Atmospheric Change in Canada: An Integrated Overview

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Canada

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EXECUTIVE SUMMARY

A New Initiative

To fully understand integration, it is suggested that we need to construct a model of the two thousand and ten atmosphere. Mitigation actions are already moving towards reduction targets, generally defined for the year 2010. At this point in time, there are no adaptation actions in place to help Canadians, socially and economically, prepare for this 2010 Atmosphere. The integrated discussion throughout this paper provides a background overview of current atmospheric issues, their many interactions, and their future directions, respectively.

The Challenges

The integration of atmospheric issues is not a simple task in the context of different levels of knowledge, expertise, information and historical accomplishments. The challenges are many, but we must accept the current views and future emission reduction targets. Likewise, we must recognize integrated science and monitoring are essential elements needed for the on-going assessment of atmospheric issues. The lack of integrated research, monitoring, models, resources and policy infrastructure, nationally and internationally, creates significant challenges, but in return, would help stabilize many activities.

An integrated assessment of the 2010 Atmosphere, including progressive adaptation actions, would also help identify, collectively, the positive and negative consequences of new mitigation actions, such as, the Kyoto Protocol for climate change.

Atmospheric Change Issues

The atmosphere is not static, it is dynamic, evolving and extreme. Energy, moisture and pollution are transported in the dynamic "battleground" that exists between winter and summer air masses in North America. Air mass interactions, volcanic eruptions, El Niño events, changes in solar radiation, climate extremes and pollution episodes all play an integrated role in the shaping of regional atmospheric patterns in Canada.

Atmospheric change in Canada, as evidenced by proxy records, such as tree rings, ice cores and ocean sediments, has occurred naturally through millennia. Human induced change has now become significant. Anthropogenic releasing of greenhouse gases and other chemicals into the atmosphere play an increasing role in determining these changes. Among the issues related to atmospheric change are climate variability and extremes; climate change; stratospheric ozone depletion; acid deposition; tropospheric ozone episodes; suspended particulate matter; and hazardous air pollutants.

Forecasting environmental pollution episodes continues to be challenging within the context of the many meteorological influences on Canada. For example, there is an apparent relation-

ship between stagnating anti-cyclone (high pressure) events and air pollution. However, not all stagnant anticyclones result in high air pollution episodes. Environmental assessments and predictions will require a greater effort to integrate the physical and chemical atmosphere, especially at regional scales, for environmental predictors.

Climate variability and extremes are associated with many different factors. Disasters due to extreme events, such as severe floods, storms, droughts, ice storms and other weather related calamities have been on the increase for the last 30 years. Economic losses, registered by Munich Re – one of the world's largest insurance firms – due to weather related disasters, show an increase by a factor of 43 for the same period. In contrast, global wealth, as measured by the GDP, increased by factor of 2.5 and population by 25%. That means that, economic growth and population increases account for less than a fourfold rise in these losses.

Greenhouse gas concentrations of carbon dioxide, methane, ozone, and nitrous oxide have increased since the 1700s due to increased emissions caused by industrialization and deforestation. Carbon dioxide measurements in Canada, as well as Hawaii, show a rate of increase of 0.5% per year. Global climate models suggest a global warming between 1.0 °C and 3.5 °C by the year 2100, based on elevated carbon dioxide concentrations. Canada has initiated studies to examine the implications of the Kyoto Protocol that include actions to meet the target of reducing greenhouse gases 6% below the 1990 level. Although actions will focus on direct reductions, it is recognized that significant co-reductions will simultaneously occur in other air pollutants, nationally and regionally.

In recent years, the stratosphere has been perturbed by the addition of synthetic organic chemicals including chloro-fluorocarbons (CFCs). Stratospheric ozone depletion translates into an increase in UV-B radiation that leads to significant human health, plant and animal damage (eg. skin cancer). If the Montreal Protocol (1987) and amendments are fully implemented, stratospheric ozone recovery may start to occur around 2005 to 2010. However, the cooling of the stratosphere due to the enhanced greenhouse effect could further delay this recovery in Polar Regions.

Sulphur and nitrogen oxides from smelters and fossil-fuel power stations are transformed into sulfate and nitrate particles, which turn into sulfuric and nitric acids. These pollutants travel long distances, transported aloft by air masses, before being washed out by precipitation or deposited on lakes, vegetation and buildings as acid deposition. With reductions of 40% of SO_2 emissions from 1980 levels following the signing of the first (1985) and second (1994) Sulphur Protocols between Canada and the United States, total acid deposition has been reduced. Currently, for example, at Egbert, Ontario, the dry deposition rates are 6-12 kg/ha/yr and the wet deposition rate was 15.92 kg/ha/yr in 1997 making the total greater than 20 kg/ha/yr, a target set for the year 2010. However, in spite of the schedule to achieve these emission and deposition targets by 2010, sulphate deposition will still exceed critical loads across portions of eastern Canada. In addition, eastern Canada is particularly

vulnerable to re-acidification, if El Niño events become more frequent.

Ground-level ozone is an indirect by-product of the burning of fossil fuels. It is the main component of smog in many cities. Ozone is closely linked with episodes of high concentrations of fine particulate matter, hazardous air pollutants and acid deposition, and is characterized by reductions in visibility. The effects of ozone damage to plants and human health are widely recognized. Even low concentrations of ozone with intermittent high peaks can result in chronic symptoms. For example, ozone levels of 40 ppb can cause respiratory problems in humans resulting in increases in hospital admissions. One effort to model regional ozone trends for Ontario showed a trend increasing at a rate of 1.2%/yr. Ozone trends are difficult to determine due to the close linkages with meteorological conditions, nitric oxides and episodes of suspended particulate matter. Air quality management strategies, at present, focus on short-term exceedences of >82 ppb for an hour, Canada's Air Quality Objective.

Suspended particulate matter refers to a variety of solid and liquid particles (aerosols) of microscopic size. Particles are classified as "primary" if they are emitted directly into the atmosphere, such as smoke, road dust and wind blown dust from soil erosion. "Secondary" particles result from reactions in the atmosphere of gases emitted from a variety of sources, such as sulphates (SO_2) and nitrates (NO_x). Particulate matter (PM) is harmful even at very low levels. Every major urban city currently has PM concentrations that pose a risk to human health. SO_2 and NO_x are responsible for a significant fraction of fine particulate matter in the atmosphere and are closely linked to acid rain and ground-level ozone. Strategies to reduce both will also reduce particulate matter and vice-versa. By the year 2010, NO_x emissions are expected to decrease by 10 from 1990 levels.

Hazardous air pollutants, such as PCBs and pesticides, are chemicals in the atmosphere that, in sufficient concentrations, have toxic effects on the health of humans and other animal species, and cause damage to ecological and societal systems. Benzene is a carcinogenic substance produced by automobile exhausts among other methods. Atmospheric scientists found that concentrations of gas-phase mercury were positively correlated with ambient air temperatures and humidity and inversely correlated with atmospheric ozone concentrations. Through modeling, the revolatilization of mercury from the Great Lakes was found to be of comparable magnitude to that of deposition (SENES, 1998). Under the Canadian Environmental Protection Act (CEPA), industries are required to report on their discharges above a limit to the National Pollutant Release Inventory.

It is apparent that methods to examine the suite of inter-related atmospheric issues, such as acid deposition; climate change; stratospheric ozone depletion; tropospheric ozone episodes; hazardous air pollutants and suspended particulate matter require a comprehensive integrated approach, not a simple expansion of a single-issue assessment or model. Continuing to resolve the problems individually may lead to conflicting policy and regulatory actions. For example,

sulphate aerosols cause acid deposition while at the same time they absorb and scatter solar radiation, thus masking the full impact of greenhouse gas warming. Integration and cumulative air assessments reach beyond the boundary of a single discipline and consider more than one aspect of the problem. Whether qualitative or quantitative, environmental prediction assessments and models need to build an integrated framework, which would provide a long-term perspective in which externalities may change. It would include people, ecological and political boundaries and landscape modifications.

Future science directions will need to continue building on single-issue accomplishments, models, assessments and policy agreements. At the same time, it is suggested that integrated atmospheric models and assessments develop along five pathways:

- Utilize an integrated framework for multi-issue assessments that combine GIS-type technologies, downscaling methodologies and/or models to support the development of environmental prediction strategies.
- Focus on the cumulative timing of atmospheric changes based on individual science-policy targets. For example, many atmospheric issues are working toward target deadlines around the year 2010. Should these targets be met, what would be the new structure and function of the atmosphere and what would be in conflict?
- Develop an integrated assessment framework and model that functionally predicts the co-impacts of the reduction in one air issue, such as greenhouse gases, on all other air issues and the net science-policy consequences.
- Functionally link the **whole** atmosphere to other fully integrated issues, such as human health and biodiversity, to fully assess the net benefits and the feedback effects on the atmosphere.
- Develop mitigation and adaptation actions within the context of the **whole** atmosphere and its changing condition.

ATMOSPHERIC CHANGE IN CANADA: AN INTEGRATED OVERVIEW

1. Introduction

The atmosphere is a thin layer of gases and particles that cover the Earth to a vertical depth exceeding 100 km. This area can be divided into four distinct layers: troposphere (0-10 km), stratosphere (10-50 km), mesosphere (50-80 km), and thermosphere/ionosphere (>80 km). The gases that compose the atmosphere, mainly nitrogen and oxygen, are more dense close to the surface. This dense layer, called the troposphere, is where most pollution problems exist. It also accounts for 80% of the mass and virtually all the water vapor, clouds and precipitation (Battan, 1966).

The atmosphere is not static. Drafts or masses of air rising under the influence of temperature can range in size from very small volumes to large areas many miles across which can penetrate the stratosphere in the form of giant thunderstorms. The troposphere in particular is characterized by strong vertical mixing. Dirty air near the ground is carried aloft in this way. Winds, on the other hand, are the result of pressure changes in the atmosphere and rotate counter-clockwise around low pressure centres in the Northern Hemisphere and clockwise in the Southern (Fig. 1). Winds at 10 km of altitude and at mid latitudes are called westerly jets. These winds are stronger and flow further south in the winter and weaken and flow further north in the summer.

General circulation of the atmosphere

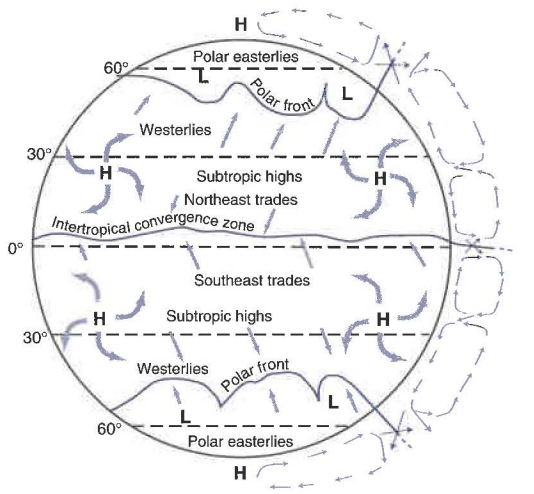


Figure 1. Source: Critchfield (1983) adapted by Hengeveld (1995).

The air mass expands as temperature and pressure decrease with height while the relative humidity increases. Rising air collects moisture and forms clouds. When the relative humidity approaches saturation, water molecules condense on particles to form clouds. Thus, clouds scavenge pollutants from the air in a two step process: using pollutants as condensation nuclei and cleaning pollutants from the atmosphere when rain droplets fall. Aerosols, however, also respond to gravity, precipitating directly onto the ground, a process called "dry deposition." Consequently, the mean residence time of tropospheric aerosols is relatively short (Battan, 1966; Wallace and Hobbs, 1977).

The first few kilometers above the troposphere is characterized by a sharp decrease in water vapor while ozone concentrations increase. There is little mixing between the relatively moist troposphere and the dry, ozone-rich stratosphere. Remnants of past nuclear explosions as well as volcanic eruptions are found here in higher concentrations than in the troposphere and testify to little mixing with lower levels. Aerosols in this area have a long residence time. It takes 3-5 years for the whole stratosphere to turn over (Fergusson, 1998). The stratosphere behaves as a reservoir for certain types of atmospheric pollution.

Atmospheric change in Canada, as evidenced by proxy records, such as tree-rings, ice cores and ocean sediments, has occurred naturally through millennia. Human induced change has now become significant. Anthropogenic releasing of greenhouse gases and other chemicals into the atmosphere play an increasing role in determining these changes. Among the issues related to atmospheric change are:

- climate change (global warming);
- stratospheric ozone depletion (leading to UV-B increases);
- acid deposition;
- tropospheric ozone episodes (associated with SO_x, NO_x and VOCs);
- suspended particulate matter (PM) (sulfates, nitrates, dust particles, etc.);
- hazardous air pollutants (HAPs) (heavy metals, pesticides, radionuclides, etc.).

The purpose of this paper is to serve as an overview assessment to support scientific research on the integration of air issues. Past attempts to solve individual problems through regulations, based on a single-issue approach (such as acid rain) need to become more holistic. An integrated approach is necessary to avoid any conflicting science and regulatory actions. Acknowledging the complexity of interactions among air issues, this paper only focuses on the foundation atmospheric issues high-lighted by the boxes in Fig. 2.

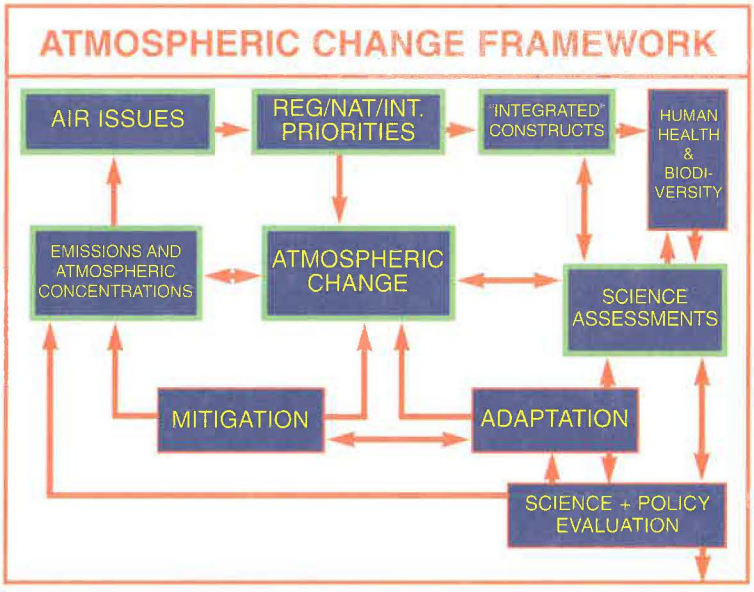


Figure 2.

2. Atmospheric Variability

To understand regional atmospheric variations, it is important to identify natural variations in climate. Most of Canada lies within the belt known as the zone of the westerlies. Weather patterns tend to move from the west to the east, bringing with them large pressure systems associated with cold Arctic air from the north or hot humid air from the south. Fig. 3 depicts the dynamics of this "battleground" between the winter and summer air masses and circulation (Phillips, 1990).

Climate variability and extremes are associated with many different factors (Francis and Hengeveld, 1998):

1. Volcanic eruptions such as Mt. Pinatubo in the Philippines during the summer of 1991 -the largest eruption in the 20th century- brought cooler temperatures to most of the world for the next two years. This cooling results from sulphur particles emitted into the stratosphere that partially block incoming radiation for subsequent years.

2. El Niño (the periodic warming of the surface waters of the eastern half of the equatorial Pacific) is probably the most influential phenomenon. This event is the result of weak easterly trade winds, which cause the eastward spread

Circulation of winter and summer air masses

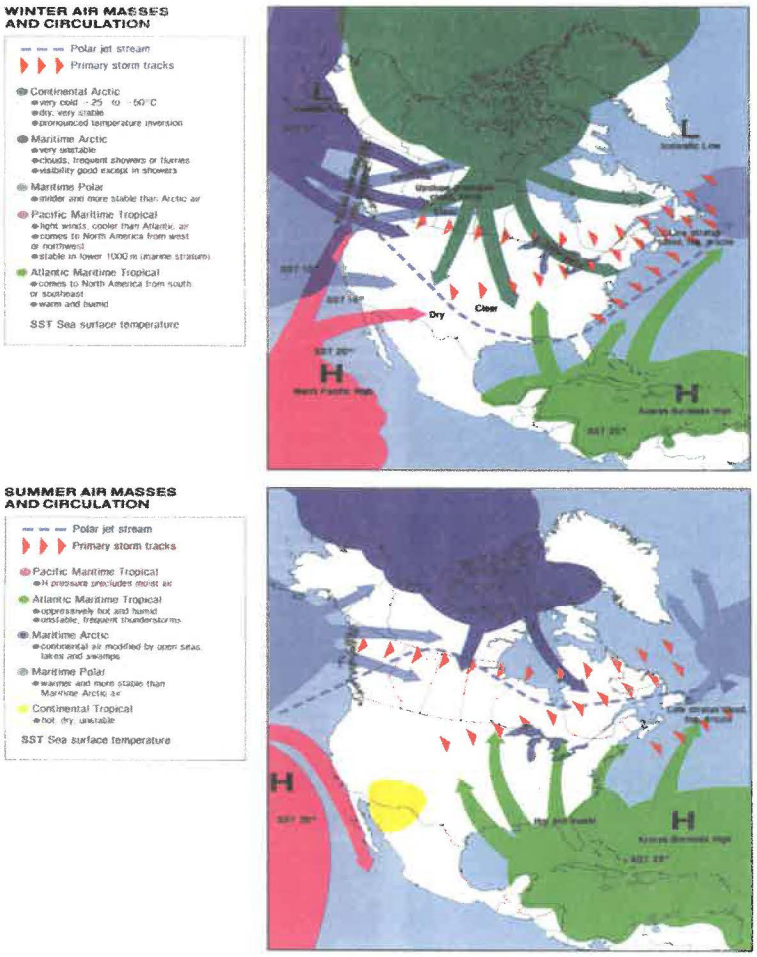


Figure 3. Source: Phillips (1990).

of warm water accumulated in the western Pacific. This prevents the cooler water of South America from reaching the surface. As a result, the pattern of rising and falling air masses changes over the equatorial Pacific with serious consequences to the atmospheric circulation over much of the world.

These El Niño events appear to have contributed to severe ice storms in Canada, droughts in Australia and Africa, floods in Brazil and Paraguay, freak storms in the Middle East, and weak monsoon rains in India and Indonesia. It also affects hurricane patterns, suppressing the hurricane formation in the Atlantic and enhancing it in the Southeast Pacific. The persistence and frequency of this phenomenon has increased since the mid-1970s (Fig. 4). According to some researchers, it is unprecedented within the last 1000 years. Why is it happening now? Is it natural or a response to human activity?

3. Changes in the intensity of the sun's radiation that are associated with the sunspot cycle might be related to short term climatic variability. The number of sunspots on the sun surface increases and decreases over a cycle that varies from 7.5 to 16 years. Sunspot peaks are linked with the warming of the stratosphere, which is believed to affect circulation patterns in the rest of the atmosphere. For example, The Little Ice Age between 1645 and 1715 was associated with minimal sunspot activity. The output of solar energy is estimated to have been somewhere between 0.1% and 0.7% lower than it is today. The sun's output has been increasing since 1850, and one third of recent warming may be attributed to this increase.

4. The other two thirds of the current global warming are difficult to explain on the basis of natural variability alone, and are likely attributable to the greenhouse effect (see page 9). If we are in the midst of a long-term shift in climate, it is the changing greenhouse effect that is likely accelerating the change.

El Niño frequency and intensity in the 20th century

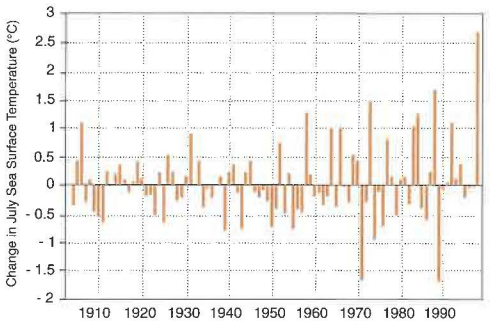


Figure 4. Source: James P. Bruce cited by Francis and Hengeveld (1998).

Disasters due to extreme events such as severe floods, storms, droughts, ice storms and other weather related calamities have been on the increase for the last 30 years (Fig. 5 and 6). Thunderstorms characterized by heavy rainfall have increased during the summer in the United States, northern Australia and France where severe hail events have become common. Tropical regions also show a general increase in thunderstorm activity. Economic losses, registered by Munich Re -one of the world's largest insurance firms- due to weather related disasters, show an increase by a factor of

43 for the same period. In contrast global wealth (measure by the GDP) increased by a factor of 2.5 and population by 25%. That means that economic growth and population increase account for less than a fourfold rise in these loses (Francis and Hengeveld, 1998).

Rate of increase of natural disasters (floods, tropical storms, drought, and earthquakes), 1963-1967 to 1998-1992

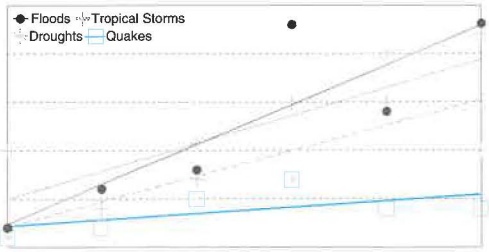


Figure 5. Source: McCulloch and Etkin (1993) adapted by Francis and Hengeveld (1998).

Air quality is closely linked with meteorological parameters in Canada. High concentrations of ozone (>82 ppb) and particle matter (>80µg/m^3) over southwestern Ontario, for example, are associated with hot sunny days in summer, and with slow-moving or stagnant high pressure systems located south of the Great Lakes. High temperatures and clear skies that provide high levels of solar radiation are ideal for the formation of ground-level ozone. Approximately 50-60% of the total ground-level ozone concentrations in southern Ontario result from the transboundary transport of ozone and ozone precursors from the U.S. High PM_{10} episodes tend to be associated with the higher winds of the outer rim of a high-pressure system. (SENES, 1998).

Frequency of Winter Storms in the Northern Hemisphere

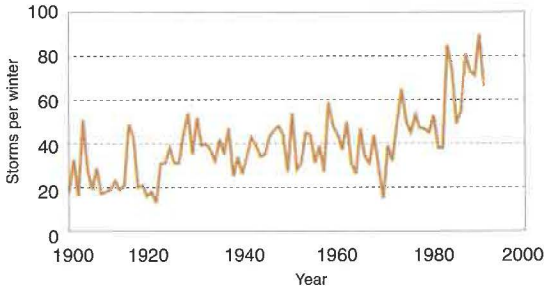


Figure 6. Source: Lambert (1996) adapted by Francis and Hengeveld (1998).

In the same way, the amount of UV radiation reaching the surface is dependent on columnar ozone concentrations, meteorology and many other factors that attenuate UV transmission. There are strong links between UV flux to the surface and atmospheric circulation. Precipitation and pollutant transport in the lower troposphere also depend on these circulation patterns. Bass and Brook (1997) state that upper-level low pressure/height troughs are not only associated with high ozone levels but with a greater incidence of precipitation and cloud cover. They suggest the use of downscaling methodologies (a semi-empirical approach to derive and classify weather patterns) to assess and forecast the probability of occurrence of any of these meteorological based pollution episodes.

In the stratosphere, chlorofluorocarbons (CFCs) result in a chain reaction due not just to increased UV radiation but mainly to temperature increases in the troposphere (SENES, 1998). The temperature increase would lead to increased water vapour, cloud cover, precipitation, and general patterns in atmospheric circu-

lation which may increase the frequency of stagnating anticyclonic systems. Meanwhile, colder stratospheric temperatures cause the formation of polar stratospheric clouds that are a factor in polar ozone 'holes.' Increased surface air temperature and UV radiation may result in (SENES, 1998):

- increased emissions of volatile organics from vegetation,
- increased biogenic NO_x,
- increased production of ozone,
- increased secondary organic aerosols, sulphate/nitrate aerosols,
- changes in relative proportion of gas-phase versus aqueous-phase oxidation of SO_2 to SO_4,
- changes in the geographical distribution of acid deposition,
- more sulphate aerosols would increase cloud cover resulting in a possible cooling of the troposphere.

High sulphate (SO_4) and high ozone concentrations in eastern North America are associated with high temperatures, high absolute humidity, moderately low wind speeds and slow-moving high pressure systems, all of which are indicative of high oxidation potential (SENES, 1998). This is not to imply that high SO_4 concentrations do not occur in cool seasons. Low temperatures associated with near-surface inversions and poor ventilation result in SO_4 pollution episodes. The meteorological conditions conducive to the accumulation and transport of sulphate are summarized in Table 1. In contrast, high nitrate (NO_3) episodes are associated with cool, dry air, lower hourly average precipitation and low ozone concentrations (SENES, 1998).

Elevated concentrations of fine particle ($PM_{2.5}$) appear to be related to the variability in the frequency and trajectory of anticyclonic systems and the meteoro-

Table 1.

METEOROLOGICAL REGIMES CONDUCIVE TO SULPHATE ACCUMULATION AND TRANSPORT IN EASTERN NORTH AMERICA

Type	Synoptic Pattern	Seasonal Preference	Transport winds (300 m)	Afternoon Mixing Height	Thermodynamic
stagnation	dominant continental high-pressure cell (surface and aloft) over the Appalachian Mountains	any season	light (<5 m/s)	low (<1000m)	any temperature generally moist
channelling or ducting	Bermuda high; stationary or slowly advancing frontal system over the Great Lakes eastward to the Atlantic Coast	Summer	moderate SW winds (7-12 m/s)	high (1500 - 2000 m)	warm, moist

Source: SENES (1998)

logical parameters associated with these systems. Episodes of ozone, PM_{10}, $PM_{2.5}$, SO_4 are likely to be affected by changes in weather patterns induced by global warming.

Another example of circulation patterns affecting the air quality in Canada is illustrated by the detection of DDT and Toxaphene at Egbert, a non-urban site in Ontario. These hazardous pollutants, banned since the early 1970s, are traceable, using back trajectory models, (Fig. 7 and 8) to air masses coming from Mexico and the southern United States (IADN, 1998).

Forecasting environmental pollution episodes continues to be difficult due to the lack of integration of inter-annual or inter-decadal variability with air quality issues, also to the lack of monitoring and many other reasons. There is an apparent relationship between stagnating anticyclones (high-pressure) events and air pollution. However, not all stagnant anticyclones result in high air pollution episodes. Furthermore, the intensity of the anticyclones decrease with the frequency of anticyclonic activity, thus making it very difficult to accurately forecast without integrated climate/air-quality (physical-chemical) assessments and models at the regional scale.

Back trajectories at 850 mb showing potential sources of toxaphene to the IADN satellite site at Egbert, Ontario. The trajectories correspond to the five highest concentrations.

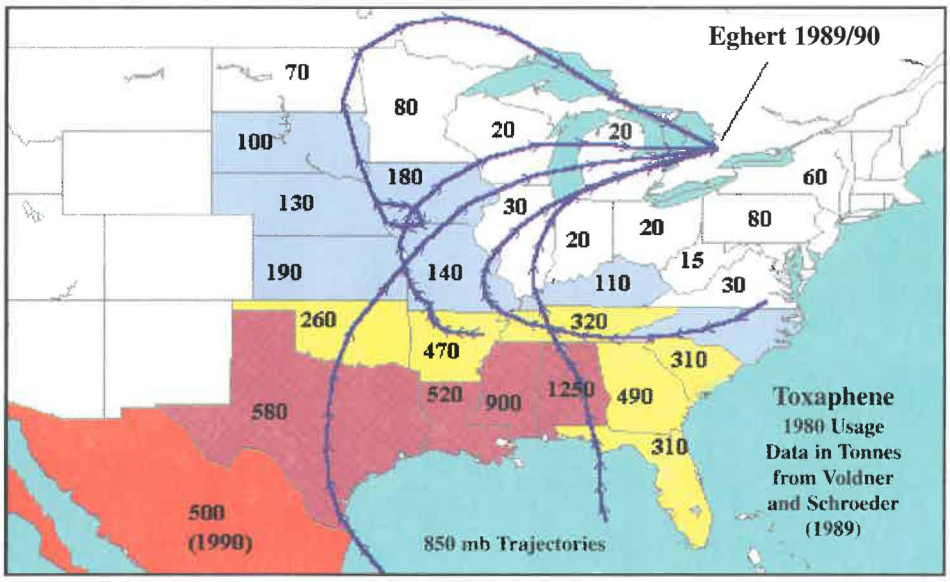


Figure 7. Source: IADN (1998).

Back trajectories at 850 mb showing potential sources of p,p'-DDT to the IADN sites at Egbert and Point Petre, Ontario. The four highest concentration cases from 1988/9 Egbert and Point Petre 1990 data are shown.

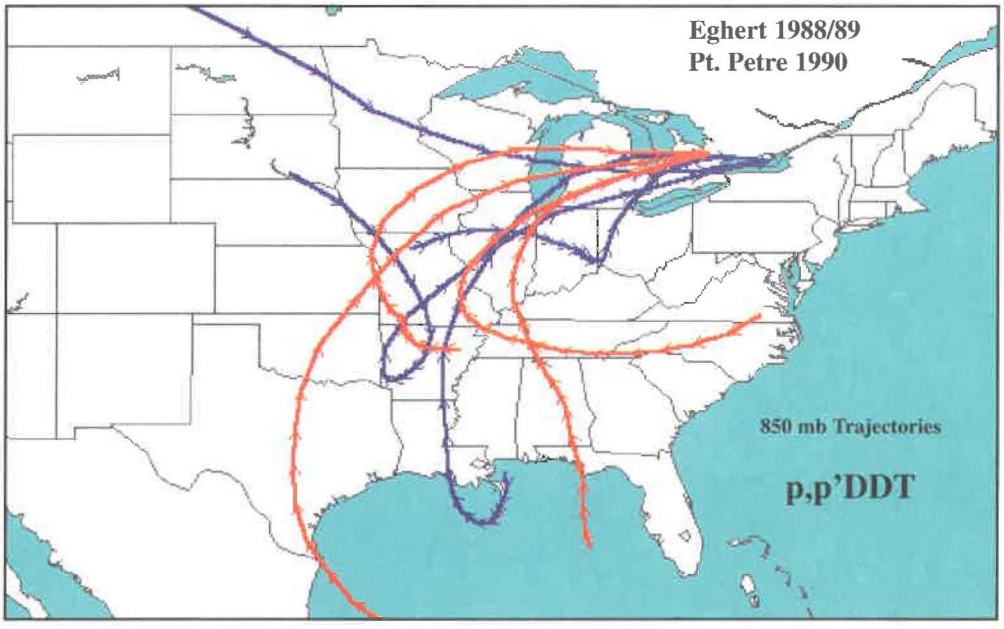


Figure 8. Source: IADN (1998).

3. The Changing Atmosphere

3.1 Climate Change

A notable increase in solar irradiance has been observed since the 1940s (Fig. 9). The earth's surface and lower atmosphere release the heat from the sun in the form of infrared radiation. This radiation is intercepted by two means: clouds and absorbing gases. Besides reflecting incoming radiation, clouds also absorb large quantities of outgoing heat radiation. The amount of radiation absorbed and re-radiated depends on the thickness and type of cloud. Greenhouse gases, on the other hand, absorb most of the infrared heat energy transmitted by

Estimated Solar Irradiance, 1974 – 1988

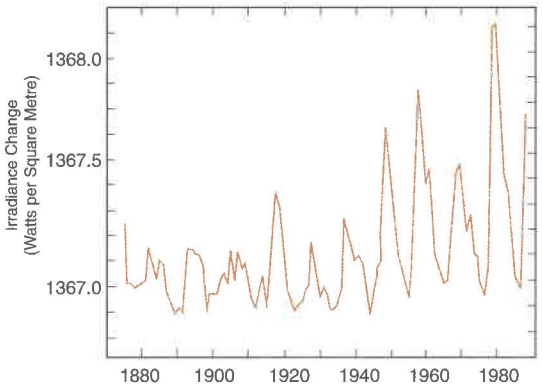


Figure 9. Source: Foukal and Lean (1990) adapted by Francis and Hengeveld (1998).

the Earth towards space. They re-radiate that energy in every direction until only the upper layer releases radiation (Hengeveld, 1995). This mechanism induces the formation of water clouds rather than ice clouds, which are less likely to precipitate; thus perpetuating the cycle of maintaining radiation in the troposphere (Slingo, 1989).

Among the naturally produced greenhouse gases are water vapour, carbon dioxide, methane, ozone, and nitrous oxide. Concentrations of carbon dioxide, methane, and nitrous oxide have increased since the 1700s due to increased emissions caused by industrialization and deforestation. For instance, methane concentration in the atmosphere has more than doubled during this period (Fig. 10). Other anthropogenic greenhouse gases include nitrous oxide, ozone and halocarbons. It is the latter that are considered the most potent of greenhouse gases and also responsible for contributing to the depletion of ozone from the stratosphere. In fact, CFCs are 15,000 times more powerful than carbon dioxide, NO_2 206 times and methane 21 times (Hengeveld, 1995).

Changes in atmospheric methane concentrations during the past 1000 years

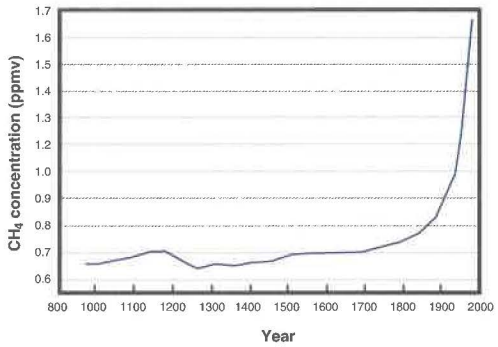


Figure 10. Source: IPCC (1994) adapted by Hengeveld (1995).

Carbon dioxide measurements in Canada, as well as in Hawaii, show a rate of increase of 0.5% per year (Fig. 11). The cumulative effects of such a steep increase are difficult to predict. So far, nature has been forgiving by taking up almost 50% of the carbon dioxide releases through absorption into the terrestrial biosphere and oceans (Francis and Hengeveld,

1998). Whether this pattern will continue is unclear.

Atmospheric carbon dioxide concentrations

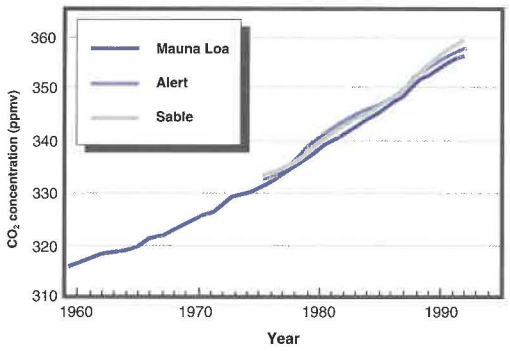


Figure 11. Source: Boden et al. (1994) and Environment Canada, AES cited by Hengeveld (1995).

Global climate models, called General Circulation Models (GCMs), based on elevated carbon dioxide concentrations, suggest a global warming between 1.0°C to 3.5°C by the year 2100. Monitoring evidence confirms that recent years have been the warmest since 1860 (Fig. 12) (Hengeveld, 1995). Particularly, the last six months of 1998 have broken records of being the warmest around the globe.

Global and Canadian surface temperature trends since 1860

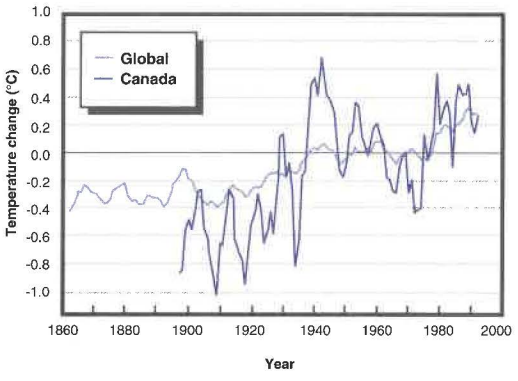


Figure 12. Source: Boden et al. (1994) and Environment Canada, AES cited by Hengeveld (1995).

The recent Kyoto Protocol (Dec. 1997) includes six key greenhouse gases in the calculation of the targets to reduce greenhouse gas emissions. The three most important gases -carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) will be assessed against the 1990 base year whereas either 1990 or 1995 will be used for hydrofluorocarbons (HFCs), perfluorocabons (PFCs) and sulphur hexafluoride (SF_6).

Canada has initiated studies to examine the implications of the Kyoto Protocol, including actions to meet the target of reducing greenhouse gases 6% below the 1990 level. Although action will focus on the direct reductions, it is recognized that significant co-reductions will simultaneously occur in the other air pollutants, nationally and regionally.

3.2 Stratospheric Ozone Depletion

The stratosphere, located between 10 to 50 km above ground, is where ozone is being simultaneously formed and destroyed by natural processes. In recent years, this area has been perturbed by the addition of synthetic organic chemicals including chlorofluorocarbons (CFCs), halons and other chemically similar substances. Halocarbons are very stable, they can remain in the atmosphere for decades and even centuries. When they finally reach the upper atmosphere, they break down under intense ultraviolet radiation. The breakdown releases chlorine and/or bromine; the substances responsible for ozone depletion. Periodic ozone losses over the Antarctic have been severe reaching more than 65% since 1975 (Fig. 13). Over mid-latitudes ozone has been declining at a rate of 5% per decade (Wardle *et al.*, 1997). Its feared that this decline may be larger following the reports by NASA that 1998

has broken records on the size and depth of the ozone hole over the Antarctica. The ozone level fell to 90 Dobson units on September 30, 1998. This is the lowest value ever recorded since 1994 (NASA, 1998).

Global ozone depletion trend

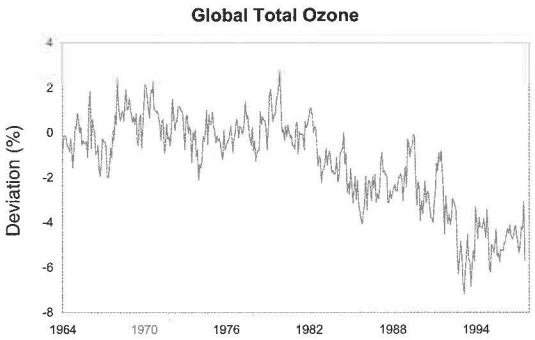


Figure 13. Source: D. Wardle and V. Fioletov, AES (1998).

Ozone depletion translates into an increase of UV-B radiation which leads to:

- increases in skin cancer,
- suppression of the cellular components of the human immune system,
- damages of the membrane surrounding the cell, the chloroplasts and the DNA of plants,
- cataracts,
- and is responsible for many other biological defects (Wardle, *et al.*, 1997).

The signing of the Montreal Protocol in 1987 called for a modest control on substances that deplete stratospheric ozone. When monitoring and research clearly identified chlorine products as the ones responsible for ozone depletion, a more convincing case was made to the public for the need for more controls. As a result, the Protocol has been strengthened twice in five years. Canada has since met and exceeded her obligation under the protocol and its amendments. If the Montreal Protocol and amendments are fully implemented, stratospheric ozone recovery may start to occur around 2005 to 2010 (Wardle *et al.*, 1997). However, the cooling of the stratosphere due to the enhanced greenhouse effect could further delay the recovery in Polar Regions (Hengeveld, 1998).

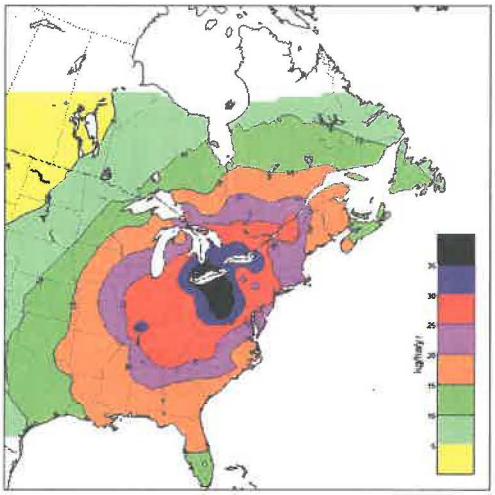
3.3 Acid Deposition

Sulphur and nitrogen oxides from smelters and fossil-fuel power stations are transformed into sulfate and nitrate particles, which turn into sulfuric and nitric acids. These pollutants travel long distances, transported aloft by air masses, before being washed out by precipitation or deposited on lakes, vegetation, buildings, etc. Wet sulphate deposition in eastern Canada is still of concern. Considering only wet deposition, the area of southeastern Ontario and southwestern Quebec receive between 20 to 30 kg/ha/yr (Fig. 14).

Atmospheric oxidation of sulphur dioxide (SO_2) by hydroxyl peroxide (H_2O_2) is considerably faster in the presence of ozone, oxygen and iron catalysts. The conversion rate of SO_2 into SO_4 aerosols is believed to be several orders of magnitude lower than the rate of gas-phase or aqueous-phase reactions.

Five-year mean excess sulphate wet deposition patterns for 1980-84 and 1990-94 in kg/ha/year

a) Deposition levels 1980-1984



b) Deposition levels 1991-1995

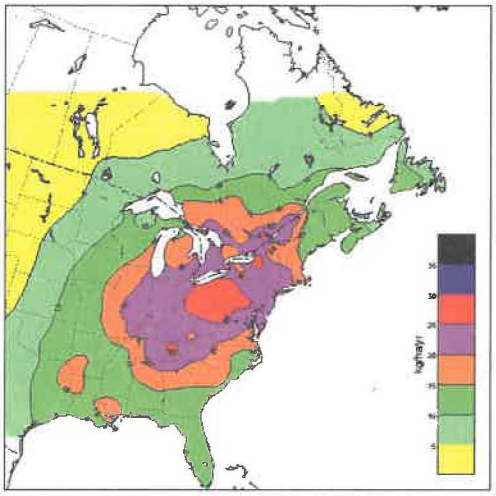


Figure 14. Source: Chul-Un Ro, Environment Canada (1999).

Nevertheless, this process persists day after day. Dry deposition of sulphur and nitrogen contribute as much as 50% of the total acidifying substances on the Great Lakes area. Most of this deposition occurs during the day. In Egbert, Ontario the dry deposition rates alone are 6-12 kg/ha/yr (SENES, 1998). The wet deposition rate for the same location in 1997 was 15.92 kg/ha/yr (Ro, 1998) making the total greater than 20 kg/ha/yr, a target set for the year 2010.

With reductions of 40% of SO_2 emissions from 1980 levels following the signing of the first (1985) and second (1994) Sulphur Protocols between Canada and the United States, total acid deposition has been reduced (Fig. 14, a and b). Both countries are on schedule to meet their emission reduction commitments in the Agreement (The Acidifying Emissions Task Group, 1997). However, in spite of this schedule to achieve emission and deposition targets by 2010, sulphate deposition will still exceed critical loads[1] across large portions of eastern Canada (Environment Canada, 1997).

Eastern Canada is particularly vulnerable to re-acidification, if El Niño events become more frequent. Following each El Niño event, a drought was observed in Ontario (Dillon *et al.*, 1997). It has been found that drought may negatively affect lake recovery. For example, during drought periods, reduced sulphur that has been stored during years of high sulphate deposition is oxidized and released with the first rains, resulting in re-acidification or delayed lake recovery (Bayley *et al.*, 1986). Other equally important effects on human health, forests and materials are discussed in the 1997 Canadian Acid Rain Assessment on The Effects of Human Health.

[1] It is the highest deposition of acidifying compounds that will not cause chemical changes leading to a long-term harmful effects on the over-all structure or function of the ecosystem.

3.4 Ground-level Ozone

Ground-level ozone, which is a secondary by-product of the burning of fossil fuels, is the main component of smog in many cities. Ozone is closely linked with episodes of high concentrations of fine particulate matter (< 2.5 micrometer (μm)), hazardous air pollutants and acid deposition, and thus characterized by reductions in visibility.

Tropospheric (ground-level) ozone results from the photochemical transformations of oxides of nitrogen (NO_x) and volatile organic compounds (VOCs) emitted from both natural and anthropogenic sources. In fact, high temperatures lead to greater vapourization of solvents and gasoline, the principal sources of VOCs (Last *et al.*, 1998). Chemical reactions are driven by ultraviolet (UV) radiation in the presence of chemical catalysts, such as hydroxyl radical (OH) and peroxy radical (H_2O_2). Because these reactions are temperature and radiation dependent, ozone episodes tend to be more acute on hot sunny summer days with stagnant high-pressure systems.

The effects of ozone damage to plants and human health are widely recognized. It is a well established fact that plants respond to long-term cumulative ozone exposures and are more sensitive than humans to ozone stress (Heck *et al.*, 1998). Even low concentrations of ozone with intermittent high peaks can result in chronic symptoms. Changes in growth productivity and quality can occur without visible symptoms. Acute symptoms include chlorosis, delayed early season growth, premature senescence and uni- or bifacial necrosis (The Federal-Provincial Working Group, 1998). Detoxification in plants is not unusual but depends on the respite time between exposures. Considering these particular properties, the standard to protect vegetation is based on the summation of hourly values during the photosynthetic period. The SUM60 refers to cumulative exposures during daylight hours of less than 6000 – 7000 ppb (The Federal Provincial Working Group, 1998).

Ozone levels of 40 ppb can cause respiratory problems in humans (SENES, 1998). Ozone is responsible for damaging lung tissue, particularly among the elderly and children, reducing breathing function, and sensitizing airways to irritants and other allergens (Last *et al.*, 1998). When ozone concentrations peak, hospital admissions increase (Fig. 15). In Ontario, 20% of hospital admissions for acute bronchitis, bronchiolitis and pneumonia in infants under one year can be attributed to the summer pollutants, ozone and sulphates (Last *et al.*, 1998).

Ozone concentrations and hospital admissions

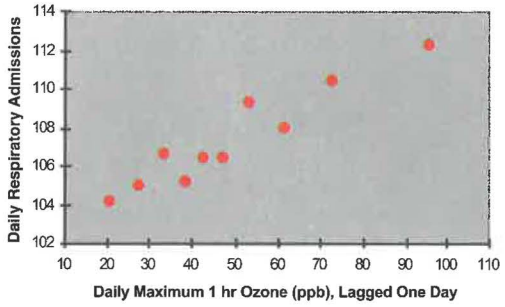


Figure 15. Source: Burnett *et al.* (1997).

Air quality management strategies, at present, focus on short-term exceedances of >82 ppb as an hour average. Respiratory hospitalization, however, is occurring at concentrations well below the set objective. With the exception of

one of 16 cities studied nationally, the ozone level was found to be 60 ppb. The ozone risk associated with hospitalization for respiratory diseases is 1.04%/10 ppb increase in daily one hour maximum ozone (The Federal-Provincial Working Group, 1998).

The spatial distribution for all eastern North America of the composite average (1986-1993) number of days when ozone mixing ratios exceed 82 ppb is shown in Fig. 16. The areas affected by high levels of ozone in Canada are in southern Ontario with over 20 days per year. The Windsor to Quebec City corridor was identified as having the highest frequency and duration of ozone exceedances of the maximum acceptable 1-hour average air quality objective of 82 ppb. Isolated areas around the Great Lakes, where the hours greater than 82 ppb occur during the day, as well as at night, are the result of long-range transport. These areas can experience more than 150 hours per year with ozone over 82 ppb. While considerable differences exist in the prevailing time of the day when high ozone concent- rations occur, the areas of southwestern Ontario exhibit a peak between 1600-1700 hours (Data Analysis Working Group, 1996).

Ozone trends are difficult to determine due to the close correlation with meteorological conditions. Meteorology not only has a substantial impact on ozone concentrations but it is likely to mask any long-term trend in ozone that may be due to changes in NO_x and VOC emissions. One effort to model ozone trends for Ontario showed an increasing ozone level at a rate of 1.2%/yr (Data Analysis Working Group, 1996).

Ozone mixing ratios exceeding 82 ppb

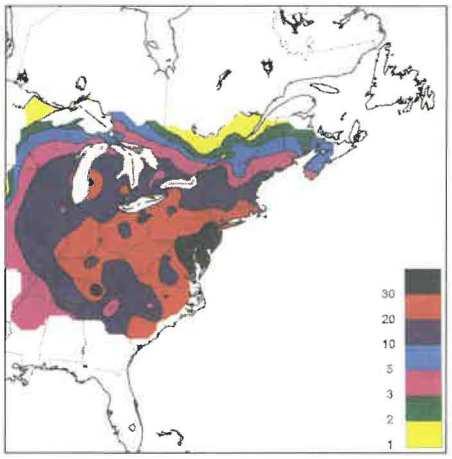


Figure 16. Source: Data Analysis Working Group (1996).

Ozone concentrations have a unique behavior. In large cities, such as Toronto, ozone combines with nitric oxide (NO, a product of combustion) to produce nitrogen dioxide (NO_2) and oxygen, all of which moderate the build up of ozone. However, ozone levels increase further downwind in suburban and rural areas, at distances about 40 km from the urban area where there is less NO present.

There are also clear regional differences. Some modeling systems for the Lower Fraser Valley in the Pacific Region for reduced emissions scenarios recognize that USA emissions do not have a long-range transport effect on the area. More importantly, that significant reductions will be required in Canada (Fig. 17). Elsewhere in Canada reductions in smog episodes require significant reductions in both NO_x and VOCs, nationally and internationally.

Ozone episodes are also closely linked with episodes of suspended particulate matter.

3.5 Suspended Particulate Matter

The term suspended particulate matter refers to a variety of solid and liquid particles (aerosols) of microscopic size. Coarse PM (of diameter <10 μm and >2.5 μm) and fine PM (of diameter <2.5 μm) are the cause of reduced visibility and greatest human health concern.

Maximum one-hour concentrations (ppb) resulting from controls in NO_x and VOC anthropogenic sources in the Lower Fraser Valley, B.C.

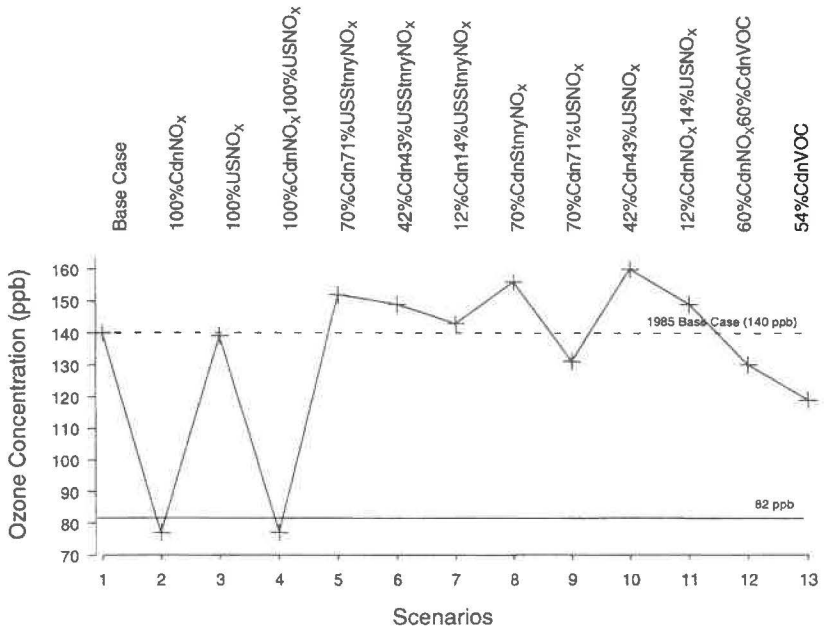


Figure 17. Source: Canadian 1996 NO_X/VOC Science Assessment (1997).

Particulate matter has residence times of a few days mainly in the lower troposphere (below 2 km). Among natural sources of particles and aerosols are sea salt, soil dust, debris from forest fires, pollen, spores, bacteria, terrestrial and marine biogenic emissions and volcanic eruptions. The latter can reach the stratosphere where aerosols remain for many months. Aerosols go through chemical and physical transformations, especially within clouds, which may result in precipitation.

Most of these natural particles are coarse (PM_{10}). Anthropogenic aerosols include sulfates, nitrates, black carbon (soot), organic compounds, and wind blown dust. Most of the fine PM is the result of fossil fuel combustion.

Particles are classified as "primary" if they are emitted directly into the atmosphere, such as smoke, road dust, and wind blown dust from soil erosion. "Secondary" particles result from reactions in the atmosphere of gases emitted from a variety of sources. Within the latter category are the majority of sulphates and nitrates. A fraction of organic aerosols are also formed from the transformation of volatile organic gases.

Most of the mass of "secondary" aerosols resides in the fine fraction or $PM_{2.5}$. These particles are responsible for the reduction in visibility due to their ability to scatter and absorb light. Furthermore, their inhalable nature makes them most likely to be deposited in the pulmonary tract of the human respiratory system and are responsible for increased mortality and morbidity in large urban populations. The first targets of the management plan for Air Quality Objective are the "primary" particles along with some emissions of well established precursor gases (The Federal-Provincial Working Group, 1999).

Since 1974, The National Air Pollution Surveillance network (NAPS) monitors TSP with 154 stations (Furmanczyk, 1998). All levels of government, from Municipal to Federal, are involved in the monitoring of particulate matter. Across the country 129 stations monitor PM_{10} and 59 monitor $PM_{2.5}$. Within this context, specific monitoring of PM_{10} and $PM_{2.5}$ only began in 1984.

Particulate matter (PM) is harmful even at very low levels. There is not a known threshold below which effects will not occur (The Federal-Provincial Working Group, 1999). Every major Canadian city currently has PM concentrations that pose a risk to human health. Sudbury, Windsor, Hamilton and Toronto exhibit high PM_{10} values. Windsor, in particular, exceeds the USEPA standard for $PM_{2.5}$, likely due to the intrusion of fine particle emissions from Michigan. Observations taken at Windsor, Toronto, Walpole Island and Egbert, Ontario showed that $PM_{2.5}$ levels were higher in the summer than in the winter in contrast to most other regions in Canada. Long range transport of air pollutants is most likely the reason for this discrepancy. A large portion of the total particle mass in summer is composed of sulphate (SO_4) aerosols. Likewise, extreme concentrations for both PM_{10} and $PM_{2.5}$ were observed to be higher in the summer than in the winter for southern Ontario (SENES, 1998).

Recognizing the negative effect of PM_{10} and $PM_{2.5}$ the Harmonization Accord was signed between the Canadian Council of Ministers of the Environment (CCME) in January 1998. This Accord is currently developing the Canada Wide Standards (CWS) for particulate matter. The Federal-Provincial Working Group responsible for the PM Science Assessment recommends the following levels (The Federal-Provincial Working Group, 1999):

Particle Types	**Concentration in µm/m³ Daily Avg. (µg/m³)**
PM_{10}	25 - 40
$PM_{2.5}$	15 - 25

Since SO_2 and NO_x are responsible for a significant fraction of fine particulate matter in the atmosphere and are closely linked to acid rain and ground-level ozone, strategies to reduce both will also reduce particulate matter and vice-versa. With reduction in SO_2 emissions since 1986, the national median PM_{10} and sulphate concentrations have decreased by 9 µg/m³ and 0.5 µg/m³, respectively (Dann and Brook, 1997). For the period of 1987 to 1996 the decrease for PM_{10} was 28% and 27% for $PM_{2.5}$ (Brook, 1998). By the year 2010, NO_x emissions are expected to decrease by 10% from 1990 levels (Government of Canada, 1998) and with this there will be further particle matter decreases.

3.6 Hazardous Air Pollutants (HAPs)

Hazardous air pollutants are chemicals in the atmosphere that, in sufficient concentrations, have toxic effects on the health of humans and other animal species, and cause damage to ecological and societal systems.

According to the Canadian Environmental Protection Act (CEPA), substances that meet the following criteria pose the greatest environmental threat:

- ❖ persistent compounds (once released they remain in the environment for a long time),
- ❖ compounds that accumulate in biological tissues,
- ❖ compounds that are the result of human activity, and
- ❖ compounds that are defined as "toxic."

Not all toxic substances are on the CEPA list. Industries that discharge above the National Pollutant Release Inventory (NPRI) minimum criterion level are included in the inventory. The amount discharged in Ontario alone for the 23 substances listed in the CEPA is 4,095 tonnes per year, with polychlorinated biphenyls (PCBs) considered as markers for other persistent and hazardous pollutants. Around the Great Lakes Basin, PCB concentrations seem relatively homogenous. Pesticides and their usage are another set of hazardous pollutants. These, however, show a seasonal variation, which is especially pronounced during episodes of unusual climatic conditions (SENES, 1998).

Scientists at the Centre for Atmospheric Research Experiments (CARE), Egbert-Ontario, found that concentrations of gas-phase mercury were positively correlated with ambient air temperatures and humidity and inversely correlated with atmospheric ozone concentrations. This correlation indicates that changes in airflow and/or changes in average temperatures, humidity levels or ozone concentrations, due to weather conditions, also affect the concentrations of gaseous mercury. Through modeling, the revolatilization of mercury from the Great Lakes waters was found to be of comparable magnitude to that of deposition (SENES, 1998).

At the Egbert and Point Petre observing sites in Ontario, elevated levels of 12 elemental species from anthropogenic sources were identified. These were silver, bromine, chlorine, copper, iodine, indium, antimony, selenium, tin, tungsten, and zinc. Possible sources of these elements were identified as oil and coal combustion, road salt, mining, incineration and smelting. Approximately 20% of the ambient air chromium was hexavalent chromium (Cr(vi)) which has been identified as carcinogenic. The majority of the Cr(vi) was in the form of inhalable particulate matter (i.e. PM_{10}). There are few studies of the seasonal variations of these elements (SENES, 1998).

Another carcinogenic substance is benzene, which is prevalent near major streets and at industrial sites, such as refineries. The primary source of benzene is automobile exhaust. During the period 1989-94 the levels of benzene decreased by 38%. Unfortunately, only urban areas were studied for benzene levels (SENES, 1998).

Much remains unknown about HAPs such as: emission estimations of loadings of dry and wet deposition; volatilization from surface waters; seasonal variations; transfer rates; etc.

4. Integrated Approaches to Understanding Atmospheric Change

All of these issues are linked by a complex set of relationships between emissions, atmospheric processes, uptake by the biosphere, and environmental interactions. Determining single-issue effects are an important first step towards understanding the integrated and cumulative effects of the atmosphere. The few studies trying to understand the most significant exchanges, timing and interactions among multiple air issues have highlighted the need for increased research to understand the connectivity and dynamics between them and the related weather systems.

It is apparent that methods to examine the suite of inter-related atmospheric issues, such as acid deposition; climate change; stratospheric ozone depletion; tropospheric ozone episodes; hazardous air pollutants; and suspended particulate matter require a comprehensive integrated approach, not a simple expansion of a single-issue assessment or model (Fig. 18). To a large extent, scientists and policy analysts have addressed each of these issues separately at varying temporal and spatial scales. Continuing to resolve the problems individually may lead to conflicting policy and regulatory actions. For example, sulphate aerosols cause acid deposition while at the same time they absorb and scatter solar radiation, thus masking the full impact of greenhouse gas warming. In industrialized regions, where sulphate aerosols are particularly high, the aerosol-induced cooling may be larger than 25% of the warming caused by carbon dioxide (Rodhe *et al.*, 1995). Science, models and policies towards controlling one and not the other could exacerbate environmental problems.

Integrated and cumulative air assessments, reach beyond the boundary of a single discipline and consider more than one sector or one aspect of the problem.

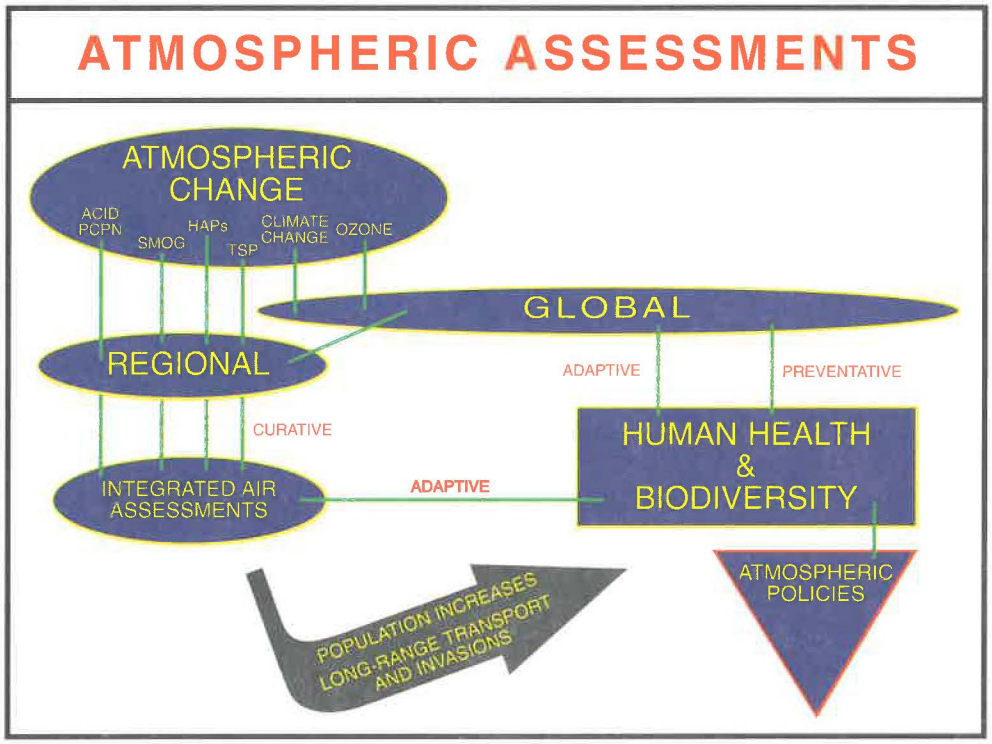


Figure 18. Source: MacIver (1998).

Table 2.

A qualitative summary of the linkages among the air issues. Effects of the atmospheric change issues listed in the top row and the air issues listed in the left column are shown as 0 (no effect); 1 (some effect); 2 (strong effect); U (unknown). HAPs are not included because of the great variety of types.

AIR ISSUE	Climate Change	Stratos. Ozone Depletion	Acidic Deposition	SMOG	Suspended Particulates
Climate Change	-1 but several counteracting effects	-1 but several counteracting effects		+ 1	-1 (globally) -2 (regionally)
Stratos. Ozone Depletion	+ 1		0	- 1	+ 1
Acidic Deposition	+ 2	+ 1		U	+ 1
SMOG	+ 2	+ 1	+ 1		highly correlated
Suspended Particulates	+ 1	+ 1	+ 1	highly correlated	

Integrated air assessments offer a more egalitarian treatment of different disciplines. They can be seen as a "knowledge net" which forces a true integration process. This integration is of great importance to the understanding of scientific links among these issues and their multiple effects on biodiversity and human health (Rothman and Robinson, 1997).

A qualitative approach developed by Maarouf and Smith (1997), showed in Table 2, stresses the interactions between all six air issues. Using scores from 0 (no effect) to 2 (strong effect) illustrates the positive or negative direction of the effect. For example, global warming will contribute to the destruction of stratospheric ozone through a number of chemical reactions involving greenhouse gases (score +1). The depletion of ozone in the lower stratosphere, on the other hand, is causing a net cooling effect on climate (score -1).

In comparison, the quantitative approach contains many environment prediction

models and scenarios, the most known and accepted of these integrated approaches is the Ecosystem Approach (Munn et al., 1997). Regier (1995) states that there are three definitions of the ecosystem approach: (1) ecological systems; (2) analysis of complex systems; and (3) the emergence of a cultural regime. Here the ecological, socio-economic and political structures are integrated within a single conceptual framework. This approach has proven to be successful in the Great Lakes and other science assessments. This framework provides a long-term perspective in which externalities may change and it includes people, political boundaries and landscape modifications.

Within this approach there are several methods (Munn *et al.*, 1997):

- Biogeochemical cycle models
- Dose-response/stress-response models
- Risk assessments
- No-regrets principle
- Ecological economics/the precautionary principle
- Cumulative environmental assessment

Many of these methods might be useful in multi-issue assessments, either using GIS-type technology, downscaling classifications and/or models, but all of them require integrated development and testing in specific settings. The following is a brief summary of a few of these methods:

4.1 Biogeochemical cycle models (BGC)

BGC models represent the cycling of one or more substances (often one element i.e. sulphate) among various reservoirs in the natural and human environment. This model provides not only quantitative estimates of the stocks and flows of the substance but also describes the processes that induce change. It could be used to link different atmospheric issues, if the model includes more than one substance. For instance, methane in addition to being a greenhouse gas takes part in the chemical process leading to tropospheric ozone depletion and acidification from sulphur and nitrogen oxides.

This approach helps find pathways and processes that are common to more than one element. In the sulphur and carbon cycles, for example, fossil fuel combustion provides a common pathway of injection to the atmosphere, and both elements play a role in the radiative forcing of climate, though their individual roles are different. Sulphate particles reflect incoming sunlight back to space. They are also highly efficient cloud condensation nuclei. A larger number of nuclei would result in an increase in droplet number and a decrease in droplet size. This, in turn, will change droplet lifetime and the optical properties such as cloud albedo. Sulphur emissions may partially mask the radiative effects of carbon dioxide emissions, thus attenuating the climate change effect. On the other hand, the fertilization effect resulting from anthropogenic loading of nitrogen and/or phosphorus would encourage growth of marine phytoplankton, simultaneously removing carbon dioxide and increasing the production of dimethylsulfide, increasing condensation nuclei and brightening the global albedo (degree of reflectivity).

This synergetic effect caused by the three elements -carbon, nitrogen and sulphur- may tend to decrease global temperatures. An additional negative effect of sulfate aerosols is their capacity to deplete the stratospheric ozone layer (Whelpdale and Williams, 1997).

The limitation of this approach is the detailed scientific understanding required to describe the behavior of an individual element. It does not easily address two or more cycles at the same time, nor does it adequately explain the interactions among various cycles (Whelpdale and Williams, 1997). Nevertheless, these models are useful for assessing risk and uncertainty.

4.2 Dose-Response/Stress-Response models

These models aim at determining the quantitative relationship between the magnitude of an imposed stress and the response of a receiving system. Examples of stressors could be ground-level ozone concentrations, intensity of UV-B radiation, acid deposition, or changing CO_2 levels. Receptors to these stressors are human populations, phytoplankton and the entire terrestrial ecosystem. The dose of the stressor must increase past a threshold value to induce a response. If the dose keeps increasing, it reaches a saturation point where there is no additional effect (Whelpdale and Williams, 1997). A recent study of the effects of high carbon dioxide has been associated with greater plant production but containing lower nutritious value. Experiments on wheat fields exposed to 200 ppm above the usual level contained lower protein content than under optimum levels (Thompson, 1998). One of the advantages of this approach is that it allows the establishment of a quantitative relationship between cause and effect. If used properly in a variety of receptors, it is possible to establish relative responses and determine the most sensitive receptor. One limitation is that extrapolation from controlled laboratory conditions to field conditions is difficult. In addition, relationships that are developed for single stressors may not apply to situations with concurrent additional stressors.

Describing the rest of the methods used by the ecosystem approach is outside of the scope of this paper. It is important, however, to state the three types of integration (Rothman and Robinson, 1997):

a) Vertical integration where human activity exerts pressure leading to a change of state in the environment. This in turn results in impacts on non-human systems, and either directly or indirectly on human systems. As a result there may or may not be a change in human activity, and so the cycle continues.

b) Horizontal integration incorporates perspectives of the sectoral, regional and issue scope. It asks questions such as what is the substantive scope of the assessment? Does it focus on more than a single sector of human endeavors and/or the environment? Are connections between different regions considered? Are interactions between different social and environmental factors considered?

c) Total integration where human and environmental responses are incorporated into a more dynamic picture. It works with scenarios to identify the degree of change and evaluate their impacts. This means a greater expansion of the issues by incorporating the complexity of the feedbacks and linkages in the analysis. Care must be taken to make the whole study easy to follow.

Samples of integrated approaches could be seen in the development of numerous models. A brief description of a couple of these models should give an idea of their depth and scope.

4.3 Integrated Assessment Model (IAM)

The Integrated Assessment Model (IAM) is a PC/Windows-based modeling system designed to model the entire acid deposition system from emissions and control costs through to aquatic, forest, wildlife, materials, and health effects. The current version of the IAM consists of an inventory of SO_2 emissions, an atmospheric source-receptor module (40 source regions, 15 receptors) for wet SO_4 deposition, an aquatic-chemistry module, and several waterfowl and fish effects modules. The IAM can be run in either a scenario mode to predict the impact of SO_2 emission changes on wet SO_4 deposition or in an optimization mode to calculate the SO_2 emission changes required to achieve a desired reduction in wet SO_4 deposition levels. It is a useful tool for screening evaluations of the impact and environmental effects of SO_2 emission changes (Gong, 1998).

Some integrated models such as RAINS and IMAGE make the integration of more than one air issue possible. Integrated assessment models have also been used for climate change studies (Maarouf and Smith, 1997).

4.4 AURAMS (AES Unified Regional Air-Quality Model)

The AES Unified Regional Air-Quality Model (AURAMS), is a new, multi-pollutant, multi-issue air-quality modeling system, by coupling new and existing models or modules into a unified modeling framework (Gong, 1998). Existing models include:

a) the Mesoscale Compressible Community model/Chemical Tracer Model (MC2/CTM), a prognostic meteorological model, MC2, coupled to a regional-scale photo-chemical oxidant model,CTM,
b) the Acid Deposition and Oxidant Model (ADOM), a regional acid deposition model, and
c) the Canadian Aerosol Module (CAM), an aerosol module currently being used within both a global and a regional climate model.

The fourth building block is the Canadian Emissions Processing System (CEPS), an emissions modeling system for regional-scale air quality models that is needed to create emissions input files. The development of the model is initially driven by the need to support the Canada Wide Standards for particulate matter and ground-level ozone. However, since the chemical and physical processes that must be considered for modeling PM include those for other issues, e.g. ground-level ozone and acidic deposition, the development of this PM model is effectively equivalent to the development

of a multi-pollutant, multi-issue air quality model. Therefore this "unified" model will be ultimately capable of converting emission estimates to air quality and thereby assessing the impact of emission reduction scenarios (separately or simultaneously) for PM, ground-level ozone, acidic deposition and, eventually, air toxic compounds.

In all these integrated models, timing as a parameter of policy implementation, must be considered. By 2010 the Kyoto protocol for greenhouse gas reductions will be implemented, which also means a co-reduction of sulphates, nitrates and VOCs. These reductions will also reduce ground-level ozone, with unknown consequences to clear-water lakes, which will continue to be affected by UV-B radiation since the stratospheric ozone will also be at its greatest depletion during this same period.

5. Conclusion

The complexity of the air issues calls for multiple levels of integration in order to develop a coherent approach to solving individual as well as synergistic and non-linear interactions amongst all atmospheric issues. All six air issues are linked directly and depend upon atmospheric circulation. In the development of tools to help forecast and assess the risks, it is necessary to evaluate the trade-offs and future co-benefits.

Cumulative air assessments and integrated modeling approaches within a science-policy framework require the cooperation of diverse disciplines to incorporate environmental science, atmospheric research, economics (costs and costs of inaction), social and political science in the development of adaptation and mitigation strategies. All of these feed-backs will be necessary to answer the fundamental questions of how is the atmosphere changing and what are the net consequences?

For instance, Canada has signed a legally binding agreement in Kyoto to reduce greenhouse gases. However, sulphate aerosols (eg. acid deposition) are attenuating climate warming. Furthermore, water vapor, NO_2 and greenhouse gases that induce polar stratospheric clouds perpetuate stratospheric ozone depletion. In addition, carbon dioxide fertilization benefits to plants may be ameliorating the effects of acid rain and ground-level ozone.

Future science directions will need to continue building on single-issue accomplishments, models, assessments and policy agreements. At the same time, it is suggested that integrated atmospheric models and assessments develop along five pathways:

- Utilize an integrated framework for multi-issue assessments that combine GIS-type technologies, downscaling methodologies and/or models to support the development of environmental prediction strategies.

- Focus on the cumulative timing of atmospheric changes based on individual science-policy targets. For example, many atmospheric issues are working toward target deadlines around the year 2010. Should these targets be met, what would be the new structure and function of the atmosphere and what would be in conflict?

- Develop an integrated assessment framework and model that functionally predicts the co-impacts of the reduction in one air issue, such as greenhouse gases, on all other air issues and the net science-policy consequences.

- Functionally link the **whole** atmosphere to other fully integrated issues, such as human health and biodiversity, to fully assess the net benefits and the feedback effects on the atmosphere.

- Develop mitigation and adaptation actions within the context of the **whole** atmosphere and its changing condition.

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