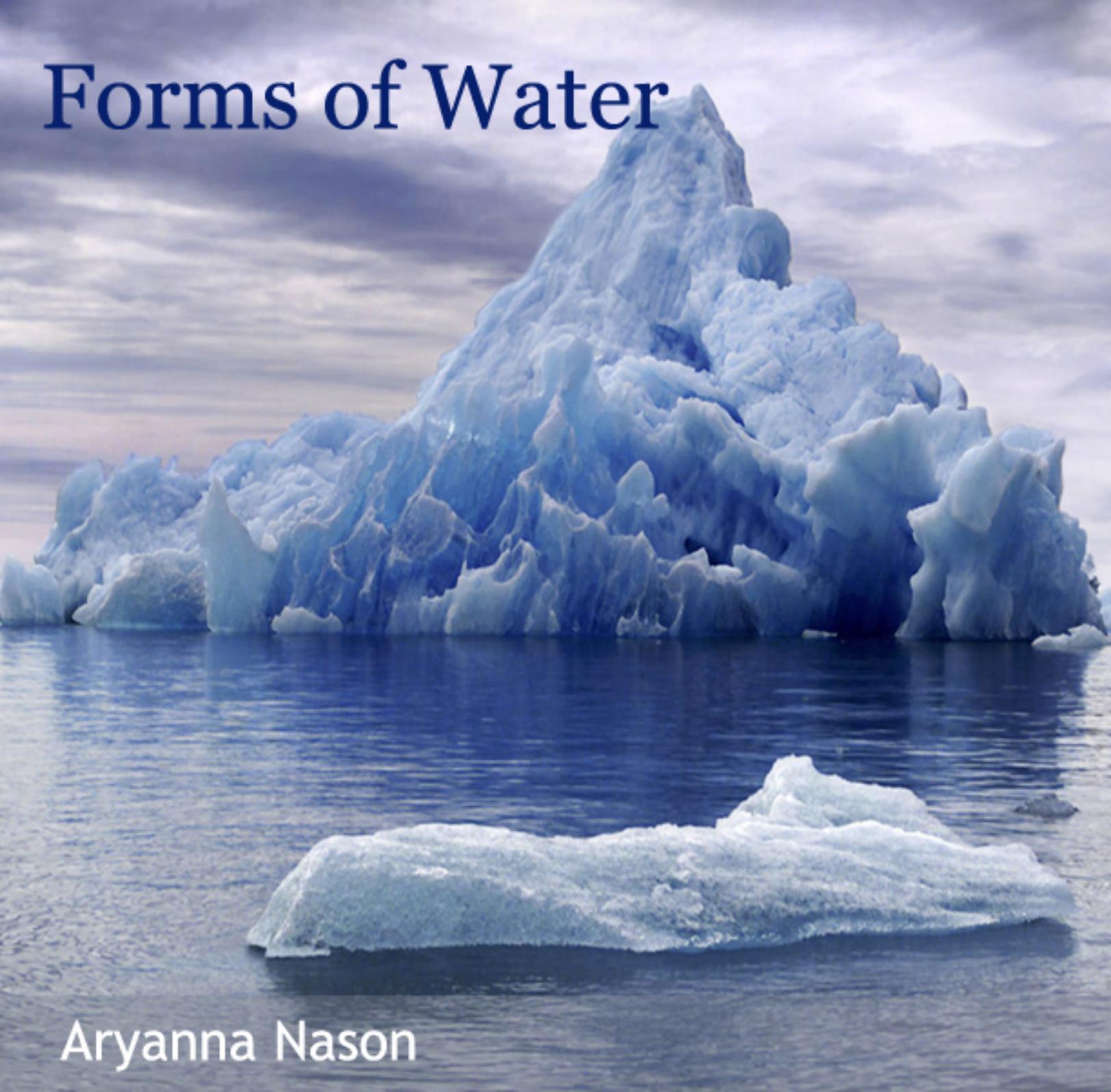


# Forms of Water

A large, jagged iceberg with a sharp peak floats in the ocean. The ice is a deep blue color, indicating its thickness. In the foreground, a smaller, smoother iceberg floats on the water. The sky is overcast with grey clouds.

Aryanna Nason

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## Chapter- 1

# Cryosphere



Overview of the Cryosphere and its larger components, from the UN Environment Programme Global Outlook for Ice and Snow.

The **cryosphere** is the term which collectively describes the portions of the Earth's surface where water is in solid form, including sea ice, lake ice, river ice, snow cover, glaciers, ice caps and ice sheets, and frozen ground (which includes permafrost). Thus there is a wide overlap with the hydrosphere. The cryosphere is an integral part of the global climate system with important linkages and feedbacks generated through its influence on surface energy and moisture fluxes, clouds, precipitation, hydrology, atmospheric and oceanic circulation. Through these feedback processes, the cryosphere plays a significant role in global climate and in climate model response to global change.

## Structure

Frozen water is found on the Earth's surface primarily as snow cover, freshwater ice in lakes and rivers, sea ice, glaciers, ice sheets, and frozen ground and permafrost (permanently-frozen ground). The residence time of water in each of these cryospheric sub-systems varies widely. Snow cover and freshwater ice are essentially seasonal, and most sea ice, except for ice in the central Arctic, lasts only a few years if it is not seasonal. A given water particle in glaciers, ice sheets, or ground ice, however, may

remain frozen for 10-100,000 years or longer, and deep ice in parts of East Antarctica may have an age approaching 1 million years.

Most of the world's ice volume is in Antarctica, principally in the East Antarctic Ice Sheet. In terms of areal extent, however, Northern Hemisphere winter snow and ice extent comprise the largest area, amounting to an average 23% of hemispheric surface area in January. The large areal extent and the important climatic roles of snow and ice, related to their unique physical properties, indicate that the ability to observe and model snow and ice-cover extent, thickness, and physical properties (radiative and thermal properties) is of particular significance for climate research.

There are several fundamental physical properties of snow and ice that modulate energy exchanges between the surface and the atmosphere. The most important properties are the surface reflectance (albedo), the ability to transfer heat (thermal diffusivity), and the ability to change state (latent heat). These physical properties, together with surface roughness, emissivity, and dielectric characteristics, have important implications for observing snow and ice from space. For example, surface roughness is often the dominant factor determining the strength of radar backscatter. Physical properties such as crystal structure, density, length, and liquid-water content are important factors affecting the transfers of heat and water and the scattering of microwave energy.

The surface reflectance of incoming solar radiation is important for the surface energy balance (SEB). It is the ratio of reflected to incident solar radiation, commonly referred to as albedo. Climatologists are primarily interested in albedo integrated over the shortwave portion of the electromagnetic spectrum (~0.3 to 3.5  $\mu\text{m}$ ), which coincides with the main solar energy input. Typically, albedo values for non-melting snow-covered surfaces are high (~80-90%) except in the case of forests. The higher albedos for snow and ice cause rapid shifts in surface reflectivity in autumn and spring in high latitudes, but the overall climatic significance of this increase is spatially and temporally modulated by cloud cover. (Planetary albedo is determined principally by cloud cover, and by the small amount of total solar radiation received in high latitudes during winter months.) Summer and autumn are times of high-average cloudiness over the Arctic Ocean so the albedo feedback associated with the large seasonal changes in sea-ice extent is greatly reduced. Groisman *et al.* (1994a) observed that snow cover exhibited the greatest influence on the Earth radiative balance in the spring (April to May) period when incoming solar radiation was greatest over snow-covered areas.

The thermal properties of cryospheric elements also have important climatic consequences. Snow and ice have much lower thermal diffusivities than air. Thermal diffusivity is a measure of the speed at which temperature waves can penetrate a substance. Snow and ice are many orders of magnitude less efficient at diffusing heat than air. Snow cover insulates the ground surface, and sea ice insulates the underlying ocean, decoupling the surface-atmosphere interface with respect to both heat and moisture fluxes. The flux of moisture from a water surface is eliminated by even a thin skin of ice, whereas the flux of heat through thin ice continues to be substantial until it attains a thickness in excess of 30 to 40 cm. However, even a small amount of snow on

top of the ice will dramatically reduce the heat flux and slow down the rate of ice growth. The insulating effect of snow also has major implications for the hydrological cycle. In non-permafrost regions, the insulating effect of snow is such that only near-surface ground freezes and deep-water drainage is uninterrupted.

While snow and ice act to insulate the surface from large energy losses in winter, they also act to retard warming in the spring and summer because of the large amount of energy required to melt ice (the latent heat of fusion,  $3.34 \times 10^5$  J/kg at  $0^\circ\text{C}$ ). However, the strong static stability of the atmosphere over areas of extensive snow or ice tends to confine the immediate cooling effect to a relatively shallow layer, so that associated atmospheric anomalies are usually short-lived and local to regional in scale. In some areas of the world such as Eurasia, however, the cooling associated with a heavy snowpack and moist spring soils is known to play a role in modulating the summer monsoon circulation. Gutzler and Preston (1997) recently presented evidence for a similar snow-summer circulation feedback over the southwestern United States.

The role of snow cover in modulating the monsoon is just one example of a short-term cryosphere-climate feedback involving the land surface and the atmosphere. From Figure 1 it can be seen that there are numerous cryosphere-climate feedbacks in the global climate system. These operate over a wide range of spatial and temporal scales from local seasonal cooling of air temperatures to hemispheric-scale variations in ice sheets over time-scales of thousands of years. The feedback mechanisms involved are often complex and incompletely understood. For example, Curry *et al.* (1995) showed that the so-called “simple” sea ice-albedo feedback involved complex interactions with lead fraction, melt ponds, ice thickness, snow cover, and sea-ice extent.

## **Snow**

Snow cover has the second-largest areal extent of any component of the cryosphere, with a mean maximum areal extent of approximately 47 million  $\text{km}^2$ . Most of the Earth's snow-covered area (SCA) is located in the Northern Hemisphere, and temporal variability is dominated by the seasonal cycle; Northern Hemisphere snow-cover extent ranges from 46.5 million  $\text{km}^2$  in January to 3.8 million  $\text{km}^2$  in August. North American winter SCA has exhibited an increasing trend over much of this century (Brown and Goodison 1996; Hughes *et al.* 1996) largely in response to an increase in precipitation. However, the available satellite data show that the hemispheric winter snow cover has exhibited little interannual variability over the 1972-1996 period, with a coefficient of variation ( $\text{COV}=\text{s.d./mean}$ ) for January Northern Hemisphere snow cover of  $< 0.04$ . According to Groisman *et al.* (1994a) Northern Hemisphere spring snow cover should exhibit a decreasing trend to explain an observed increase in Northern Hemisphere spring air temperatures this century. Preliminary estimates of SCA from historical and reconstructed in situ snow-cover data suggest this is the case for Eurasia, but not for North America, where spring snow cover has remained close to current levels over most of this century. Because of the close relationship observed between hemispheric air temperature and snow-cover extent over the period of satellite data (IPCC 1996), there is

considerable interest in monitoring Northern Hemisphere snow-cover extent for detecting and monitoring climate change.

Snow cover is an extremely important storage component in the water balance, especially seasonal snowpacks in mountainous areas of the world. Though limited in extent, seasonal snowpacks in the Earth's mountain ranges account for the major source of the runoff for stream flow and groundwater recharge over wide areas of the midlatitudes. For example, over 85% of the annual runoff from the Colorado River basin originates as snowmelt. Snowmelt runoff from the Earth's mountains fills the rivers and recharges the aquifers that over a billion people depend on for their water resources. Further, over 40% of the world's protected areas are in mountains, attesting to their value both as unique ecosystems needing protection and as recreation areas for humans. Climate warming is expected to result in major changes to the partitioning of snow and rainfall, and to the timing of snowmelt, which will have important implications for water use and management. These changes also involve potentially important decadal and longer time-scale feedbacks to the climate system through temporal and spatial changes in soil moisture and runoff to the oceans. (Walsh 1995). Freshwater fluxes from the snow cover into the marine environment may be important, as the total flux is probably of the same magnitude as desalinated ridging and rubble areas of sea ice. In addition, there is an associated pulse of precipitated pollutants which accumulate over the Arctic winter in snowfall and are released into the ocean upon ablation of the sea-ice.

## **Sea ice**

Sea ice covers much of the polar oceans and forms by freezing of sea water. Satellite data since the early 1970s reveal considerable seasonal, regional, and interannual variability in the sea-ice covers of both hemispheres. Seasonally, sea-ice extent in the Southern Hemisphere varies by a factor of 5, from a minimum of 3-4 million km<sup>2</sup> in February to a maximum of 17-20 million km<sup>2</sup> in September. The seasonal variation is much less in the Northern Hemisphere where the confined nature and high latitudes of the Arctic Ocean result in a much larger perennial ice cover, and the surrounding land limits the equatorward extent of wintertime ice. Thus, the seasonal variability in Northern Hemisphere ice extent varies by only a factor of 2, from a minimum of 7-9 million km<sup>2</sup> in September to a maximum of 14-16 million km<sup>2</sup> in March.

The ice cover exhibits much greater regional-scale interannual variability than it does hemispherical. For instance, in the region of the Seas of Okhotsk and Japan, maximum ice extent decreased from 1.3 million km<sup>2</sup> in 1983 to 0.85 million km<sup>2</sup> in 1984, a decrease of 35%, before rebounding the following year to 1.2 million km<sup>2</sup>. The regional fluctuations in both hemispheres are such that for any several-year period of the satellite record some regions exhibit decreasing ice coverage while others exhibit increasing ice cover. The overall trend indicated in the passive microwave record from 1978 through mid-1995 shows that the extent of Arctic sea ice is decreasing 2.7% per decade. Subsequent work with the satellite passive-microwave data indicates that from late October 1978 through the end of 1996 the extent of Arctic sea ice decreased by 2.9% per decade while the extent of Antarctic sea ice increased by 1.3% per decade.

## **Lake ice and river ice**

Ice forms on rivers and lakes in response to seasonal cooling. The sizes of the ice bodies involved are too small to exert other than localized climatic effects. However, the freeze-up/break-up processes respond to large-scale and local weather factors, such that considerable interannual variability exists in the dates of appearance and disappearance of the ice. Long series of lake-ice observations can serve as a proxy climate record, and the monitoring of freeze-up and break-up trends may provide a convenient integrated and seasonally specific index of climatic perturbations. Information on river-ice conditions is less useful as a climatic proxy because ice formation is strongly dependent on river-flow regime, which is affected by precipitation, snow melt, and watershed runoff as well as being subject to human interference that directly modifies channel flow, or that indirectly affects the runoff via land-use practices.

Lake freeze-up depends on the heat storage in the lake and therefore on its depth, the rate and temperature of any inflow, and water-air energy fluxes. Information on lake depth is often unavailable, although some indication of the depth of shallow lakes in the Arctic can be obtained from airborne radar imagery during late winter (Sellman *et al.* 1975) and spaceborne optical imagery during summer (Duguay and Lafleur 1997). The timing of breakup is modified by snow depth on the ice as well as by ice thickness and freshwater inflow.

## **Frozen ground and permafrost**

Frozen ground (permafrost and seasonally frozen ground) occupies approximately 54 million km<sup>2</sup> of the exposed land areas of the Northern Hemisphere (Zhang *et al.*, 2003) and therefore has the largest areal extent of any component of the cryosphere. Permafrost (perennially frozen ground) may occur where mean annual air temperatures (MAAT) are less than -1 or -2°C and is generally continuous where MAAT are less than -7°C. In addition, its extent and thickness are affected by ground moisture content, vegetation cover, winter snow depth, and aspect. The global extent of permafrost is still not completely known, but it underlies approximately 20% of Northern Hemisphere land areas. Thicknesses exceed 600 m along the Arctic coast of northeastern Siberia and Alaska, but, toward the margins, permafrost becomes thinner and horizontally discontinuous. The marginal zones will be more immediately subject to any melting caused by a warming trend. Most of the presently existing permafrost formed during previous colder conditions and is therefore relic. However, permafrost may form under present-day polar climates where glaciers retreat or land emergence exposes unfrozen ground. Washburn (1973) concluded that most continuous permafrost is in balance with the present climate at its upper surface, but changes at the base depend on the present climate and geothermal heat flow; in contrast, most discontinuous permafrost is probably unstable or "in such delicate equilibrium that the slightest climatic or surface change will have drastic disequilibrium effects".

Under warming conditions, the increasing depth of the summer active layer has significant impacts on the hydrologic and geomorphic regimes. Thawing and retreat of

permafrost have been reported in the upper Mackenzie Valley and along the southern margin of its occurrence in Manitoba, but such observations are not readily quantified and generalized. Based on average latitudinal gradients of air temperature, an average northward displacement of the southern permafrost boundary by 50-to-150 km could be expected, under equilibrium conditions, for a 1°C warming.

Only a fraction of the permafrost zone consists of actual ground ice. The remainder (dry permafrost) is simply soil or rock at subfreezing temperatures. The ice volume is generally greatest in the uppermost permafrost layers and mainly comprises pore and segregated ice in Earth material. Measurements of bore-hole temperatures in permafrost can be used as indicators of net changes in temperature regime. Gold and Lachenbruch (1973) infer a 2-4°C warming over 75 to 100 years at Cape Thompson, Alaska, where the upper 25% of the 400-m thick permafrost is unstable with respect to an equilibrium profile of temperature with depth (for the present mean annual surface temperature of -5°C). Maritime influences may have biased this estimate, however. At Prudhoe Bay similar data imply a 1.8°C warming over the last 100 years (Lachenbruch *et al.* 1982). Further complications may be introduced by changes in snow-cover depths and the natural or artificial disturbance of the surface vegetation.

The potential rates of permafrost thawing have been established by Osterkamp (1984) to be two centuries or less for 25-meter-thick permafrost in the discontinuous zone of interior Alaska, assuming warming from -0.4 to 0°C in 3-4 years, followed by a further 2.6°C rise. Although the response of permafrost (depth) to temperature change is typically a very slow process (Osterkamp 1984; Koster 1993), there is ample evidence for the fact that the active layer thickness quickly responds to a temperature change (Kane *et al.* 1991). Whether, under a warming or cooling scenario, global climate change will have a significant effect on the duration of frost-free periods in both regions with seasonally- and perennially-frozen ground.

## **Glaciers and ice sheets**

Ice sheets and glaciers are flowing ice masses that rest on solid land. They are controlled by snow accumulation, surface and basal melt, calving into surrounding oceans or lakes and internal dynamics. The latter results from gravity-driven creep flow ("glacial flow") within the ice body and sliding on the underlying land, which leads to thinning and horizontal spreading. Any imbalance of this dynamic equilibrium between mass gain, loss and transport due to flow results in either growing or shrinking ice bodies.

Ice sheets are the greatest potential source of global freshwater, holding approximately 77% of the global total. This corresponds to 80 m of world sea-level equivalent, with Antarctica accounting for 90% of this. Greenland accounts for most of the remaining 10%, with other ice bodies and glaciers accounting for less than 0.5%. Because of their size in relation to annual rates of snow accumulation and melt, the residence time of water in ice sheets can extend to 100,000 or 1 million years. Consequently, any climatic perturbations produce slow responses, occurring over glacial and interglacial periods. Valley glaciers respond rapidly to climatic fluctuations with typical response times of 10-

50 years. However, the response of individual glaciers may be asynchronous to the same climatic forcing because of differences in glacier length, elevation, slope, and speed of motion. Oerlemans (1994) provided evidence of coherent global glacier retreat which could be explained by a linear warming trend of 0.66°C per 100 years.

While glacier variations are likely to have minimal effects upon global climate, their recession may have contributed one third to one half of the observed 20th Century rise in sea level (Meier 1984; IPCC 1996). Furthermore, it is extremely likely that such extensive glacier recession as is currently observed in the Western Cordillera of North America, where runoff from glacierized basins is used for irrigation and hydropower, involves significant hydrological and ecosystem impacts. Effective water-resource planning and impact mitigation in such areas depends upon developing a sophisticated knowledge of the status of glacier ice and the mechanisms that cause it to change. Furthermore, a clear understanding of the mechanisms at work is crucial to interpreting the global-change signals that are contained in the time series of glacier mass balance records.

Combined glacier mass balance estimates of the large ice sheets carry an uncertainty of about 20%. Studies based on estimated snowfall and mass output tend to indicate that the ice sheets are near balance or taking some water out of the oceans. Marinebased studies suggest sea-level rise from the Antarctic or rapid ice-shelf basal melting. Some authors (Paterson 1993; Alley 1997) have suggested that the difference between the observed rate of sea-level rise (roughly 2 mm/y) and the explained rate of sea-level rise from melting of mountain glaciers, thermal expansion of the ocean, etc. (roughly 1 mm/y or less) is similar to the modeled imbalance in the Antarctic (roughly 1 mm/y of sea-level rise; Huybrechts 1990), suggesting a contribution of sea-level rise from the Antarctic.

Relationships between global climate and changes in ice extent are complex. The mass balance of land-based glaciers and ice sheets is determined by the accumulation of snow, mostly in winter, and warm-season ablation due primarily to net radiation and turbulent heat fluxes to melting ice and snow from warm-air advection, (Munro 1990). However, most of Antarctica never experiences surface melting. Where ice masses terminate in the ocean, iceberg calving is the major contributor to mass loss. In this situation, the ice margin may extend out into deep water as a floating ice shelf, such as that in the Ross Sea. Despite the possibility that global warming could result in losses to the Greenland ice sheet being offset by gains to the Antarctic ice sheet, there is major concern about the possibility of a West Antarctic Ice Sheet collapse. The West Antarctic Ice Sheet is grounded on bedrock below sea level, and its collapse has the potential of raising the world sea level 6–7 m over a few hundred years.

Most of the discharge of the West Antarctic Ice Sheet is via the five major ice streams (faster flowing ice) entering the Ross Ice Shelf, the Rutford Ice Stream entering Ronne-Filchner shelf of the Weddell Sea, and the Thwaites Glacier and Pine Island Glacier entering the Amundsen Ice Shelf. Opinions differ as to the present mass balance of these systems (Bentley 1983, 1985), principally because of the limited data. The West

Antarctic Ice Sheet is stable so long as the Ross Ice Shelf is constrained by drag along its lateral boundaries and pinned by local grounding.

## Chapter- 2

# Frost



Hoar frost or soft rime on a cold winter day in Lower Saxony

**Frost** is the solid deposition of water vapor from saturated air. It is formed when solid surfaces are cooled to below the dew point of the adjacent air as well as below the freezing point of water. Frost crystals' size differ depending on time and water vapour available. Frost is also usually translucent in appearance. There are many types of frost, such as radiation and window frost. Frost causes economic damage when it destroys plants or hanging fruits.

## Formation

If a solid surface is chilled below the dew point of the surrounding air and the surface itself is colder than freezing, frost will form on the surface. Frost consists of spicules of ice which grow out from the solid surface. The size of the crystals depends on time,

temperature, and the amount of water vapor available. Based on wind direction, "Frost arrows" might form.

In general, for frost to form the deposition surface must be colder than the surrounding air. For instance frost may be observed around cracks in cold wooden sidewalks when moist air escapes from the ground below. Other objects on which frost tends to form are those with low specific heat or high thermal emissivity, such as blackened metals; hence the accumulation of frost on the heads of rusty nails. The apparently erratic occurrence of frost in adjacent localities is due partly to differences of elevation, the lower areas becoming colder on calm nights. It is also affected by differences in absorptivity and specific heat of the ground which in the absence of wind greatly influences the temperature attained by the superincumbent air.

The formation of frost is an example of meteorological deposition.

## **Types**

### **Radiation frost**



A spider web covered in hoar frost

**Radiation frost** (also called **hoar frost** or **hoarfrost** or **pruina**) refers to the white ice crystals, loosely deposited on the ground or exposed objects, that form on cold clear nights when heat losses into the open skies cause objects to become colder than the surrounding air. A related effect is **flood frost** which occurs when air cooled by ground-level radiation losses travels downhill to form pockets of very cold air in depressions, valleys, and hollows. Hoar frost can form in these areas even when the air temperature a few feet above ground is well above freezing. Nonetheless the frost itself will be at or below the freezing temperature of water.

Hoar frost may have different names depending on where it forms. For example, **air hoar** is a deposit of hoar frost on objects above the surface, such as tree branches, plant stems,

wires; **surface hoar** is formed by fernlike ice crystals directly deposited on snow, ice or already frozen surfaces; **crevasse hoar** consists in crystals that form in glacial crevasses where water vapour can accumulate under calm weather conditions; **depth hoar** refers to cup shaped, faceted crystals formed within dry snow, beneath the surface.



Frost on a nettle



Rime frost

Surface hoar is a cause of avalanches when it forms on top of snow. Conditions that are ideal are cold clear nights, with a very light wind that is able to circulate more humidified air around the snow surface. Wind that is too abrupt will destroy the crystals. When buried by subsequent snows they may remain standing for easy identification, or become laid down, but still dangerous because of the weakness of the crystals. In low temperatures surface hoar can also be broken apart and blown across the surface forming yukimarimo.

Hoar frost also occurs around man-made environments such as freezers or industrial cold storage facilities. It occurs in adjacent rooms that are not well insulated against the cold or around entry locations where humidity and moisture will enter and freeze instantly depending on the freezer temperature.

### **Advection frost**

**Advection frost** (also called **wind frost**) refers to tiny ice spikes forming when there is a very cold wind blowing over branches of trees, poles and other surfaces. It looks like rimming the edge of flowers and leaves and usually it forms against the direction of the wind. It can occur at any hour of day and night.



Frost on branches

### **Frost flowers**

Frost flowers occur when there is a freezing weather condition but the ground is not already frozen. The water contained in the plant stem expands and causes long cracks along the stem. Water, via capillary action, goes out from the cracks and freezes on contact with the air. Also the frost can literally look like a flower, even a dead flower from the previous summer. These are rare and wonderful to see as they are very delicate and last usually less than a day. Due to their fleeting nature, they are difficult to find to photograph and the locations of these Frost Flowers are elusive as terrain plays a big part in their formation as well.

### **Window frost**

**Window frost** (also called **fern frost**) forms when a glass pane is exposed to very cold air on the outside and moderately moist air on the inside. If the pane is not a good insulator (such as a single pane window), water vapour condenses on the glass forming patterns. With very low temperatures outside frost can appear on the bottom of the window even with double pane energy efficient windows, due to air convection between two panes of glass. The bottom part of the glazing unit is always colder than the top part. The glass surface influences the shape of crystals, so imperfections, scratches or dust can

modify the way ice nucleates. If the indoor air is very humid, rather than moderately so, water will first condense in small droplets and then freeze into clear ice.

## **Rime**

Rime is a type of frost that occurs quickly, often under conditions of heavily saturated air and windy conditions. Ships travelling through Arctic seas may accumulate rime on the rigging. Unlike hoar frost, which has a feathery appearance, rime generally has an icy solid appearance. In contrast to the formation of hoar frost, in which the water vapour condenses slowly and directly into icy feathers, Rime typically goes through a liquid phase where the surface is wet by condensation before freezing.



Large feathery crystals



Frosted plants in Peoples' park on Nov 29 2010

## **Effect on plants**

### **Overview**

Many plants can be damaged or killed by freezing temperatures or frost. This will vary with the type of plant and tissue exposed to low temperatures.

Tender plants, like tomatoes, die when they are exposed to frost. Hardy plants, like radish, tolerate lower temperatures. Perennials, such as the hosta plant, become dormant after first frosts and regrow when spring arrives. The entire visible plant may turn completely brown until the spring warmth, or will drop all of its leaves and flowers, leaving the stem and stalk only. Evergreen plants, such as pine trees, will withstand frost although all or most growth stops. Frost crack is a bark defect caused by a combination of low temperatures and heat from the winter sun.

Vegetation will not necessarily be damaged when leaf temperatures drop below the freezing point of their cell contents. In the absence of a site nucleating the formation of ice crystals, the leaves remain in a supercooled liquid state, safely reaching temperatures of  $-4^{\circ}\text{C}$  to  $-12^{\circ}\text{C}$ . However, once frost forms, the leaf cells may be damaged by sharp ice crystals. Hardening is the process by which a plant becomes tolerant to low temperatures.

Certain bacteria, notably *Pseudomonas syringae*, are particularly effective at triggering frost formation, raising the nucleation temperature to about  $-2^{\circ}\text{C}$ . Bacteria lacking ice nucleation-active proteins (ice-minus bacteria) result in greatly reduced frost damage.

### **Protection methods**

The selective inverted sink prevents frost by drawing cold air from the ground and blowing it up through a chimney. It was originally developed to prevent frost damage to citrus fruits in Uruguay.

In New Zealand, helicopters are used in a similar function, especially in the vineyard regions like Marlborough. By dragging down warmer air from the inversion layers, and preventing the ponding of colder air on the ground, the low-flying helicopters prevent damage to the fruit buds. As the operations are conducted at night, and have in the past involved up to 130 aircraft per night in one region, safety rules are strict.

### **Personifications**

Frost is personified in Russian culture as Ded Moroz. Indigenous peoples of Russia such as the Mordvins have their own traditions of frost deities.

English folklore tradition holds that Jack Frost, an elfish creature, is responsible for feathery patterns of frost found on windows on cold mornings.

## Chapter- 3

# Hard water



A tap showing calcification left by the use of hard water.

**Hard water** is water that has high mineral content (in contrast with *soft water*). Hard water has high concentrations of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  ions. Hard water is generally not harmful to one's health but can pose serious problems in industrial settings, where water hardness is monitored to avoid costly breakdowns in boilers, cooling towers, and other equipment that handle water. In domestic settings, the hardness of water is often indicated by the *non*-formation of froth when soap or toothpaste is agitated in the water sample.

## Sources of hardness

Hardness in water is defined as concentration of multivalent cations. Multivalent cations are cations with a charge greater than 1+, mainly dications. These *dications* include  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ . These ions enter a water supply by leaching from minerals. Common calcium-containing minerals are limestone, a form of calcium carbonate ( $\text{CaCO}_3$ ), and chalk (calcium sulphate,  $\text{CaSO}_4$ ). A common magnesium mineral is dolomite ( $\text{CaMg}(\text{CO}_3)_2$ ), which also contains calcium. Rainwater and distilled water are soft, because they contain few ions.

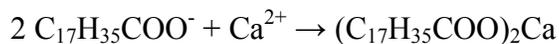
The following equilibrium reaction describes the formation of calcium carbonate scales:



Thus,  $\text{CO}_2$ , which occurs in air, can solubilize calcium carbonate. Calcium and magnesium ions can be removed by water softeners.

## Effects of hard water

With hard water, soap solutions form a white precipitate (scum) instead of producing lather. This effect arises because the dications destroy the surfactant properties of the soap by forming a solid precipitate ("soap scum"). A major component of such scum is calcium stearate, which arises according from sodium stearate, the main component of soap:



Hardness can thus be defined as the soap-consuming capacity of a water sample, or the capacity of precipitation of soap as a characteristic property of water that prevents the lathering of soap. Synthetic detergents do not form such scums.

Second, hard water also leaves deposits that can clog plumbing and interfere with heat exchangers. These deposits, called "scale", are composed mainly of calcium carbonate ( $\text{CaCO}_3$ ), magnesium hydroxide ( $\text{Mg}(\text{OH})_2$ ), and calcium sulfate ( $\text{CaSO}_4$ ). Calcium and magnesium carbonates tend to precipitate out as hard deposits to the surfaces of pipes and heat exchanger surfaces. This is principally caused by thermal decomposition of bi-carbonate ions but also happens to some extent even in the absence of such ions. The resulting build-up of scale can restrict water flow in pipes. In boilers, the deposits act as

an insulation that impairs the flow of heat into water, reducing the heating efficiency and allowing the metal boiler components to overheat. In a pressurized system, this can lead to failure of the boiler. The damage caused by calcium carbonate deposits varies depending on the crystalline form, for example, calcite or aragonite.

Third, the presence of ions in an electrolyte, in this case, hard water, can also lead to galvanic corrosion, in which one metal will preferentially corrode when in contact with another type of metal, when both are in contact with an electrolyte. The softening of hard water by ion exchange does not increase its corrosivity per se. Similarly, where lead plumbing is in use, softened water does not substantially increase plumbo-solvency.

## **Softening**

For the reasons discussed above, it is often considered desirable to soften hard water. Most detergents contain ingredients that counteract the effects of hard water on soap. For this reason, water softening is often unnecessary. Where softening is practiced it is often recommended to soften only the water sent to domestic hot water systems so as to prevent or delay inefficiencies and damage due to scale formation in water heaters. Water softening aims mainly to remove calcium and magnesium ions. A common method involves the use of ion exchange resins, which replace ions like  $\text{Ca}^{2+}$  by twice the number of monocations such as sodium or potassium ions.

## **Health considerations**

The World Health Organization says that "there does not appear to be any convincing evidence that water hardness causes adverse health effects in humans."

Some studies have shown a weak inverse relationship between water hardness and cardiovascular disease in men, up to a level of 170 mg calcium carbonate per litre of water. The World Health Organization has reviewed the evidence and concluded the data were inadequate to allow for a recommendation for a level of hardness.

Recommendations have been made for the maximum and minimum levels of calcium (40-80 ppm) and magnesium (20-30 ppm) in drinking water, and a total hardness expressed as the sum of the calcium and magnesium concentrations of 2-4 mmol/L.

Other studies have shown weak correlations between cardiovascular health and water hardness.

Some studies correlate domestic hard water usage with increased eczema in children.

The Softened-Water Eczema Trial (SWET), a multicenter randomized controlled trial of ion-exchange softeners for treating childhood eczema, was undertaken in 2008.

## **Measurement**

Quantitative measures of hardness can be obtained through instrumental analysis. The total water 'hardness', including both  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  ions, is reported in parts per million (ppm) or weight/volume (mg/L) of calcium carbonate ( $\text{CaCO}_3$ ) in the water. Although water hardness usually measures only the total concentrations of calcium and magnesium (the two most prevalent divalent metal ions), iron, aluminium, and manganese can also be present at elevated levels in some locations. The presence of iron characteristically confers a brownish (rust-like) colour to the calcification, instead of white (the color of most of the other compounds).

Because it is the precise mixture of minerals dissolved in the water, together with the water's pH and temperature, that determines the behavior of the hardness, a single-number scale does not adequately describe hardness. Descriptions of hardness correspond roughly with ranges of mineral concentrations:

Soft:	0–60 mg/L
Moderately hard:	61–120 mg/L
Hard:	121–180 mg/L
Very hard:	>181 mg/L

The level of total hardness in water can be evaluated with commercial testing kits, which measure the concentrations of calcium and magnesium. Several scales are used to describe the hardness of water in different contexts.

- Parts per million (ppm)  
Usually defined as one milligram of calcium carbonate ( $\text{CaCO}_3$ ) per liter of water (the definition used below).
- Grains per Gallon (gpg)  
Defined as 1 grain (64.8 mg) of calcium carbonate per U.S. gallon (3.79 litres), or 17.118 ppm
- mmol/L (millimoles per litre)  
One millimole of calcium (either  $\text{Ca}^{2+}$  or  $\text{CaCO}_3$ ) per litre of water corresponds to a hardness of 100.09 ppm or 5.608 dGH, since the molar mass of calcium carbonate is 100.09 g/mol.
- Degrees of General Hardness (dGH)  
One degree of General Hardness is defined as 10 milligrams of calcium oxide per litre of water, which is the same as one German degree (17.848 ppm).
- Various alternative "degrees":
  - Clark degrees ( $^{\circ}\text{Clark}$ )/English degrees ( $^{\circ}\text{e}$  or e)  
One degree Clark is defined as one grain (64.8 mg) of calcium carbonate per Imperial gallon (4.55 litres) of water, equivalent to 14.254 ppm.
  - German degrees (*Deutsche Härte*,  $^{\circ}\text{dH}$  or dH)  
One degree German is defined as 10 milligrams of calcium oxide per litre of water. This is equivalent to 17.848 milligrams of calcium carbonate per litre of water, or 17.848 ppm.

- French degrees (°F or f) (letter written in lower-case to avoid confusion with degree Fahrenheit — not always adhered to)  
One degree French is defined as 10 milligrams of calcium carbonate per litre of water, equivalent to 10 ppm.
- American degrees  
One degree American is defined as one milligram of calcium carbonate per litre of water, equivalent to 1 ppm.

Although most of the above measures define hardness in terms of concentrations of calcium in water, any combination of calcium and magnesium cations having the same total molarity as a pure calcium solution will yield the same degree of hardness. Consequently, hardness concentrations for naturally occurring waters (which will contain both  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  ions), are usually expressed as an equivalent concentration of pure calcium in solution. For example, water that contains 1.5 mmol/L of elemental calcium ( $\text{Ca}^{2+}$ ) and 1.0 mmol/L of magnesium ( $\text{Mg}^{2+}$ ) is equivalent in hardness to a 2.5 mmol/L solution of calcium alone (250.2 ppm).

## Indices

Several indices are used to describe the behaviour of calcium carbonate in water, oil, or gas mixtures.

### Langelier Saturation Index (LSI)

The Langelier Saturation Index (sometimes Langelier Stability Index) is a calculated number used to predict the calcium carbonate stability of water. It indicates whether the water will precipitate, dissolve, or be in equilibrium with calcium carbonate. In 1936, Wilfred Langelier developed a method for predicting the pH at which water is saturated in calcium carbonate (called pHs). The LSI is expressed as the difference between the actual system pH and the saturation pH:

$$\text{LSI} = \text{pH (measured)} - \text{pHs}$$

- For  $\text{LSI} > 0$ , water is super saturated and tends to precipitate a scale layer of  $\text{CaCO}_3$ .
- For  $\text{LSI} = 0$ , water is saturated (in equilibrium) with  $\text{CaCO}_3$ . A scale layer of  $\text{CaCO}_3$  is neither precipitated nor dissolved.
- For  $\text{LSI} < 0$ , water is under saturated and tends to dissolve solid  $\text{CaCO}_3$ .

If the actual pH of the water is below the calculated saturation pH, the LSI is negative and the water has a very limited scaling potential. If the actual pH exceeds pHs, the LSI is positive, and being supersaturated with  $\text{CaCO}_3$ , the water has a tendency to form scale. At increasing positive index values, the scaling potential increases.

In practice, water with an LSI between -0.5 and +0.5 will not display enhanced mineral dissolving or scale forming properties. Water with an LSI below -0.5 tends to exhibit

noticeably increased dissolving abilities while water with an LSI above +0.5 tends to exhibit noticeably increased scale forming properties.

It is also worth noting that the LSI is temperature sensitive. The LSI becomes more positive as the water temperature increases. This has particular implications in situations where well water is used. The temperature of the water when it first exits the well is often significantly lower than the temperature inside the building served by the well or at the laboratory where the LSI measurement is made. This increase in temperature can cause scaling, especially in cases such as hot water heaters.

## **Ryznar Stability Index (RSI)**

The Ryznar stability index (RSI) uses a database of scale thickness measurements in municipal water systems to predict the effect of water chemistry.

Ryznar saturation index (RSI) was developed from empirical observations of corrosion rates and film formation in steel mains. It is defined as:

$$\text{RSI} = 2 \text{ pHs} - \text{pH (measured)}$$

- For  $6,5 < \text{RSI} < 7$  water is considered to be approximately at saturation equilibrium with calcium carbonate
- For  $\text{RSI} > 8$  water is under saturated and, therefore, would tend to dissolve any existing solid  $\text{CaCO}_3$
- For  $\text{RSI} < 6,5$  water tends to be scale forming

## **Puckorius Scaling Index (PSI)**

The Puckorius Scaling Index (PSI) uses slightly different parameters to quantify the relationship between the saturation state of the water and the amount of limescale deposited.

## **Other indices**

Other indices include the Larson-Skold Index, the Stiff-Davis Index, and the Oddo-Tomson Index.

## **Regional information**

### **Hard water in Australia**

Analysis of water hardness in major Australian cities by the Australian Water Association shows a range from very soft (Melbourne) to very hard (Adelaide). Total Hardness levels of Calcium Carbonate in ppm are: Canberra: 40; Melbourne: 10 - 26; Sydney: 39.4 –

60.1; Perth: 29 – 226; Brisbane: 100; Adelaide: 134 – 148; Hobart: 5.8 – 34.4; Darwin: 31.

### **Hard water in Canada**

Prairie provinces (mainly Saskatchewan and Manitoba) contain high quantities of calcium and magnesium, often as dolomite, which are readily soluble in the groundwater that contains high concentrations of trapped carbon dioxide from the last glaciation. In these parts of Canada, the total hardness in ppm of calcium carbonate equivalent frequently exceed 200 ppm, if groundwater is the only source of potable water. The west coast, by contrast, has unusually soft water, derived mainly from mountain lakes fed by glaciers and snowmelt.

Some typical values are: Montreal 116 ppm, Calgary 165 ppm, Regina 202 ppm, Saskatoon < 140 ppm, Winnipeg 77 ppm, Toronto 121 ppm, Vancouver < 3 ppm, Charlottetown PEI 140 – 150 ppm.

### **Hard water in England and Wales**

Information from the British Drinking Water Inspectorate shows that drinking water in England is generally considered to be 'very hard', with most areas of England, particularly east of a line between the Severn and Tees estuaries, exhibiting above 200 ppm for the calcium carbonate equivalent. Wales, Devon, Cornwall and parts of North-West England are softer water areas, and range from 0 to 200 ppm. In the brewing industry in England and Wales, water is often deliberately hardened with gypsum in the process of Burtonisation.

Tap water in Manchester in England is soft because it comes from Thirlmere and Haweswater reservoirs in the Lake District, and in their headwaters areas there is not exposed to limestone or chalk.

### **Hard water in the United States**

More than 85% of American homes have hard water. The softest waters occur in parts of the New England, South Atlantic-Gulf, Pacific Northwest, and Hawaii regions. Moderately hard waters are common in many of the rivers of the Tennessee, Great Lakes, and Alaska regions. Hard and very hard waters are found in some of the streams in most of the regions throughout the country. Hardest waters (greater than 1,000 ppm) are in streams in Texas, New Mexico, Kansas, Arizona, and southern California.

## Chapter- 4

# Heavy Water

**Heavy water** is water containing a higher-than-normal proportion of the hydrogen isotope deuterium, either as **deuterium oxide**,  $D_2O$  or  $^2H_2O$ , or as **deuterium protium oxide**,  $HDO$  or  $^1H^2HO$ . Physically and chemically, it resembles water,  $H_2O$ ; in water, the deuterium-to-hydrogen ratio is about 156ppm. Heavy water is water that is highly enriched in deuterium, up to as much as 100%  $D_2O$ . The isotopic substitution with deuterium alters the bond energy of the water's hydrogen-oxygen bond, altering the physical, chemical, and, especially, the biological properties of the pure, or highly-enriched, substance to a degree greater than is found in most isotope-substituted chemical compounds. Pure heavy water is not radioactive. It is about 11% denser than water, but otherwise, is physically very similar to water.

Heavy water exhibits dose and species-dependent chemical toxicity. The adult human body naturally contains deuterium equivalent to that in five grams of heavy water, which is thought to be harmless. Comparable laboratory doses are used as non-radioactive tracers in human and animal metabolic experimentation. However, larger concentrations of heavy water are toxic in eukaryotic organisms, when heavy water replaces about 25% to 50% of the body's water. At these levels, the substance interferes with cellular mitotic apparatus, preventing cell-division. Single-celled prokaryotic organisms such as bacteria, which do not have a mitotic apparatus, may survive and grow slowly in heavy water. However, eukaryotic organisms as simple as single-celled protozoa, and including all higher (multi-cellular) organisms, if given only heavy water, soon stop dividing and growing. For example, plant seeds will not germinate in heavy water. Mammals given heavy water fall ill from lack of needed blood-cell and intestinal-cell replacement, and die when about 50% of their body-water has been replaced with heavy water.

Relatively pure heavy water was produced in 1933, soon after the discovery of deuterium, the stable heavy isotope of hydrogen. With the discovery of nuclear fission in late 1938, and the need for a neutron moderator that captured few neutrons, heavy water became an important component of early nuclear energy programs during World War II (1939–1945). Partly because of Nazi Germany's (1933–1945) technological reliance upon scarce heavy water for nuclear reactor research, they failed to produce a functioning nuclear reactor for the duration of the war. Since then, heavy water is an essential component in the design of some nuclear reactors, either for generating electric power or for producing nuclear-weapons isotopes, such as plutonium-239. Most contemporary

enriched-uranium nuclear reactors use normal "light water" (H<sub>2</sub>O) for neutron moderation.

## Other meanings

### Semiheavy water

**Semiheavy water**, HDO, exists whenever there is water with <sup>1</sup>H (or protium) and deuterium (<sup>2</sup>H) present in the mixture. This is because hydrogen atoms (hydrogen-1 and deuterium) are rapidly exchanged between water molecules. Water containing 50% H and 50% D in its hydrogen actually contains about 50% HDO and 25% each of H<sub>2</sub>O and D<sub>2</sub>O, in dynamic equilibrium. Semiheavy water, HDO, occurs naturally in regular water at a proportion of about 1 molecule in 3,200 (each hydrogen has a probability of one in 6,400 of being D). Heavy water, D<sub>2</sub>O, by comparison, occurs naturally at a proportion of about 1 molecule in 41 million (i.e., one in 6,400<sup>2</sup>). This makes semiheavy water far more prevalent than "normal" heavy water.

### Heavy-oxygen water

A common type of heavy-oxygen water H<sub>2</sub><sup>17</sup>O and H<sub>2</sub><sup>18</sup>O is available commercially for use as a non-radioactive isotopic tracer, and it qualifies as "heavy water" in that it has a higher density than normal water (in this case, similar density to deuterium oxide). At higher expense (due to the greater difficulty in separation of <sup>17</sup>O and <sup>18</sup>O, less common heavy isotopes of oxygen), water is available in which the oxygen is enriched to varying degrees with <sup>17</sup>O and <sup>18</sup>O. These types of heavy-isotope water are rarely referred to as "heavy water", as they do not contain the deuterium which gives D<sub>2</sub>O its characteristically different nuclear and biological properties. Heavy-oxygen waters with normal hydrogen, for example, would not be expected to show any toxicity whatsoever.

## Physical properties (with comparison to light water)

Property	D <sub>2</sub> O (Heavy water)	H <sub>2</sub> O (Light water)
Freezing point (°C)	3.82	0.0
Boiling point (°C)	101.4	100.0
Density at STP (g/mL)	1.1056	0.9982
Temp. of maximum density (°C)	11.6	4.0
Dynamic viscosity (at 20°C, mPa·s)	1.25	1.005
Surface tension (at 25°C, μJ)	7.193	7.197
Heat of fusion (cal/mol)	1,515	1,436
Heat of vaporisation (cal/mol)	10,864	10,515
pH (at 25°C)	7.41 (sometimes "pD")	7.00
Refractive index (at 20°C, 0.5893 μm)	1.32844	1.33335

No physical properties are listed for "pure" semi-heavy water, because it cannot be isolated in bulk quantities. In the liquid state, a few water molecules are always in an ionised state, which means the hydrogen atoms can exchange among different oxygen atoms. A sample of hypothetical "pure" semi-heavy water would rapidly transform into a dynamic mixture of 25% light water, 25% heavy water, and 50% semi-heavy water.

*Physical properties obvious by inspection:* Heavy water is 10.6% denser than ordinary water, a difference which is difficult to notice in a sample of it (an early experiment reported not the "slightest difference" in taste between pure ordinary water and pure heavy water; on the other hand, rats given a choice between distilled water and heavy water were able to avoid the heavy water based on smell, and it may be possible that it has a different taste). One of the few ways to demonstrate heavy water's physically different properties without equipment is to freeze a sample and drop it into normal water. Ice made from heavy water sinks in normal water. If the normal water is ice-cold this phenomenon may be observed long enough for a good demonstration, since heavy-water ice has a slightly higher melting temperature (3.8 °C) than normal ice, and thus holds up very well in ice-cold normal water.

## History

Harold Urey discovered the isotope deuterium in 1931 and was later able to concentrate it in water. Urey's mentor Gilbert Newton Lewis isolated the first sample of pure heavy water by electrolysis in 1933. George de Hevesy and Hoffer used heavy water in 1934 in one of the first biological tracer experiments, to estimate the rate of turnover of water in the human body. The history of large-quantity production and use of heavy water in early nuclear experiments is given below.

## Effect on biological systems

Heavy isotopes of chemical elements have slightly different chemical behaviors, but for most elements the differences in chemical behavior between isotopes are far too small to use, or even detect. For hydrogen, however, this is not true. The larger chemical isotope-effects seen with deuterium and tritium manifest because bond energies in chemistry are determined in quantum mechanics by equations in which the quantity of reduced mass of the nucleus and electrons appears. This quantity is altered in heavy-hydrogen compounds (of which deuterium oxide is the most common and familiar) more than for heavy-isotope substitution in other chemical elements. This isotope effect of heavy hydrogen is magnified further in biological systems, which are very sensitive to small changes in the solvent properties of water.

Heavy water is the only known chemical substance that affects the period of circadian oscillations, consistently increasing the length of each cycle. The effect is seen in unicellular organisms, green plants, isopods, insects, birds, mice, and hamsters. The mechanism is unknown.

To perform their tasks, enzymes rely on their finely tuned networks of hydrogen bonds, both in the active center with their substrates, and outside the active center, to stabilize their tertiary structures. As a hydrogen bond with deuterium is slightly stronger than one involving ordinary hydrogen, in a highly deuterated environment, some normal reactions in cells are disrupted.

Particularly hard-hit by heavy water are the delicate assemblies of mitotic spindle formation necessary for cell division in eukaryotes. Plants stop growing and seeds do not germinate when given only heavy water, because heavy water stops eukaryotic cell division.

It has been proposed that low doses of heavy water can slow the aging process by helping the body resist oxidative damage via the isotope effect. A team at the Institute for the Biology of Ageing, located in Moscow, conducted an experiment to determine the effect of heavy water on longevity using fruit flies and found that while large amounts were deadly, smaller quantities increased lifespans by up to 30%.

### **Effect on animals**

Experiments in mice, rats, and dogs have shown that a degree of 25% deuteration causes (sometimes irreversible) sterility, because neither gametes nor zygotes can develop. High concentrations of heavy water (90%) rapidly kill fish, tadpoles, flatworms, and *Drosophila*. Mammals, such as rats, given heavy water to drink die after a week, at a time when their body water approaches about 50% deuteration. The mode of death appears to be the same as that in cytotoxic poisoning (such as chemotherapy) or in acute radiation syndrome (though deuterium is not radioactive), and is due to deuterium's action in generally inhibiting cell division. It is more toxic to malignant cells than normal cells but the concentrations needed are too high for regular use. As in chemotherapy, deuterium-poisoned mammals die of a failure of bone marrow (bleeding and infection) and intestinal-barrier functions (diarrhea and fluid loss).

Notwithstanding the problems of plants and animals in living with too much deuterium, prokaryotic organisms such as bacteria, which do not have the mitotic problems induced by deuterium, may be grown and propagated in fully deuterated conditions, resulting in replacement of all hydrogen atoms in the bacterial proteins and DNA with the deuterium isotope. Full replacement with heavy atom isotopes can be accomplished in higher organisms with other non-radioactive heavy isotopes (such as carbon-13, nitrogen-15, and oxygen-18), but this cannot be done for the stable heavy isotope of hydrogen.

Deuterium oxide is used to enhance boron neutron capture therapy, but this effect does not rely on the biological effects of deuterium per se, but instead on deuterium's ability to moderate (slow) neutrons without capturing them.

## **Toxicity in humans**

Because it would take a very large amount of heavy water to replace 25% to 50% of a human being's body water (which in turn is 70% of body weight) with heavy water, accidental or intentional poisoning with heavy water is unlikely to the point of practical disregard. For a poisoning, large amounts of heavy water would need to be ingested without significant normal water intake for many days to produce any noticeable toxic effects.

Oral doses of heavy water in the range of several grams, as well as heavy oxygen  $^{18}\text{O}$ , are routinely used in human metabolic experiments. See doubly-labeled water testing. Since one in about every 6400 hydrogen atoms is deuterium, a 50 kg human containing 32 kg of body water would normally contain enough deuterium (about 1.1 gram) to make 5.5 grams of pure heavy water, so roughly this dose is required to double the amount of deuterium in the body.

The American patent U.S. Patent 5,223,269 is for the use of heavy water to treat hypertension (high blood pressure). A loss of blood pressure may partially explain the reported incidence of dizziness upon ingestion of heavy water.

## **Heavy water radiation contamination confusion**

Although many people associate heavy water primarily with its use in nuclear reactors, *pure* heavy water is not radioactive. Commercial-grade heavy water is *slightly* radioactive due to minute traces of natural tritium present in it, but the same is true of ordinary water as well. Heavy water which has been used as a coolant in nuclear power plants contains substantially more tritium due to neutron bombardment of the deuterium in the heavy water (Tritium is a health risk when ingested in large quantities).

In 1990, a disgruntled employee at the Point Lepreau Nuclear Generating Station in Canada obtained a sample (estimated as about a "half cup") of heavy water from the primary heat transport loop of the nuclear reactor, and loaded it into the employee water cooler. Eight employees drank some of the contaminated water. The incident was discovered when employees began leaving bioassay urine samples with elevated tritium levels. The quantity of heavy water involved was far below levels that could induce heavy water toxicity, but several employees received elevated radiation doses from tritium and neutron-activated chemicals in the water. This was not an incident of heavy water poisoning, but rather radiation poisoning from other isotopes in the heavy water. Some news services were not careful to distinguish these points, and some of the public were left with the impression that heavy water is normally radioactive and more severely toxic than it is. Even if pure heavy water had been used in the water cooler indefinitely, it is not likely the incident would have been detected or caused harm, since no employees would be expected to get as much as 25% of their daily drinking water from such a source.

## **Production**

On Earth, deuterated water, HDO, occurs naturally in regular water at a proportion of about 1 molecule in 3200. This means that 1 in 6400 hydrogen atoms is deuterium, which is 1 part in 3200 by weight (hydrogen weight). The HDO may be separated from regular water by distillation or electrolysis and also by various chemical exchange processes, all of which exploit a kinetic isotope effect.

The difference in mass between the two hydrogen isotopes translates into a difference in the zero-point energy and thus into a slight difference in the speed at which the reaction proceeds. Once HDO becomes a significant fraction of the water, heavy water will become more prevalent as water molecules trade hydrogen atoms very frequently. To produce pure heavy water by distillation or electrolysis requires a large cascade of stills or electrolysis chambers, and consumes large amounts of power, so the chemical methods are generally preferred. The most important chemical method is the Girdler sulfide process.

An alternative process, patented by Graham M. Keyser, uses lasers to selectively dissociate deuterated hydrofluorocarbons to form deuterium fluoride, which can then be separated by physical means. Although the energy consumption for this process is much less than for the Girdler sulfide process, this method is currently uneconomical due to the expense of procuring the necessary hydrofluorocarbons.

### **United States**

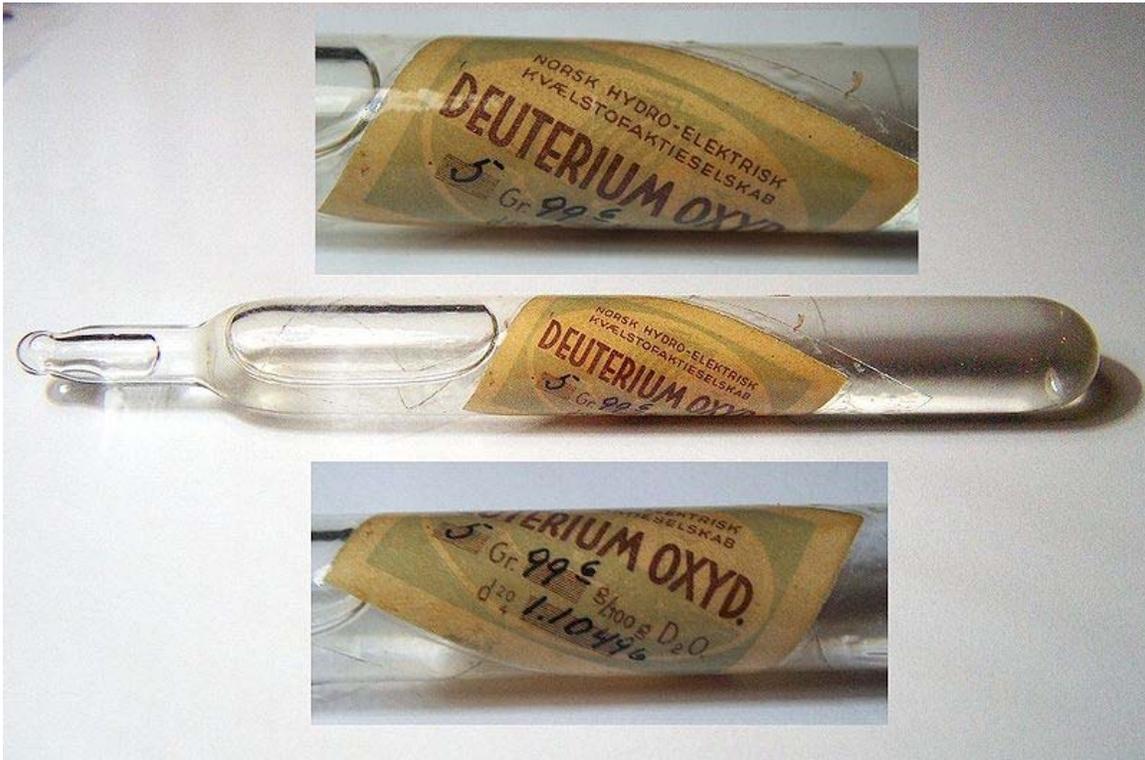
In 1953, the United States began using heavy water in plutonium production reactors at the Savannah River Site. The first of the five heavy water reactors came online in 1953, and the last was placed in cold shutdown in 1996. The SRS reactors were heavy water reactors so that they could produce both plutonium and tritium for the US nuclear weapons program.

The U.S. developed the Girdler sulfide chemical exchange production process which was first demonstrated on a large scale at the Dana, Indiana plant in 1945 and at the Savannah River Plant, South Carolina in 1952. The SRP was operated by DuPont for the USDOE until 1 April 1989 at which time the operation was taken over by Westinghouse.

### **India**

India is the world's second largest producer of heavy water through its Heavy Water Board.

## Norway



"Heavy water" made by Norsk Hydro

In 1934, Norsk Hydro built the first commercial heavy water plant at Vemork, Tinn, with a capacity of 12 tonnes per year. From 1940 and throughout World War II, the plant was under German control and the allies decided to destroy the plant and its heavy water to inhibit German development of nuclear weapons. In late 1942, a planned raid by British airborne troops failed, both gliders crashing. The raiders were killed in the crash or subsequently executed by the Germans. In the night of 27 February 1943 Operation Gunnerside succeeded. Norwegian commandos and local resistance managed to demolish small but key parts of the electrolytic cells, dumping the accumulated heavy water down the factory drains. Had the German nuclear program followed similar lines of research as the U.S. Manhattan Project, such heavy water would have been crucial to obtaining plutonium from a nuclear reactor. The Norsk Hydro operation is one of the great commando sabotage operations of the war.

On 16 November 1943, the allied air forces dropped more than 400 bombs on the site. The allied air raid prompted the Nazi government to move all available heavy water to Germany for safekeeping. On 20 February 1944, a Norwegian partisan sank the ferry *M/F Hydro* carrying the heavy water across Lake Tinn, at the cost of 14 Norwegian civilians' lives, and most of the heavy water was presumably lost. A few of the barrels were only half full, and therefore could float, and may have been salvaged and transported to Germany. (These events were dramatized in the 1965 movie, *The Heroes*

of Telemark, and also in a level of the PlayStation 2/Xbox game, *Secret Weapons Over Normandy*.)

Recent investigation of production records at Norsk Hydro and analysis of an intact barrel that was salvaged in 2004 revealed that although the barrels in this shipment contained water of pH 14 — indicative of the alkaline electrolytic refinement process — they did not contain high concentrations of D<sub>2</sub>O. Despite the apparent size of shipment, the total quantity of pure heavy water was quite small, most barrels only containing between 1/2–1% pure heavy water. The Germans would have needed a total of about 5 tons of heavy water to get a nuclear reactor running. The manifest clearly indicated that there was only half a ton of heavy water being transported to Germany. The *Hydro* was carrying far too little heavy water for even one reactor, let alone the 10 or more tons needed to make enough plutonium for a nuclear weapon.

## **Canada**

As part of its contribution to the Manhattan Project, Canada built and operated a 6 tonnes per year electrolytic heavy water plant at Trail, BC, which started operation in 1943.

The Atomic Energy of Canada Limited (AECL) design of power reactor requires large quantities of heavy water to act as a neutron moderator and coolant. AECL ordered two heavy water plants which were built and operated in Atlantic Canada at Glace Bay (by Deuterium of Canada Limited) and Port Hawkesbury, Nova Scotia (by General Electric Canada). These plants proved to have significant design, construction and production problems and so AECL built the Bruce Heavy Water Plant (map location), which it later sold to Ontario Hydro, to ensure a reliable supply of heavy water for future power plants. The two Nova Scotia plants were shut down in 1985 when their production proved to be unnecessary.

The Bruce Heavy Water Plant in Ontario was the world's largest heavy water production plant with a capacity of 700 tonnes per year. It used the Girdler sulfide process to produce heavy water, and required 340,000 tonnes of feed water to produce one tonne of heavy water. It was part of a complex that included 8 CANDU reactors which provided heat and power for the heavy water plant. The site was located at Douglas Point near Tiverton, Ontario on Lake Huron where it had access to the waters of the Great Lakes.

The Bruce plant was commissioned in 1979 to provide heavy water for a large increase in Ontario's nuclear power generation. The plants proved to be significantly more efficient than planned and only three of the planned four units were eventually commissioned. In addition, the nuclear power programme was slowed down and effectively stopped due to a perceived oversupply of electricity, later shown to be temporary, in 1993. Improved efficiency in the use and recycling of heavy water plus the over-production at Bruce left Canada with enough heavy water for its anticipated future needs. Also, the Girdler process involves large amounts of hydrogen sulfide, raising environmental concerns if there should be a release. The Bruce heavy water plant was shut down in 1997, after which the plant was gradually dismantled and the site cleared.

Atomic Energy of Canada Limited (AECL) is currently researching other more efficient and environmentally benign processes for creating heavy water. This is essential for the future of the CANDU reactors since heavy water represents about 20% of the capital cost of each reactor.

## **Iran**

On 26 August 2006, Iranian President Ahmadinejad inaugurated an expansion of the country's heavy-water plant near Arak. Iran has indicated that the heavy-water production facility will operate in tandem with a 40 MW research reactor that has a scheduled completion date in 2009.

## **Pakistan**

The 50 MWt, heavy water and natural uranium research reactor at Khushab, in Punjab province, is a central element of Pakistan's program for production of plutonium, deuterium and tritium for advanced compact warheads. Pakistan succeeded in illicitly acquiring a tritium purification and storage plant, and deuterium and tritium precursor materials from two German firms.

## **Other countries**

Argentina is another declared producer of heavy water, using an ammonia/hydrogen exchange based plant supplied by Switzerland's Sulzer company.

Romania also produces heavy water at the Drobeta Girdler Sulfide plant and is exporting it from time to time.

France operated a small plant during the 1950s and 1960s.

# **Applications**

## **Nuclear magnetic resonance**

Deuterium oxide is used in nuclear magnetic resonance spectroscopy when the solvent of interest is water and the nuclide of interest is hydrogen. This is because the signal from the water solvent would interfere with the signal from the molecule of interest. Deuterium has a different magnetic moment from hydrogen and therefore does not contribute to the NMR signal at the hydrogen resonance frequency.

## **Organic chemistry**

Deuterium oxide is often used as the source of deuterium for preparing specifically-labelled isotopologs of organic compounds. For example, C-H bonds adjacent to ketonic carbonyl groups can be replaced by C-D bonds, using acid or base catalysis.

Trimethylsulfoxonium iodide, made from dimethyl sulfoxide and methyl iodide can be recrystallized from deuterium oxide, and then dissociated to regenerate methyl iodide and dimethyl sulfoxide, both deuterium labelled. In cases where specific double labelling by deuterium and tritium is contemplated, the researcher needs to be aware that deuterium oxide, depending upon age and origin, can contain some tritium.

### **Fourier transform spectroscopy**

Deuterium oxide is often used instead of water when collecting FTIR spectra of proteins in solution. H<sub>2</sub>O creates a strong band that overlaps with the amide I region of proteins. The band from D<sub>2</sub>O is shifted away from the amide I region.

### **Neutron moderator**

Heavy water is used in certain types of nuclear reactors where it acts as a neutron moderator to slow down neutrons so that they are more likely to react with the fissile uranium-235 than with uranium-238 which captures neutrons without fissioning. The CANDU reactor uses this design. Light water also acts as a moderator but because light water absorbs more neutrons than heavy water, reactors using light water must use enriched uranium rather than natural uranium, otherwise criticality is impossible.

Because they do not require uranium enrichment, heavy water reactors are of concern in regards to nuclear proliferation. The breeding and extraction of plutonium can be a relatively rapid and cheap route to building a nuclear weapon, as chemical separation of plutonium from fuel is easier than isotopic separation of U-235 from natural uranium. Among current and past nuclear weapons states, Israel, India, and North Korea first used plutonium from heavy water moderated reactors burning natural uranium, while China, South Africa and Pakistan first built weapons using highly enriched uranium. However, in the U.S., the first experimental atomic reactor (1942), as well as the Manhattan Project Hanford production reactors which produced the plutonium for the Trinity test and Fat Man bombs, all used pure carbon neutron moderators and functioned with neither enriched uranium nor heavy water. Russian and British plutonium production also used graphite-moderated reactors.

There is no evidence that civilian heavy water power reactors, such as the CANDU or Atucha designs, have been used for military production of fissile materials. In states which do not already possess nuclear weapons, the nuclear material at these facilities is under IAEA safeguards to discourage any such diversion.

Due to its potential for use in nuclear weapons programs, the possession or import/export of large industrial quantities of heavy water are subject to government control in several countries. Suppliers of heavy water and heavy water production technology typically apply IAEA (International Atomic Energy Agency) administered safeguards and material accounting to heavy water. (In Australia, the *Nuclear Non-Proliferation (Safeguards) Act 1987*.) In the U.S. and Canada, non-industrial quantities of heavy water (i.e., in the gram to kg range) are routinely available without special license through chemical supply

dealers and commercial companies such as the world's former major producer Ontario Hydro. Current (2006) cost of a kilogram of 99.98% reactor-purity heavy water, is about \$600 to \$700. Smaller quantities of reasonable purity (99.9%) may be purchased from chemical supply houses at prices of roughly \$1 per gram.

### **Neutrino detector**

The Sudbury Neutrino Observatory (SNO) in Sudbury, Ontario used 1000 tonnes of heavy water on loan from Atomic Energy of Canada Limited. The neutrino detector is 6,800 feet (2,100 m) underground in a deep mine, in order to shield it from muons produced by cosmic rays. SNO was built to answer the question of whether or not electron-type neutrinos produced by fusion in the Sun (the only type the Sun should be producing directly, according to theory) might be able to turn into other types of neutrinos on the way to Earth. SNO detects the Čerenkov radiation in the water from high-energy electrons produced from electron-type neutrinos as they undergo reactions with neutrons in deuterium, turning them into protons and electrons (only the electrons move fast enough to be detected in this manner). SNO also detects the same radiation from neutrino↔electron scattering events, which again produces high energy electrons. These two reactions are produced only by electron-type neutrinos. The use of deuterium is critical to the SNO function, because all three "flavours" (types) of neutrinos may be detected in a third type of reaction, neutrino-disintegration, in which a neutrino of any type (electron, muon, or tau) scatters from a deuterium nucleus (deuteron), transferring enough energy to break up the loosely-bound deuteron into a free neutron and proton. This event is detected when the free neutron is absorbed by  $^{35}\text{Cl}^-$  present from NaCl which has been deliberately dissolved in the heavy water, causing emission of characteristic capture gamma rays. Thus, in this experiment, heavy water not only provides the transparent medium necessary to produce and visualize Čerenkov radiation, but it also provides deuterium to detect exotic mu type ( $\mu$ ) and tau ( $\tau$ ) neutrinos, as well as a non-absorbent moderator medium to preserve free neutrons from this reaction, until they can be absorbed by an easily-detected neutron-activated isotope.

### **Metabolic rate testing in physiology/biology**

Heavy water is employed as part of a mixture with  $\text{H}_2^{18}\text{O}$  for a common and safe test of mean metabolic rate in humans and animals undergoing their normal activities. This metabolic test is usually called the doubly-labeled water test.

### **Tritium production**

Tritium is an important material in nuclear weapon design for boosted fission weapons and initiators, and also has civilian industrial applications. Some is created in heavy water moderated reactors when deuterium captures a neutron. This reaction has a small cross-section and produces only small amounts of tritium, although enough so that cleaning tritium from the moderator may be desirable after several years to reduce the risk of tritium escape and radiation exposure.

Production of large amounts of tritium in this way would require reactors with very high neutron fluxes, or with a very high proportion of heavy water to nuclear fuel and very low neutron absorption by other reactor material. The tritium would then have to be recovered by isotope separation from a much larger quantity of deuterium, unlike tritium production from lithium-6 (the present method of tritium production), where only chemical separation is needed.

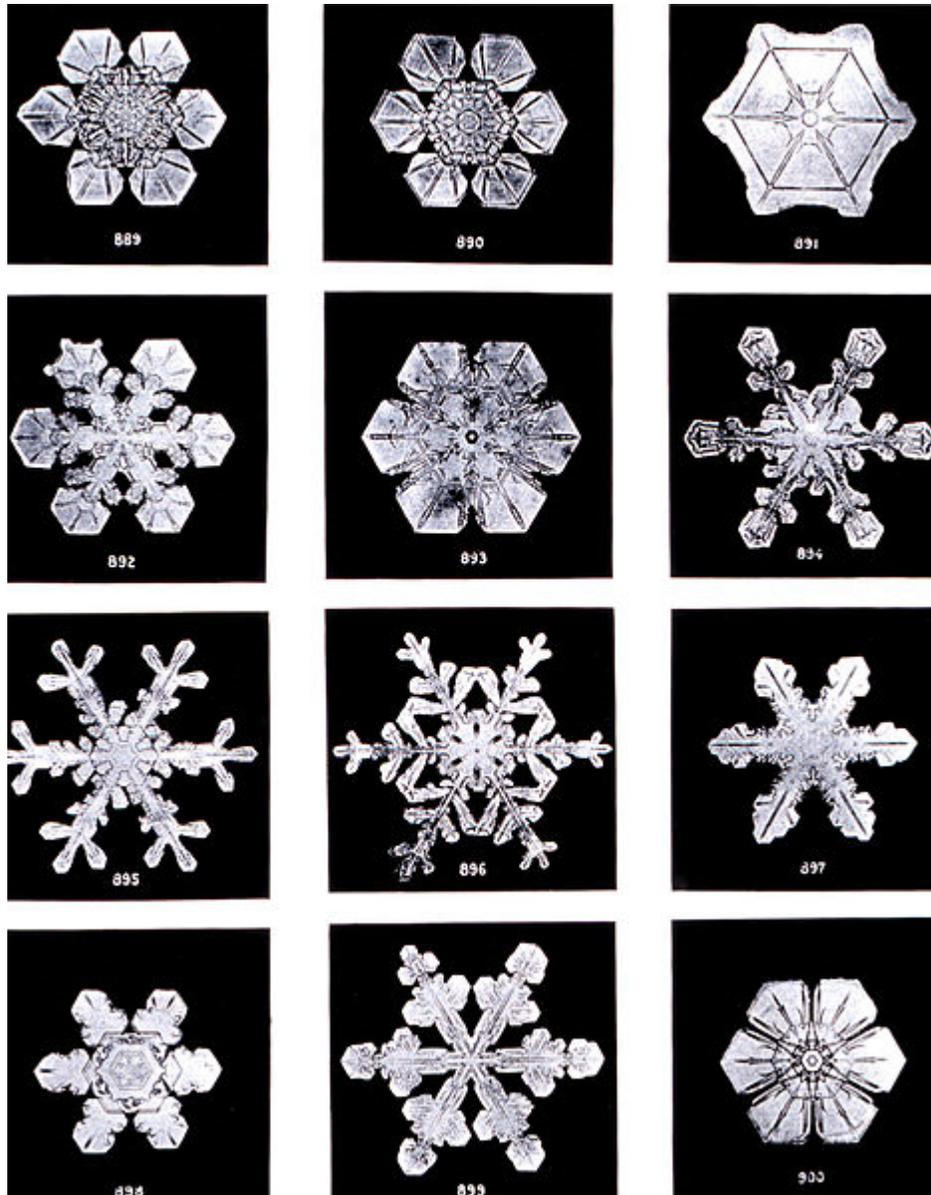
Deuterium's absorption cross section for thermal neutrons is .52 millibarns, while oxygen-16's is .19 millibarns and oxygen-17's is .24 millibarns.  $^{17}\text{O}$  makes up .038% of natural oxygen, which has an overall absorption cross section of .28 millibarns. Therefore in  $\text{D}_2\text{O}$  with natural oxygen, 21% of neutron captures are on oxygen, a proportion that may rise further as  $^{17}\text{O}$  accumulates from neutron capture on  $^{16}\text{O}$ . Also,  $^{17}\text{O}$  emits an alpha particle on capture, producing radioactive carbon-14.

## Chapter- 5

# Ice



A natural block of (water) ice



Snowflakes (ice crystals) by Wilson Bentley, 1902

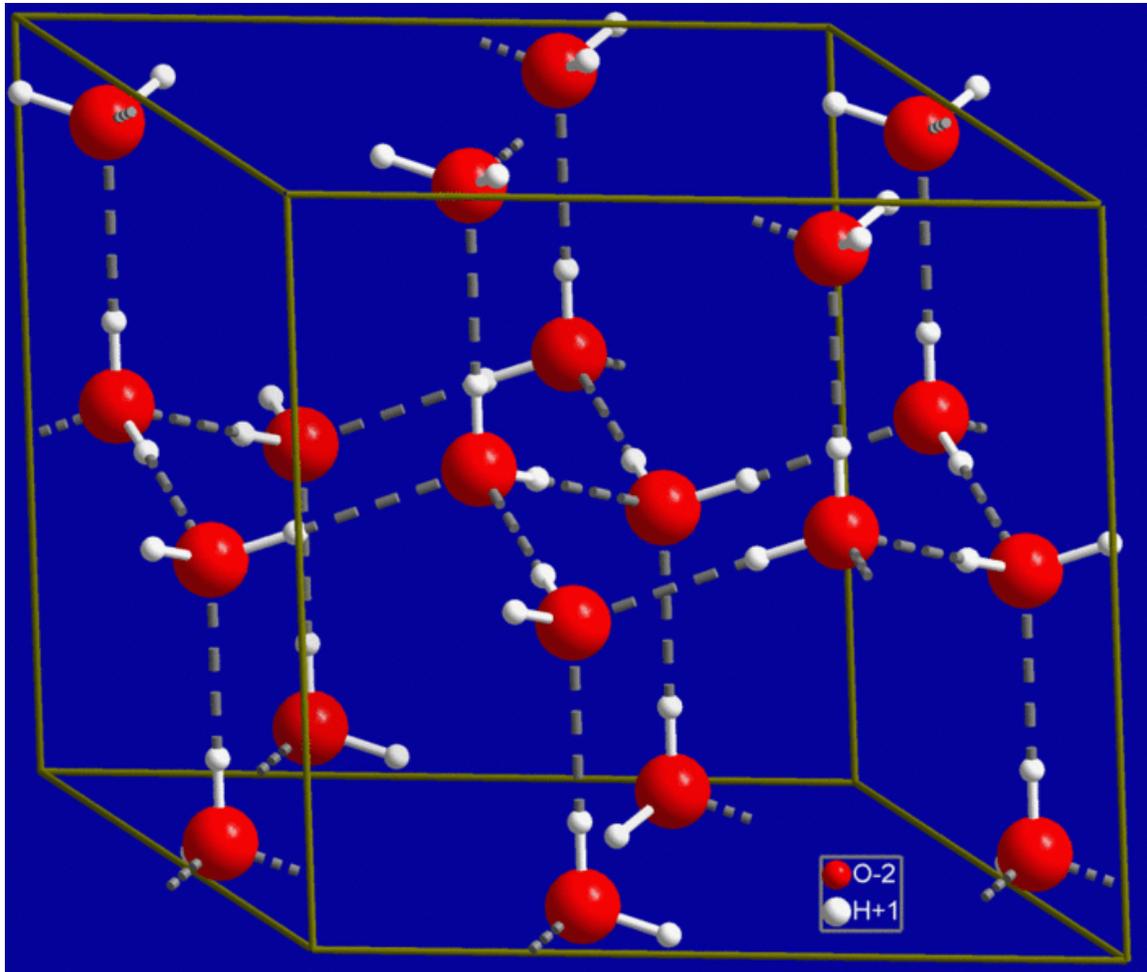
**Ice** may be any one of the 15 known crystalline phases of water. Usually ice is the phase known as ice  $I_h$ , which is the most abundant of these solid phases on the Earth's surface. It can appear transparent or opaque bluish-white color, depending on the presence of impurities or air inclusions. The addition of other materials such as soil may further alter the appearance.

The most common phase transition to ice  $I_h$  occurs when liquid water is cooled below  $0^{\circ}\text{C}$  ( $273.15\text{K}$ ,  $32^{\circ}\text{F}$ ) at standard atmospheric pressure. It can also deposit from vapour with no intervening liquid phase, such as in the formation of frost.

Ice appears in nature in forms of precipitation snowflakes, hail, icicles, glaciers, pack ice, and entire polar ice caps. It is an important component of the global climate, and plays an important role in the water cycle. Furthermore, ice has numerous cultural applications, from ice cooling of drinks to winter sports and the art of ice sculpting.

The word is derived from Old English *īs*, which in turn stems from Proto-Germanic *\*isaz*.

## Characteristics



Crystal structure of hexagonal ice. Grey dashed lines indicate hydrogen bonds.

As a naturally occurring crystalline inorganic solid with an ordered structure, ice is considered a mineral. It possesses a regular crystalline structure based on the molecule of water, which consists of a single oxygen atom covalently bonded to two hydrogen atoms, or H-O-H. However, many of the physical properties of water and ice are controlled by the formation of hydrogen bonds between adjacent oxygen and hydrogen atoms. It is a weak bond, but is critical in controlling the structure of both water and ice.

An unusual property of ice frozen at atmospheric pressure is that the solid is approximately 9% less dense than liquid water. Ice is the only known non-metallic substance to expand when it freezes. The density of ice is  $0.9167 \text{ g/cm}^3$  at  $0^\circ\text{C}$ , whereas water has a density of  $0.9998 \text{ g/cm}^3$  at the same temperature. Liquid water is densest, essentially  $1.00 \text{ g/cm}^3$ , at  $4^\circ\text{C}$  and becomes less dense as the water molecules begin to form the hexagonal crystals of ice as the freezing point is reached. This is due to hydrogen bonding dominating the intermolecular forces, which results in a packing of molecules less compact in the solid. Density of ice increases slightly with decreasing temperature and has a value of  $0.9340 \text{ g/cm}^3$  at  $-180^\circ\text{C}$  (93 K).

The effect of expansion during freezing can be dramatic, and is a basic cause of freeze-thaw weathering of rock in nature. It is also a common cause of the flooding of houses when water pipes burst due to the pressure of expanding water when it freezes, then leak water after thawing.

The result of these properties is that ice floats on liquid water, which is an important factor in Earth's climate. It has been argued that natural bodies of water would freeze from the bottom up without this property, resulting in the annual loss of wild life and vegetation.

When ice melts, it absorbs as much energy as it would take to heat an equivalent mass of water by  $80^\circ\text{C}$ . During the melting process, the temperature remains constant at  $0^\circ\text{C}$ . While melting, any energy added breaks the hydrogen bonds between ice (water) molecules. Energy becomes available to increase the thermal energy (temperature) only after enough hydrogen bonds are broken that the ice can be considered liquid water. The amount of energy consumed in breaking hydrogen bonds in the transition from ice to water is known as the heat of fusion.

It has been theoretically shown that ice may be superheated beyond its equilibrium melting point. Simulations of ultrafast laser pulses acting on ice suggest it may be heated to room temperature for an extremely short period (250 ps) without melting.

Light reflecting from ice often appears blue due to the properties of Rayleigh scattering, the same reason the sky is blue. Blue light is scattered much more strongly than red in matter which does not absorb visible light, such as ice. Other colors can appear in the presence of light absorbing impurities, where the impurity is dictating the color rather than the ice itself. For instance, icebergs containing impurities (e.g., sediments, algae, air bubbles) can appear brown, grey or green.

## **Slipperiness**



Frozen waterfall in southeast New York

Until recently, it was widely believed that ice was slippery because the pressure of an object in contact with it caused a thin layer to melt. For example, the blade of an ice skate, exerting pressure on the ice, melted a thin layer, providing lubrication between the ice and the blade.

This explanation is no longer accepted. There is still debate about why ice is slippery. The explanation gaining acceptance is that ice molecules in contact with air cannot properly bond with the molecules of the mass of ice beneath (and thus are free to move like molecules of liquid water). These molecules remain in a semiliquid state, providing lubrication regardless of pressure against the ice exerted by any object.

## **Formation**



Feather ice on the plateau near Alta, Norway. The crystals form at temperatures below  $-30\text{ }^{\circ}\text{C}$  (i.e.  $-22\text{ }^{\circ}\text{F}$ ).

Ice that is found at sea may be in the form of sea ice, pack ice, or icebergs. The term that collectively describes all of the parts of the Earth's surface where water is in frozen form is the *cryosphere*. Ice is an important component of the global climate, particularly in regard to the water cycle. Glaciers and snowpacks are an important storage mechanism for fresh water; over time, they may sublime or melt. Snowmelt is often an important source of seasonal fresh water.

Rime is a type of ice formed on cold objects when drops of water crystallize on them. This can be observed in foggy weather, when the temperature drops during the night. Soft rime contains a high proportion of trapped air, making it appear white rather than transparent, and giving it a density about one quarter of that of pure ice. Hard rime is comparatively denser.

Aufeis is layered ice that forms in Arctic and subarctic stream valleys. Ice, frozen in the stream bed, blocks normal groundwater discharge, and causes the local water table to rise, resulting in water discharge on top of the frozen layer. This water then freezes, causing the water table to rise further and repeat the cycle. The result is a stratified ice deposit, often several meters thick.

Ice can also form icicles, similar to stalactites in appearance, or stalagmite-like forms as water drips and re-freezes.

Clathrate hydrates are forms of ice that contain gas molecules trapped within its crystal lattice.

Pancake ice is a formation of ice generally created in areas with less calm conditions.

Candle Ice is a form of Rotten Ice that develops in columns perpendicular to the surface of a lake.

Ice discs are circular formations of ice surrounded by water in a river.

### **Ice pellets**



An accumulation of ice pellets

Ice pellets are a form of precipitation consisting of small, translucent balls of ice. This form of precipitation is also known as **sleet**. Ice pellets are usually (but not always) smaller than hailstones. They often bounce when they hit the ground, and generally do not freeze into a solid mass unless mixed with freezing rain. The METAR code for ice pellets is **PL**.

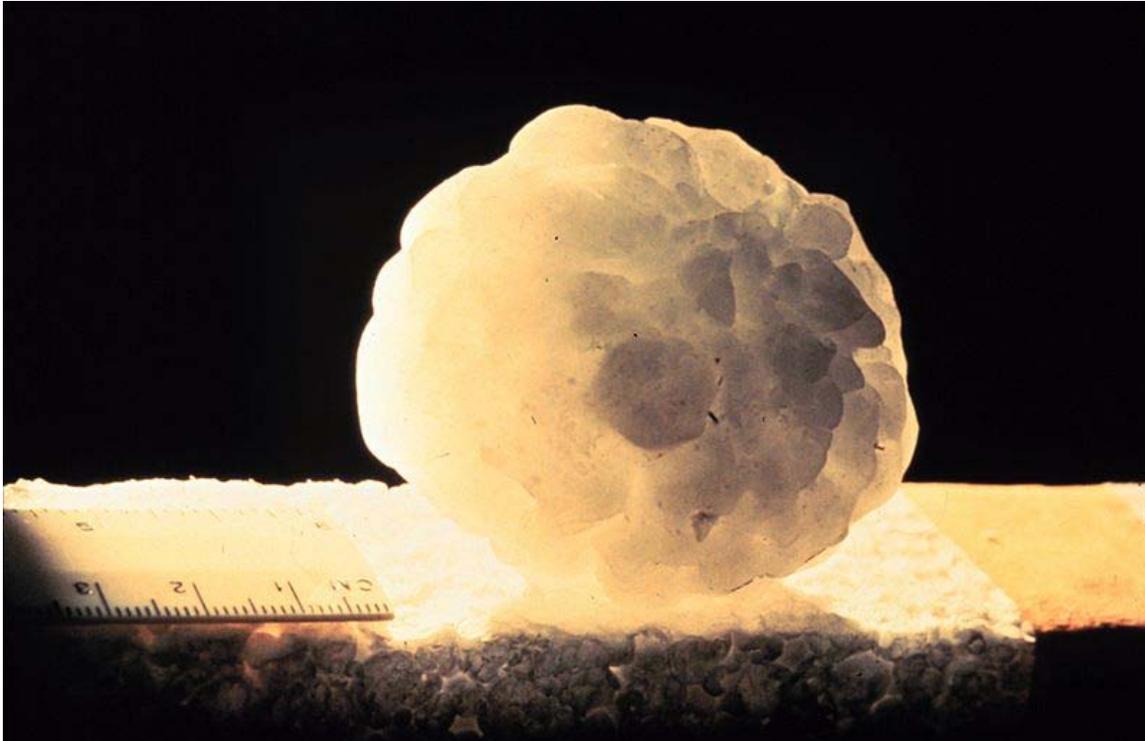
Ice pellets form when a layer of above-freezing air is located between 1,500 metres (4,900 ft) and 3,000 metres (9,800 ft) above the ground, with sub-freezing air both above and below it. This causes the partial or complete melting of any snowflakes falling through the warm layer. As they fall back into the sub-freezing layer closer to the surface, they re-freeze into ice pellets. However, if the sub-freezing layer beneath the warm layer is too small, the precipitation will not have time to re-freeze, and freezing rain will be the result at the surface. A temperature profile showing a warm layer above the ground is most likely to be found in advance of a warm front during the cold season, but can occasionally be found behind a passing cold front.

## **Hail**

**Hail** is a form of solid precipitation which consists of balls or irregular lumps of ice, that are individually called hail stones. Hail stones on Earth consist mostly of water ice and measure between 5 millimetres (0.20 in) and 150 millimetres (5.9 in) in diameter, with the larger stones coming from severe thunderstorms. The METAR reporting code for hail 5 millimetres (0.20 in) or greater in diameter is **GR**, while smaller hailstones and graupel are coded **GS**. Hail is possible with most thunderstorms as it is produced by **cumulonimbi** (thunderclouds), usually at the leading edge of a severe storm system. Hail is possible within 2 nautical miles (3.7 km) of its parent thunderstorm. Hail formation requires environments of strong, upward motion of air with the parent thunderstorm (similar to tornadoes) and lowered heights of the freezing level. Hail is most frequently formed in the interior of continents within the mid-latitudes of Earth, with hail generally confined to higher elevations within the tropics.

Unlike ice pellets, hail stones are layered and can be irregular and clumped together. Hail is composed of transparent ice or alternating layers of transparent and translucent ice at least 1 millimetre (0.039 in) thick, which are deposited upon the hail stone as it cycles through the cloud multiple times, suspended aloft by air with strong upward motion until its weight overcomes the updraft and falls to the ground. There are methods available to detect hail-producing thunderstorms using weather satellites and radar imagery. Hail stones generally fall at faster rates as they grow in size, though complicating factors such as melting, friction with air, wind, and interaction with rain and other hail stones can slow down their descent through Earth's atmosphere. Severe weather warnings are issued for hail when the stones reach a damaging size, as it can cause serious damage to man-made structures, and most commonly, farmers' crops. In the United States, the National Weather Service issues severe thunderstorm warnings for hail 1" or greater in diameter. This threshold, effective January 2010, marked an increase over the previous threshold of 3/4" hail. The change was made for two main reasons: a) public complacency and, b) recent research suggesting that damage does not occur until a hailstone reaches 1" in diameter.

## **Formation**



A large hailstone, about 6 cm (2.36 in) in diameter

Like other precipitation, hail forms in cumulonimbus clouds when supercooled water droplets freeze on contact with condensation nuclei. The storm's updraft, with upwardly directed wind speeds as high as 110 miles per hour (180 km/h), blow the hailstones back up the cloud. The updraft dissipates and the hailstones fall down, back into the updraft, and are lifted up again. These type of strong updrafts can also indicate the presence of a tornado. Any thunderstorm which produces hail that reaches the ground is known as a hailstorm. Hail has a diameter of 5 millimetres (0.20 in) or more. Stones just larger than golf ball-sized are one of the most frequently reported hail sizes. Hail stones can grow to 15 centimetres (6 in) and weigh more than 0.5 kilograms (1.1 lb). In large hailstones, latent heat released by further freezing may melt the outer shell of the hailstone. The hailstone then may undergo 'wet growth', where the liquid outer shell collects other smaller hailstones. The hailstone gains an ice layer and grows increasingly larger with each ascent. Once a hail stone becomes too heavy to be supported by the storm's updraft, it falls from the cloud.

Hail forms in strong thunderstorm clouds, particularly those with intense updrafts, high liquid water content, great vertical extent, large water droplets, and where a good portion of the cloud layer is below freezing  $0^{\circ}\text{C}$  ( $32^{\circ}\text{F}$ ). The growth rate is maximized where air is near a temperature of  $-13^{\circ}\text{C}$  ( $9^{\circ}\text{F}$ ). Hail growth becomes vanishingly small when air temperatures fall below  $-30^{\circ}\text{C}$  ( $-22^{\circ}\text{F}$ ) as supercooled water droplets become rare at these temperatures. Around thunderstorms, hail is most likely within the cloud at elevations above 20,000 feet (6,100 m). Between 10,000 feet (3,000 m) and 20,000 feet (6,100 m), 60 percent of hail is still within the thunderstorm, though 40 percent now lies

within the clear air under the anvil. Below 10,000 feet (3,000 m), hail is equally distributed in and around a thunderstorm to a distance of 2 nautical miles (3.7 km).



#### Hail shaft

Hail is most common within continental interiors of the mid-latitudes, as hail formation is considerably more likely when the freezing level is below the altitude of 11,000 feet (3,400 m). Movement of dry air into strong thunderstorms over continents can increase the frequency of hail by promoting evaporational cooling which lowers the freezing level of thunderstorm clouds giving hail a larger volume to grow in. Accordingly, hail is actually less common in the tropics despite a much higher frequency of thunderstorms than in the mid-latitudes because the atmosphere over the tropics tends to be warmer over a much greater depth. Hail in the tropics occurs mainly at higher elevations.



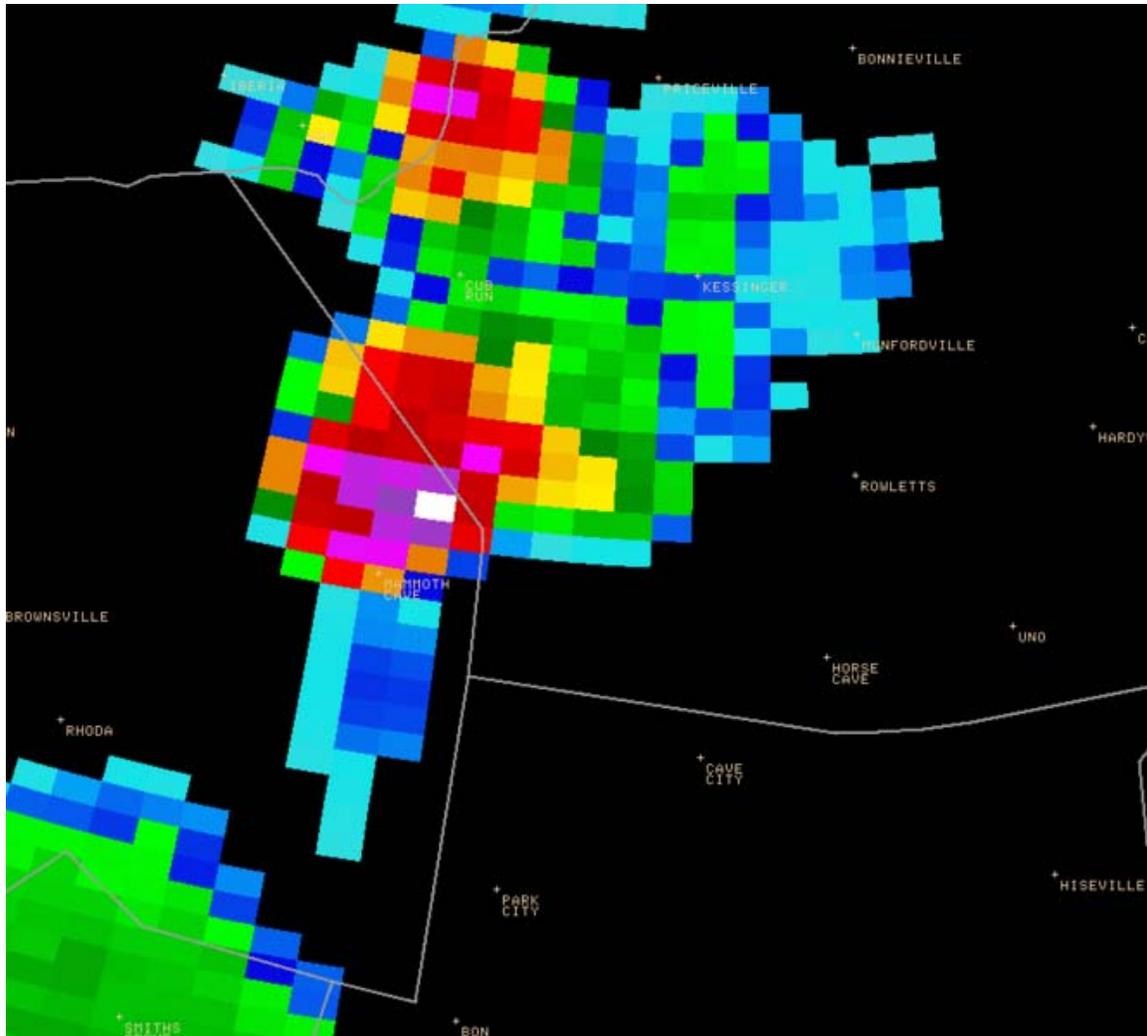
Hail clouds often exhibit a characteristic green coloration.

## **Climatology**

Hail is also much more common along mountain ranges because mountains force horizontal winds upwards (known as orographic lifting), thereby intensifying the updrafts within thunderstorms and making hail more likely. One of the more common regions for large hail is across mountainous northern India, which reported one of the highest hail-related death tolls on record in 1888. China also experiences significant hailstorms. Central Europe experiences also a lot of hailstorms. Popular regions for hailstorms are southern and western Germany, northern and eastern France and southern and eastern BeNeLux. In south-eastern Europe, Croatia experiences frequent occurrences of hail.

In North America, hail is most common in the area where Colorado, Nebraska, and Wyoming meet, known as "Hail Alley." Hail in this region occurs between the months of March and October during the afternoon and evening hours, with the bulk of the occurrences from May through September. Cheyenne, Wyoming is North America's most hail-prone city with an average of nine to ten hailstorms per season.

## **Short-term detection**



Example of a three body spike : the weak triangular echoes behind the red and white thunderstorm core is related to hail inside the storm.

Weather radar is a very useful tool to detect the presence of hail producing thunderstorms. However, radar data has to be complemented by a knowledge of current atmospheric conditions which can allow one to determine if the current atmosphere is conducive to hail development.

Modern radar scans many angles around the site. Reflectivity values at multiple angles above ground level in a storm are proportional to the precipitation rate at those levels. Summing reflectivities in the Vertically Integrated Liquid or VIL, gives the liquid water content in the cloud. Research shows that hail development in the upper levels of the storm is related to the evolution of VIL. VIL divided by the vertical extent of the storm, called VIL density, has a relationship with hail size, although this varies with atmospheric conditions and therefore is not highly accurate. Traditionally, hail size and probability can be estimated from radar data by computer using algorithms based on this

research. Some algorithms include the height of the freezing level to estimate the melting of the hailstone and what would be left on the ground.

Certain patterns of reflectivity are important clues for the meteorologist, too. The three body scatter spike is one of them. This is the result of energy from the radar hitting hail and being deflected to the ground, where they deflect back to the hail and then to the radar. The energy took more time to go from the hail to the ground and back, as opposed to the energy that went direct from the hail to the radar, and the echo is further away from the radar than the actual location of the hail on the same radial path, forming a cone of weaker reflectivities.

More recently, the polarization properties of weather radar returns have been analyzed to differentiate between hail and heavy rain. The use of differential reflectivity ( $Z_{dr}$ ), in combination with horizontal reflectivity ( $Z_h$ ) has led to a variety of hail classification algorithms. Visible satellite imagery is beginning to be used to detect hail, but false alarm rates remain high using this method.

## **Size and terminal velocity**

The size of hail stones is best determined by measuring their diameter with a ruler. In the absence of a ruler, hail stone size is often visually estimated by comparing its size to that of known objects, such as coins. Below is a table of commonly used objects for this purpose. Note that using the objects such as hen's eggs, peas, and marbles for comparing hailstone sizes is often inaccurate, due to their varied dimensions. The UK organisation, TORRO, also scales for both hailstones and hailstorms. When observed at an airport, METAR code is used within a surface weather observation which relates to the size of the hail stone. Within METAR code, GR is used to indicate larger hail, of a diameter of at least 0.25 inches (6.4 mm). GR is derived from the French word grêle. Smaller-sized hail, as well as snow pellets, use the coding of GS, which is short for the French word grésil.

Terminal velocity of hail, or the speed at which hail is falling when it strikes the ground, varies by the diameter of the hail stones. A hail stone of 1 centimetre (0.39 in) in diameter falls at a rate of 9 metres per second (20 mph), while stones the size of 8 centimetres (3.1 in) in diameter fall at a rate of 48 metres per second (110 mph). Hail stone velocity is dependent on the size of the stone, friction with air it is falling through, the motion of wind it is falling through, collisions with raindrops or other hail stones, and melting as the stones fall through a warmer atmosphere.



Hailstones ranging in size from Pea to Nickel



A large hailstone, approximately 5 1/4 inches in diameter, that fell in Harper, Kansas on May 14, 2004.

## **Hazards**



The largest recorded hailstone in the United States by diameter (8 inches) and weight (1.93 pounds). The hailstone fell in Vivian, South Dakota on July 23, 2010.



Hailstorm in Bogotá, Colombia.

Hail can cause serious damage, notably to automobiles, aircraft, skylights, glass-roofed structures, livestock, and most commonly, farmers' crops. Hail damage to roofs often goes unnoticed until further structural damage is seen, such as leaks or cracks. It is hardest to recognize hail damage on shingled roofs and flat roofs, but all roofs have their own hail damage detection problems. Metal roofs are fairly resistant to hail damage, but may accumulate cosmetic damage in the form of dents and damaged coatings.

Hail is one of the most significant thunderstorm hazards to aircrafts. When hail stones exceed 0.5 inches (13 mm) in diameter, planes can be seriously damaged within seconds. The hailstones accumulating on the ground can also be hazardous to landing aircraft. Hail is also a common nuisance to drivers of automobiles, severely denting the vehicle and cracking or even shattering windshields and windows. Wheat, corn, soybeans, and tobacco are the most sensitive crops to hail damage. Hail is one of Canada's most expensive hazards. Rarely, massive hailstones have been known to cause concussions or fatal head trauma. Hailstorms have been the cause of costly and deadly events throughout history. One of the earliest recorded incidents occurred around the 9th century in Rookkund, Uttarakhand, India. The largest hailstone in terms of diameter and weight ever recorded in the United States fell on July 23, 2010 in Vivian, South Dakota, USA; it measured 8 inches (20 cm) in diameter and 18.62 inches (47.3 cm) in circumference, weighing in at 1.93 pounds (0.88 kg). This broke the previous record for diameter set by

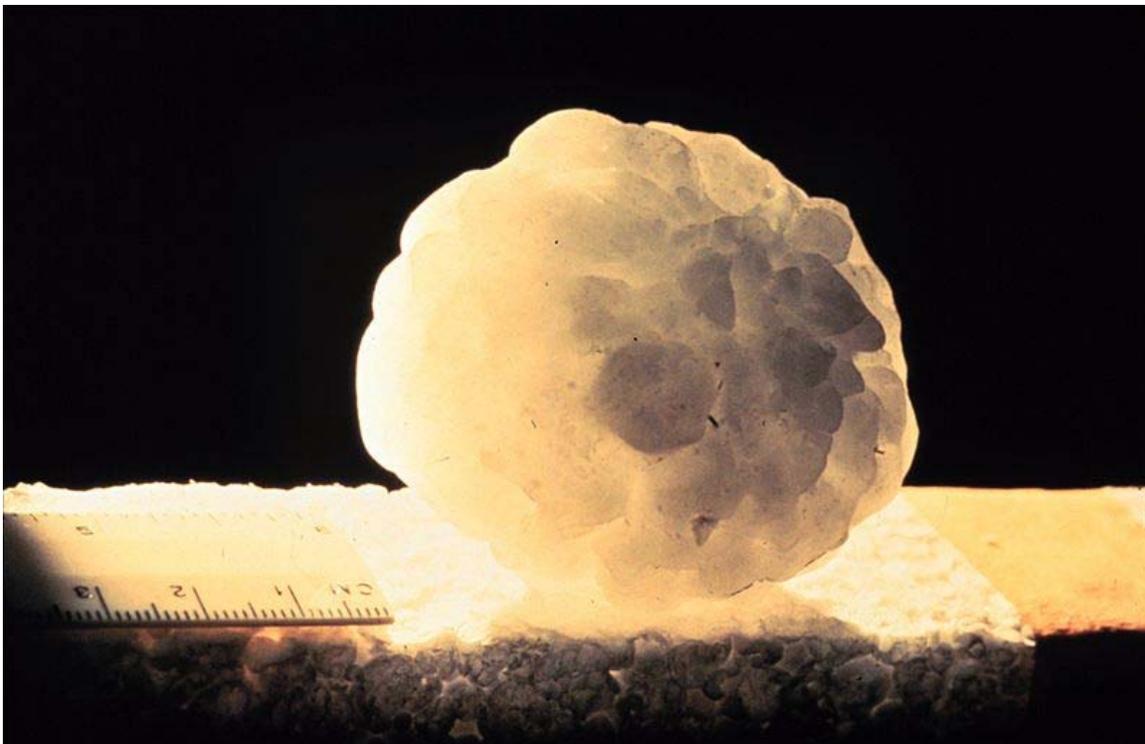
a hailstone 7 inches diameter and 18.75 inches circumference which fell in Aurora, Nebraska, USA on June 22, 2003, as well as the record for weight, set by a hailstone of 1.67 pounds (0.76 kg) that fell in Coffeyville, Kansas in 1970.

## **Accumulations**

Narrow zones where hail accumulates on the ground in association with thunderstorm activity are known as hail streaks or hail swaths, which can be detectable by satellite after the storms pass by. Hailstorms normally last from a few minutes up to 15 minutes in duration. Accumulating hail storms can blanket the ground with over 2 inches (5.1 cm) of hail, cause thousands to lose power, and bring down many trees. Flash flooding and mudslides within areas of steep terrain can be a concern with accumulating hail.

## **Suppression and prevention**

During the Middle Ages, people in Europe used to ring church bells and fire cannons to try to prevent hail. After World War II, cloud seeding was done to eliminate the hail threat, particularly across Russia. Russia claimed a 50 to 80 percent reduction in crop damage from hail storms by deploying silver iodide in clouds using rockets and artillery shells. Their results have not been able to be verified. Hail suppression programs have been undertaken by 15 countries between 1965 and 2005. To this day, no hail prevention method has been proven to work.

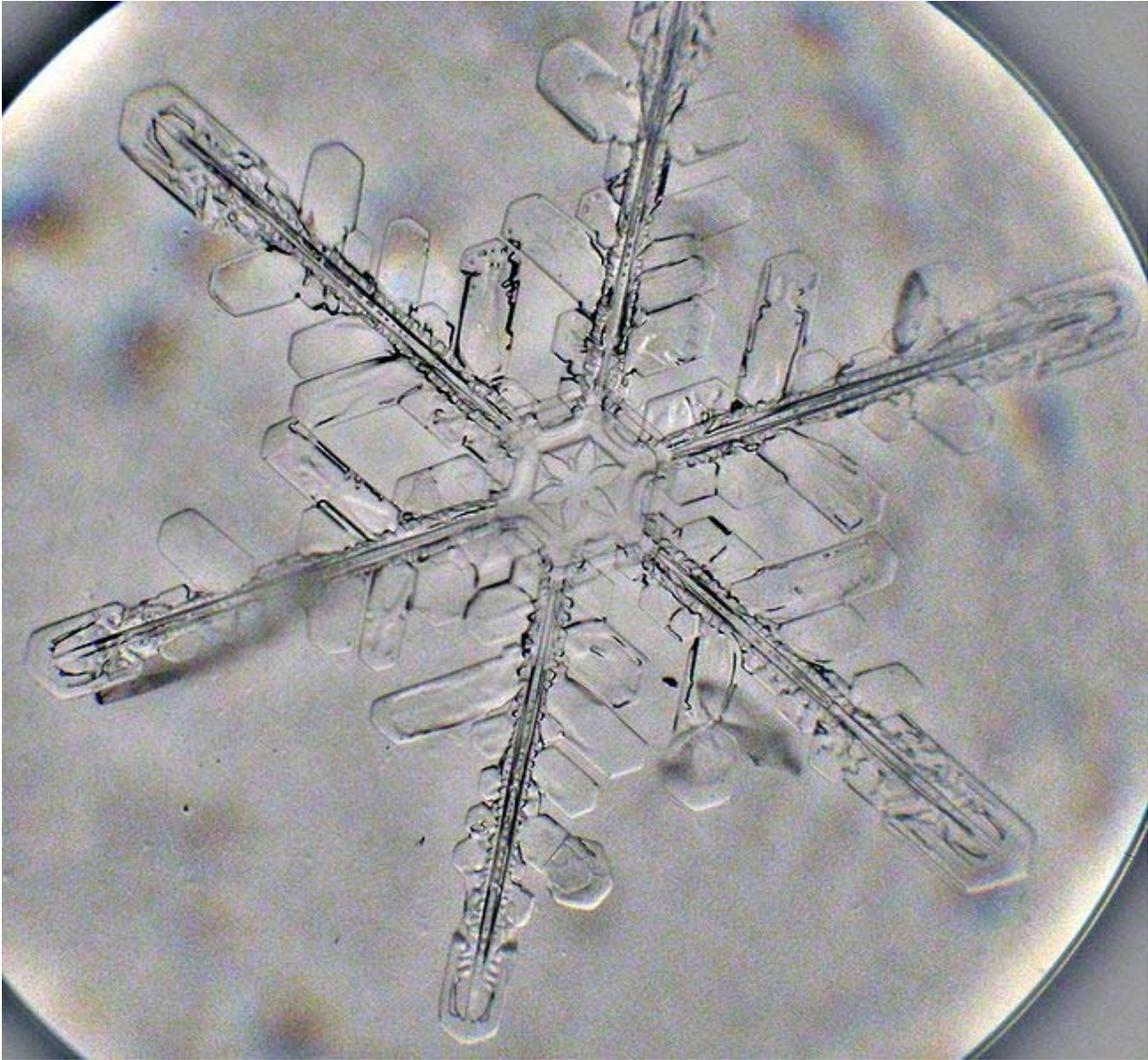


A large hailstone, about 6 cm (2.36 in) in diameter

Like other precipitation, hail forms in storm clouds when supercooled water droplets freeze on contact with condensation nuclei, such as dust or dirt. The storm's updraft blows the hailstones to the upper part of the cloud. The updraft dissipates and the hailstones fall down, back into the updraft, and are lifted up again. Hail has a diameter of 5 millimetres (0.20 in) or more. Within METAR code, GR is used to indicate larger hail, of a diameter of at least 6.4 millimetres (0.25 in). GR is derived from the French word grêle. Smaller-sized hail, as well as snow pellets, use the coding of GS, which is short for the French word grésil. Stones just larger than golf ball-sized are one of the most frequently reported hail sizes. Hailstones can grow to 15 centimetres (6 in) and weigh more than .5 kilograms (1.1 lb). In large hailstones, latent heat released by further freezing may melt the outer shell of the hailstone. The hailstone then may undergo 'wet growth', where the liquid outer shell collects other smaller hailstones. The hailstone gains an ice layer and grows increasingly larger with each ascent. Once a hailstone becomes too heavy to be supported by the storm's updraft, it falls from the cloud.

Hail forms in strong thunderstorm clouds, particularly those with intense updrafts, high liquid water content, great vertical extent, large water droplets, and where a good portion of the cloud layer is below freezing 0 °C (32 °F). Hail-producing clouds are often identifiable by their green coloration. The growth rate is maximized at about -13 °C (9 °F), and becomes vanishingly small much below -30 °C (-22 °F) as supercooled water droplets become rare. For this reason, hail is most common within continental interiors of the mid-latitudes, as hail formation is considerably more likely when the freezing level is below the altitude of 11,000 feet (3,400 m). Entrainment of dry air into strong thunderstorms over continents can increase the frequency of hail by promoting evaporational cooling which lowers the freezing level of thunderstorm clouds giving hail a larger volume to grow in. Accordingly, hail is actually less common in the tropics despite a much higher frequency of thunderstorms than in the mid-latitudes because the atmosphere over the tropics tends to be warmer over a much greater depth. Hail in the tropics occurs mainly at higher elevations.

## **Snowflakes**



Snowflake viewed in an optical microscope

Snow crystals form when tiny supercooled cloud droplets (about  $10\ \mu\text{m}$  in diameter) freeze. These droplets are able to remain liquid at temperatures lower than  $-18\ ^\circ\text{C}$  ( $0\ ^\circ\text{F}$ ), because to freeze, a few molecules in the droplet need to get together by chance to form an arrangement similar to that in an ice lattice; then the droplet freezes around this "nucleus." Experiments show that this "homogeneous" nucleation of cloud droplets only occurs at temperatures lower than  $-35\ ^\circ\text{C}$  ( $-31\ ^\circ\text{F}$ ). In warmer clouds an aerosol particle or "ice nucleus" must be present in (or in contact with) the droplet to act as a nucleus. Our understanding of what particles make efficient ice nuclei is poor — what we do know is they are very rare compared to that cloud condensation nuclei on which liquid droplets form. Clays, desert dust and biological particles may be effective, although to what extent is unclear. Artificial nuclei include particles of silver iodide and dry ice, and these are used to stimulate precipitation in cloud seeding.

Once a droplet has frozen, it grows in the water-supersaturated air, when the temperature remains below the freezing point. The droplet then grows by condensation of water vapor

onto the ice surfaces. Air saturation with water is maintained by continuous simultaneous evaporation of water droplets. Thus ice crystals grow at the expense of water droplets in a process called the Wegner-Bergeron-Findeison process. These large crystals are an efficient source of precipitation, since they fall through the atmosphere due to their weight, and may collide and aggregate in clusters. These aggregates are snowflakes, and are usually the type of ice particle that falls to the ground. Guinness World Records list the world's largest snowflakes as those of January 1887 at Fort Keogh, Montana; allegedly one measured 38 cm (15 inches) wide.

The exact details of the sticking mechanism remain controversial. Possibilities include mechanical interlocking, sintering, electrostatic attraction as well as the existence of a "sticky" liquid-like layer on the crystal surface. The individual ice crystals often have hexagonal symmetry. Although the ice is clear, scattering of light by the crystal facets and hollows/imperfections mean that the crystals often appear white in color due to diffuse reflection of the whole spectrum of light by the small ice particles. The shape of the snowflake is determined broadly by the temperature and humidity at which it is formed. Rarely, at a temperature of around  $-2\text{ }^{\circ}\text{C}$  ( $28\text{ }^{\circ}\text{F}$ ), snowflakes can form in threefold symmetry — triangular snowflakes. The most common snow particles are visibly irregular, although near-perfect snowflakes may be more common in pictures because they are more visually appealing. It is unlikely that any two snowflakes are alike due to the estimated 10,000,000,000,000,000 water molecules which make up a typical snowflake, which grow at different rates and in different patterns depending on the changing temperature and humidity within the atmosphere that the snowflake falls through on its way to the ground. The METAR code for snow is SN, while snow showers are coded SHSN.

## **Diamond dust**

Diamond dust, also known as ice needles or ice crystals, forms at temperatures approaching  $-40\text{ }^{\circ}\text{F}$  ( $-40\text{ }^{\circ}\text{C}$ ) due to air with slightly higher moisture from aloft mixing with colder, surface based air. The METAR identifier for diamond dust within international hourly weather reports is IC.

## **Production**

Ice is now mechanically produced on an large scale, but before appropriate coolants were developed ice was harvested from natural sources for human use.

### **Ice harvesting**

Ice has long been valued as a means of cooling. Until recently, the Hungarian Parliament building used ice harvested in the winter from Lake Balaton for air conditioning. Icehouses were used to store ice formed in the winter, to make ice available all year long, and early refrigerators were known as iceboxes, because they had a block of ice in them. In many cities, it was not unusual to have a regular ice delivery service during the summer. For the first half of the 19th century, ice harvesting had become big business in

America. Frederic Tudor, who became known as the “Ice King,” worked on developing better insulation products for the long distance shipment of ice, especially to the tropics. The advent of artificial refrigeration technology has since made delivery of ice obsolete.



Harvesting ice on Lake Saint Clair in Michigan, *circa* 1905

In 400 BC Iran, Persian engineers had already mastered the technique of storing ice in the middle of summer in the desert. The ice was brought in during the winters from nearby mountains in bulk amounts, and stored in specially designed, naturally cooled *refrigerators*, called *yakhchal* (meaning *ice storage*). This was a large underground space (up to 5000 m<sup>3</sup>) that had thick walls (at least two meters at the base) made out of a special mortar called *sārooj*, composed of sand, clay, egg whites, lime, goat hair, and ash in specific proportions, and which was known to be resistant to heat transfer. This mixture was thought to be completely water impenetrable. The space often had access to a Qanat, and often contained a system of windcatchers which could easily bring temperatures inside the space down to frigid levels on summer days. The ice was then used to chill treats for royalty on such occasions.



Ice being transported by cart in Mumbai, India

## **Commercial production**

Ice is now produced on an industrial scale, for uses including food storage and processing, chemical manufacturing, concrete mixing and curing, and consumer or packaged ice. Most commercial ice makers produce three basic types of fragmentary ice: flake, tubular and plate, using a variety of techniques. Large batch ice makers can produce up to 75 tons of ice per day.

Ice production is a large business; in 2002, there were 426 commercial ice-making companies in the United States, with a combined value of shipments of \$595,487,000.

For small-scale ice production, many modern home refrigerators can also make ice with a built in icemaker, which will typically make ice cubes or crushed ice. Stand-alone icemaker units that make ice cubes are often called ice machines.



B&W film of 1919 ice harvest at Pocono Manor in the Poconos

## Uses

## Sports



Ice sailing on the Žnin Small Lake

Ice also plays a central role in winter recreation and in many sports such as ice skating, tour skating, ice hockey, ice fishing, ice climbing, curling, broomball and sled racing on bobsled, luge and skeleton. Many of the different sports played on ice get international attention every four years during the Winter Olympic Games.

A sort of sailboat on blades gives rise to ice yachting. The human quest for excitement has even led to ice racing, where drivers must speed on lake ice, while also controlling the skid of their vehicle (similar in some ways to dirt track racing). The sport has even been modified for ice rinks.

## Other uses



Ice pier during 1983 cargo operations. McMurdo Station, Antarctica

- Engineers used formidable strength of pack ice when they constructed Antarctica's first floating ice pier in 1973. Such ice piers are used during cargo operations to load and offload ships. Fleet operations personnel make the floating pier during the winter. They build upon naturally-occurring frozen seawater in McMurdo Sound until the dock reaches a depth of about 22 feet (6.7 m). Ice piers have a lifespan of three to five years.
- Ice cubes or crushed ice can be used to cool drinks. As the ice melts, it absorbs heat and keeps the drink near 0 °C.

- Structures and ice sculptures are built out of large chunks of ice. The structures are mostly ornamental (as in the case with ice castles), and not practical for long-term habitation. Ice hotels exist on a seasonal basis in a few cold areas. Igloos are another example of a temporary structure, made primarily from snow.
- During World War II, Project Habbakuk was a British programme which investigated the use of pykrete (wood fibers mixed with ice) as a possible material for warships, especially aircraft carriers, due to the ease with which a large deck could be constructed, but the idea was given up when there were not enough funds for construction of a prototype.
- Ice can be used to start a fire by carving it into a lens which will focus sunlight onto kindling. A fire will eventually start.
- Ice has even been used as the material for a variety of musical instruments, principally by percussionist Terje Isungset.
- Ice can be used to reduce swelling (by decreasing blood flow) and pain by pressing it against an area of the body.

## Ice and transportation



U.S. Coast Guard icebreakers near McMurdo Station, February 2002

Ice can also be an obstacle; for harbors near the poles, being ice-free is an important advantage; ideally, all year long. Examples are Murmansk (Russia), Petsamo (Russia, formerly Finland) and Vardø (Norway). Harbors which aren't ice-free are opened up using icebreakers.

Ice forming on roads is a dangerous winter hazard. Black ice is very difficult to see, because it lacks the expected frosty surface. Whenever there is freezing rain or snow which occurs at a temperature near the melting point, it is common for ice to build up on the windows of vehicles. Driving safely requires the removal of the ice build-up. Ice scrapers are tools designed to break the ice free and clear the windows, though removing the ice can be a long and laborious process.

Far enough below the freezing point, a thin layer of ice crystals can form on the inside surface of windows. This usually happens when a vehicle has been left alone after being driven for a while, but can happen while driving, if the outside temperature is low enough. Moisture from the driver's breath is the source of water for the crystals. It is troublesome to remove this form of ice, so people often open their windows slightly when the vehicle is parked in order to let the moisture dissipate, and it is now common for cars to have rear-window defrosters to solve the problem. A similar problem can happen in homes, which is one reason why many colder regions require double-pane windows for insulation.

When the outdoor temperature stays below freezing for extended periods, very thick layers of ice can form on lakes and other bodies of water, although places with flowing water require much colder temperatures. The ice can become thick enough to drive onto with automobiles and trucks. Doing this safely requires a thickness of at least 30 cm (one foot).

For ships, ice presents two distinct hazards. Spray and freezing rain can produce an ice build-up on the superstructure of a vessel sufficient to make it unstable, and to require it to be hacked off or melted with steam hoses. And icebergs — large masses of ice floating in water (typically created when glaciers reach the sea) — can be dangerous if struck by a ship when underway. Icebergs have been responsible for the sinking of many ships, the most famous probably being the Titanic.



Ice formation on window glass of high altitude flying airplane

For aircraft, ice can cause a number of dangers. As an aircraft climbs, it passes through air layers of different temperature and humidity, some of which may be conducive to ice formation. If ice forms on the wings or control surfaces, this may adversely affect the flying qualities of the aircraft. During the first non-stop flight of the Atlantic, the British aviators Captain John Alcock and Lieutenant Arthur Whitten Brown encountered such icing conditions – Brown left the cockpit and climbed onto the wing several times to remove ice which was covering the engine air intakes of the Vickers Vimy aircraft they were flying.

A particular icing vulnerability associated with reciprocating internal combustion engines is the carburetor. As air is sucked through the carburetor into the engine, the local air

pressure is lowered, which causes adiabatic cooling. So, in humid near-freezing conditions, the carburettor will be colder, and tend to ice up. This will block the supply of air to the engine, and cause it to fail. For this reason, aircraft reciprocating engines with carburettors are provided with carburettor air intake heaters. The increasing use of fuel injection—which does not require carburettors—has made "carb icing" less of an issue for reciprocating engines.

Jet engines do not experience carb icing, but recent evidence indicates that they can be slowed, stopped, or damaged by internal icing in certain types of atmospheric conditions much more easily than previously believed. In most cases, the engines can be quickly restarted and flights are not endangered, but research continues to determine the exact conditions which produce this type of icing, and find the best methods to prevent, or reverse it, in flight.

## Phases

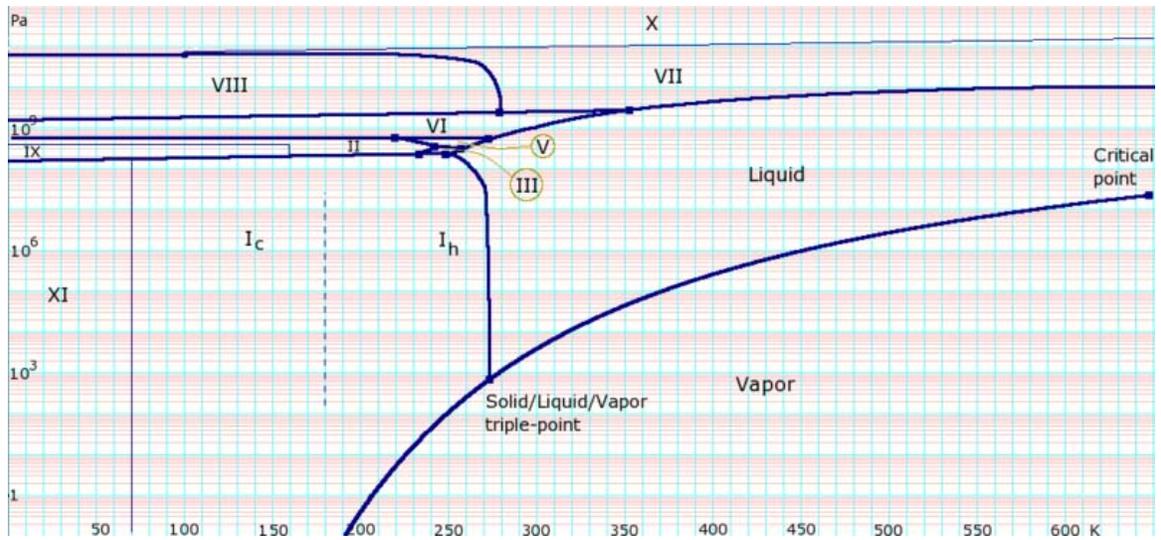
Most liquids freeze at a higher temperature under pressure, because the pressure helps to hold the molecules together. However, the strong hydrogen bonds in water make it different: water freezes at a temperature below 0 °C under a pressure higher than 1 atm (0.10 MPa). Consequently, water also remains frozen at a temperature above 0 °C under a pressure lower than 1 atm. The melting of ice under high pressures is thought to contribute to the movement of glaciers.

Ice formed at high pressure has a different crystal structure and density from ordinary ice. Ice, water, and water vapour can coexist at the triple point, which is exactly 0.01 °C or 273.16 K (by definition) at a pressure of 611.73 Pa.

Subjected to higher pressures and varying temperatures, ice can form in fifteen separate known phases. With care all these types can be recovered at ambient pressure. The types are differentiated by their crystalline structure, ordering and density. There are also two metastable phases of ice under pressure, both fully hydrogen-disordered; these are IV and XII. Ice XII was discovered in 1996. In 2006, XIII and XIV were discovered. Ices XI, XIII, and XIV are hydrogen-ordered forms of ices I<sub>h</sub>, V, and XII respectively. In 2009, ice XV was found at extremely high pressures and −143 °C.

As well as crystalline forms, solid water can exist in amorphous states as amorphous solid water (ASW), low-density amorphous ice (LDA), high-density amorphous ice (HDA), very high-density amorphous ice (VHDA) and hyperquenched glassy water (HGW).

In outer space, hexagonal crystalline ice (the predominant form found on Earth) is extremely rare. Amorphous ice is more common; however, hexagonal crystalline ice can be formed via volcanic action.



Pressure-temperature phase diagram of water showing several ice phases listed in the table below

## Other ices



Detail of an ice cube

The solid phases of several other volatile substances are also referred to as *ices*; generally a volatile is classed as an ice if its melting point lies above  $\sim 100$  K. The best known example is dry ice, the solid form of carbon dioxide.

A "magnetic analogue" of ice is also realized in some insulating magnetic materials in which the magnetic moments mimic the position of protons in water ice and obey energetic constraints similar to the Bernal-Fowler ice rules arising from the geometrical frustration of the proton configuration in water ice. These materials are called spin ice.

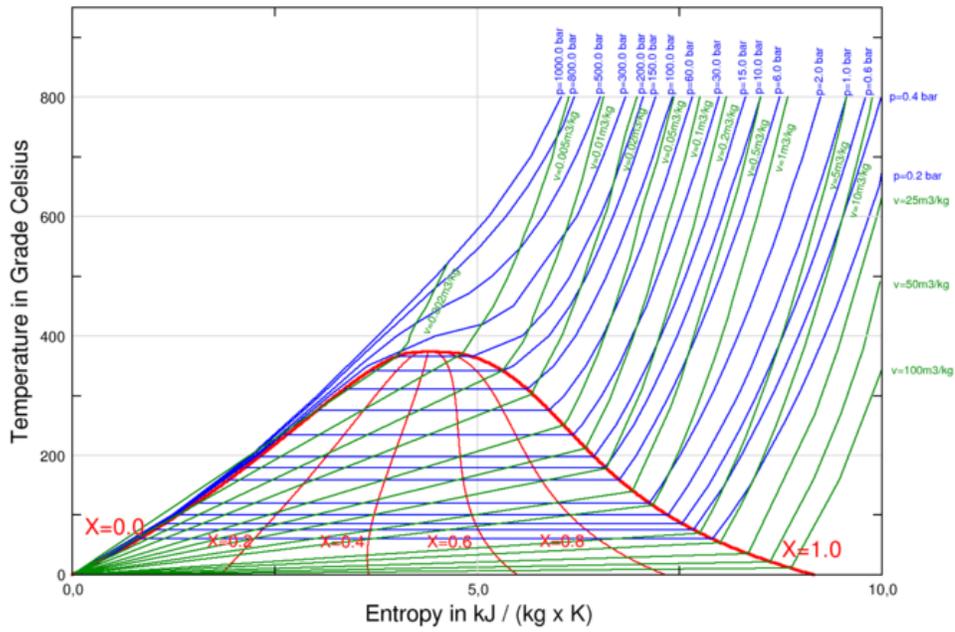
## Chapter- 6

# Steam

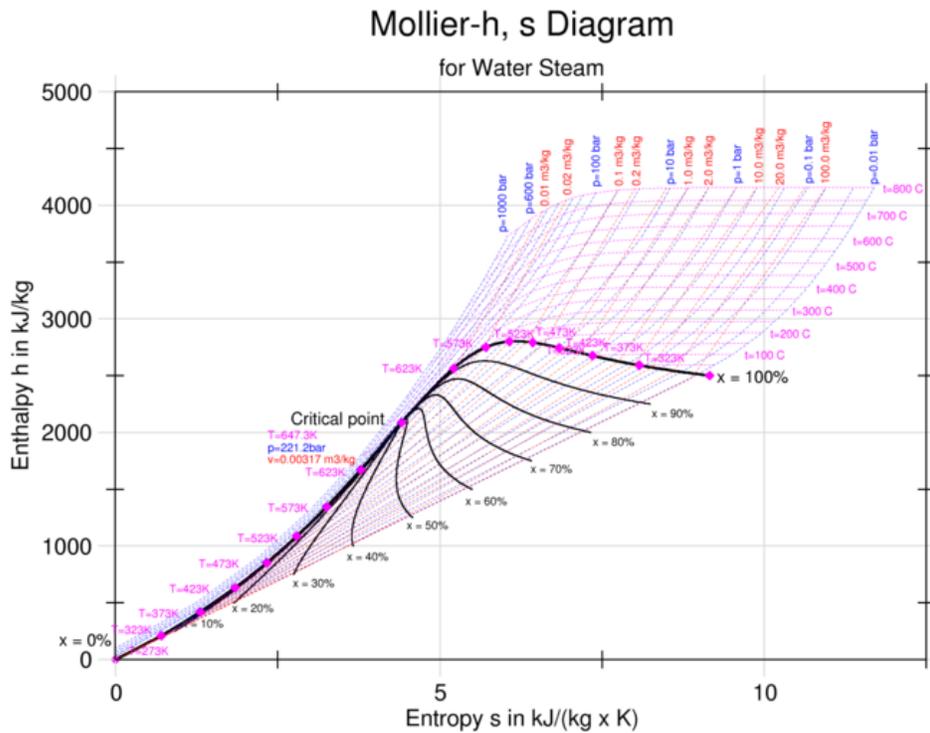


Steam phase eruption of Castle Geyser in Yellowstone Park

# Water Steam Temperature-Entropy-Diagram



A temperature-versus-entropy diagram for steam



A Mollier enthalpy-versus-entropy diagram for steam

**Steam** is either mist (as seen from a kettle), or the gas phase of water (water vapor).

*In common speech, **steam** most often refers to the visible white mist that condenses above boiling water as the hot vapor mixes with the cooler air. This mist consists of tiny droplets of liquid water. Pure steam emerges at the base of the spout of a steaming kettle where there is no visible vapor.*

Pure steam is a transparent gas. At standard temperature and pressure, pure steam (unmixed with air, but in equilibrium with liquid water) occupies about 1,600 times the volume of an equal mass of liquid water. In the atmosphere, the partial pressure of water is much lower than 1 atm, therefore gaseous water can exist at temperatures much lower than 100 °C (212 °F).

## Saturated steam

Saturated steam is steam at equilibrium with liquid water . It defines the boundary between wet steam and superheated steam on the temperature-enthalpy diagram.

## Superheated steam

Superheated steam is steam at a temperature higher than its boiling point at a given pressure. For superheating to take place one of two things must occur. Either all of the liquid water must have evaporated or, in the case of steam generators (boilers), the saturated steam must be conveyed out of the steam drum before superheating can occur, as steam can not be superheated in the presence of liquid water.

There are three stages of heating to convert liquid water to superheated steam. First the liquid water's sensible temperature (the property that can be measured with a thermometer) is raised. Then latent heat (this heat does not raise the temperature of the fluid) is added. After all of the liquid is evaporated or the saturated steam is taken from the steam drum sensible heat is again added superheating the steam.

## **Industrial uses**

### **Steam engines and steam turbines**

A steam engine uses the expansion of steam in order to drive a piston or turbine to perform mechanical work. The ability to return condensed steam as water-liquid to the boiler at high pressure with relatively little expenditure of pumping power is important. Engineers use an idealised thermodynamic cycle, the Rankine cycle, to model the behavior of steam engines.

Steam turbines are often used in the production of electricity.

Condensation of steam to water often occurs at the low-pressure end of a steam turbine, since this maximizes the energy efficiency, but such wet-steam conditions have to be limited to avoid excessive turbine blade erosion.

### **Energy storage**

In other industrial applications steam is used for energy storage, which is introduced and extracted by heat transfer, usually through pipes. Steam is a capacious reservoir for thermal energy because of water's high heat of vaporization.

### **Electricity generation**

In the U.S., more than 86% of electricity is generated using steam as the working fluid, nearly all by steam turbines.

### **Cogeneration**

In electric generation, steam is typically condensed at the end of its expansion cycle, and returned to the boiler for re-use. However in cogeneration, steam is piped into buildings through a district heating system to provide heat energy after its use in the electric generation cycle. The world's biggest steam generation system is the New York City

steam system which pumps steam into 100,000 buildings in Manhattan from seven cogeneration plants.

## **Sterilization**

An autoclave, which uses steam under pressure, is used in microbiology laboratories and similar environments for sterilization.

## **Steam in piping**

Steam is used in piping for utility lines. It is also used in jacketing and tracing of piping to maintain the uniform temperature in pipelines and vessels.

## **Lifting gas**

Owing to its low molecular mass, steam is an effective lifting gas, providing approximately 60% as much lift as helium and twice as much as hot air. It is not flammable, unlike hydrogen, and is cheap and abundant, unlike helium. The required heat, however, leads to condensation problems and requires an insulated envelope. These factors have limited its use thusfar to mostly demonstration projects.

## **Agricultural use**

In agriculture, steam is used for soil sterilization to avoid the use of harmful chemical agents and increase soil health.

## **Domestic uses**

Steam's capacity to transfer heat is also used in the home: for cooking vegetables, steam cleaning of fabric and carpets, and heating buildings. In each case, water is heated in a boiler, and the steam carries the energy to a target object. "Steam showers" are actually low-temperature mist-generators, and do not actually use steam.

## **Steam tables**

**Steam tables** are tables of thermodynamic data for water/steam. They are often used by engineers and scientists in design and operation of equipment where thermodynamic cycles involving steam are used.

## **Steam charts**

Steam charts are an alternative to tables for analysing thermodynamic cycles.

## **Steam explosion**

When liquid water comes in contact with a very hot substance (such as lava, or molten metal) it can flash into steam almost instantaneously; this is called a **steam explosion**. Such an explosion was probably responsible for much of the damage in the Chernobyl accident and for many so-called foundry accidents.

## Chapter- 7

# Snow

**Snow** is a type of precipitation within the Earth's atmosphere in the form of crystalline water ice, consisting of a multitude of snowflakes that fall from clouds. Since snow is composed of small ice particles, it is a granular material. It has an open and therefore soft structure, unless packed by external pressure. Snowflakes come in a variety of sizes and shapes. Types which fall in the form of a ball due to melting and refreezing, rather than a flake, are known as graupel, with ice pellets and snow grains as examples of graupel. Snowfall amount and its related liquid equivalent precipitation amount are determined using a variety of different rain gauges.

The process of precipitating snow is called **snowfall**. Snowfall tends to form within regions of upward motion of air around a type of low-pressure system known as an extratropical cyclone. Snow can fall poleward of these systems' associated warm fronts and within their comma head precipitation patterns (called such due to the comma-like shape of the cloud and precipitation pattern around the poleward and west sides of extratropical cyclones). Where relatively warm water bodies are present, for example due to water evaporation from lakes, lake-effect snowfall becomes a concern downwind of the warm lakes within the cold cyclonic flow around the backside of extratropical cyclones. Lake-effect snowfall can be locally heavy. Thundersnow is possible within a cyclone's comma head and within lake effect precipitation bands. In mountainous areas, heavy snow is possible where upslope flow is maximized within windward sides of the terrain at elevation, if the atmosphere is cold enough.



Snow on trees, Germany

## **Forms**



Photo of snow on the ground in the mountains of Southern California.



Fresh snow on a thin twig – Poland

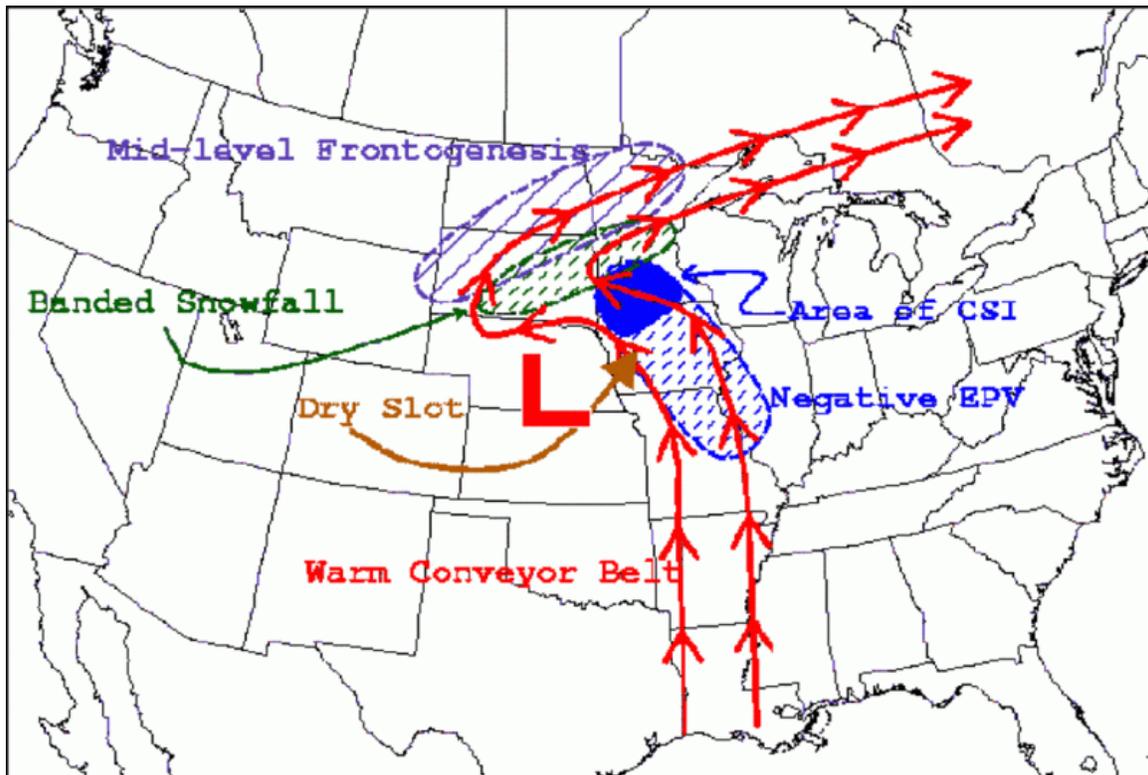
Once on the ground, snow can be categorized as powdery when fluffy, granular when it begins the cycle of melting and refreezing, and eventually ice once it packs down, after multiple melting and refreezing cycles, into a dense mass called snow pack. When powdery, snow moves with the wind from the location where it originally landed, forming deposits called snowdrifts which may have a depth of several meters. After attaching to hillsides, blown snow can evolve into a snow slab, which is an avalanche hazard on steep slopes. The existence of a snowpack keeps temperatures colder than they would be otherwise, as the whiteness of the snow reflects most sunlight, and the absorbed heat goes into melting the snow rather than increasing its temperature. The water equivalent of snowfall is measured to monitor how much liquid is available to flood rivers from meltwater which will occur during the following spring. Snow cover can protect crops from extreme cold. If snowfall stays on the ground for a series of years uninterrupted, the snowpack develops into a mass of ice called glacier. Fresh snow absorbs sound, lowering ambient noise over a landscape because the trapped air between snowflakes attenuates vibration. These acoustic qualities quickly minimize and reverse, once a layer of freezing rain falls on top of snow cover. Walking across snowfall produces a squeaking sound at low temperatures.

The energy balance of the snowpack itself is dictated by several heat exchange processes. The snowpack absorbs solar shortwave radiation that is partially blocked by cloud cover

and reflected by snow surface. A long-wave heat exchange takes place between the snowpack and its surrounding environment that includes overlying air mass, tree cover and clouds. Heat exchange takes place by convection between the snowpack and the overlying air mass, and it is governed by the temperature gradient and wind speed. Moisture exchange between the snowpack and the overlying air mass is accompanied with latent heat transfer that is influenced by vapor pressure gradient and air wind. Rain on snow can add significant amounts of thermal energy to the snowpack. A generally insignificant heat exchange takes place by conduction between the snowpack and the ground. The small temperature change from before to after a snowfall is a result of the heat transfer between the snowpack and the air.

The term *snow storm* can describe a heavy snowfall while a *blizzard* involves snow and wind, obscuring visibility. *Snow shower* is a term for an intermittent snowfall, while *flurry* is used for very light, brief snowfalls. Snow can fall more than a meter at a time during a single storm in flat areas, and meters at a time in rugged terrain, such as mountains. When snow falls in significant quantities, travel by foot, car, airplane and other means becomes highly restricted, but other methods of mobility become possible: the use of snowmobiles, snowshoes and skis. When heavy snow occurs early in the fall, significant damage occurs to trees still in leaf. Areas with significant snow each year can store the winter snow within an ice house, which can be used to cool structures during the following summer. A variation on snow has been observed on Venus, though composed of metallic compounds and occurring at a substantially higher temperature.

## Cause



Preferred region of heavy snowfall ("Banded Snowfall") around the comma head of a wintertime low pressure area, shaded in green



Lake-effect snow bands near the Korean Peninsula

Extratropical cyclones can bring cold and dangerous conditions with heavy rain and snow with winds exceeding 119 km/h (74 mph), (sometimes referred to as windstorms in Europe). The band of precipitation that is associated with their warm front is often extensive, forced by weak upward vertical motion of air over the frontal boundary which condenses as it cools and produces precipitation within an elongated band, which is wide and stratiform, meaning falling out of nimbostratus clouds. When moist air tries to dislodge an arctic air mass, overrunning snow can result within the poleward side of the elongated precipitation band. In the Northern Hemisphere, poleward is towards the North Pole, or north. Within the Southern Hemisphere, poleward is towards the South Pole, or south.

Within the *cold sector*, poleward and west of the cyclone center, small scale or mesoscale bands of heavy snow can occur within a cyclone's comma head pattern. The cyclone's comma head pattern is a comma-shaped area of clouds and precipitation found around mature extratropical cyclones. These snow bands typically have a width of 20 miles (32

km) to 50 miles (80 km). These bands in the comma head are associated with areas of frontogenesis, or zones of strengthening temperature contrast.

Southwest of extratropical cyclones, curved cyclonic flow bringing cold air across the relatively warm water bodies can lead to narrow lake-effect snow bands. Those bands bring strong localized snowfall which can be understood as follows: Large water bodies such as lakes efficiently store heat that results in significant temperature differences (larger than 13 °C or 23 °F) between the water surface and the air above. Because of this temperature difference, warmth and moisture are transported upward, condensing into vertically oriented clouds which produce snow showers. The temperature decrease with height and cloud depth are directly affected by both the water temperature and the large-scale environment. The stronger the temperature decrease with height, the deeper the clouds get, and the greater the precipitation rate becomes.

In mountainous areas, heavy snowfall accumulates when air is forced to ascend the mountains and squeeze out precipitation along their windward slopes, which in cold conditions, falls in the form of snow. Because of the ruggedness of terrain, forecasting the location of heavy snowfall remains a significant challenge.

## **Snowflakes**



## Snowflakes

Snow crystals form when tiny supercooled cloud droplets (about 10  $\mu\text{m}$  in diameter) freeze. These droplets are able to remain liquid at temperatures lower than  $-18\text{ }^{\circ}\text{C}$  ( $0\text{ }^{\circ}\text{F}$ ), because to freeze, a few molecules in the droplet need to get together by chance to form an arrangement similar to that in an ice lattice; then the droplet freezes around this "nucleus." Experiments show that this "homogeneous" nucleation of cloud droplets only occurs at temperatures lower than  $-35\text{ }^{\circ}\text{C}$  ( $-31\text{ }^{\circ}\text{F}$ ). In warmer clouds an aerosol particle or "ice nucleus" must be present in (or in contact with) the droplet to act as a nucleus. Ice nuclei are very rare compared to that cloud condensation nuclei on which liquid droplets form. Clays, desert dust and biological particles may be effective, although to what extent is unclear. Artificial nuclei include particles of silver iodide and dry ice, and these are used to stimulate precipitation in cloud seeding.

Once a droplet has frozen, it grows in the supersaturated environment, which is one where air is saturated with respect to ice when the temperature is below the freezing point. The droplet then grows by diffusion of water molecules in the air (vapor) onto the ice crystal surface where they are collected. Because water droplets are so much more numerous than the ice crystals due to their sheer abundance, the crystals are able to grow to hundreds of micrometers or millimeters in size at the expense of the water droplets by a process known as the Wegner-Bergeron-Findeison process. The corresponding depletion of water vapor causes the ice crystals grow at the droplets' expense. These large crystals are an efficient source of precipitation, since they fall through the atmosphere due to their mass, and may collide and stick together in clusters, or aggregates. These aggregates are snowflakes, and are usually the type of ice particle that falls to the ground. Guinness World Records list the world's largest snowflakes as those of January 1887 at Fort Keogh, Montana; allegedly one measured 38 cm (15 in) wide. Although the ice is clear, scattering of light by the crystal facets and hollows/imperfections mean that the crystals often appear white in color due to diffuse reflection of the whole spectrum of light by the small ice particles.

The shape of the snowflake is determined broadly by the temperature and humidity at which it is formed. The most common snow particles are visibly irregular. Planar crystals (thin and flat) grow in air between  $0\text{ }^{\circ}\text{C}$  ( $32\text{ }^{\circ}\text{F}$ ) and  $-3\text{ }^{\circ}\text{C}$  ( $27\text{ }^{\circ}\text{F}$ ). Between  $-3\text{ }^{\circ}\text{C}$  ( $27\text{ }^{\circ}\text{F}$ ) and  $-8\text{ }^{\circ}\text{C}$  ( $18\text{ }^{\circ}\text{F}$ ), the crystals will form needles or hollow columns or prisms (long thin pencil-like shapes). From  $-8\text{ }^{\circ}\text{C}$  ( $18\text{ }^{\circ}\text{F}$ ) to  $-22\text{ }^{\circ}\text{C}$  ( $-8\text{ }^{\circ}\text{F}$ ) the shape reverts back to plate-like, often with branched or dendritic features. At temperatures below  $-22\text{ }^{\circ}\text{C}$  ( $-8\text{ }^{\circ}\text{F}$ ), the crystal development becomes column-like, although many more complex growth patterns also form such as side-planes, bullet-rosettes and also planar types depending on the conditions and ice nuclei. If a crystal has started forming in a column growth regime, at around  $-5\text{ }^{\circ}\text{C}$  ( $23\text{ }^{\circ}\text{F}$ ), and then falls into the warmer plate-like regime, then plate or dendritic crystals sprout at the end of the column, producing so called "capped columns."

A snowflake consists of roughly  $10^{19}$  water molecules, which are added to its core at different rates and in different patterns, depending on the changing temperature and

humidity within the atmosphere that the snowflake falls through on its way to the ground. As a result, it is extremely difficult to encounter two identical snowflakes. Initial attempts to find identical snowflakes by photographing thousands their images under a microscope from 1885 onward by Wilson Alwyn Bentley found the wide variety of snowflakes we know about today. It is more likely that two snowflakes could become virtually identical if their environments were similar enough. Matching snow crystals were discovered in Wisconsin in 1988. The crystals were not flakes in the usual sense but rather hollow hexagonal prisms.

## Types



Hoar frost that grows on the snow surface due to water vapor moving up through the snow on cold, clear nights



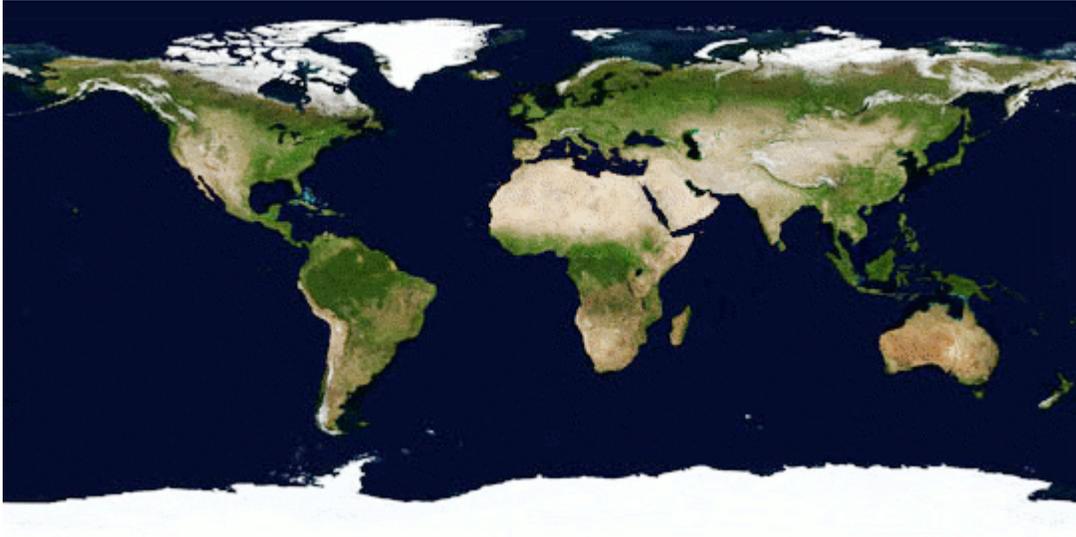
A snow avalanche

Types of snow can be designated by the shape of the flakes, the rate of accumulation, and the way the snow collects on the ground. Types which fall in the form of a ball due to melting and refreezing cycles, rather than a flake, are known as graupel, with ice pellets and snow pellets as types of graupel associated with wintry precipitation. Once on the ground, snow can be categorized as *powdery* when fluffy, *granular* when it begins the cycle of melting and refreezing, and eventually *ice* once it packs down into a dense drift after multiple melting and refreezing cycles. When powdery, snow drifts with the wind from the location where it originally fell, forming deposits with a depth of several meters in isolated locations. Snow fences are constructed in order to help control snow drifting in the vicinity of roads, to improve highway safety. After attaching to hillsides, blown snow can evolve into a snow slab, which is an avalanche hazard on steep slopes. A frozen equivalent of dew known as hoar frost forms on a snow pack when winds are light and there is ample low-level moisture over the snow pack.

Snowfall's intensity is determined by visibility. When the visibility is over 1 kilometer (0.62 mi), snow is considered light. Moderate snow describes snowfall with visibility restrictions between 0.5 and 1 km. Heavy snowfall describes conditions when visibility is less than 0.5 km. Steady snows of significant intensity are often referred to as "snowstorms". When snow is of variable intensity and short duration, it is described as a "snow shower". The term snow flurry is used to describe the lightest form of a snow shower.

A blizzard is a weather condition involving snow which has varying definitions in different parts of the world. In the United States, a blizzard is occurring when two conditions are met for a period of three hours or more: A sustained wind or frequent gusts to 35 miles per hour (56 km/h), and sufficient snow in the air to reduce visibility to less than 0.4 kilometers (0.25 mi). In Canada and the United Kingdom, the criteria are similar. While heavy snowfall often occurs during blizzard conditions, falling snow is not a requirement, as blowing snow can create a ground blizzard.

## Density



An image (satellite images) showing seasonal snow changes



Firn

Snow remains on the ground until it melts or sublimates. Sublimation of snow directly into water vapor is most likely to occur on a dry and windy day such as when a strong downslope wind, such as a Chinook wind, exists. The *water equivalent* of a given amount of snow is the depth of a layer of water having the same mass and upper area. For example, if the snow covering a given area has a water equivalent of 50 centimeters (20 in), then it will melt into a pool of water 50 centimeters (20 in) deep covering the same area. This is a much more useful measurement to hydrologists than snow *depth*, as the density of cool freshly fallen snow widely varies. New snow commonly has a density of around 8% of water. This means that 33 centimeters (13 in) of snow melts down to 2.5 centimeters (1 in) of water. Cloud temperatures and physical processes in the cloud affect the shape of individual snow crystals. Highly branched or dendritic crystals tend to have more space between the arms of ice that form the snowflake and this snow will therefore have a lower density, often referred to as "dry" snow. Conditions that create columnar or plate-like crystals will have much less air space within the crystal and will therefore be denser and feel "wetter".

Once the snow is on the ground, it will settle under its own weight (largely due to differential evaporation) until its density is approximately 30% of water. Increases in density above this initial compression occur primarily by melting and refreezing, caused by temperatures above freezing or by direct solar radiation. In colder climates, snow lies on the ground all winter. By late spring, snow densities typically reach a maximum of 50% of water. When the snow does not all melt in the summer it evolves into firn, where individual granules become more spherical in nature, evolving into a glacier as the ice flows downhill.

## **Acoustic properties**



Snow falling in Scotland (21 seconds)

Under water, snowfall has a unique sound when compared to other forms of precipitation. Despite the different sizes and shapes on individual snowflakes, the sound made when individual flakes fall upon the surface of a freshwater lake are quite similar. On the ground, newly fallen snow acts as a sound-absorbing material, which minimizes sound over its surface. This is due to the trapped air between the individual crystalline flakes which act to trap sound waves and dampen vibrations. Once it is blown around by the wind and exposed to sunshine, snow hardens and its sound-softening quality diminishes. Snow cover as thin as 2 centimeters (0.79 in) thick changes the acoustic properties of a landscape. Studies concerning the acoustic properties of snow have revealed that loud sounds, such as from a pistol, can be used to measure snow cover permeability and depth. Within motion pictures, the sound of walking through snow is simulated using cornstarch, salt, or cat litter. When the temperature falls below  $-10\text{ }^{\circ}\text{C}$  ( $14.0\text{ }^{\circ}\text{F}$ ), snow will squeak when walked upon due to the crushing of the ice crystals within the snow. If covered by a layer of freezing rain, the hardened frozen surface acts to echo sounds, similar to concrete.

## **Snowfall measurement**



An ultrasonic snow depth sensor

The liquid equivalent of snowfall may be evaluated using a snow gauge or with a standard rain gauge having a diameter of 100 mm (4 in; plastic) or 200 mm (8 in; metal). Rain gauges are adjusted to winter by removing the funnel and inner cylinder and allowing the snow/freezing rain to collect inside the outer cylinder. Antifreeze liquid may be added to melt the snow or ice that falls into the gauge. In both types of gauges once the snowfall/ice is finished accumulating, or as its height in the gauge approaches 300 mm (12 in), the snow is melted and the water amount recorded.

Another type of gauge used to measure the liquid equivalent of snowfall is the weighing precipitation gauge. The wedge and tipping bucket gauges will have problems with snow measurement. Attempts to compensate for snow/ice by warming the tipping bucket meet with limited success, since snow may sublime if the gauge is kept much above the freezing temperature. Weighing gauges with antifreeze should do fine with snow, but again, the funnel needs to be removed before the event begins. At some automatic weather stations an ultrasonic snow depth sensor may be used to augment the precipitation gauge.

Spring snow melt is a major source of water supply to areas in temperate zones near mountains that catch and hold winter snow, especially those with a prolonged dry summer. In such places, water equivalent is of great interest to water managers wishing to

predict spring runoff and the water supply of cities downstream. Measurements are made manually at marked locations known as *snow courses*, and remotely using special scales called *snow pillows*. Snow stakes and simple rulers can be used to determine the depth of the snow pack, though they will not evaluate either its density or liquid equivalent.

When a snow measurement is made, various networks exist across the United States and elsewhere where rainfall measurements can be submitted through the Internet, such as CoCoRAHS or GLOBE. If a network is not available in the area where one lives, the nearest local weather office will likely be interested in the measurement.

The world record for the highest seasonal total snowfall was measured in the United States at Mount Baker Ski Area, outside of the town Bellingham, Washington during the 1998–1999 season. Mount Baker received 2,896 cm (1,140 in) of snow, thus surpassing the previous record holder, Mount Rainier, Washington, which during the 1971–1972 season received 2,850 cm (1,120 in) of snow.

## **Snow blindness**



Traditional Inuit goggles used to combat snow blindness

Fresh snow reflects 90% or more of ultraviolet radiation that causes snow blindness and reduces absorption of sunlight by the ground. Snow blindness (also known as ultraviolet keratitis, photokeratitis or niphablepsia) is a painful eye condition, caused by exposure of unprotected eyes to the ultraviolet (UV) rays in bright sunlight reflected from snow or ice. This condition is a problem in polar regions and at high altitudes, as with every 1,000 feet (300 m) of elevation (above sea level), the intensity of UV rays increases by 4%. Snow's large reflection of light makes night skies much brighter, since reflected light is directed back up into the sky. However, when there is also cloud cover, light is then reflected back to the ground. This greatly amplifies light emitted from city lights, causing the 'bright night' effect. A similar brightening effect occurs when no snow is falling and there is a full moon and a large amount of snow.

## Relation to river flow

Many rivers originating in mountainous or high-latitude regions receive a significant portion of their flow from snowmelt. This often makes the river's flow highly seasonal resulting in periodic flooding. In contrast, if much of the melt is from glaciated or nearly glaciated areas, the melt continues through the warm season, with peak flows occurring in mid to late summer.

## Effects on human society



A snow blockade in southern Minnesota, US in 1881

Substantial snowfall can disrupt public infrastructure and services, slowing human activity even in regions that are accustomed to such weather. Air and ground transport may be greatly inhibited or shut down entirely. Populations living in snow-prone areas have developed various ways to travel across the snow, such as skis, snowshoes, and sleds pulled by horses, dogs, or other animals and later, snowmobiles. Basic utilities such as electricity, telephone lines, and gas supply can also fail. In addition, snow can make roads much harder to travel and vehicles attempting to use them can easily become stuck.

The combined effects can lead to a "snow day" on which gatherings such as school, work, or church are officially canceled. In areas that normally have very little or no snow, a snow day may occur when there is only light accumulation or even the threat of

snowfall, since those areas are unprepared to handle any amount of snow. In some areas, such as some states in the United States, schools are given a yearly quota of snow days (or "calamity days"). Once the quota is exceeded, the snow days must be made up. In other states, all snow days must be made up. For example, schools may extend the remaining school days later into the afternoon, shorten spring break, or delay the start of summer vacation.

Accumulated snow is removed to make travel easier and safer, and to decrease the long-term impact of a heavy snowfall. This process utilizes shovels and snowplows, and is often assisted by sprinkling salt or other chloride-based chemicals, which reduce the melting temperature of snow. In some areas with abundant snowfall, such as Yamagata Prefecture, Japan, people harvest snow and store it surrounded by insulation in ice houses. This allows the snow to be used through the summer for refrigeration and air conditioning, which requires far less electricity than traditional cooling methods.



Snow in Old Fort, North Carolina caused by the 2009 Blizzard

## **Agriculture**

Snowfall can be beneficial to agriculture by serving as a thermal insulator, conserving the heat of the Earth and protecting crops from subfreezing weather. Some agricultural areas depend on an accumulation of snow during winter that will melt gradually in spring,

providing water for crop growth. If it melts into water and refreezes upon sensitive crops, such as oranges, the resulting ice will protect the fruit from exposure to lower temperatures.

## Recreation



Making a giant snowball



### Making a snow angel

Many winter sports, such as skiing, snowboarding, snowmobiling, and snowshoeing depend upon snow. Where snow is scarce but the temperature is low enough, snow cannons may be used to produce an adequate amount for such sports. Children and adults can play on a sled or ride in a sleigh. Although a person's footsteps remain a visible lifeline within a snow-covered landscape, snow cover is considered a general danger to hiking since the snow obscures landmarks and makes the landscape itself appear uniform.

One of the recognizable recreational uses of snow is in building snowmen. A snowman is created by making a man shaped figure out of snow – often using a large, shaped snowball for the body and a smaller snowball for the head which is often decorated with simple household items – traditionally including a carrot for a nose, and coal for eyes, nose and mouth; occasionally including old clothes such as a top hat or scarf.

Snow can be used to make snow cones, also known as snowballs, which are usually eaten in the summer months. Flat areas of snow can be used to make snow angels, a popular pastime for children.

Snow can be used to alter the format of outdoor games such as Capture the flag, or for snowball fights. The world's biggest snowcastle, the SnowCastle of Kemi, is built in Kemi, Finland every winter. Since 1928 Michigan Technological University in

Houghton, Michigan has held an annual Winter Carnival in mid-February, during which a large Snow Sculpture Contest takes place between various clubs, fraternities, and organizations in the community and the university. Each year there is a central theme, and prizes are awarded based on creativity. Snowball softball tournaments are held in snowy areas, usually using a bright orange softball for visibility, and burlap sacks filled with snow for the bases.

## Damage



Damage caused by Lake Storm "Aphid" in October 2006

When heavy, wet snow with a snow-water equivalent (SWE) ratio of between 6:1 and 12:1 and a weight in excess of 10 pounds per square foot ( $\sim 50 \text{ kg/m}^2$ ) piles onto trees or electricity lines – particularly if the trees have full leaves or are not adapted to snow – significant damage may occur on a scale usually associated with hurricanes. An avalanche can occur upon a sudden thermal or mechanical impact upon snow that has accumulated on a mountain, which causes the snow to rush downhill en masse. Preceding an avalanche is a phenomenon known as an avalanche wind caused by the approaching avalanche itself, which adds to its destructive potential. Large amounts of snow which accumulate on top of man-made structures can lead to structural failure. During

snowmelt, acidic precipitation which previously fell into the snow pack is released, which harms marine life.

## **Design of structures considering snow load**

The design of all structures and buildings use the ground snow load to some extent by professional engineers and designers. In North America, the northern states will be designed to accommodate the live load design contributed by the ground snow load in a pounds per square foot (PSF) loading analysis. (*Snow loads are typically treated as 'dead loads' within the ASCE 7-latest edition.*) This load is typically the governing design factor on roofs and structural elements exposed to the effects of snow. Closer to the Equator, the snow load becomes less of a factor and snow may or may not be the governing factor. Ground snow in North America is provided by the American Society of Civil Engineers (ASCE7-latest edition) for most jurisdictions.

## **Extraterrestrial snow**

Very light snow is known to occur at high latitudes on Mars. A "snow" of hydrocarbons is also theorized to occur on Saturn's moon Titan.

While there is little or no water on Venus, there is a phenomenon which is quite similar to snow. The Magellan probe imaged a highly reflective substance at the tops of Venus's highest mountain peaks which bore a strong resemblance to terrestrial snow. This substance arguably formed from a similar process to snow, albeit at a far higher temperature. Too volatile to condense on the surface, it rose in gas form to cooler higher elevations, where it then fell as precipitation. The identity of this substance is not known with certainty, but speculation has ranged from elemental tellurium to lead sulfide (galena).

## Chapter- 8

# Fresh Water

**Fresh water** is naturally occurring water on the Earth's surface in bogs, ponds, lakes, rivers and streams, and underground as groundwater in aquifers and underground streams. Freshwater is generally characterized by having low concentrations of dissolved salts and other total dissolved solids. The term specifically excludes seawater and brackish water although it does include mineral rich waters such as chalybeate springs..

## Systems

Scientifically, freshwater habitats are divided into lentic systems, which are the stillwaters including ponds, lakes, swamps and mires; lotic systems, which are running water; and groundwater which flows in rocks and aquifers. There is, in addition, a zone which bridges between groundwater and lotic systems, which is the hyporheic zone, which underlies many larger rivers and can contain substantially more water than is seen in the open channel. It may also be in direct contact with the underlying underground water.

## Source

The source of almost all freshwater is precipitation from the atmosphere, in the form of mist, rain and snow. . Freshwater falling as mist, rain or snow contains materials dissolved from the atmosphere and material from the sea and land over which the rain bearing clouds have traveled. In industrialized areas rain is typically acidic because of dissolved oxides of sulfur and nitrogen formed from burning of fossil fuels in cars, factories, trains and aircraft and from the atmospheric emissions of industry. In extreme cases this acid rain results in pollution of lakes and rivers in parts of Scandinavia, Scotland, Wales and the United States.

In coastal areas freshwater may contain significant concentrations of salts derived from the sea if windy conditions have lifted drops of seawater into the rain-bearing clouds. This can give rise to elevated concentrations of sodium, chloride, magnesium and sulfate as well as many other compounds in smaller concentrations.

In desert areas, or areas with impoverished or dusty soils, rain bearing winds can pick up sand and dust and this can be deposited elsewhere in precipitation and causing the

freshwater flow to be measurably contaminated both by insoluble solids but also by the soluble components of those soils. Significant quantities of iron may be transported in this way including the well documented transfer of iron rich rainfall falling in Brazil derived from sand-storms in the Sahara in northern Africa.

## Numerical definition



The surface of a freshwater lake

Freshwater can be defined as water with less than 500 parts per million (ppm) of dissolved salts.

### Water salinity based on dissolved salts in parts per thousand (ppt)

Freshwater	Brackish water	Saline water	Brine
< 0.5	0.5 – 30	30 – 50	> 50

Other sources give higher upper salinity limits for freshwater, e.g. 1000 ppm or 3000 ppm.

## Water distribution

Water is a critical issue for the survival of all living organisms. Some can use salt water but many organisms including the great majority of higher plants and most mammals must have access to freshwater to live. Some terrestrial mammals, especially desert rodents appear to survive without drinking but they do generate water through the metabolism of cereal seeds and they also have mechanisms to conserve water to the maximum degree.

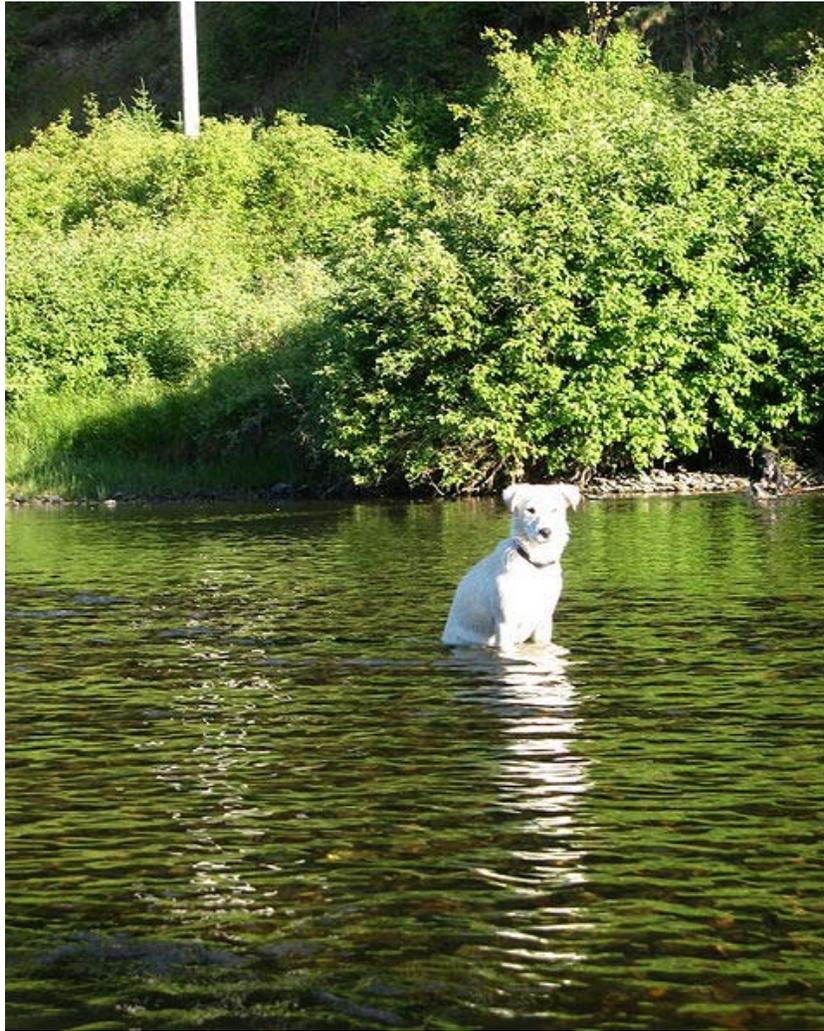
Out of all the water on Earth, only 2.75 percent is freshwater, including 2.05 percent frozen in glaciers, 0.68 percent as groundwater and 0.0101 percent of it as surface water in lakes and rivers. Freshwater lakes, most notably Lake Baikal in Russia and the Great Lakes in North America, contain seven-eighths of this fresh surface water. Swamps have most of the balance with only a small amount in rivers, most notably the Amazon River. The atmosphere contains 0.04% water. In areas with no freshwater on the ground surface, freshwater derived from precipitation may, because of its lower density, overlies saline ground water in lenses or layers.

## Aquatic organisms

Freshwater creates a hypotonic environment for aquatic organisms. This is problematic for some organisms with pervious skins or with gill membranes, whose cell membranes may burst if excess water is not excreted. Some protists accomplish this using contractile vacuoles, while freshwater fish excrete excess water via the kidney. Although most aquatic organisms have a limited ability to regulate their osmotic balance and therefore can only live within a narrow range of salinity, diadromous fish have the ability to migrate between freshwater and saline water bodies. During these migrations they undergo changes to adapt to the surroundings of the changed salinities; these processes are hormonally controlled. The eel (*Anguilla anguilla*) uses the hormone prolactin, while in salmon (*Salmo salar*) the hormone cortisol plays a key role during this process.

Many sea birds have special glands at the base of the bill through which excess salt is excreted. Similarly the Marine Iguanas on the Galápagos Islands excrete excess salt through a nasal gland and they sneeze out a very salty excretion.

## **Freshwater as a resource**



Grande Ronde River flowing through Hilgard Junction State Recreation Area in Eastern Oregon. An important concern for hydrological ecosystems is securing minimum streamflow, especially preserving and restoring instream water allocations.

Freshwater is an important natural resource necessary for the survival of all ecosystems. The use of water by humans for activities such as irrigation and industrial applications can have adverse impacts on down-stream ecosystems. Chemical contamination of freshwater can also seriously damage eco-systems.

Pollution from human activity, including oil spills, also presents a problem for freshwater resources. The largest oil spill that has ever occurred in freshwater was caused by a Shell tank ship in Magdalena, Argentina, on January 15, 1999, polluting the environment, drinkable water, plants and animals.

### **Agriculture**

Changing landscape for the use of agriculture has a great effect on the flow of freshwater. Changes in landscape by the removal of trees and soils changes the flow of freshwater in the local environment and also affects the cycle of freshwater. As a result more freshwater is stored in the soil which benefits agriculture. However, since agriculture is the human activity that consumes the most freshwater, this can put a severe strain on local freshwater resources resulting in the destruction of local ecosystems. In Australia, over-abstraction of freshwater for intensive irrigation activities has caused 33% of the land area to be at risk of salination.

### **Limiting resource**

Freshwater is a renewable and changeable, but limited natural resource. Freshwater can only be renewed through the process of the water cycle, where water from seas, lakes, rivers, and dams evaporates, forms clouds, and returns to water sources as precipitation. However, if more freshwater is consumed through human activities than is restored by nature, the result is that the quantity of freshwater available in lakes, rivers, dams and underground waters is reduced which can cause serious damage to the surrounding environment.

### **Freshwater withdrawal**

Freshwater withdrawal is the quantity of water removed from available sources for use in any purpose. Water drawn-off is not necessarily entirely consumed and some portion may be returned for further use downstream.

### **Causes of limited fresh water**

There are many causes of the apparent decrease in our fresh water supply. Principal amongst these is the increase in population through increasing life expectancy, the increase in per capita water use and the desire of many people to live in warm climates that have naturally low levels of freshwater resources. Climate change is also likely to change the availability and distribution of freshwater across the planet.

"If global warming continues to melt glaciers in the polar regions, as expected, the supply of freshwater may actually decrease. First, freshwater from the melting glaciers will mingle with salt water in the oceans and become too salty to drink. Second, the increased ocean volume will cause sea levels to rise, contaminating freshwater sources along coastal regions with seawater".

Water pollution and subsequent eutrophication also reduces the availability of freshwater.