# Project Atmosphere Canada

MODULE 7

## Clouds

Teacher's guide

Canadian Meteorological and Oceanographic Society
La Société Canadienne de Météorologie et d'Océanographie

Environment Canada
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Canada

## Project Atmosphere Canada

Project Atmosphere Canada (PAC) is a collaborative initiative of Environment Canada and the Canadian Meteorological and Oceanographic Society (CMOS) directed towards teachers in the primary and secondary schools across Canada. It is designed to promote an interest in meteorology amongst young people, and to encourage and foster the teaching of the atmospheric sciences and related topics in Canada in grades K-12.

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On behalf of
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## MODULE 7 Clouds

# BASIC UNDERSTANDINGS

1. Clouds are collections of tiny water droplets and/or ice crystals in the atmosphere in concentrations great enough to be seen.
2. Clouds present visible signs of air motions.
3. Clouds are essential atmospheric components of the water cycle, producing the rain and snow that return water to the earth's surface.

## Cloud Formation

4. Clouds form when air is cooled to temperatures at which some of the water vapour in the atmosphere condenses to liquid or sublimates to ice. This happens because, as the temperature of a parcel of air decreases, there is a corresponding decrease in the amount of water vapour that can exist within it.
5. Most cloud formation and growth result from the cooling that occurs due to the expansion of rising air.
6. Cloud particles form when water vapour condenses on salt, dust and other minute particles in the atmosphere.
7. Clouds particles can be composed of liquid droplets or frozen crystals, or both. Clouds can contain liquid droplets through a broad range of below-freezing temperatures.
8. Fog is a cloud in contact with the earth's surface

## Air Motions and Temperatures

9. Rising air encounters lower atmospheric pressures. This allows expansion that results in the lowering of temperatures within the upward moving air.
10. Rising air, as long as it is not fully saturated with water vapour, cools by expansion at the rate of 10 Celsius degrees for each kilometre gain in altitude.
11. Condensation will begin when the temperature of the rising air drops to the dew point and continues to cool beyond that temperature. The height at which the air becomes saturated will determine the height of the cloud base.
12. Rising air, when saturated with water vapour, cools at a slower rate than air that is not saturated with water vapour. The release of latent heat during the condensation process in saturated rising air decreases the parcel's cooling rate to 5 Celsius degrees per kilometre.
13. Sinking air encounters greater air pressures and warms by compression. Warming leads to the full or partial evaporation of any existing clouds.

## Cloud Shapes and Air Motions

14. Cloud shapes are keys to determining atmospheric conditions and motions.
15. Widespread, smooth, layered cloud forms are generally indicators of more horizontal than vertical air motions. They signal a *stable* atmosphere.
16. Air is *stable* when, if forced to rise, its cooling produces temperatures lower than those in the surrounding air at the same levels. The uplifted air, being cooler, is denser than the air around it

and will sink back to its original level and only continue to rise if compelled to do so by other forces.

17. Heaped" or "lumpy" clouds result when strong vertical motions exist in the atmosphere. They point to *unstable* atmospheric conditions that can mean stormy or severe weather.

18. Air is *unstable* when, if forced to rise, its temperatures are higher than those in the surrounding air at the same elevations. The rising air, now being relatively warmer and less dense, accelerates upward producing turbulent eddies and strong vertical movements.

19. Local surface heating on sunny days can produce clouds with large vertical development. The clouds form where air is rising and are separated by clear regions where air is sinking.

20. The tops of towering clouds lean downstream when winds aloft are faster than those at lower levels. Thunderstorm anvils are examples of such high-level wind patterns.

## Clouds and Precipitation

21. Cloud particles, water droplets and ice crystals must be greatly enlarged if they are to attain sizes large enough to fall as rain or snow. Typically, it takes close to a million cloud droplets to provide enough water for each raindrop.

22. Precipitation at middle and high latitudes ordinarily begins in clouds where ice crystals and supercooled water droplets co-exist. Supercooled water is liquid water whose temperature is below the freezing point (0 degrees Celsius) while remaining in the liquid state. Such supercooled water droplets in clouds can exist at temperatures as cold as minus 17 degrees Celsius. Small pure water droplets may remain unfrozen at even colder temperatures. At temperatures below 0 degrees Celsius, ice crystals grow at the expense of surrounding water droplets. As the crystals enlarge, they fall faster through the cloud.

23. Ice crystals falling through a cloud can grow by adhering to other crystals or by accumulating supercooled droplets that freeze to them. These cloud particles may grow large enough to overcome the push of rising air currents and fall earthward as precipitation.

24. When below-freezing temperatures exist down to the earth's surface, falling ice crystals arrive at ground level as snow. If temperatures warm to above freezing as the crystals descend, they will melt to fall as raindrops. Occasionally, a shallow layer of below-freezing air near the earth's surface will cause the raindrops to become supercooled and freeze on contact with the surface, producing hazardous freezing rain. But if this second freezing layer is thick enough, the droplets will freeze and form ice pellets.

25. Precipitation can begin as rain in clouds whose temperatures are entirely above freezing. In this case, drops of many different sizes fall at different rates, causing larger droplets to intercept and capture smaller ones. After many such collisions, raindrops large enough to fall earthward are formed.

26. Large variations in raindrop sizes can result from wide variations in the strength of upward motions within clouds. Larger

drops are formed in strong updrafts that can hold them aloft longer. Smaller drops are generally associated with weaker rising motions in the clouds.

27. The heights of cloud bases indicate the atmosphere's humidity conditions and the likelihood of precipitation. Clouds with low bases have formed easily in humid air with precipitation being possible. High-based clouds mean drier air which had to rise further to achieve saturation, and there is less likelihood of precipitation reaching the ground.

28. Severe thunderstorms formed under very unstable atmospheric conditions can produce heavy rains with localized flooding, frequent lightning, hail, damaging winds and tornadoes.

**NARRATIVE** Clouds

## Introduction

Clouds are an ever-present feature of the earth's atmosphere. Everyday, around the world, many different types of clouds are seen overhead. We often look at the clouds above us and try to imagine the shapes and figures that they resemble. But clouds tell us much more. They are visible signatures of the motion and conditions of the air in which they exist.

Clouds consist of tiny liquid water droplets or ice crystals or a combination of both. Because these particles are so small, even weak swirls of air movement can keep them suspended indefinitely. It is the multitude of tiny water particles, whether liquid or ice, that interacts with rays of light to make clouds visible.

## Water Vapour and Clouds

If you have ever been in a fog (literally) or have seen your breath on a cold day, or perhaps, flown in an airplane through the clouds, you have seen clouds first hand. To make a cloud, air needs only to be cooled to saturation and beyond. What does this mean?

The atmosphere contains a mixture of invisible gases, primarily nitrogen and oxygen. A small portion of the mixture is <u>always</u> water vapour, although the amount can vary widely. Water vapour is the only atmospheric gas that can change its state from a gas to a liquid or solid under temperature and pressure conditions that occur naturally in the atmosphere. When cooled sufficiently, the invisible water vapour will change into a visible form, water droplets or ice crystals, thus forming clouds and fog.

There are limits to how much water vapour can be present in the air. Temperature is the factor that best relates to the maximum amount of water vapour that can exist. Usually the amount of water vapour in an air mass is less than the maximum possible. We describe such air as being *unsaturated*.

If we add more vapour to that same air mass, we could reach the maximum capacity for its particular temperature. This air would then be *saturated.* More commonly, saturated conditions in the atmosphere are achieved by the cooling of air. As the temperature of a parcel of air decreases, so does the potential quantity of water vapour that may exist within it. Consequently, cooling of an air parcel will eventually reduce its water vapour capacity until it is equal to the amount of water vapour actually present. The air is then saturated. The temperature at which saturation is achieved by cooling is called the *dew point temperature*, or simply, *dew point.*

Most clouds are produced by the cooling of air that, for one reason or another, moves upward in the atmosphere. Air may move upward through lifting at a weather frontal surface, flow up a mountainside or solar heating of the ground. The cooling occurs when rising air encounters lower air pressures at higher altitudes and thus expands. This expansion cools the unsaturated air by 10 Celsius degrees for each kilometre of rise. With cooling comes a lower capacity for water vapour. Continued cooling will eventually cause saturation after which the condensation of water vapour to cloud droplets begins. When condensation begins, the heat that was originally required to evaporate the water and stored within the water vapour molecule as latent heat is released. The release of latent heat to the air offsets some of the cooling caused by expansion, thus the cooling rate of the rising saturated air decreases to 5 Celsius degrees per kilometre.

Conversely, a parcel of air sinking through the atmosphere is compressed and thus warmed. Unsaturated air warms 10 Celsius degrees for each kilometre it descends. However, when cloud droplets evaporate away within the sinking air, it warms at a slower rate because the process of evaporation requires heat energy to transform the liquid to the vapour state (the latent heat of evaporation). Clouds can, and often do, disappear entirely through evaporation of their water droplets in sinking air.

## Cloud Formation

The actual process of cloud formation is quite complex. First, particles, called condensation nuclei, on which the water can condense must be present in the air. Fortunately there are almost always enough particles including sea salts, smoke, and automobile exhaust particles to act as condensation nuclei.

Next, we must have rising motions in the air. These upward motions may be the consequence of airflow over rising terrain, along a weather front, or from local heating of air by warm surfaces. If unstable atmospheric conditions exist, upward motions may be accelerated. Once condensation begins, the release of latent heat by the forming droplets will also help the air to continue rising. If lifting continues to altitudes where temperatures are cold enough, ice crystals may form. Rising motions must also be sufficiently persistent to continually supply excess vapour to growing droplets.

## Convection and Clouds

Sunlight passing through the atmosphere strikes the earth's surface where a portion of its radiant energy is absorbed to heat the surface. The air located just above the heated surface is then warmed by direct contact, a transfer of energy called *conduction*. Heated air expands and becomes less dense than the cooler air above. Variations in surface heating and other factors cause surrounding cooler, denser air to push in and force the lighter, warm air upward. This motion of the air, resulting in the transport and mixing of its properties, is called *convection*. Convection is a major transport process for heat energy and water vapour in the atmosphere.

Rising currents of warm air, called *thermals*, are produced by solar heating throughout the year, but they are especially strong during the spring through autumn months when the sun's energy is strongest. Soaring birds and sailplane pilots seek these currents to gain altitude for long glides across the countryside. If a thermal remains warmer than its surroundings, it may rise sufficiently high to cool to its saturation point. Thermals usually make their presence known to us by producing cumulus clouds atop the rising air column. Such clouds are known as *convective clouds*. The various forms of cumulus clouds from the small puffs of fair-weather cumulus to the towering cumulonimbus are all convective clouds.

Thermals can also be generated when cold air moves over comparatively warm surfaces such as large bodies of open water. This phenomenon is particularly common over large lakes such as the Great Lakes in autumn and early winter because the lakes cool much slower than adjacent land areas. The cumulus clouds that form in cold Arctic air as it traverses a much warmer water surface often grow quite tall, feeding on the heat and moisture supplied by the lake.

## Clouds and Air Motions

The resulting shape, number, size and motion of clouds give clues to the properties of the surrounding, invisible air and what that air is doing. While rising unsaturated air cools at the 10 C° per kilometre rate (or at a lower rate within a saturated cloud), it may be warmer or cooler than its surroundings because the temperature of the surrounding air also varies with height above the ground.

The graphic which describes the change of temperature with height is called the *temperature profile* curve and in Canada the temperature profile is often depicted on form called a *tephigram.*

When an air parcel is cooler than the surrounding air, it is "heavier" and tends to sink back to a lower level. This is called *stable* air. Clouds formed in stable air tend to produce long, flat layers of cloud, termed *stratus*-type clouds (for "layer"). The airflow within stratus clouds is generally smooth, and associated precipitation, if any, is light and steady.

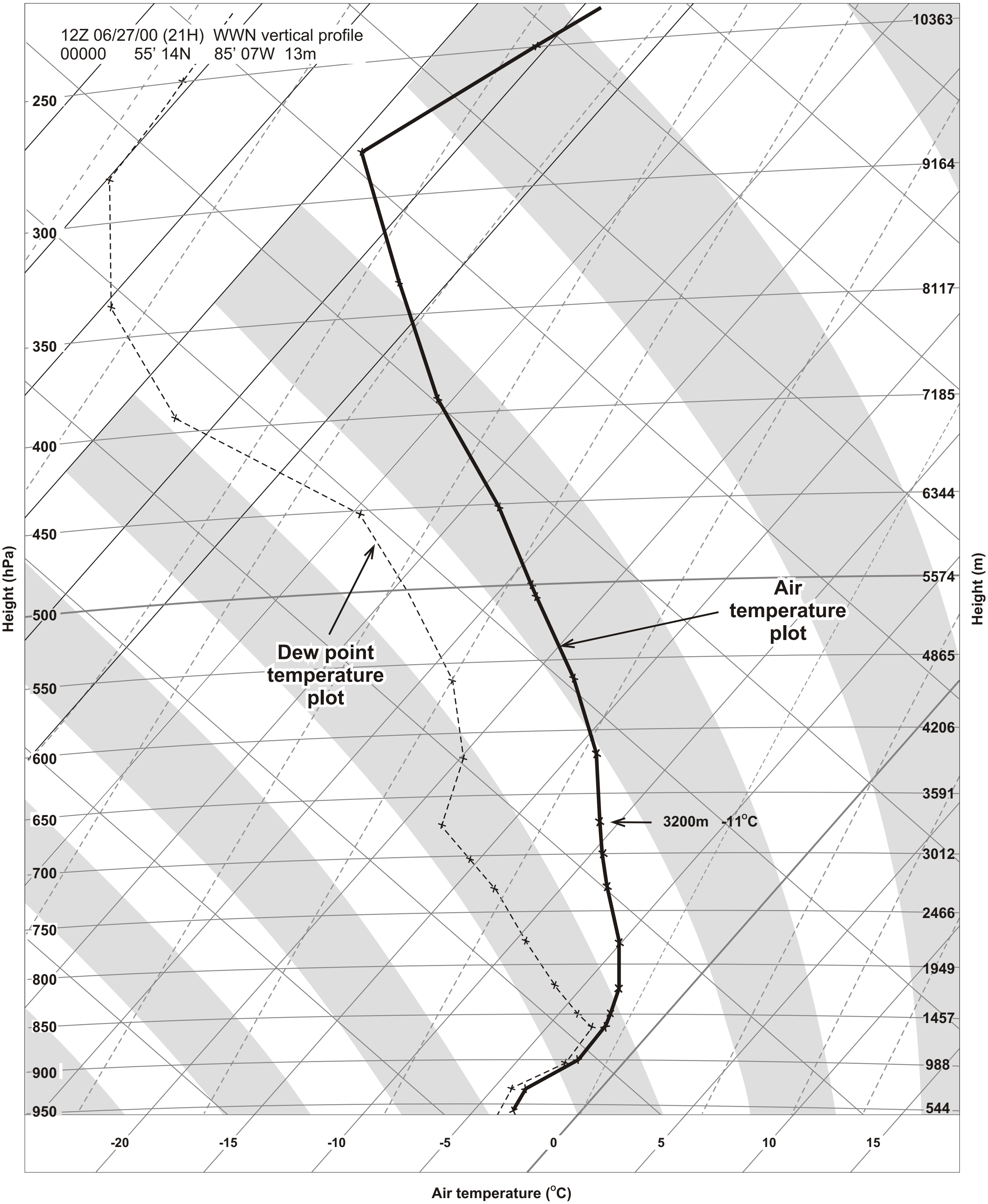
Stable air is likely to be present in fair weather as well. Those vertical temperature patterns that make air stable can also lead to air pollution episodes. The smoke plumes from chimneys and smokestacks during stable conditions do not readily spread. As a result, concentrations of harmful pollutants within them can remain high causing potentially unhealthy situations.

On the other hand, rising air, even though cooling, may still remain relatively warmer than the surrounding air through which it rises. The rising air is thus lighter than its environment, and ascends like a hot-air balloon. Rising vertical currents known as updrafts are characteristic of *unstable* air. The updrafts can cause turbulent swirls and eddies along their edges. Such turbulence is another characteristic of unstable air and can be seen in the "lumpy" look of clouds formed in unstable air.

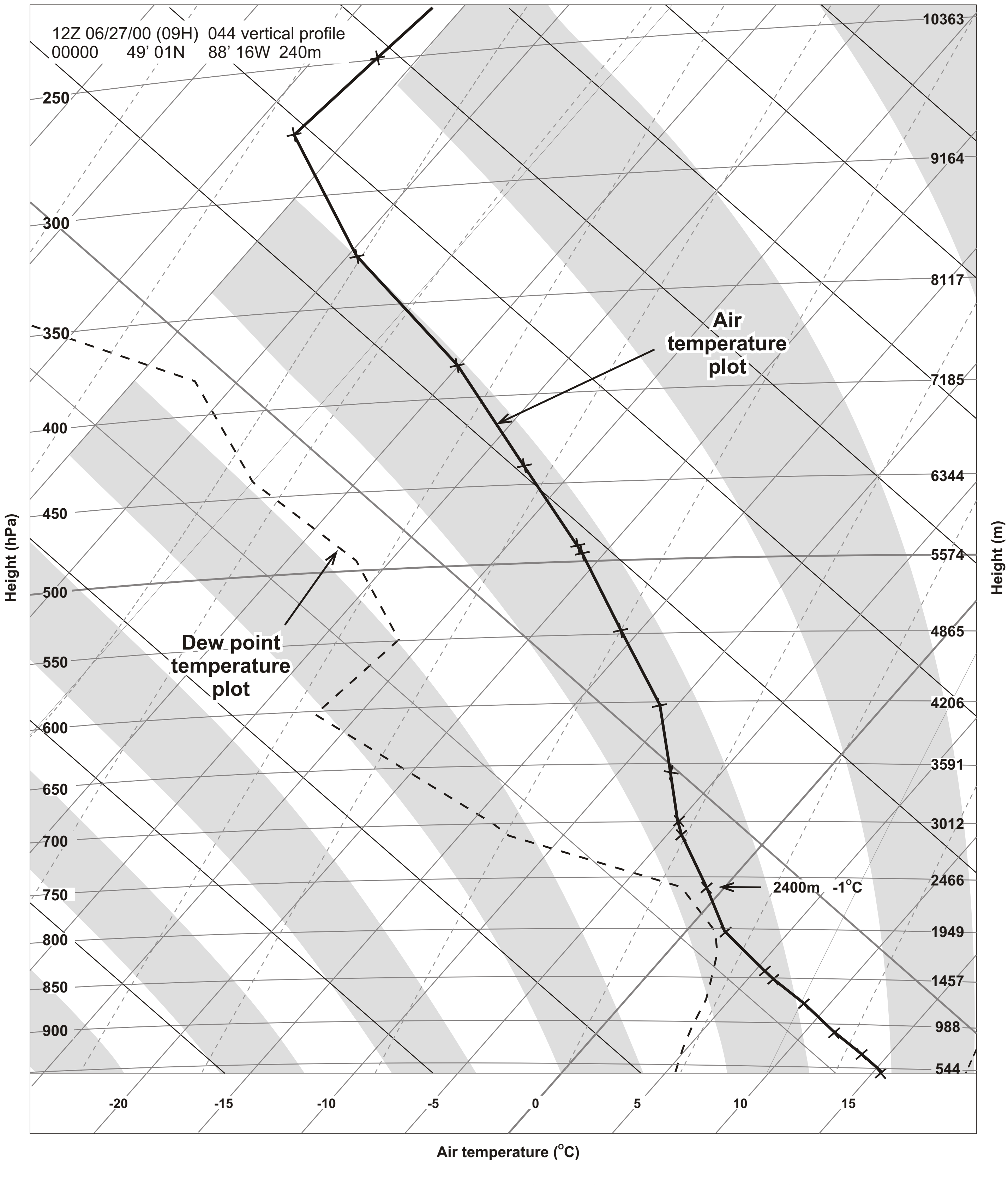
"Lumpy" and "heaped" clouds formed under unstable conditions are categorized as *cumulus*-type clouds. Solar heating of the ground during clear weather can produce locally rising currents over which fair-weather cumulus clouds develop while sinking air motions between them surrounds the cumulus with blue skies. Widespread and strong unstable conditions lead to the development of dramatic cumulonimbus clouds which produce thunderstorms and other severe weather. Showers and rapidly changing weather usually accompany the largest cumulus clouds.

Each cumulus cloud variation has individual properties that characterize the environment in which it forms. On very windy days, the fair-weather cumulus clouds may be torn and scattered, while calmer days produce the classic "cotton puffs" that seem to hang motionless in the sky. Strong winds at higher altitudes can cause cloud tops to tip relative to their bases. The most dramatic example of the impact of such winds is seen when the tops of thunderstorms take on the classic "anvil" shapes when seen from a distance. Wave patterns may even form on cloud tops or in bands of clouds as the air moves up and down in its travels. Often such patterns can be seen in air crossing mountains or similar topographical features.

The accompanying figure shows the basic classification scheme for cloud patterns as determined by their appearance and process of formation. Cirrus-type clouds are always composed of ice crystals, while most other cloud types may be either entirely liquid drops or a mix of ice crystals and water droplets. Mid-level clouds have names beginning with *alto* (meaning "middle"). Clouds having precipitation falling from them are referred to as *nimbus* (meaning "rain") clouds. Along with *cumulus* (heap) and *stratus* (layered), the various basic terms can be combined to describe ten general cloud forms.

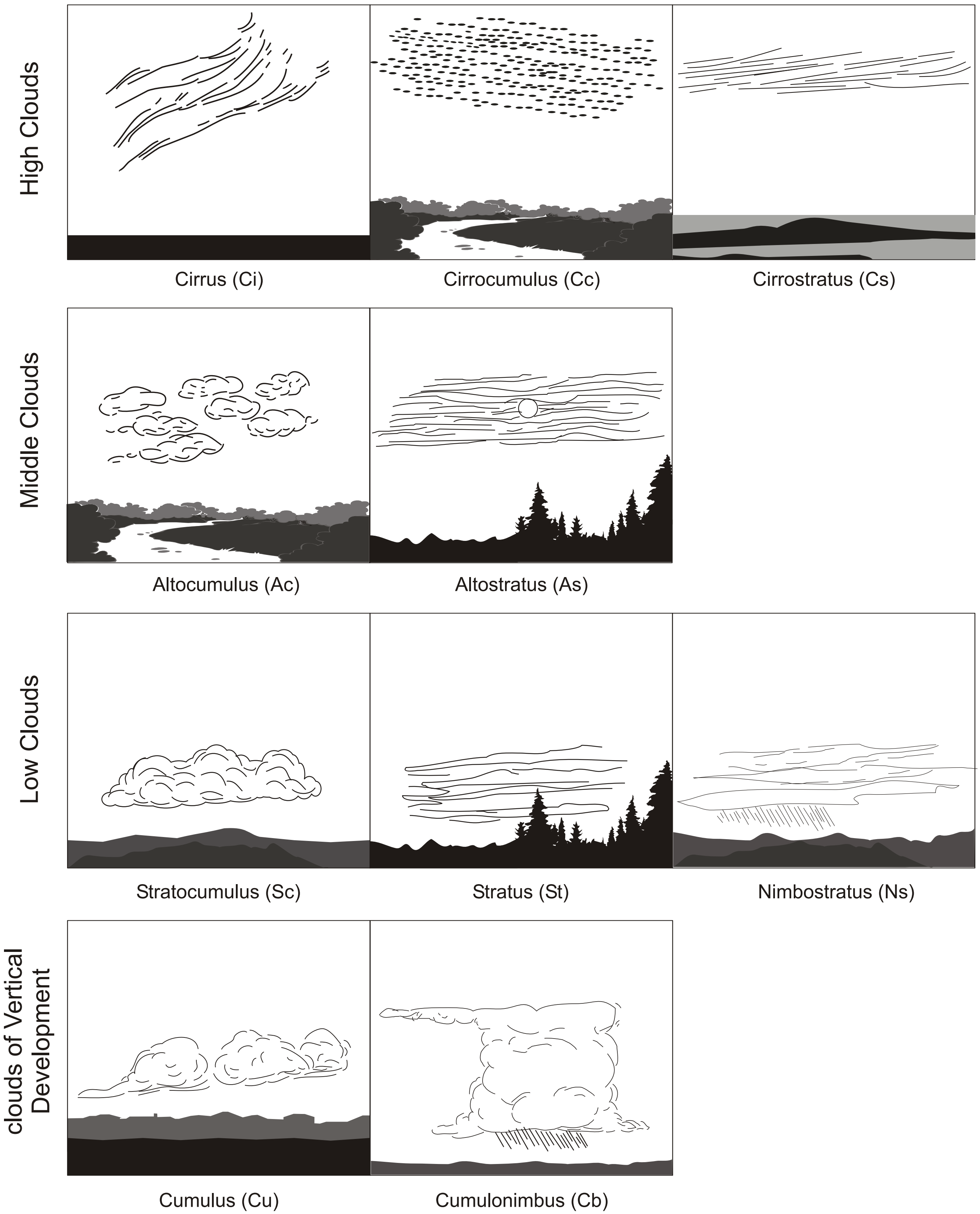



A Tephigram plot of the vertical temperature profiles of the air temperature (solid line) and dew point temperature (dashed line) in stable air. The vertical heights shown on the Tephigram are above Mean Sea Level values.




A Tephigram plot of the vertical temperature profiles of the air temperature (solid line) and dew point temperature (dashed line) in unstable air. The vertical heights shown on the Tephigram are above Mean Sea Level values.

# Cloud Types


High Clouds
Cirrus (Ci)
Cirrocumulus (Cc)
Cirrostratus (Cs)
Middle Clouds
Altocumulus (Ac)
Altostratus (As)
Low Clouds
Stratocumulus (Sc)
Stratus (St)
Nimbostratus (Ns)
clouds of Vertical Development
Cumulus (Cu)
Cumulonimbus (Cb)

**Web page references for additional information on cloud types and pictures:**
A cloud boutique from Plymouth State College in New Hampshire
http://vortex.plymouth.edu/clouds.html

Cloud types from the University of Illinois
http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/cld/cldtyp/home.rxml

Cloudman's (Dr John Day) Gallery of Clouds
http://www.cloudman.com/index.htm

Wolken - Der Karlsruher Cloud Atlas
http://www.wolkenatlas.de/

The Weather Doctor (Dr. Keith Heidorn)- Cloud Atlas
http://www.islandnet.com/~see/weather/eyes/cloudatlas.htm

## Clouds and Precipitation

With one exception, clouds are necessary for precipitation to occur; however, not all clouds produce rain or snow. In fact, precipitation is a relatively rare event considering clouds are so common. For precipitation to occur, conditions within the cloud must include sufficient rising motion to create adequate condensation. Additionally, there must be enough water vapour fed into the cloud to sustain the growth of cloud particles. A number of processes must operate on a massive scale to bring together the huge number of cloud particles required to make precipitation happen. On average, one million cloud droplets have to combine to form one typical raindrop! Once formed, the raindrops or ice crystals must then grow heavy enough to overcome the updraft of air in which they formed before they can fall earthward. Finally, they must survive evaporation as they drop to the surface.

The one previously noted exception is a form of cloudless precipitation called *ice crystals* which occur when moisture sublimates into minute particles of ice in very cold air near the surface. These tiny ice particles can fall from a cloudless sky and often fall so slowly they seem to be suspended in the air. Because they glitter in the sunshine, ice crystal precipitation is sometimes referred to as *diamond dust*. This type of precipitation is most common in polar regions because it only occurs at very low temperatures in stable air, but may be seen in many other areas of Canada during very cold conditions.

Clouds generally form first as water droplets or supercooled water droplets in rising air motions. Supercooled water droplets are merely small cloud droplets that remain in their liquid form at temperatures well below freezing. The more water vapour present in the air, the sooner the air can be cooled to saturation and the more moisture can become available for droplet growth.

Continued rising and cooling will condense more water into cloud droplets, but ice crystals are usually needed to initiate precipitation. At below-freezing temperatures where ice crystals and liquid droplets co-exist, the crystals grow faster than the droplets from the surrounding water vapour. Ice crystals soon collide with each other or with droplets that freeze on them, causing further enlargement. When large ice particles form, they may more easily overcome the cloud's updrafts than smaller liquid droplets. The large quantity of water vapour in summer thunderstorms, combined with very strong updrafts, may produce large ice particles that finally plummet to earth as hailstones.

The type of precipitation that arrives at ground level is closely related to the atmospheric temperatures in which it forms and eventually falls through. If the temperature remains below freezing from the cloud down to the ground, precipitation reaches the earth as *snow*. When those same ice particles fall through an air layer with temperature above 0°C, they melt in the warmer air to become *rain*. With surface temperatures hovering around the freezing point, precipitation may fall as a mixture of types.

When multiple temperature layers are present, other forms of precipitation may fall, some of which can be especially hazardous. Snow falling through a warm layer may melt into rain, but then may cool sufficiently while falling through a thick second cold air layer near the surface to be refrozen into *ice pellets*. However, if the rain falls through a *shallow* layer of below-freezing air near the surface, it may remain liquid but be supercooled, ready to solidify on contact with the surface as *freezing rain*.

## Severe Local Weather

Large convective clouds can produce severe weather that is local in nature. Local severe weather is usually confined to a relatively small area, in contrast to severe weather generated by large synoptic-scale weather systems such as hurricanes and winter storms forms described in the "Hazardous Weather" module.

The most common forms of severe local weather in Canada arise from thunderstorms and lake-effect snow squalls.

## Severe Thunderstorms

Local severe weather most often develops from massive cumulonimbus clouds, or "thunderheads" which produce thunderstorm of varying strength. Most severe thunderstorm outbreaks form when the air temperature is above 20°C. Thus, for most of Canada they occur from mid-spring until late summer.

The Meteorological Service of Canada maintains Weather Centres across the country that closely monitor local weather conditions that could develop into severe weather and issue *watches* and *warnings* when warranted. When conditions appear favourable for severe thunderstorm development, the Meteorological Service of Canada issues a Severe Thunderstorm Watch, usually a number of hours in advance of the potential storm's occurrence. When severe thunderstorms are imminent, the Meteorological Service of Canada issues a Severe Thunderstorm Warning. Severe thunderstorms can produce frequent lightning, heavy rain, strong winds, hail and even tornadoes.

The ideal conditions for severe

thunderstorm formation are found when the lowest two kilometres or so of the atmosphere are very warm and humid. Warm, humid air may arise from strong solar heating and ground evaporation, or from the northward flow of tropical air from the Gulf of Mexico under large-scale weather patterns. Severe thunderstorm development is greatly enhanced when the hot, humid air in the lower atmosphere has a cool, dry air layer above it. This cool, dry air - a few kilometres above the surface - generally flows off the western continental mountain ranges and moves eastward across the Great Plains of the U.S. and the Prairies.

The formation of severe local thunderstorms usually proceeds in the following manner. As the day progresses, a strong sun heats the air near the ground. When parcels of air become warm enough, thermals will form and begin to rise. As the thermals rise, they eventually reach the level where their air becomes saturated. At this altitude, a cumulus cloud begins to form. If the air above the thermal is sufficiently cool and dry, the warm rising air remains much more buoyant than its surroundings, and the thermal with its capping cloud may rise dozens of kilometres into the sky, often with explosive speed. Under such very unstable and strongly convective conditions, extremely large cumulonimbus clouds develop. These clouds can produce strong thunderstorms with heavy rains, lightning and strong, gusty winds. With enough instability and the proper wind patterns within the storms, tornadoes can also be spawned.

While property damage from tornadoes may cost Canadians millions of dollars yearly, tornado deaths are uncommon in this country.  Most years go by without a single tornado fatality.  However, Canada is not totally immune: in the period 1985-2000, the country experienced 3 of its 5 deadliest tornadoes in more than a century.

In Canada, wind damage during severe thunderstorms is more commonly caused by *downbursts* or *microbursts* and not by tornadoes. Downbursts and microbursts are powerful downdrafts within cumulonimbus clouds that can achieve speeds in excess of 100 km/h. When these downdrafts strike the earth, they fan out at or just above the surface. The results are" straight-line" winds of sufficient strength to tear roofs off buildings and uproot trees. Because of their destructive nature, downbursts and microbursts are often mistaken for tornadoes.

Lightning, on the other hand, kills an average of 7 people each year in this country, and over 100 people each year in North America. Lightning is responsible for starting over 40% of Canada's forest fires, costing the nation's economy billions of dollars annually.

Across the continent, hail, too, produces hundreds of millions of dollars of damage each year, mainly to crops and property. Complete crops can be destroyed in minutes when a hailstorm sweeps across a region. Canada's "hailstorm alley," located in the high plains of Alberta between Edmonton and Calgary, destroys about three percent of the total crop in that region on average each year.

## Lake-Effect Snowsqualls

The change of seasons brings a different severe weather threat from convective clouds: *lake-effect snowsqualls*. Large water bodies such as the Great Lakes are slow to cool down from their summer maximum water temperatures, and therefore, in autumn and early winter, they can be several degrees warmer than adjacent land areas.

Cold air moving across such a large reservoir of heat and moisture will receive an increase in the temperature and humidity of its lowest air layer. Thus, rising thermal currents develop in the now unstable air (warm air below, cold air above). Towering cumulus clouds will form as this air flows across the lake. By the time the air reaches the leeward shore, snow may be ready to fall in the form of snow showers or snowsqualls. The longer the trajectory of the cold air over the warm lake, the greater the likelihood of heavy snowsqualls. Strong low-level winds often channel these squalls into rows or "streamers" that come onshore in bands, bringing sudden bursts of heavy snow and near-zero visibility.  Snowfall accumulations of 25 cm in 12 hours are not uncommon in "snowbelts" on the lee side of large lakes during persistent snowsqualls.