in asthmatic adults;
- increases in respiratory stress which can lead to absenteeism from work or school and to activity restrictions;
- long term or chronic effects including reduced survival, reduced lung function and capacity in children and increases in development of chronic bronchitis and asthma in some adults.

Children, asthmatics and others with cardiorespiratory disease, and the elderly have been identified as being particularly susceptible to exposure to PM.

Table 2:Mean Particle Levels and Health Effects

Health Endpoint	Range of mean 24 hr PM levels where statistically significant health effects reported
School Absenteeism	PM10 40.9 - 50.9
Respiratory Health / Pulmonary Function	PM2.5 0.5 - 11.0
Hospital Admissions	PM10 29.6 – 50.0
Mortality	PM2.5 11.0 - 29.6 PM10 18.2 - 47.9

The magnitude of observed effects are small, though in most cases they are highly statistically significant and therefore likely to be true effects. The observed increases in mortality per 10 µg/m^3 rise in PM are on the order of 0.5% to 1.7% for PM10, 1.5% for PM2.5 and 2.2% for sulphate. The increase in hospitalizations (per 10 µg/m^3 rise in PM) is of the order of 0.7% to 0.8% for PM2.5 and 2% to 2.7% for sulphate. PM2.5 and sulphate appear to be more potent than PM10 in inducing mortality and morbidity. Slightly larger impacts have been associated with effects such as the exacerbation of asthma, increases in respiratory symptoms and loss of lung function.

Two aspects of these findings need highlighting. First, unlike the situation with many other toxins, there is no known threshold concentration above which effects begin to be observed or below which exposures are deemed safe. This lack an of observed "safe" threshold, with estimates of mortality and morbidity increasing with increasing particle concentrations, beginning at very low concentrations, has been observed with remarkable consistency in many epidemiological studies. Human populations are highly "heterogeneous" (non-uniform) including individuals who have a wide range of susceptibilities to pollutants due to differences in health status, activity levels and exposures. Therefore, even at very low levels of ambient particles, susceptible individuals such as the elderly, children and people with pre-existing respiratory or cardiovascular disease may react adversely. At higher exposure levels, healthy individuals are also at risk of developing symptoms.

Secondly, although the magnitude of the estimated of increased risk appear small, they represent large numbers of people when extrapolated to the entire population. Furthermore, it can be argued that the effects captured by epidemiological studies may represent only the "tip of the iceberg" (Figure 8). These high profile effects could be masking a much greater burden of illness in the general population that, although less critical, may nonetheless be impairing quality of life.

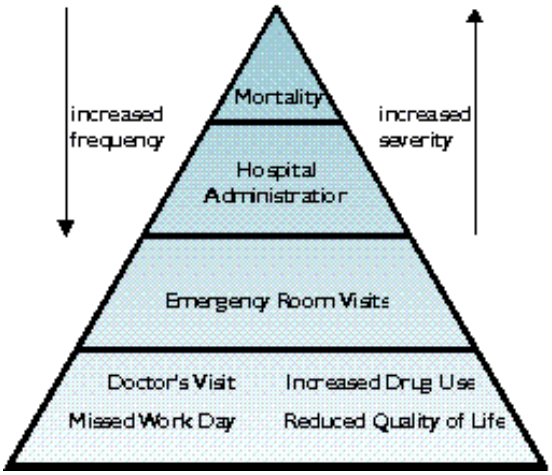
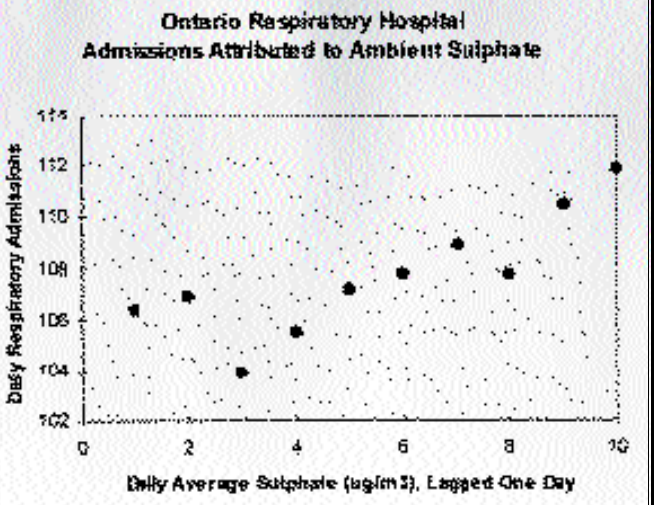


Figure 8: The cascading effects of air pollution on human health

Box 4: No Safe Level

Current health effects research has not been able to determine a concentration threshold below which PM does not affect cardio - respiratory health. Health effects can be observed at very low particulate matter levels, and the effects increase steadily as particle concentrations increase. Therefore, it is not possible to define a safe level at which all members of the population will be spared adverse cardio-respiratory health effects due to particulate matter. This no-threshold response for human health and environmental air quality impacts is being observed for other air pollutants as well, such as ground-level ozone.

A Health Canada study of the impacts of particulate sulphate (as a surrogate for PM2.5 impacts) illustrates the response of the population down to very low concentrations.



Cause and Effect?

Epidemiological studies explore the statistical relationships between ambient levels of particulate matter and an effect (e.g., cardio-respiratory illness). The relationships observed are identified as "associations"; that is, when concentrations of PM increase, we observe a correlated increase in cardiorespiratory illness. This does not necessarily mean that the two are causally related. The challenge is to combine different types of evidence to try to build a case for causality. Currently, on the strength of the burgeoning epidemiological evidence, a causal link between PM and cardiorespiratory effects is strongly suggested. However, alternative explanations could be put forth. One of the main criticisms of the epidemiological studies has been that confounding factors such as temperature, weather and seasonal factors, or co-occurring pollutants could be contributing to the observed effects. Recently, a number of carefully designed studies have been able to tease out many such factors and give some confidence to the hypothesis that PM itself is responsible for at least some of the effects. Still, a number of issues remain unresolved. The problem of deciphering what components of particulate matter are responsible for the range of observed health effects is one such issue. The evidence in favour of a major role for fine particles and ultrafine particles is accumulating. Whether the toxicity of these particles is related to the particle itself or to its chemistry is still uncertain, and requires further research. Toxicological studies will help shed light on this issue.

Box 5:
PM - The Causal Agent or the Air Pollution Indicator?

It is has not been possible to conclude absolutely what aspect of PM (size, mass, or composition) is directly responsible for the observed health impacts. Health scientists are uncertain whether PM is *the* causal agent of the cardio-respiratory impacts observed in the population, or whether it is an indicator of the overall burden of air pollution on human health. In either case, sufficient health effects information exists to warrant the development of management strategies to reduce emissions of particulate matter and its precursor gas emissions (NO_x, VOC and SO_2).

Evidence from Clinical and Toxicological Studies

In general, the findings from clinical studies and toxicological studies lend minimal support to the observations of epidemiological studies. In these experimental conditions, health effects have been seen only following exposures to much higher concentrations of PM than those linked to effects in the epidemiological studies. This discrepancy may be the result of a number of factors, many of which are related to the limitations of experimental studies to reflect real-world conditions. However, clinical studies have identified asthmatics as a susceptible group, and toxicological studies support the finding that smaller particles, perhaps ultrafine particles in particular, are most important in inducing effects.

Environmental Effects of Particulate Matter

Box 6: PM Impacts on Materials and Vegetation

The effects of PM on materials have been investigated in a limited way for metals, wood, stone, painted surfaces, electronics and fabrics. The deposition of PM on these materials may cause soiling and discolouration, thus reducing their aesthetic appeal. Exposure to PM also causes physical and chemical degradation of materials, through the action of acidic particles for example.

The most obvious effect of particle deposition on vegetation is a physical smothering of the leaf surface. This will reduce light transmission to the plant, in turn causing a decrease in photosynthesis. Stomata (microscopic openings on the leaf surface) are also susceptible to blockage by particles. Particle composition may also be relevant, causing both direct chemical effects on the plant and indirect effects through impacts on the soil environment. Particle accumulation on the leaf surface may also increase the plant's susceptibility to disease.

The most significant environmental impact of PM is reduced visibility (an aesthetic impact on the atmosphere). PM also affects materials (metals and wood) and vegetation (both agricultural and forest species), though minimal information exists that would enable these effects to be quantified. In addition to direct effects resulting from exposure to PM, there are also indirect environmental impacts associated with the acidity of particles. These are being investigated through programs that address the issue of acid deposition. All these environmental impacts have both social and economic costs.

Most people, when questioned, would readily associate reduced visibility with poor air quality. What many may not know is that it is primarily the fine particles in the air that are responsible for the reduced visibility. The presence of particles in the air reduces the distance at which we can see the colour, clarity and contrast of far-away objects (Figure 9) because the particles in the atmosphere scatter and absorb light. This is done most efficiently by particles in the size range of 0.3-0.7 μm (i.e., PM2.5) although coarse particles also contribute to reduced visibility. Since the smaller particles are primarily of anthropogenic origin, reduced visibility is primarily an anthropogenic impact.

The chemistry as well as the size of particles influences their ability to scatter light. Sulphates and nitrates, two major components of PM2.5, are very effective at scattering light and play a large role in reducing visibility. Organic carbon compounds are much less effective. Relative humidity is another important factor affecting visibility. As relative humidity increases, so does the ability of particles to scatter light. Thus we may expect seasonal and geographic differences in visibility that stem from differences in particle concentrations and composition, and from different climates.

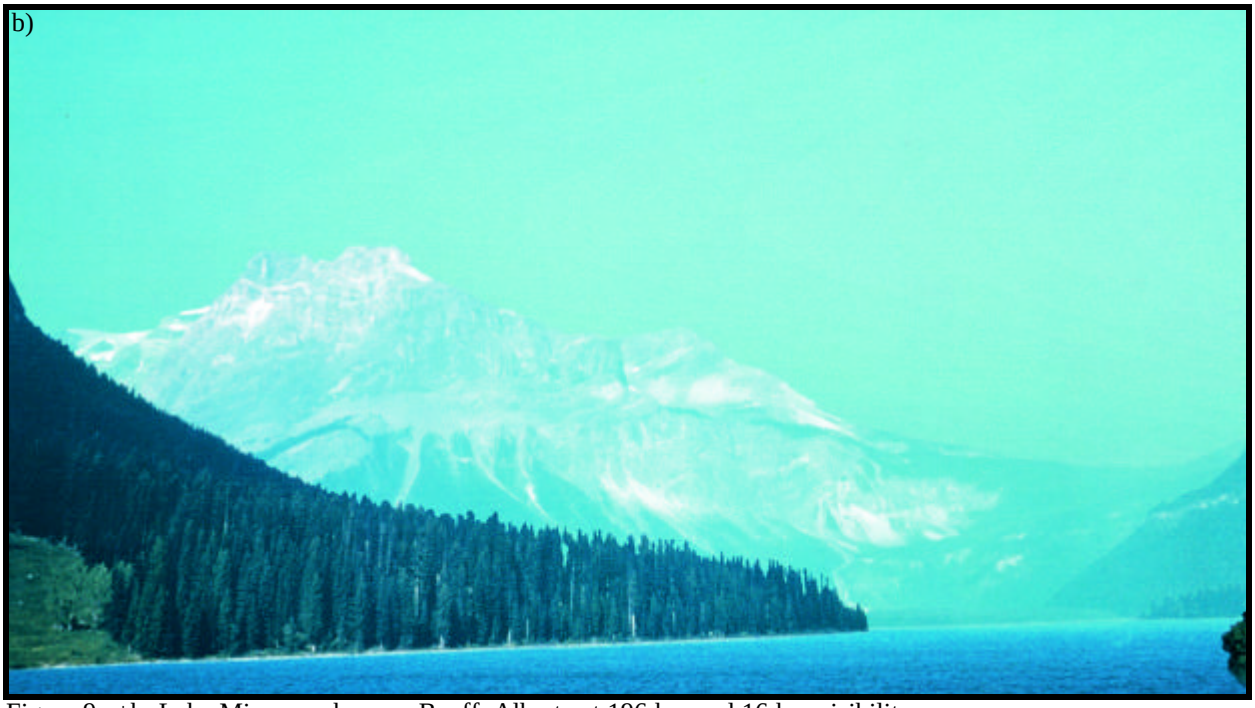


Figure 9 a+b: Lake Minnewanka near Banff, Alberta at 196 km and 16 km visibility.
Average visibility in the mountain parks is estimated at 115 km.

Box 7: A Just Noticeable Change in Visibility

Research has shown that a noticeable change in visibility will occur with a 10% increase or decrease in PM2.5 concentrations. This "Just Noticeable Change" will therefore occur at different particle concentrations in different regions at different times of the year. For example, in areas of scenic value, such as remote wilderness areas, where ambient PM2.5 levels are generally low, only a small change in particle concentrations is required for a noticeable change in visibility to be observed.

In other words, in clean environments, a little increase in particulate matter has a big impact on visibility.

Natural visual ranges in parts of Canada relatively unaffected by anthropogenic PM have been estimated to vary from 86-350 km (Table 3). Estimated PM2.5 levels for the three sites listed in Table 3 range from about 3-13 $\mu g/m^3$. Visual range at urban sites can be estimated from known concentrations of PM2.5 and PM10, and from mathematical relationships between PM2.5 and visual range. On this basis, visual range at the NAPS urban sites is estimated to vary from 34 km at a site in Montréal to 73 km. in Saint John, N.B.

Clearly, the impact of particles on visibility has the potential to result in loss of tourism dollars in areas such as National and Provincial Parks and wilderness areas, where people are drawn to the scenic vistas (Figure 9). In urban areas also the public may be unwilling to tolerate substantial reductions in visibility. Acceptable visibilities or acceptable changes in visibility in different regions of Canada have not yet been determined.

Responding to the Particulate Matter Issue

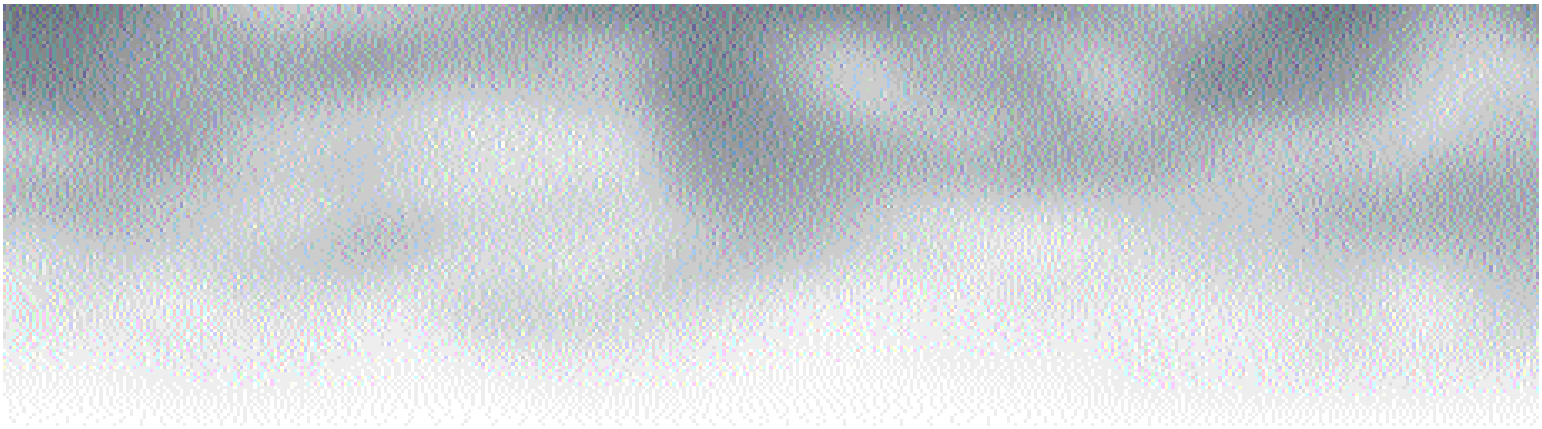
Governments at all levels are responding to the growing concern over the health and environmental effects of particles on a number of fronts. In order to develop effective policies and programs for the control of particulate matter, it is essential to have a firm scientific basis for decision-making. To this end, a Federal and Provincial working group has recently completed the first major Canadian Science Assessment of PM10 and PM2.5. The PM Science Assessment includes discussion of the knowledge gaps which are important to provide direction to particulate matter research programs, and to understand what limits there may be to the science advice for policy making.

As reviewed in the Science Assessment Document, preliminary studies have clearly shown that current ambient levels of PM in most regions of Canada exceed the levels which have been associated with adverse cardio-respiratory health on a regular basis. In recognition of this, PM10 and PM2.5 have been designated as priority, candidate substances for the development of Canada Wide Standards (CWSs) (Box 8). The Science Assessment Document provides the core of the scientific input to development of CWSs. A range of exposure levels for PM10 and PM2.5 have been identified that reflect current understanding of

Table 3: Estimated Natural Visual Ranges in Canada

Site Location	Visual Range (km)*	Estimated PM2.5 ($\mu g/m^3$)**
Western Canada - Waterton Alberta	210-350	3.2-5.5
Southeastern Canada - Egbert, Ontario	86-120	9.7-13.0
Eastern Canada - St. Andrews, N.B.	165-210	5.5-6.1

* Visual range estimated from nephelometer measurements of light scattering (b_{sca}), and using $b_{sca}/b_{ext} = 0.9$, $VR = 3.91/b_{sca}$. ** PM2.5 estimated from $b_{sca}/PM2.5 = 3.1\ m^2/g$



Box 8: National Ambient Air Quality Objectives (NAAQOs) and Canada Wide Standards (CWSs)

NAAQOs are national goals for outdoor air quality that protect public health, the environment, or aesthetic properties of the environment. NAAQOs are developed cooperatively by federal and provincial governments, and provide a focus for developing air quality management strategies. The current NAAQOs for Particulate Matter are expressed in terms of Total Suspended Particulates. The maximum acceptable level is 120 $\mu g/m^3$, 24 hr average.

Many of the existing NAAQOs, including that for TSP, have been in place since the mid 1970s and are in need of revision. New targets are required that better reflect advances in scientific understanding of the effects of air pollutants on human health and the environment. For PM, this means a shift to smaller particles, such as PM10 and PM2.5. Some air pollutants have been identified as candidates for development of Canada Wide Standards. PM10 and PM2.5 are among these pollutants. For some other pollutants, new targets will be set through the development of new or revised NAAQOs.

Canada Wide Standards for particulate matter are currently under development within the framework of the Harmonization Accord (and its Sub-Agreement on Standards), which was signed by the Canadian Council of Ministers of the Environment (CCME) in January, 1998. The CWSs for PM will be in the form of ambient air management targets, with schedules for achieving the target levels.

the risks to human health due to ambient exposures to particulate matter, while recognizing that not all Canadians will be protected at even these levels (Box 9).

Given the extensive commonality of sources for ambient particulate matter and the other regional air quality issues of ground-level ozone, acid deposition and hazardous air pollutants, current air quality management strategies to reduce

Box 9: Recommended Range of Effects-Based Exposure Levels

The Federal-Provincial Working Group responsible for the PM Science Assessment has agreed upon a range of recommended ambient PM exposure levels, which, if met, would provide for substantial reductions in the risks to human health and the environment from exposure to PM.

The range of values are:

PM10	25-40 $\mu g/m^3$
PM2.5	15-25 $\mu g/m^3$

emissions of NO_x, VOC and SO_2 and toxic substances will lead to some improvement in PM levels. It has yet to be determined what additional emission control measures would be required to meet particulate matter air quality goals. The emission sources targeted by current air quality management efforts involve the federal, provincial and municipal governments. These may have a greater impact on decreasing atmospheric levels of PM2.5 rather than PM10, given that they target the precursor gases that are responsible for PM2.5.

Box 10: Air Quality Management Initiatives Relevant to PM Management

- United Nations Protocols on SO_2, NO_x, VOCs, Heavy Metals and Persistent Organic Pollutants
- Canada/U.S. Air Quality Agreement and Proposed Annexes on PM and Ground Level Ozone
- Acidifying Emissions Strategy
- Cleaner Vehicles and Fuels Initiative
- Sulphur in Fuels Initiative
- CEPA Toxics Substances Management Policy
- NOx/VOC Smog Plans
- Canada Wide Standards for Particulate Matter and Ozone

Box 11: Particulate Matter Research Activities

Environment Canada:

Research within Environment Canada includes:

1. ongoing characterization of ambient levels (spatially and temporally) and particle composition;
2. atmospheric chemistry process research to identify key chemical and physical transformations integral to the formation and transport of particles;
3. verification of primary PM emission inventories and development of precursor gas (NO_x, VOC, SO_2 and NH_3) emission contributions to PM2.5 levels;
4. development of air quality models capable of predicting ambient PM and ground level ozone concentrations as a function of current and forecast emissions; and
5. assessment of long range transport of PM10 and PM2.5 to determine the impact of distant sources on Canadian regional PM levels.

The PM modelling research builds upon previous work undertaken through the NO_x/VOC Science Program (to assess ground-level ozone) and the Acid Deposition programs. The next step will be to expand modelling capability to include hazardous air pollutants.

Health Canada:

Further study is required to assess the toxic character of PM and to understand the biological mechanisms causing the effects. This will include research on the interactions between PM and other gaseous pollutants in the air. Epidemiological studies are planned that will clarify which component of PM is most strongly correlated with health effects and will help to identify risk factors that may redispose individuals to the adverse effects of PM exposure.

Particulate Matter Research Activities

Health and environment research communities continue to actively study particulate matter air quality and corresponding health impacts. The development of an effective management strategy to reduce ambient PM levels will depend upon the resolution of certain scientific uncertainties, including quantification of the relationship between primary particle and precursor emissions, and ambient PM10 and PM2.5 levels. This quantified "source - ambient relationship" is necessary to support detailed cost and benefit analyses used in evaluating various management strategies. These can then be used to identify strategies that will be most effective in improving air quality to protect human health and the environment in Canada.

For Additional Information:

The material for this brochure has been drawn primarily from the report *National Ambient Air Quality Objectives for Particulate Matter: Science Assessment Document (1998)* by the Federal - Provincial Working Group on Air Quality Objectives and Guidelines.

For additional information on air quality issues contact:

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