3.0 WHY IS WEATHER IN TORONTO THE WAY IT IS?

The main factor driving the weather is the exchange of energy between the sun and the earth's atmosphere. This energy exchange generates a global atmospheric circulation pattern which in turn carries air masses and weather systems around the globe and across the land, bringing changes to the weather that we experience day-by-day.

3.1 THE SUN-EARTH ENERGY EXCHANGE

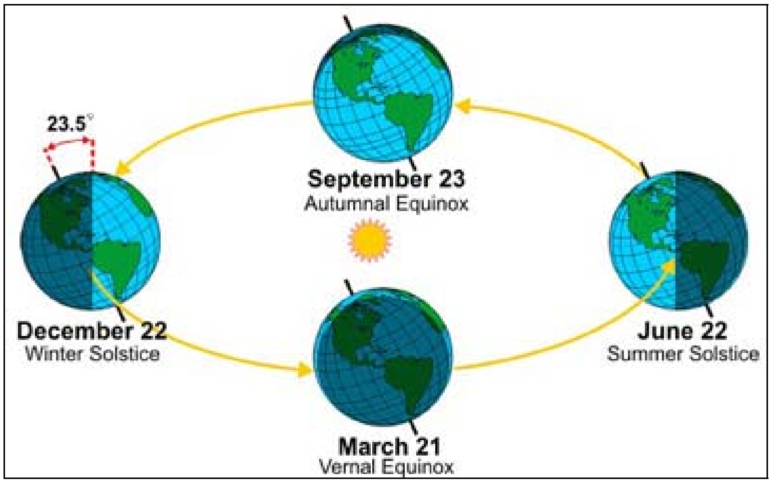
Different locations on earth receive different amounts of solar energy. This is simply a result of geographic location in conjunction with two technical, but fundamental things: 1) the rotation of the earth on its polar axis (which creates differences of day and night); and 2) the tilt of the polar axis relative to the path that the earth travels around the sun along its plane of rotation. This latter effect creates the seasons. Another factor which creates seasonal differences in different areas of the globe includes the elliptic nature of earth's orbit around the sun such that the sun is not at the focal point of the ellipse. As a result, the distance between the earth and sun is not constant causing Toronto to be closer to the sun in January and further away in July.

The tilt of the earth's axis relative to the path it travels around the sun is currently 23.5° (Figure 14). Without this tilt, the sun would be directly overhead the equator all year round meaning that each location on earth would experience the same amount of daylight and darkness each day of the year. Instead, the latitude at which the sun is directly overhead shifts between 23.5°N and 23.5°S (the Tropic of Cancer and the Tropic of Capricorn, respectively) giving rise to changes in the length of day over the course of a year and to the location on earth which receives solar energy from directly overhead during the day. This variation in the length of day and less important, the elliptical path travelled by the earth around the sun, is what causes the seasons.

Not only does the axial tilt affect the length of a day, but it also determines the amount of atmosphere through which the sun's rays must travel through to get to the surface. It also determines the amount surface area which will intercept incoming solar radiation. More of the atmosphere to travel through means less energy reaches the surface because it interacts with, and gets reflected, deflected or absorbed by particles/gaseous components of the atmosphere. Additionally, when the sun's rays are at an oblique angle relative to the earth's surface, solar energy is effectively spread over a larger surface area. Consequently, surface locations tilted away from the sun receive less solar energy because the sun's rays must travel through more of the atmosphere and are dispersed over a larger area once they reach the surface.

Toronto is geographically located north of the Tropic of Cancer and south of the North Polar Circle at latitude 43.75° north. Therefore, the maximum angle that the sun will ever be relative to the horizon in Toronto is 69.75° which occurs at the summer solstice and the minimum angle is 22.75° which occurs at the winter solstice (assuming that the axial tilt of the earth is 23.5°). As a result, the sun will never be directly overhead Toronto (i.e., 90° to the horizon) and Toronto will never experience 24 hours of complete daylight or darkness.

Figure 14 Earth's Orbit and Axial Tilt



Source: NOAA, 2009a

Note that the dates specified in Figure 14 are not constant. Over the next ten years the Winter Solstice will varyingly occur on either the 21st or 22nd of December, the Vernal Equinox on either the 20th or 21st of March, the Summer Solstice on either the 20th or 21st of June, and finally, the Autumnal Equinox will varyingly occur on either the 22nd or 23rd of September. For instance, in 2011 the specific dates of the solstices/equinoxes will be December 22nd, March 20th, June 21st and September 23rd.

There are two basic types of radiation – short wave and long wave. Radiation at temperatures that occur on the Earth's surface is long-wave radiation (this is radiation longer than 4 µm). Radiation reaching the Earth from the sun is short-wave radiation (this is radiation that is shorter than 4 µm). Since the atmosphere has temperatures in the same general range as the Earth's surface, the radiation from the clouds and air molecules is also long-wave radiation. But because the atmosphere is made up of gases, rather than being solid, the atmosphere does not radiate at all wavelengths but only at those at which it can absorb.

The atmosphere is much more transparent for short-wave radiation than for long-wave radiation, particularly in the visible range (0.38-0.77µm). For long-wave radiation, there is a band from 8-11 µm in which the atmosphere absorbs very little radiation. It is in this band, called the "atmospheric window" that heat escapes from the Earth at night. Radiation from the Earth and the cloud-tops in this band passes directly through the atmosphere and almost all goes out into space unimpeded. At other wavelengths, the radiation from the ground is absorbed at various levels in the atmosphere and in turn the atmosphere at these levels radiates this energy up and down. The biggest absorbers of long-wave radiation are water vapour and carbon dioxide. As CO_2 (and other greenhouse gases) increases, less long-wave radiation escapes.

The result of the atmosphere being transparent to incoming solar radiation and more absorptive to outgoing long-wave radiation from the Earth is that the Earth's surface is kept at a much higher temperature on average than it would be if there was no atmosphere. The energy radiated outward and absorbed by the atmosphere is partially radiated back to the Earth's surface, increasing the total energy received there. This raising of the Earth's surface temperature because of the back-radiation from the atmosphere is known as the natural greenhouse effect.

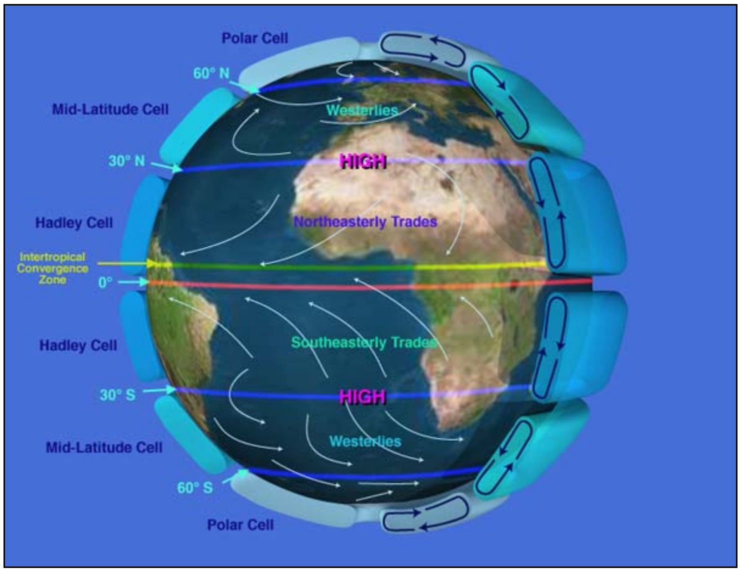
Over the long run, the processes of absorption and emission of radiation at the ground and in various layers of the atmosphere have produced a balance between the incoming and outgoing energy, keeping our world a warm enough place to live and providing the driving forces for atmospheric motion. The problem with climate change is the increase in man-made GhGs is altering this balance, leading to greater absorption of long-wave energy.

3.2 THE GENERAL ATMOSPHERIC CIRCULATION PATTERN

The latitudinal variation in solar energy means that there is an unequal distribution of heat across surface of the globe. Part of the atmosphere's heating comes from the earth's surface and because there are different types of surfaces the atmosphere is heated unevenly around the globe. Air with different temperatures has different densities. The hotter air becomes lighter and rises, the colder air heavier and sinks. Nature effectively compensates for this unequal distribution of heat (energy) by moving masses of water in ocean currents, and air within the atmosphere mixing it. The ocean and the atmospheric motion re-distributes the heat more evenly around the globe. This atmospheric motion is the foundation for the general circulation of the atmosphere.

As shown in Figure 15, warm, moist air in the tropics rises and moves poleward transferring energy to higher latitudes while creating a zone of low pressure in the tropics. Around 30°N, air descends, creating a zone of high pressure. The descending air spreads out in the lower atmosphere and some of it flows back to the equator creating a closed loop called the Hadley Cell. Around 60°N, a polar circulation cell is formed as air rises and flows poleward and descends over the high latitudes creating another area of high pressure. This closed loop is called the Polar Cell. A third cell, the Ferrell (or Mid-latitude) Cell, owes its existence to the other two cells (NASA, 2008). If the earth did not rotate, the large scale circulation cells would just move air in a north-south direction. However, the rotation of the earth causes winds to shift direction. This is known as the Coriolis Effect and it causes winds to shift slowly to the right in the northern hemisphere (clockwise) and shift slowly to the left in the southern hemisphere (counter clockwise). Three global wind zones result: the polar easterlies; the westerlies; and the easterly trade winds. Note that winds are named after the direction from which they blow.

Figure 15 Idealized Global Circulation Pattern



Source: NASA, 2008

Canada is predominantly under the influence of the westerlies. As a result, the prevailing winds in Toronto blow from a westerly direction throughout the year. The prevailing westerlies tend to carry Pacific air to the eastern portions of Canada and are the reason why one of the predominant influences on our climate is the Pacific Ocean. In general, strong upper level westerly air streams (i.e., the Polar jet stream) steer high and low pressure cells which form mostly above areas of cold contracting and sinking air and warm expanding and rising air, respectively, over Canada and the U.S. towards the east, bringing variation to Toronto's day-to-day weather.

3.3 GLOBAL WEATHER DRIVERS

Since the middle of the 20th century, the Earth's climate has been warming rapidly compared to previous centuries, with the rate of warming increasing more significantly over the last 25 years (IPCC, 2007b). Temperature records from thermometers are sufficiently reliable and cover enough of the globe to allow an estimation of global mean temperatures since about 1850. The period from 2000 to 2009 was 0.17 ºC warmer on average than the 1990s[3]. All years since 1998 fall within the top 15 warmest years on record. There is strong evidence that this warming is attributable to human activities, in particular to the emission of greenhouse gases. Further details of the land and marine temperature records are given by Brohan *et al*. (2006) and Rayner *et al*. (2006) respectively. These datasets are continually updated and collected by the World Meteorological Organization (WMO), along with agencies in individual member nations (like Environment Canada).

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[3] Reference in this document to periods such as the 1990s and the 2000s always infers the periods 1990-1999 and 2000-2009, respectively.

The Earth is able to support life because naturally occurring levels of greenhouse gases allow the planet's average surface temperature to be approximately 15 ºC rather than the -23 ºC it would be in the absence of the greenhouse effect. Greenhouse gases such as methane (CH_4), carbon dioxide (CO_2), water vapour (H_2O) and nitrous oxide (N_2O) are chemical species which can absorb most of the outgoing long-wave radiation emitted by the surface of the earth inducing a warming of the atmosphere. Humans have, for many years, been modifying the chemical composition of the atmosphere through industrial activity, specifically burning fossil fuels, as well as through agricultural activities which have resulted in increased emissions of greenhouse gases to the atmosphere, and higher levels of those gases in the atmosphere. Such a modification has resulted in increased temperatures in the atmosphere which in turn has allowed more water to be in the form of vapour, a process which has further increased the amount of warming. Even if all the greenhouse gas emissions from human activities were to stop, the presently observed warming trend is highly likely to continue due to the thermal inertia of the climate system and the long lifetimes of some of the greenhouse gases in the atmosphere.

Aerosols are small particles in the atmosphere which have a variety of sources, both natural and anthropogenic. Their impact on the Earth's climate is more complex, because their concentrations vary considerably between different locations of the earth, and they have a range of effects of the Earth's climate. Aerosols which scatter incoming shortwave radiation act to reduce the amount of radiation reaching the Earth's surface. Some aerosols partly absorb incoming radiation, and their overall effect is more complex. Over dark surfaces, such as the oceans and forests, they lead to a cooling of the climate, whereas over bright surfaces, such as snow, ice and crops, they produce an overall warming. The scattering and absorption of radiation is known as the direct effect.

Aerosols can also modify the properties of clouds. They can act as cloud condensation nuclei which encourage water vapour to condense on their surfaces. A polluted cloud (one containing many aerosols) will generally consist of a large number of small water droplets, which makes the cloud highly reflective and have a long lifetime. Non-polluted clouds reflect less radiation and have larger droplets, which are more likely to form rain drops, and so the cloud has a shorter lifetime. Aerosols which absorb incoming solar radiation have another effect on clouds. They act to warm the surrounding atmosphere which changes the stability and humidity of the surrounding air, and may cause clouds to dissipate.

Other global processes are likely to have contributed to global warming. Deforestation, triggered by the need for new arable land to produce the food needed by an ever-growing population, has reduced the ability of the biosphere to store carbon. It is quite likely that the fraction of emitted carbon which remains in the atmosphere will increase in the future (Denman *et al*., 2007). This has the potential to exacerbate the effects that our emissions have on the climate system.

Another potentially important process which could influence future climate is linked to the melting of permafrost. Permafrost consists of soils containing deposits of methane and methane hydrates. If they melt, the methane could be released to the atmosphere. Methane, whose current concentration in the atmosphere is much lower than that of carbon dioxide, is a much more powerful greenhouse gas. A massive release of methane into the atmosphere would dramatically increase the greenhouse effect and trigger a further warming of the climate system (e.g. Thorpe *et al*., 1996; Shindell *et al*., 2005).

3.3.1 Air Masses and Semi-Permanent Pressure Patterns

Air masses are defined as large volumes of air that have mostly horizontally homogeneous properties (i.e., uniform temperature and moisture) in the lower atmosphere (after Phillips, 1990). Persistent levels of incoming solar radiation and moisture occurring over an extensive area having light winds will result in horizontal homogeneity. If air remains over such a location for an extended period of time, its properties will become characteristic of the surface below it. An air mass may have a surplus of energy and moisture (a Tropical air mass) or a deficit of energy and moisture (an Arctic air mass).

There are two types of air masses: travelling air masses and blocking air masses. Air masses that are formed in one geographic area may subsequently move to other areas and are known as travelling air masses. Travelling air masses bring their temperature and moisture characteristics with them and influence the weather of the new areas they encounter. Conversely, air masses with overly strong pressure characteristics may become almost stationary (blocking air masses) for long periods of time and can force other travelling air masses having weak pressure characteristics, to move around them.

Figure 16 and Figure 17 show the common winter and summer air masses which move within Canada (originating in the Arctic) or to Canada (originating from the oceans) and impact various areas of the country. In locations where surface temperatures are hot, the air above it is heated and subsequently rises, creating an air mass with low pressure characteristics. Conversely, where surface temperatures are cold, the air above it is chilled and sinks, creating a high pressure air mass. In locations where excessive heating or cooling occurs for long periods of time relative to adjacent areas, semi-permanent high and low air pressure systems may form.

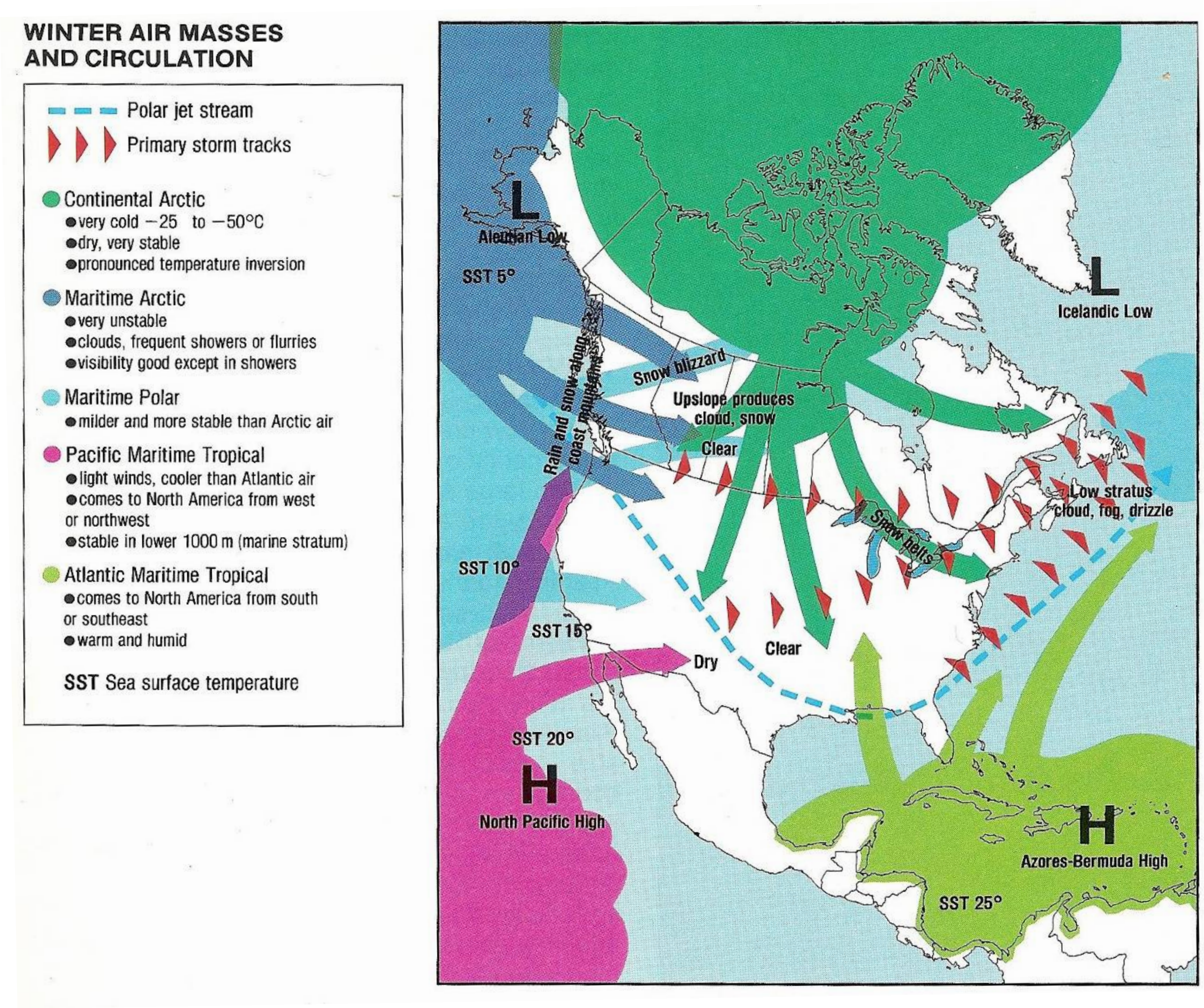
Semi-permanent high/low pressure systems become apparent when pressure patterns are averaged over several years for a given region. The winds derived from these regions of high and low pressure are what carry travelling air masses from their source regions into or across Canada. According to Hare and Thomas (1979), Phillips (1990) and Sanderson (2004), the most common semi-permanent highs and lows are:

- the Aleutian Low - situated in the Pacific near Alaska - it is strongest in winter and brings Maritime Arctic air to the western parts of Canada;
- the Icelandic Low - situated in the Atlantic near Greenland - it is strongest in winter and brings Continental Arctic air into the southern regions of Canada;

- the North Pacific High - situated in the Pacific off the U.S. west coast - it is strongest in winter and brings Maritime Tropical air in summer and winter to the west coast; and
- the Bermuda High - situated in the Caribbean - it is strongest in summer and brings Atlantic Maritime Tropical air to the eastern parts of Canada.

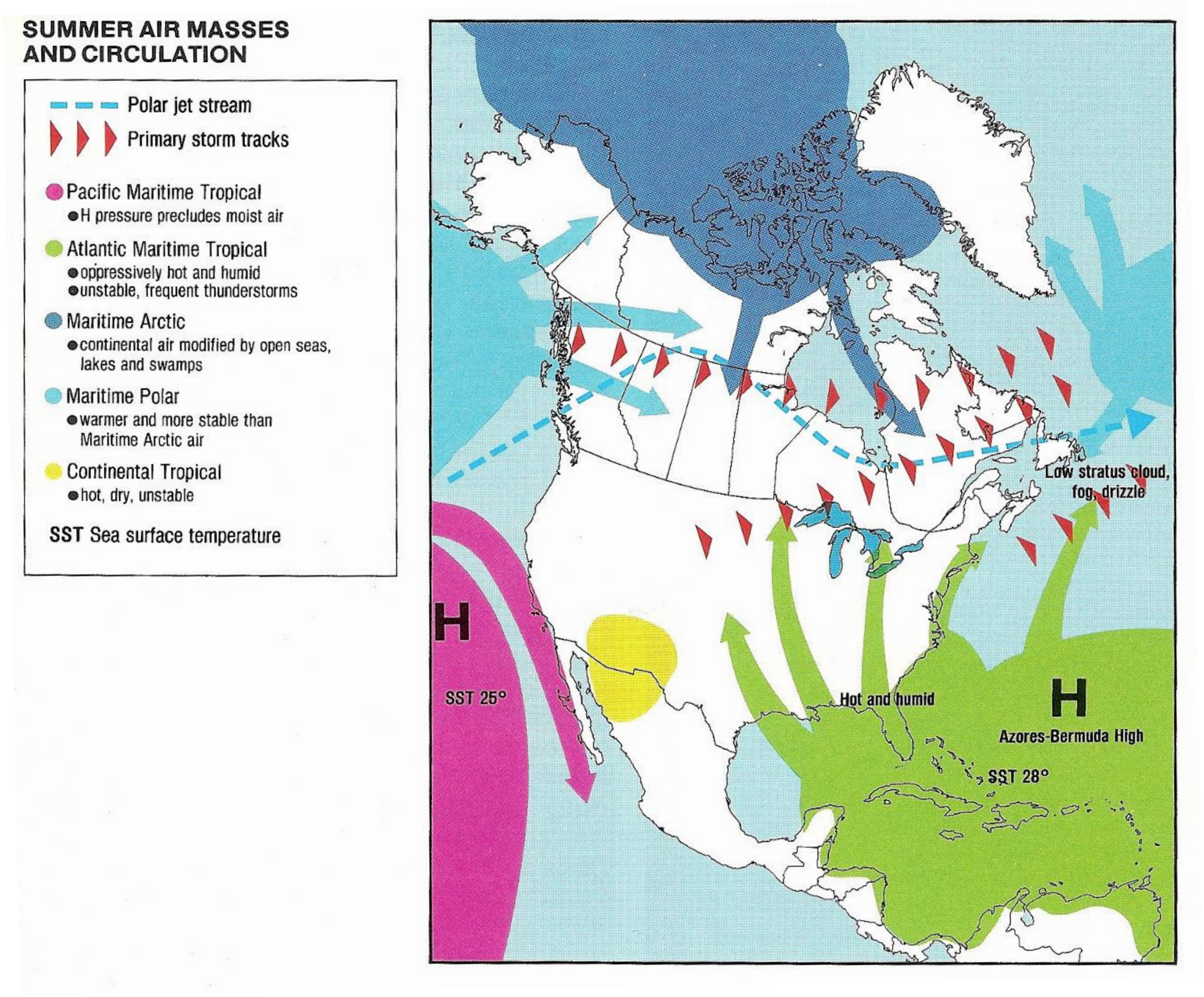
Source regions of air masses at low (equatorial) and high (polar) latitudes experience weather that is almost always the same since these regions experience less variation in incoming solar radiation. In middle latitudes, however, the weather is continually changing as one air mass after another passes overhead. Polar and arctic air masses move predominantly toward the equator and eastward; tropical and equatorial air masses move predominantly poleward and eastward (after Neiburger *et al.*; 1982).

Figure 16 Winter Air Masses and Circulations



Source: Phillips, 1990

Figure 17 Summer Air Masses and Circulations

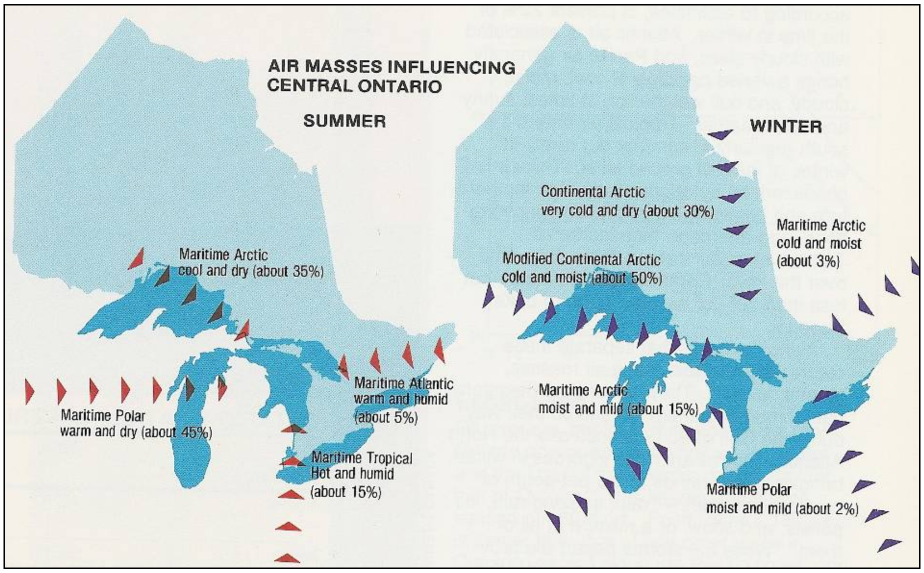


Source: Phillips, 1990

As stated by Phillips and McCulloch (1972), Phillips (1990) and Sanderson (2004), and shown in Figure 17 and Figure 18, Toronto summers are dominated by Maritime Polar (i.e., Pacific) and Maritime Arctic air masses from the west that bring warm (sometimes cool), dry air. Occurrences of Maritime Tropical air from the Gulf of Mexico can also arise which bring hot and humid days to Toronto in the summer.

Figure 16 and Figure 18 shows that in the winter, cold, dry Continental or Modified Continental Arctic air dominates Toronto. Less frequently Toronto receives mild air from the south-southwest during the winter months.

Figure 18 Winter and Summer Air Masses Influencing Ontario



Source: Phillips, 1990

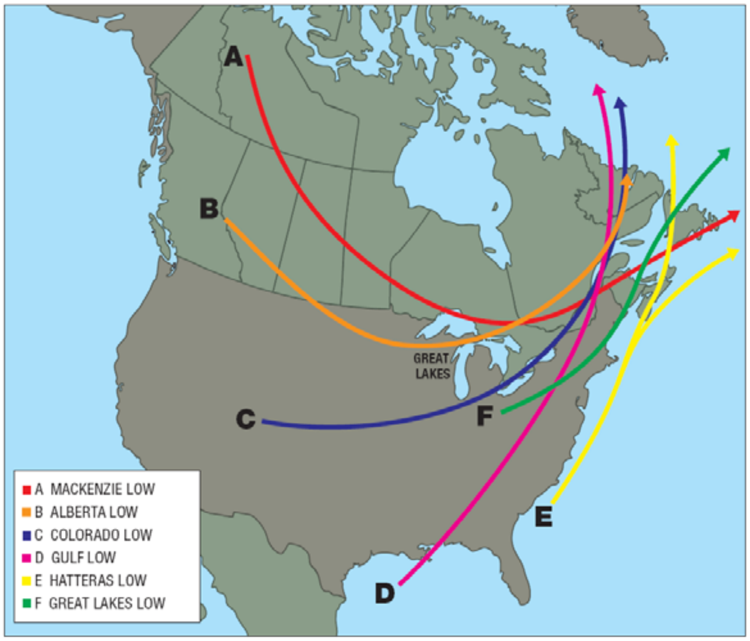
3.3.2 High and Low Pressure Systems

At the boundary between large air masses (known as fronts), the atmosphere becomes unstable and warmer air rises above colder air, and accordingly, smaller low pressure systems may form that are commonly referred to as "Lows". Lows bring unstable weather such as clouds, precipitation, and strong winds. In winter, the contrast between air masses is more pronounced and causes more frequent and more intense or deeper lows to develop. Travelling high pressure systems (commonly referred to as "Highs") bring clear, dry, and often cool weather. The alternating pattern between high and low pressure systems is responsible for the day-to-day weather in Toronto, and is also the reason for relatively consistent precipitation received month-to-month in this region (Boughner and Thomas, 1960; Shenfeld and Slater, 1960; Auld *et al.* 1990).

There are particular locations in North America which favour the development of lows. This is a result of persistent fronts (e.g., the boundary between cold Arctic air and milder Pacific air is called the Polar Front) in addition to large scale topographical features such as the Rockies, and large bodies of water. The regions of North America which favour the development of winter lows as well as their typical storm tracks are shown in Figure 19.

In North America, low pressure systems, and their associated stormy weather along their warm and cold fronts, typically move along tracks associated with strong areas of upper westerly air flow, known most commonly as a jet stream. Jet streams occur in the upper atmosphere at the boundary between two air masses having considerable contrasting characteristics. For example, the Polar Front (known as the Polar Jet), which occurs between 30°N and 40°N, strongly influences weather patterns in Canada, Ontario, and locally in Toronto. We typically observe a much stronger Polar Jet in winter when the contrast between two air masses (Polar Arctic Air and Maritime Air) is greatest.

Figure 19 Common Winter Lows and Typical Storm Tracks of Canada and the U.S.



Source: Klok *et al.,* 2002

The polar front jet stream has been likened to a meandering river winding its way from west to east around the globe's northern latitudes (between 30° and 60° north), but unlike a meandering river, it is also constantly shifting completely from further north to further south as the polar front moves with the seasons and its lobes (i.e., its meanders or turns) correspondingly change in number, shape and position (Neiburger *et al.*, 1982). A typical North American winter polar jet stream pattern, when observed on a weather map, involves a slight northeast turn east of the Rockies, then a dip southeast into the United States and finally, it turns northeast towards the Atlantic coast (Figure 20) (Hare and Thomas, 1979). This pattern is responsible for the paths taken by many winter storms and as shown in Figure 19, it can steer common winter storms such as the Gulf Low (also known as the Texas Low), the Colorado Low and the Alberta Low (also known as an Alberta Clipper) towards Southern Ontario and thus, Toronto. On the other hand, the polar jet stream also usually steers the Hatteras Low along the eastern seaboard, keeping it away from inland locations.

Figure 20 Typical Summer and Winter Jet Streams

Source: University of Maryland, Department of Atmospheric and Oceanic Science (2003)

3.4 REGIONAL WEATHER DRIVERS

As we will see later the greatest warming is projected to occur in northern Canada and Alaska, possibly reaching +10°C in the highest latitudes owing to the positive feedback from reduced snow and ice cover. Snow and ice reflect most of the incoming solar radiation back out to space. This is the reason they appear so brightly white to our eyes. When snow and ice melt, and are replaced by land or sea, a much darker surface is exposed which can absorb a large fraction of the solar radiation, leading to an increase in temperature. A warmed surface induces a warming in the lower atmosphere above which in turn promotes further melting of the snow cover giving rise to one of the most widely known positive feedbacks of the climate system. A related (and very important) phenomenon is the transport of heat from the equator to the poles which occurs through the movements of air masses which exchange heat with the surfaces below them (Barry *et al*., 2002). This transport is partly controlled by the strong temperature gradient between the poles and equator. If this temperature gradient, between the poles and the equator, changes, the rate of heat transport may also change (Caballero and Langen, 2005).

3.4.1 Topography

Topography can have a local or regional impact on climate, or an impact of a much larger scale. On a large scale, extensive mountain chains such as the Rockies can block incoming weather systems from the rest of Canada (Hare and Thomas, 1979). However, since the rest of Canada is a large, open land mass, it permits the rapid movement of weather systems through much of the country including Toronto (Boughner and Thomas, 1960; Shenfeld and Slater, 1960). As noted previously, this allows Toronto to experience variable day-to-day weather and fairly uniform precipitation through the year.

Topography also influences localized precipitation patterns. Air encountering elevated lands is forced to rise and cool, causing clouds to form and precipitation to occur. This is called orographic precipitation. When air descends along the other side of the elevated region, it is dry and warm and in Western Canada is it commonly referred to as a Chinook Wind. Additionally, in the lee side of elevated lands (such as the Niagara Escarpment, the Oak Ridges Moraine and even Toronto's downtown buildings) there is often a noticeable "rain shadow" effect (an area of reduced rainfall).

3.4.2 Regional Geography

3.4.2.1 The Great Lakes

Toronto is located within the Great Lakes Lowlands and lies along the north-western shore of Lake Ontario. This has very important implications for Toronto's climate.

Water has a large heat capacity which has two consequences: 1) it requires a large amount of energy to raise the temperature of water and 2) it takes a large period of time for water to release any acquired heat. As a result, Toronto and other areas in close proximity to the Great Lakes tend to be milder in the fall and winter because the Lakes are warm relative to the air, and the same areas are cooler throughout spring and early summer because the Lakes are cool relative to the air. In other words, the Lakes moderate the occurrence of local temperature extremes in both summer and winter. Theoretically, Toronto should have an extreme continental climate by virtue of its distance from the Pacific Ocean – especially since weather comes to Toronto largely from the west, but also by virtue of its distance from the moderating influences of the Atlantic Ocean as well. In essence, the presence of the Great Lakes reduces the severity of Toronto's winters as well as the intensity of its summers.

Lake Ontario, being quite deep, requires a larger amount of solar energy and, therefore, time to raise the temperature of even its surface waters, than the amount of energy and time required to raise the temperature of the adjacent land areas. This delay can result in temperature differences of 6 to 12 degrees between the lake and the city in the summer (Auld *et al.*, 1990). In the winter, the lake is mostly ice-free which also allows the water to have a moderating effect on the City's temperature over the entire winter season (Phillips, 1990).

The moderating effect of Lake Ontario on the climate of Toronto and its environs is as important with regards to the growing season in rural areas surrounding Toronto as it is for vegetation growing within the city. In the spring, lake temperatures keep the surrounding areas cool, preventing vegetation from growing too soon and risking exposure to frost (Phillips and McCulloch, 1972; Sanderson, 2004). In the fall, warm lake temperatures also prevent as many damaging frosts from forming as would otherwise happen. In general, the number of frost-free days within the vicinity of the Great Lakes is much greater than at locations further inland.

In addition to temperature, lakes also affect local winds, precipitation, cloud cover and fog. As well as being influenced by prevailing winds, areas adjacent to lakes are influenced by lake-breezes. Mostly occurring in summer, lake-breezes are a result of large land-lake temperature differences. Often bringing relief on a hot day, cool air from above the lake rushes under and replaces the warm air that is rising above the land. At night, the pattern can reverse, creating a land-breeze in which cool air over the land flows out over the warmer water of the lake where it rises. A lake-breeze can only really occur, and be felt, if prevailing winds are light. Strong winds will dominate and overcome the lake-breeze effect.

During the winter, lake-effect snow (snow that is created, in part, by the presence of a large body of open water, such as Lake Ontario, in the path of a prevailing wind) can develop under conditions of strong, persistent winds and a large difference between the lake's temperature and that of an approaching air mass. For lake-effect snow to be created, a large distance of open water over which the air travels is required. Due to Toronto's location in proximity to Lake Ontario, and the prevailing wind direction (NW) in winter, these requirements are not typically met for Toronto. Instead, lake-effect snow development is falls to the east of Lake Huron and to the south and east of Lake Erie and Lake Ontario. Sometimes, bands of lake-effect snowfall (from Lake Huron and Georgian Bay) may reach Toronto, but they usually only reach as far as London or Barrie, Ontario.

Depending on the storm track, the Great Lakes may intensify approaching storm systems by adding heat and moisture to the storm system. However, during spring and early summer, it is thought that lakes actually suppress thunderstorms; if the lake surface is cool enough, moisture is returned to the lake through condensation, suppressing convection and thus thunderstorms (Brown *et al.*, 1968, Phillips, 1990).

Finally, areas in the vicinity of lakes often experience more days with cloud cover as the lakes provide a source of moisture and heat (in the cooler winter months) which can cause air to rise and the moisture in it to condense. Lakes also encourage fog formation under certain circumstances. These conditions arise if cooler and less turbulent air passes slowly over warm lake water, causing moisture above the surface to condense (creating steam fog) or if warm, moist air passes slowly over cool surface waters (creating advection fog) (Klok *et al.*, 2002). Advection fog is typical in spring and early summer.

3.5 LOCAL WEATHER DRIVERS

Air masses and weather systems which influence climate are driven by the global atmospheric circulation pattern. As they move, they are further influenced by the surfaces below them. Consequently, topographic features like mountains, bodies of water, and land use all help to shape a region's climate.

3.5.1 Local Geography

3.5.1.1 Niagara Escarpment

A topographic feature in Southern Ontario that influences climate in the vicinity of Toronto is the Niagara Escarpment. To the east-southeast of Lake Huron and Georgian Bay the escarpment is roughly oriented in a northwest-southeast direction (including the Niagara Region portion) and as a result of its location, prevailing westerly winds are often forced to rise up and over the escarpment. Consequently, areas in close proximity to, and to the west of, the escarpment experience greater amounts of rainfall and a rain shadow is created to the east of it including areas near Toronto (Canadian Encyclopedia, 2009). Figure 21 shows the July mean total precipitation in Southern Ontario which shows that Toronto receives less precipitation than areas in the vicinity of the escarpment where elevations are among the highest in Southern Ontario.

3.5.1.2 River Valleys

Not only does local topography impact precipitation patterns, but it also influences local winds and temperature. In the City of Toronto, the land gently slopes towards Lake Ontario and is traversed by many valleys (e.g., the Don and Humber River valleys) which are orientated generally in a north-south direction (Shenfeld and Slater, 1960; Brown *et al.*, 1968; Auld *et al.*, 1990). Because it is denser, cold air will often drain into these valleys at night which leads to more fog and frost in these areas. Valleys also tend to channel winds making them stronger and gustier than in other parts of the city.

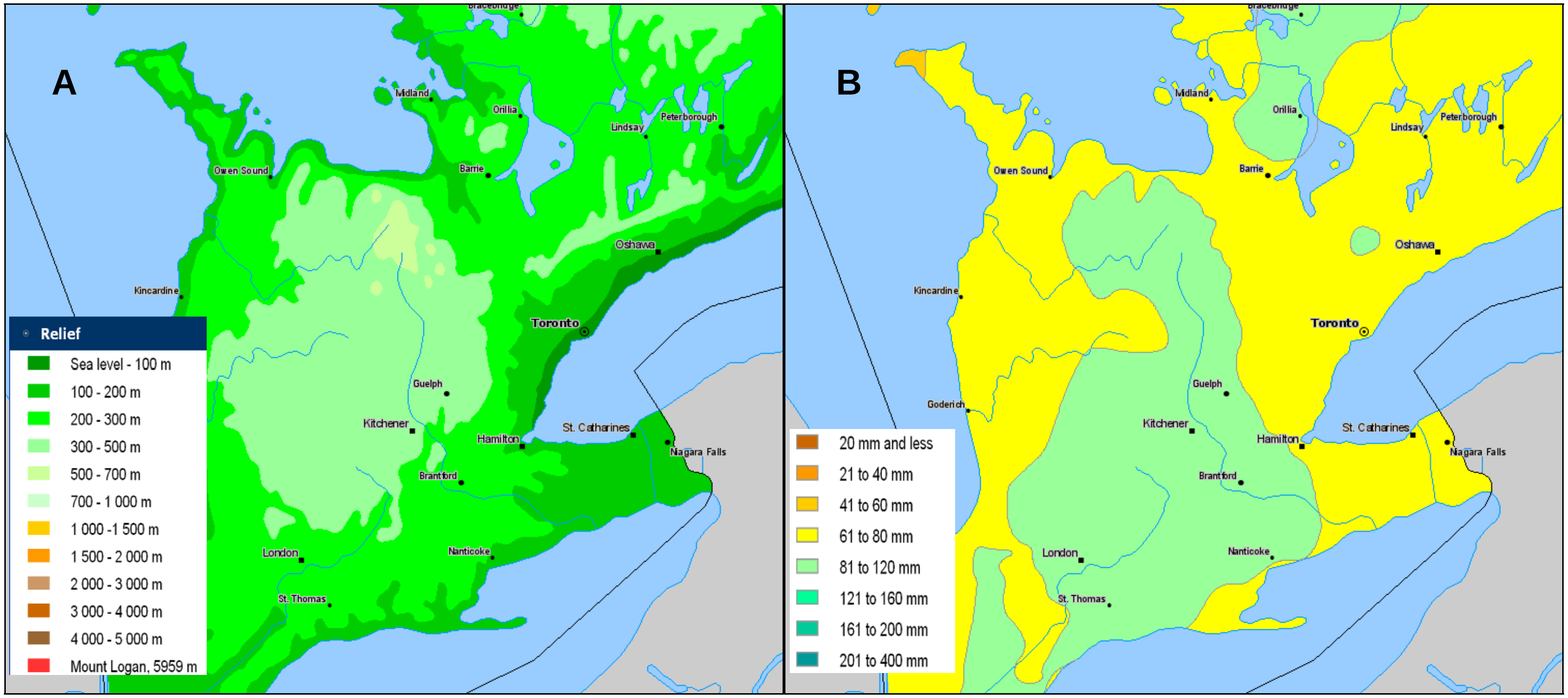
3.5.1.3 Scarborough Bluffs

East of the downtown core, cliffs known as the Scarborough Bluffs also rise to 70 metres above the Lake (Auld *et al.*, 1990). Areas of higher elevation experience colder temperatures during the day, but any south-facing slopes will be warmer than north-facing slopes because they are exposed to more sunlight. Elevated lands can also locally block winds from other areas.

3.5.1.4 Urban Land Use

Green areas in cities (parks, gardens, sports fields, etc.) generally have cooler night-time temperatures (and locally a small urban heat island) than the surrounding urban areas. Water is able to evaporate from the soils in green areas which has a cooling effect. Generally, cities with tall buildings and narrow streets will have a larger heat island effect than cities with lower buildings and broader streets, because more of the heat energy radiated during the night will be reabsorbed by surrounding buildings. The tall bank tower area of downtown Toronto is also an effective topographic, albeit artificial, feature that creates a microclimate, especially in regards to channelling winds and creating its own north and south facing vertical slopes which affect local weather.

Figure 21 Relief Map and Mean July Total Precipitation in Southern Ontario



A: Relief map of Southern Ontario. Note the lighter coloured regions of higher elevation to the west of Toronto.

B: Mean Total Precipitation in July in Southern Ontario. Note that the regions with more precipitation occur near the central regions of Southern Ontario which also have the highest elevations as outlined in Figure A. Toronto lies within the partial rain shadow to the east.

Source: Natural Resources Canada, Atlas of Canada (http://atlas.nrcan.gc.ca/site/english/maps/environment/climate/precipitation/precip)

3.5.2 Toronto's Urban Climate

It is well known that changes in land use can significantly alter the climate of a surrounding area. By removing vegetation and replacing it with man-made structures and surfaces, it changes heat, moisture and momentum exchanges (or fluxes) and thus affects temperature, cloud cover, precipitation and even wind speed. The City of Toronto is no exception; areas of tall buildings as in the high density downtown core have largely asphalt and concrete surfaces and little vegetation and make its climate much different from even lower density surrounding urban areas with more vegetation; equally, even such non-downtown urban areas have more brick, concrete and asphalt than surrounding rural areas. The significance of these differences is discussed below.

An Urban Heat Island (UHI) is the name given to an island of warmer air temperatures caused by the extra heat supplied to the air from the urban surface below it, within a generally cooler geographically broad mass of air. Any large metropolitan area, such as Toronto, will exhibit one, or more, urban heat islands (depending on the size and structure of the surface) with higher temperatures than the rural areas surrounding it. It is caused by dense materials (concrete, brick buildings, road surfaces, etc.) preferentially absorbing heat because of their dark colour and then releasing it and heating the air above; as well as being due to heat loss from buildings and vehicles in a city. As a result, significant differences in temperature occur between Toronto and its surroundings, and this is noticeable both overnight and during the winter months.

Changes in land use as well as daily anthropogenic activities are the main causes of higher urban temperatures. Specifically, the asphalt and concrete-like surfaces of the many roadways and buildings in a city are good absorbers of solar energy. At night, these surfaces release the heat they absorbed during the day thereby reducing and/or slowing the drop in night-time temperature. An additional cause of the UHI is waste heat from energy sources including vehicles as well as residential and commercial heating/cooling units. Due to the insulating effect of clouds, differences between urban and rural temperatures are greatest when skies are clear.

Compared to rural areas surrounding the city, the average **day-time** temperature is approximately 1 degree warmer in Toronto from November to February (Sanderson, 2004). During other months of the year, the average day-time temperature is not that significantly different. However, the average **night-time** temperature is on about 3 degrees warmer in the City of Toronto than in surrounding rural areas for all months of the year (Sanderson, 2004). Although people anecdotally report sensing that UHI also impacts daily temperatures, as in the summer months, implying that the downtown urban core temperatures can be much warmer than the suburban and rural counterparts, this is not always borne out in Toronto and the surrounding rural areas in the available data records (Maloney, 2010). The effect of the UHI can also be quantified by examining the number of frost free-days. In the City, the average number of frost-free days is 191, whereas Pearson Airport has only 149 frost-free days (a difference of 6 weeks) (Sanderson, 2004).

To gain an understanding of the extent of the UHI in the City of Toronto, an experiment was conducted by Koren (1998) in which a temperature sensor was attached to an automobile and driven north overnight along Yonge Street beginning at the lakeshore. He found that temperatures were significantly different from the Pearson Airport reported temperature until he reached Finch Avenue indicating that the UHI effect was present for about 18 kilometres north of the lake.

Urban areas also affect other climate parameters such as solar insolation[4], wind, cloud cover and precipitation. Clusters of tall buildings, like trees in the woods of rural areas, are known to cause shadowing effects creating pockets of cooler temperatures within the city. As well, building configurations significantly alter wind speeds and flow patterns in urban areas. As winds encounter an urban canopy, they are forced to flow up and over tall buildings resulting in a slower, more turbulent flow. However, when winds blow in between tall buildings, a tunnelling effect may result, increasing wind speeds in certain areas of a city. Urban effects on precipitation are less well understood, however, it has been postulated that increased levels of pollution in urban areas create more nuclei for cloud formation which leads to increased levels of precipitation downwind of such urban areas (Oke, 1988).

3.5.3 Toronto Weather Drivers

The significant passage of successions of "lows" (and all their attributes) over Toronto is "driven" by the meeting of tropical air from the south with polar air from the north. The temperature differences of, and between, these air masses create air masses of differing densities and pressures in close proximity to each other. Pressure gradients result; the gradients drive the winds (like water flowing over sloping land) that carry the air masses forward and create the fronts and the sequence of weather associated with their presence.

The location of the invisible line that separates tropical from polar air (of such great importance to Toronto) is itself a dynamic moving wave line, or vertical curtain, extending through the lowest layer of the atmosphere (the troposphere) from the ground to the air aloft at its upper limit the tropopause (or the boundary between the troposphere and the stratosphere above it). The distinction between them is based on temperature. Temperatures decrease with height in the troposphere and increases with height in the stratosphere. The tropopause is found at varying heights – on average at 16 km above the equator and 8 km above the poles, but these heights also change seasonally. The height of the tropopause above Toronto is typically between 10 km and 12 km.

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[4] Solar insolation is a measure of the amount of **in**coming **sol**ar radi**ation** or, more colloquially, shortwave radiation from the sun.

Where the tropical and polar air meet, intense (i.e. steep) pressure gradients are created. These are strongest near the tropopause and give rise to the polar jet stream. The jet stream is a narrow band of very strong winds at height (typically at between 8 and 12 km altitude along the polar front). The polar jet of the northern hemisphere follows (at height) the varying location of the polar front that moves in a wave like manner around the earth. The number of waves within one complete encirclement of the globe can vary from very pronounced amplitude waves, or lobes, to very weak amplitude waves, and can vary in number from as few as two to as many as six – but more typically between three and four "lobes" are present at any given time. The boundary between tropical and polar air and the jet stream between them tends "to be anchored" by the presence of the Rocky Mountains – where the jet stream typically "bends" northwards to cross over them. As such, the jet stream most typically flows south eastwards across western Canada before curving back northwards to complete the lobe form. The location of the polar jet stream across Canada (and indeed cold and warm fronts as well) can be seen in the Globe and Mail and in the Toronto Star on a daily basis.

Although the pattern of the jet stream's meandering motions is variable it does have an average latitudinal location – and if that average location were to change north or south, or the nature and frequency of the amplitudes of the lobes were to change, it would logically bring a change of climate and weather for Toronto with it.

Toronto currently lies within the belt of circumpolar westerly winds (the "westerlies") that dominate the climate of mid-latitude and sub-polar latitude regions. The belt extends from the south west of the USA to the Canadian Arctic. Disturbances flow with that air stream and other air mass streams are also pulled into the main stream. Though the specifics of its make up change, the general flow is fairly constant.

The depiction of tropical air meeting polar air is a simplification and convention that does not fully express the complexity or the nature of the situation in Canada or the Toronto region. True tropical air only enters Canada's air space infrequently (usually only in summer) because it is most often modified before it reaches southern Ontario. Much more frequent are subtropical air currents derived from the south eastern United States.

The climate and weather at the surface depends very heavily on the motions of the westerlies and the jet stream, and the disturbances and air streams that are carried along with them.

The consequences in Toronto of the variation in the directions of the general westerly air flow, in the strengths and turbulence of the associated winds, in the temperatures and humidity, and its precipitation, and the ongoing exchange of heat (as sensible and latent heat, and as radiative and convective exchanges) between the air and the land (or lake) surfaces beneath as part of the general circulation - are all very apparent on a day-to-day basis. Further direct influences include El Niño and La Niña, as well as less direct influences such as the North Atlantic

Oscillation, and the Atlantic Multi-Decadal Oscillation (MDO). These are discussed in more detail later.

Local interactions also influence the air everywhere it travels. In the Toronto areas, the Great Lakes and the seasonal vegetation changes, urban land use, urban heat island conditions and impacts, and the topography of the Oak Ridges Moraine and Niagara Escarpment, as well as Toronto's urban canyons all influence the direction and speed of air flow and its basic characteristics of temperatures and water content.

Weather events in Toronto are clearly functions of the general climate and general circulation and the weather system pattern that are created within them, but the weather events in Toronto are also functions of local phenomena and the local interactions between the global and the local phenomena.

The juxtaposition of the general wind direction from west to east and the orientation of the lower Great Lakes (Lakes Erie and Ontario) clearly results in many "snow storms" producing heavy snow in Buffalo but which produce only light snow, or even no snow, in Toronto. Obviously the lake surface over which cold winter winds blow provides extra water to the air, which condenses and ultimately falls as snow. So if the wind blows along the length of Lake Erie picking up moisture which subsequently falls as snow, when the air rises over the land and cools to form snow crystals, as at the eastern end of the lake, then the length of the contact between wind and lake makes a big difference. Whereas cold winter winds that blow across Lake Ontario toward Toronto (unless they blow from the east) do not have as much of a distance to travel over, or exposure to, the lake surface and will gain far less moisture, less snow crystals form and less snow falls. This is a simple comparison known to all Torontonians. But effectively the presence, size and orientation of all the major topographic features (the Niagara Escarpment, the Oak Ridges Moraine, Lake Ontario and Lake Erie, as well as lesser lakes such as Lake Simcoe, and features like the Holland Marsh – can all "localize" the weather experienced by Toronto.

3.6 OVERVIEW BY SEASON

Table 4 presents a summary, by season, of Toronto's weather in terms of the major and minor influences.

Table 4 Toronto's Seasonal Weather Summary

Season	Typical Weather	What Affects the Weather in Toronto?					
		Large Scale Factors			Local Factors		
		Air Masses and Circulation	High/Low Pressure Systems	Hurricanes	Great Lakes	Topography	Urban Heat Island
Spring	• Cool days and nights • Alternating periods of dry, sunny weather with periods of rain	• Transitioning into summer, the spring months become more influenced by warmer air masses such as Maritime Polar air	• Periods of cool, dry, sunny weather are associated with high pressure systems. • Low pressure systems bring overcast skies and precipitation and often milder temperatures.	Not Applicable	• After a long winter, Lake Ontario's cold waters prolong cooler temperatures in Toronto • Can also cause advection fog [3] during the spring	• Toronto is bound to the west by the Niagara Escarpment and the Oak Ridges Moraine to the North which casts a rain shadow on the city and causes Toronto to receive less precipitation than areas to the west and north of these land features • The Humber and Don River valleys create pockets of cooler air which often leads more fog and frost in the spring and fall. The valleys also channel winds. • Tall buildings in Toronto's downtown core are an artificial topographic feature which can either slow down or channel winds. Shadowing from buildings also creates pockets of differing temperatures.	• Artificial surfaces such as asphalt and brick absorb more heat during the day than vegetated surfaces. On calm, cloudy nights, this heat cannot escape. As a result, the average night-time temperature in the city is higher compared to surrounding rural areas
Summer	• Warm to hot days and nights • Moderate to high humidity • Convective precipitation common	• Dominated by cool to warm, dry air masses from the Pacific • Bermuda high strengthens in summer which brings hot and humid air from the Gulf of Mexico to Southern Ontario. Prolonged periods of southerly winds can cause several days of high temperatures and humidity.	• Low pressure systems can cause periods of mild, wet weather. Intense thunderstorms can also occur with the passage of the cold front. • Periods of high pressure create clear, sunny skies. Blocking highs can often result in a heat wave (an extended period of hot weather).	• Beginning in August and extending to late fall, tropical storms have the potential to impact Canada, but rarely reach as far inland as Ontario • Tropical storms can bring large amounts of rain and strong winds • The frequency of tropical storms in Ontario is 11.1 years [2]	• In early to mid-summer, Lake Ontario is quite cool relative to inland temperatures which creates lake-breezes during the day, and land-breezes at night • Creates more cloud cover and convective precipitation as it is a source of moisture, especially in late summer when the lake has warmed		
Fall	• Cool days and cool to cold nights • Alternating periods of dry, sunny weather with periods of rain	• Transitioning into winter, the Bermuda high begins to weaken, and the Arctic lows strengthen, bringing outbreaks of cold air into Southern Ontario	• Periods of cold, dry, sunny weather are associated with high pressure systems. • Low pressure systems bring overcast skies and precipitation and often milder temperatures.		• After the summer has passed, Lake Ontario is warm relative to the air above it. This keeps Toronto warmer longer than without the presence of the Lake. • Warmer lake temperatures keeps frost at bay in the fall • Cloud is more common in the vicinity of the lake as it is a source of heat and moisture		
Winter	• Cool to cold temperatures • Alternating periods of dry, cold days with periods of precipitation (usually snow) • Winter storms common	• Dominated by Continental Arctic air masses which are cold and dry. This air mass can also be modified by passing over lakes, making it moist. • Moist and mild air from the southwest US sometimes influences southern Ontario	• High pressure in the winter creates dry, clear skies and cold night time temperatures as heat easily escapes through a cloudless sky • Low pressure systems (or winter storms) often pass by, bringing milder air and sometimes large amounts of snow. Gulf [1] Lows bring heavy amounts of snow as they draw upon heat and moisture from the Gulf of Mexico. Alberta clippers are another common winter low affecting Toronto, but are much drier.	Not Applicable	• Cloud is more common in the vicinity of Lake Ontario in early winter when the lake is still warm relative to areas inland • Lake-effect snow typically develops over Lake Huron rather than Lake Ontario. Sometimes this snowfall can reach Toronto, but it usually only extends as far east as Middlesex County • Storms approaching Toronto from a southerly direction, can draw upon heat and moisture from Lake Erie or Lake Ontario and intensify storms • Lake ice will block the transfer of heat and moisture to the atmosphere		• Due to residential and commercial heating, the heat island effect results in higher day-time and night-time temperatures compared to rural areas

Notes:

1. Also known as Texas Lows
2. Environment Canada. 2005. *Atmospheric Hazards – Ontario Region: Hurricanes and Tropical Storms.* Available online: <http://ontario.hazards.ca/maps/background/Hurricane-e.html> [2010 October 4].
3. Advection fog occurs when warm, moist air pass slowly over cool surface waters causing the moisture in the air to condense.