# Project Atmosphere Canada

MODULE 12

# Water Vapour and The Water Cycle

Teacher's guide

Canadian Meteorological and Oceanographic Society
La Société Canadienne de Météorologie et d'Océanographie
Environment Canada
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## 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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Eldon J. Oja
Project Leader  Project Atmosphere Canada
On behalf of
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## MODULE 12 Water Vapour and The Water Cycle

# INTRODUCTION

The substance known as water exhibits a unique set of chemical and physical characteristics. These unusual properties include its ability to exist as solid, liquid or vapour at the temperatures and pressures found at and near the Earth's surface. This enables water to circulate through the atmosphere, ocean and solid earth, forming endless cycles which are known collectively as the hydrologic or water cycle. Water vapour plays a key role in the water cycle while acting as a small but critical atmospheric constituent. This module investigates the role of water vapour in the atmosphere; where it comes from, where it goes, how it is measured, and how its presence can be detected.

# BASIC UNDERSTANDINGS

## The Substance Water

1. Water is a unique substance that is essential to life and a key ingredient of our weather and climate system.
2. Water is the only naturally occurring substance found in significant quantities in solid (ice), liquid (water) and gaseous (vapour) phases at the temperatures and pressures found at and near the Earth's surface.
3. Water substance changes phase with relative ease at and near the Earth's surface, and is continually flowing to, through, and from the atmosphere.
4. The atmosphere, with water vapour playing a major role, maintains the hydrologic (water) cycle by redistributing water from land and ocean reservoirs to every place on Earth, the highest elevations included.
5. Large quantities of heat energy, called latent heat, are absorbed (released) when water changes phase from vapour to liquid to solid (solid to liquid to vapour). The energy absorbed or released during these phase changes in the atmosphere have a major impact on weather and climate.

## The Water (Hydrologic) Cycle

6. The overall picture of the exchange of water in all its phases among the atmosphere, ocean and solid earth is called the water cycle.
7. The global atmosphere contains just 0.001% of the water found near the Earth's surface, while the other major reservoirs are the oceans (97%), ice caps and glaciers (2%), ground water (0.6%), and rivers and lakes (0.01%).
8. Compared to the other global water reservoirs, the residence time of water substance in the atmosphere is very short. Every ten days, the amount that passes through the atmosphere is equal to its total water content at any one time.
9. Water enters the atmosphere by evaporation. Atmospheric motions transport the vapour elsewhere and, eventually, it condenses and may return to the Earth's surface as precipitation.
10. The atmospheric component of the water cycle is the only one that "runs up hill". The transfer of vapour by way of the atmosphere is the basic supply of water for precipitation material.
11. While there is as much water vapour entering the *global atmosphere* as there is leaving it, such a balance does <u>not</u> exist at most individual locations

## Water Vapour

12. The amount of water vapour in air can range from near zero up to about 4% in a volume.
13. Because water substance can exist in different phases within the temperature and pressure ranges found in the atmosphere, there are upper limits to the concentration of the water vapour phase

in air. The maximum capacity of a volume of air to hold water vapour depends solely on temperature, and increases as temperature increases.

14. The maximum water-vapour capacity of a volume approximately doubles for each ten Celsius degree temperature increase. Similarly, a ten-degree drop in temperature nearly halves the capacity of a volume to hold water vapour.

15. One measure of the amount of water vapour actually in the air is called the *absolute humidity*. Absolute humidity is the mass of water vapour in a unit volume (this is water vapour density, commonly measured as grams of water vapour per cubic metre). An alternative way to express absolute humidity is *mixing ratio*, which is the ratio of the mass of water vapour to the mass of dry air in the atmosphere, commonly expressed in grams (g) of water vapour per kilogram (kg) of dry air. Typical mixing ratios range from 1.5-15.0 g $kg^{-1}$ near the Earth's surface to 0.3-3.0 g $kg^{-1}$ at 500 hPa (~5.5 km ASL).

16. *Relative humidity* is expressed in per cent and is the ratio of the amount of water vapour actually present in air to its maximum capacity at that temperature, times 100.

17. *Dew point* (or dew-point temperature) is the temperature to which air must be cooled (at constant pressure) without changing the amount of water vapour, so that the amount of water vapour actually in the air is equal to the maximum amount that can be in the air at that same temperature.

## Saturation and Precipitation

18. A volume filled to its capacity by water vapour is said to be *saturated*. When air is saturated, its relative humidity is 100%, and its dew point is the same as its temperature.

19. Liquid water and ice can change to vapour at any temperature they exist. Such phase changes will occur when the region above the water or ice is not saturated with water vapour.

20. If saturated air is cooled, enough condensation will take place to maintain saturation. This process results in clouds in the atmosphere or fog formation near the ground.

21. The formation of clouds can lead to precipitation. Precipitation is composed of any or all of the forms of water particles, whether liquid or solid, that fall from clouds and reach the ground. These forms include snow, rain, drizzle, and hai1.

## Water Vapour Observation

22. Water in the forms of both invisible vapour and visible cloud particles is transported by winds and vertical motions throughout the global atmosphere.

23. Although transparent to visible light, water vapour is detectable by weather satellites because it is an efficient absorber and re-emitter of certain wavelengths of infrared radiation.

24. The special infrared sensors aboard weather satellites have revealed regions of increased atmospheric water vapour concentration. These regions, sometimes

resembling gigantic swirls or plumes, can be seen to flow within broad-scale weather patterns.

25. Current research suggests that at any one time, atmospheric water vapour may be found concentrated in several large flowing streams forming the equivalent of "rivers in the sky".

# NARRATIVE

## Water and Water Vapour

Liquid water covers over two-thirds (71%) of our planet's surface, while constituting over half the mass of protoplasm, the substance of living matter. Ice covers nearly 10% of the Earth's land surfaces in the form of ice sheets and glaciers. Atmospheric water vapour is the parent of clouds and precipitation while playing a major role of transporting energy on a global scale. Water in the Earth's environment has the remarkable property of being the only substance that exists naturally in significant quantities in all three states - solid (ice), liquid (water),and gas (vapour) - at the temperatures and pressures found at and near the Earth's surface.

Water vapour, invisible to the eye, is an extremely important atmospheric constituent. It is primarily in the vapour phase that water substance is transported in air from place to place on a global scale. Its condensation leads to clouds, which in turn can produce precipitation. The atmosphere transports huge quantities of water (vapour) and energy (latent heat), redistributing these so as to maintain a balance of water and energy all over the globe. The water vapour also continually absorbs infrared (heat) radiation, further complicating the Earth's energy balance.

## Water Vapour in the Water Cycle

The hydrologic or water cycle is an overall picture of the movement and exchange of water substance among the atmosphere, ocean and land. Within the atmosphere, an unending flow of water substance is maintained as energy from the sun evaporates enormous quantities of water from ocean and land surfaces. Winds transport the moistened air to other regions where the water vapour condenses to form clouds, some of which produce rain and snow. When precipitation falls into the ocean, the water is ready to begin its cycle again. When it falls on land, it may evaporate back to the atmosphere, or begin what can be a complex journey back to the ocean.

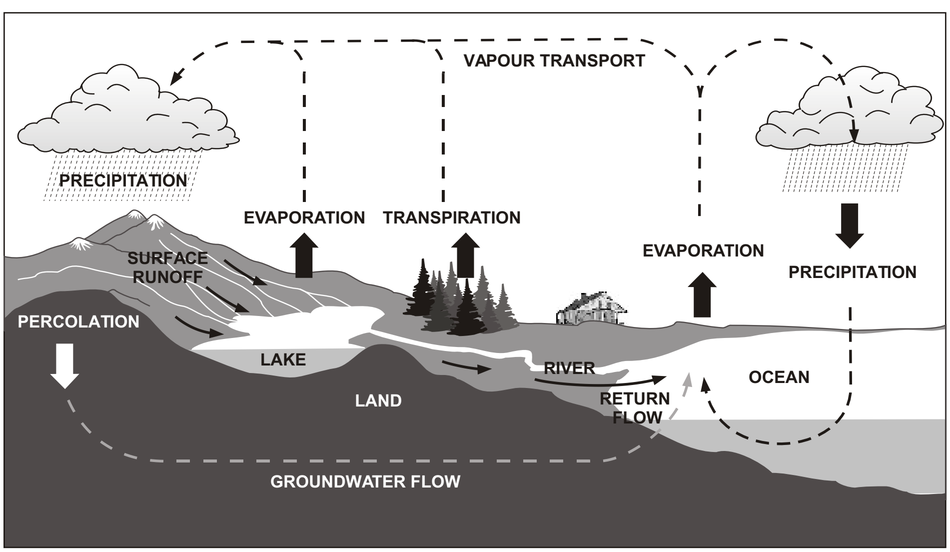


Illustration of some of the complexities of the water cycle

Although the overall water cycle is very complex, the segment with which we are most concerned has water substance travelling from the ocean to the atmosphere, through the atmosphere, and back to the Earth's surface. This produces precipitation and the fresh water necessary for life beyond the oceans. It is only the atmospheric portion of the water cycle that can restore the water substance, in vapour form, back to the level where it can begin the downward flow to completion in the ocean.

At any given time, only 0.001% of Earth's water is in the atmosphere while 97% is in the world's oceans. Additionally, approximately 2% is in ice fields and glaciers, 0.6% is in ground water, and 0.01% is in rivers and lakes.

While 24% of all precipitation on a global scale falls over land, evaporation from land surfaces amount to only about 15% of the total water vapour entering the atmosphere. The imbalance is accounted for by the oceans which lose more water by evaporation than they receive directly from storms. In other words the oceans are the sources of the net gain of water by land surfaces. However, this net gain of water is the amount eventually returned to the oceans by stream runoff and ground water to maintain a net global balance of water.

The oceans cover more than 70% of Earth's surface to an average depth of about 4,000 metres. Each year, approximately a 1-metre layer of the ocean surface is evaporated into the atmosphere. An equal amount is returned to the oceans by the combination of precipitation and runoff. The total mass of water stored in the atmosphere at any time is only enough to cover the globe with a layer of liquid water 2.5 cm in depth. This is equivalent to only a little more than a week's supply of the world's precipitation. Thus, the residence time of water in the atmosphere is approximately ten days. For comparison, the residence time of water in the oceans is 4,000 years (4,000 metres depth divided by annual evaporation rate of 1 metre per year).

Annual amounts of precipitation measured at thousands of locations around the world have been remarkably steady over the years. There have been no dramatic short-term changes in the global sea level or in the amount of ice locked in ice sheets and glaciers. Atmospheric measurements (globally averaged) also indicate a quite constant water content. Since no water reservoir is changing significantly (at least as far as we can measure with certainty), we can only conclude that the global water cycle is essentially in balance.

While there is a world-wide balance in the amount of precipitation and evaporation, a local balance does not exist at most locations on Earth. Imbalances are reflected in the types of climates observed. Moist climates (such as tropical rain forests) are found where precipitation exceeds evaporation, while dry climates (deserts) prevail where evaporation exceeds precipitation.

Even the mid-latitude temperate climates have local imbalances. One need only recall periods of several days of fine weather to be followed by a day or two of rainy skies. Evaporation dominated the sunny times while precipitation far exceeded evaporation during the storms. At the same time, the middle latitudes are the recipients of moisture transported by the atmosphere from lower latitudes.

## Evapotranspiration and Water Vapour

Water vapour reaches the atmosphere primarily through *evapotranspiration* from a water source at the earth's surface. Evapotranspiration includes *open-water evaporation* (from the ocean, a lake, river, or other surface water body), *sublimation* of solid water (ice or snow surface) directly to vapour, or *transpiration* of water from vegetation. Transpiration generally represents the highest source of vapour from land surfaces, simply because water surfaces generally constitute a smaller proportion of the total land area of continents; hence the use of the term evapotranspiration to encompass all three forms of evaporation. A fourth, relatively less important evaporation process occurs in the atmosphere itself, that is, evaporation of falling precipitation, referred to as *virga* by weather observers.

Water vapour is found in air in varying amounts ranging from near zero up to about 4% by volume, depending upon both temperature and availability of water. The highest water vapour content is found above hot, wet surfaces. The lowest is where temperatures are lowest or in desert areas where the surface water source is extremely low . It is important to remember that the total mass of water in the atmosphere at any time is only enough, if it all precipitated, to cover the globe with a layer of water 2.5 cm deep.

At any given temperature, there is a maximum amount of water vapour that can exist in a volume of air. This occurs because of the possible co-existence of vapour, liquid and solid phases within the temperature and pressure ranges found in the atmosphere. Once the maximum water vapour concentration is reached for a particular temperature, any additional vapour will change phase to liquid or solid (rain or snow).

The higher the temperature, the more water vapour a volume of air is capable of holding. Thus, any change in temperature alters the volume's water-vapour capacity. As air warms, the capacity for holding water vapour increases, and as it cools, the capacity decreases.

The maximum water vapour capacity of a volume of air increases at an increasing rate as temperature increases. For the range of temperatures normally found near the Earth's surface, this capacity approximately doubles for each 10°C of warming. Conversely, a 10°C cooling nearly halves the capacity of a volume to hold water vapour.

| Temperature ($^oC$) | Vapour Capacity ($g/m^3$) |
|---|---|
| -20 | 1.1 |
| -15 | 1.6 |
| -10 | 2.3 |
| -5 | 3.4 |
| 0 | 4.8 |
| 5 | 6.8 |
| 10 | 9.4 |
| 15 | 12.9 |
| 20 | 17.3 |
| 25 | 23.2 |
| 30 | 30.5 |

How water vapour capacity varies with temperature near sea level (Saturation Absolute Humidity)

Water vapour behaves as other gaseous components of air as long as its maximum concentration has not been reached.

When water vapour is added to a volume of air with no change in temperature or pressure, the density of the volume decreases. Whenever a mixture of gases (such as air) is kept at the same temperature and pressure, the total number of molecules will remain constant in a given volume. Adding lighter water molecules will force heavier air molecules from the volume, resulting in a lighter volume.

| GAS | WEIGHT | | NUMBER OF ATOMS | | MOLECULAR WEIGHT | | PERCENT BY VOLUME | | RELATIVE WEIGHT |
|---|---|---|---|---|---|---|---|---|---|
| Oxygen | 16 | x | 2 | = | 32 | x | 21% | = | 7 |
| Nitrogen | 14 | x | 2 | = | 28 | x | 78% | = | 22 |
| | | | | | Molecular weight of dry air | | | = | 29 |
| Water vapour ( H20 ) ( 2x1 ) + 16 | | | | | | | | | 18 |

Humid air is less dense than air without water vapour

Humidity is the measurement of the water vapour content of air. The term *humidity* is a general term referring to any one of a number of ways of specifying atmospheric water vapour content. Humidity may be given as absolute or relative, or even as a temperature reflecting moisture content, such as dew point. It can be measured with a variety of instruments, including psychrometers, hygrometers, and dew cells.

One measure of the amount of water vapour actually in the air is called *absolute humidity*. Absolute humidity is the mass of water vapour in a unit volume, or water vapour density, usually measured in grams of water vapour per cubic metre.

A commonly used measure of atmospheric water vapour content is *relative humidity*. Relative humidity, expressed in per cent, is the amount of water vapour actually present in air as compared to its maximum capacity at that temperature. Relative humidity is temperature dependent, since the maximum possible amount of water vapour contained in a volume of air is related to temperature. Consequently, relative humidity values on a typical day decrease during the day as temperatures rise, and increase at night as temperatures lower. However, the *absolute humidity* does not change unless vapour is either added or taken away.

The *dew point,* or dew-point temperature, is another common humidity measure. It is the temperature to which the air has to be cooled at constant pressure (without changing the water vapour content) so that the actual amount of water vapour in the air is equal to the maximum amount that could be in the air at that temperature. High dew points indicate high atmospheric water vapour content. Low dew points indicate low content. The addition of water vapour to the air increases the dew point, while removing water vapour lowers it.

Water vapour is extremely important to weather. It condenses to form cloud particles which can lead to precipitation. It releases large amounts of latent heat when changing from vapour to liquid or ice, serving as a major energy source for storms ranging in size from local thunderstorms to hurricanes to large extra-tropical weather systems. In addition, water vapour strongly absorbs and re-radiates Earth's long-wave infrared (heat) radiation, making it the major "Greenhouse" gas in the planet's heat and energy balance.

[Note: For a simple exercise demonstrating the relationship between temperature, water vapour content, and dew point, see **[Activity: Water Vapour Investigation].**

## Saturation, Condensation and Precipitation

A volume of air filled to its capacity for water vapour is said to be *saturated.* Saturation can be achieved in different ways. As a volume of air cools, its capacity to hold water vapour decreases. As the air is cooled, it reaches saturation when its capacity is reduced to equal the amount of water vapour it contains. Saturation can also occur if water vapour is added to a volume of air until it is filled to its capacity. When air is saturated, its relative humidity is 100%, and, by definition, its dew point and its temperature must be the same.

Vaporization can occur whenever the region above a water or ice surface is not saturated with water vapour. Evaporation increases the water vapour content in the region (unless the vapour is removed by some means). The addition of vapour can lead to saturation. If the region above the water or ice is enclosed, it will eventually become saturated.

Condensation is the general term for the change of phase from a vapour to a liquid or directly to ice. It will occur if a saturated region is cooled and there is a surface on which condensation can begin. Only enough condensation will take place to maintain saturated conditions. Condensation is taking place whenever clouds and fogs are seen forming. [Note: the change of phase directly from vapour to ice or from ice to vapour curiously are both called *sublimation* by meteorologists.]

Rising air cools by expansion. As a volume of air cools, its capacity to hold moisture decreases and it will eventually reach saturation. If cooling continues, water vapour will condense on tiny particles in the air to form minute liquid water droplets or solid ice crystals. This is the most common way that clouds are produced. Cloud bases are located at the elevation at which saturation is first achieved. Further cooling and condensation causes these small water droplets or ice crystals within clouds to multiply, eventually collecting together to form larger *precipitation* particles, which reach the earth's surface as either snow, rain, drizzle, or hail.

There are other ways that air can be cooled to saturation. One is by moving warm, humid air over a cooler surface. The air is then cooled by contact (conduction) and resulting saturation produces *advection fog, a common occurrence over Canada's coastal waters.* Another common method of cooling humid air is by radiative heat loss from the land surface overnight under clear skies, which in turn cools the air by direct contact to saturation, resulting in *radiation fog.*

Saturation can also occur if water vapour is added to already moist air. Enough condensation can then take place to maintain saturation levels of water vapour. This can be seen at times when cold air moves over a warmer, wet surface, causing evaporation which often produces saturation that is called *steam fog*. This frequently occurs over Canada's coastal and inland water bodies in the fall when cool air flows over a still relatively warm water surface. Rain evaporating into already humid air to produce *pre-frontal fog* is yet another means of achieving saturation-condensation.

## Water Vapour Observation

Due to unequal heating of the atmosphere and other factors, motions ranging from the microscopic to broad-scale planetary circulation patterns form. The water which evaporates from the surface of the ocean releases energy which helps to maintain the general circulation of the atmosphere. It is through this circulation that water, as vapour and cloud, is transported by wind and vertical motions throughout the global atmosphere.

The movement of water in all its phases through the atmosphere can be monitored on a global scale by the use of instruments aboard weather satellites. The motion of the solid and liquid water found in clouds can be observed in the visible and infrared cloud imagery used on daily TV weather reports. This is not true for the invisible water vapour phase.

Although transparent to visible light, water vapour is a very good absorber and re-emitter of infrared radiation at certain wavelengths. This property enables the atmospheric water vapour to be detected from above by the special infrared sensors carried aboard weather satellites.

The two satellite images (Figure 1 and 2) demonstrate distinctly different perspectives of the atmosphere. The visible image (Figure 1) views the Earth and the atmosphere as they would be seen by the human eye. Clouds are reflective surfaces, hence appear as grey or bright white features in the image. The water vapour image (Figure 2) depicts clouds (condensed water) and water vapour (a gas invisible to the eye) for the middle and

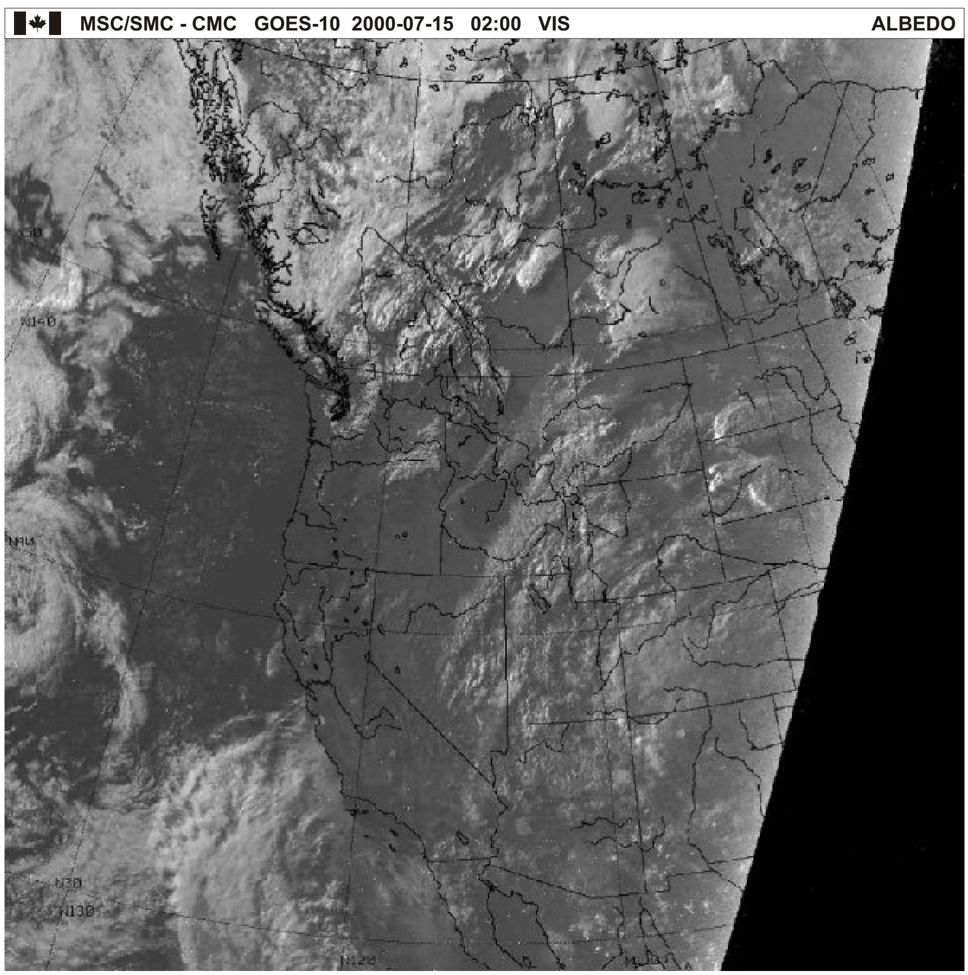


*Figure 1* - Visible satellite image

upper portions of the troposphere (especially 500 - 200 hPa).

High cloud types are bright white on the water vapour image and also quite apparent on the visible image. Low clouds may be seen in the visible image, but are not detectable in the water vapour image. The most interesting difference, however, is that regions of greater water vapour content (not condensed as cloud) appear milky white in the water vapour image, but do not appear on the visible image (since water vapour is an invisible gas).

The features of the water vapour image and how these features move and change with time are just now being related to atmospheric circulation systems and processes. Water vapour imagery is becoming a valuable tool used to confirm, modify or significantly change weather forecasts.

Recent improvements in satellite imagery from space have revealed regions of concentrated atmospheric water vapour in the middle levels of the atmosphere. These streaks of water vapour in the imagery are called plumes due to their resemblance to smoke plumes. The plumes, often originating in the tropics, have been observed in motion distributing water vapour across the globe. Their influence on weather patterns may range from local storms up to global in scale.

Satellite imagery is revealing that, at any one time, up to half a dozen streams of vapour exist in each hemisphere. These plumes are each several hundred kilometres wide and several thousand kilometres long. The total vapour amounts in one of these plumes would be equivalent to the water content of a major river on land. These "rivers in the sky" seem to be associated with the moisture supply for hurricanes, for major summer thunderstorm concentrations and for mid-latitude winter storms. Apparently, it is in this way that water vapour reaches higher latitudes to fuel much of the precipitation in the water cycle.

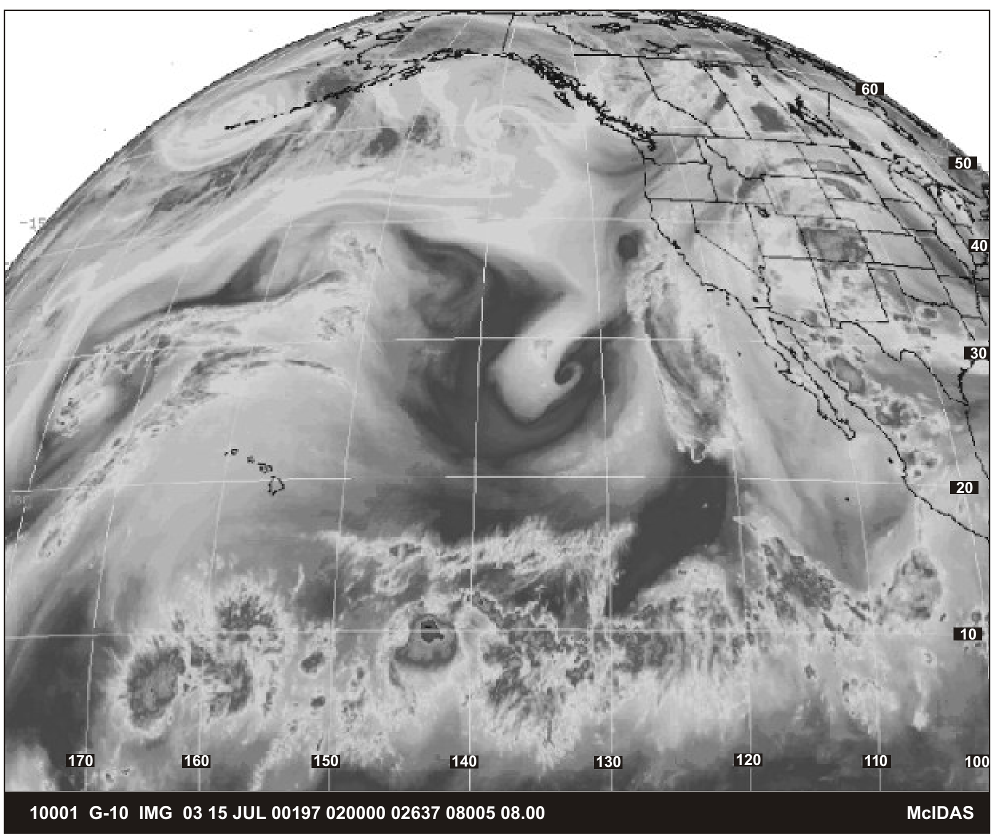


*Figure 2* - Water vapour satellite image