

Atmospheric Water

Apart from the oxygen we breathe, water is the most important constituent of the atmosphere. It makes the clouds, the rain, the snow and much of what we associate with the term 'weather'. Water exists in all its phases in the atmosphere - solid, liquid and gas. Water vapour is the most abundant form, yet neither plants nor animals can live off the water vapour in the atmosphere. We need it condensed into liquid water. The topics here are covered in Ahrens' textbook in chapter 4 of the 8th and later editions.

The average rainfall over the globe is about 1 m yr^{-1} . In Aberdeen we receive less than this global average, in spite of being on the coast. Rainfall makes an important contribution to the flux of energy reaching the Earth's surface because the latent heat of condensation comes out of the vapour in the atmosphere and into the raindrops, which then fall to Earth.

This chapter is about the three phases of water, about the energy involved in changing phase and about measuring the water vapour content of the atmosphere.

Phases of Water

Water is no different from almost any other simple material in being able to exist as a solid, a liquid or a gas. The existence of gas and liquid in the atmosphere is obvious. Solid water is there too, for high clouds in summer and winter are made of ice crystals. All the phases of water involve the same water molecules. Each molecule is composed of one oxygen atom and two hydrogen atoms - in symbol form: H_2O . You mightn't have thought about it but hydrogen, which is the most common and fundamental element in the Universe, was named by Lavoisier after its property to generate water: *hydro* + *gen*, hydro being the Latin for water. This property of hydrogen was discovered by the eccentric but brilliant Henry Cavendish and later confirmed by Lavoisier, whom I mentioned in chapter 1.

We're very familiar these days with pictures of molecules; so familiar in fact that it's easy to forget how small a molecule really is. Water molecules are about one third of a nanometre across. That statistic doesn't really convey much. Imagine a little model of a water molecule about the size of a tennis ball. Now imagine stacking these tennis ball size molecules together so as to fill this room with molecules, then to fill the whole of this building. That will be a lot of molecules but it is absolutely nothing compared with the number of molecules in a small beaker of water. You will need to fill the entire volume of the Earth with tennis ball size molecules to obtain the number of molecules in a small beaker of water of 100 ml. I've worked it out at about 10^{25} molecules, in round numbers.

Water molecules attract each other and want to come together. However, there are no such things as male or female water molecules, or even left and right-handed water molecules that somehow fit together. All water molecules are identical. Mutual attraction would form all water into a solid lump if it weren't for another property possessed by all materials: temperature. Temperature gives molecules an intrinsic motion. Solids occur when that motion is least, at the lowest temperatures. Solid water is ice, as we all know.

Solid, Liquid and Vapour

In a solid, molecules are arranged in an extremely regular pattern - not just any pattern but the particular pattern that exhibits the lowest energy. Studying how molecules are packed into

patterns in solids is the field of x-ray crystallography. Different patterns exhibit different symmetry arrangements but there aren't an unlimited number of possibilities for the symmetry of the result - only 230, in fact. Ice can form in several slightly different patterns, depending on the temperature it forms. Most ice exhibits hexagonal symmetry in the underlying pattern (arrangement) of water molecules, though you can't see this with your naked eye, because water molecules are so extremely small. What you can see with the naked eye, and even more clearly with a low power microscope, are the hexagonal patterns formed by snow crystals, each of which is a separately growing ice crystal. What is happening here is that crystal growth is taking place on the face-planes of the microscopic nucleus of an ice crystal, which has hexagonal symmetry. Conditions of pressure and temperature (and internal defects) favour the growth of particular planes and once started, they keep on growing, all symmetry related planes growing equally quickly; then a very small change in condition causes other faces to grow, and so on. The result is that different ice crystals show a wide variety of individual shapes and sizes but the underlying molecular pattern of water molecules is always the same in each.

Summary: the hexagonal shapes of ice crystals reflect atomic scale patterns of organisation of water molecules, not any hexagonal shape of the molecules.

What is the essential difference between water molecules in the solid, liquid and vapour phases? The obvious difference is structural. In the solid there is a regular, fixed molecular arrangement; a more random and varying arrangement in the liquid; a completely random, constantly differing arrangements in the vapour phase, with an average distance apart in vapour of water molecules of some 50 diameters. [Think of the analogy of the class organised in rows, packed at an open-air pop concert, walking around a park].

An important difference between phases is the amount of energy per water molecule. This increases from solid to vapour. This energy increase covers both *kinetic energy* - the energy of motion - and *potential energy* that comes from stretching the attractive bonds between water molecules. A direct measure of the difference in energy between the phases is the *latent heat*, namely the heat needed to change the phase at constant temperature. Repeating what was said in chapter 3, the latent heat is:

600 cal g⁻¹ for the change from liquid water → vapour
80 cal g⁻¹ for the change from ice → liquid water.

Phase changes

Evaporation – only the most energetic molecules in a liquid have enough energy to leave the liquid if they are at the surface - hence *an evaporating liquid cools*, for it loses its most energetic constituents. This is the fundamental reason for sweat (perspiration in ladies!). Sweat is a short-term solution to keeping cool in hot climates, for you are losing through your glands one of the most precious commodities in your body - namely water. Anyone who has been for many hours in very hot weather without access to water will know how uncomfortable this is.

When there is water vapour above liquid, some of it will spontaneously condense back into the liquid. There is always a restless interchange of molecules between liquid and gas. Why does water stay in a birdbath for a long time, even on a sunny day? Does water not evaporate? Your washing hung out on a summer's day may dry in less than a couple of

hours. What's going on? The water in the birdbath may stay for days, even in summer, because there is a limit to the water vapour content of the atmosphere at a given temperature. This limit occurs when the *rate of spontaneous condensation equals the rate of spontaneous evaporation*.

At this point the atmosphere above the water is said to be **saturated** (we'll need this word again, later). *Saturation* is a slightly unfortunate word because it implies that the atmosphere acts like a sponge. This isn't the case. Some texts talk about the atmosphere 'holding' water vapour. There is no 'holding', in the sponge sense. What the rest of the atmosphere does is set the temperature. The water vapour molecules behave quite independently of what other gases there are in the atmosphere. To come back to the birdbath shown on the slide, on a wet day the atmosphere is saturated with water and the water in the bath doesn't evaporate. To be more precise, some water does evaporate but it is replaced by an equal amount of condensation from the atmosphere. Before the bath can dry up, the saturated air must be replaced by drier air, air with less than the maximum water vapour content at the ambient temperature. Even then it will take a good while for the bird bath water to disappear, at least in our climate.

The most common sequence of phase changes is when temperature increases and water changes from solid → liquid → vapour. Snow melts into water; water evaporates. However, ice can evaporate directly. The process is called **sublimation**. Hoar frost disappears from the grass without turning into dew. Quite deep layers of snow can thin without turning into slush. Up in the clouds, the reverse happens. The underlying reason is because the saturated vapour pressure above ice is a few millibars, not zero. Ice crystals may grow not from liquid but by **vapour deposition**. [In a different context altogether, vapour deposition is used to grow the crystalline devices that are at the heart of modern electronics, including devices used in meteorology].

The hydrological cycle

See the colour illustration in Ahrens' textbook (next slide). An average rainfall of 1 m year⁻¹ over the surface area of the Earth of about 500 million sq. km converts to an annual amount of water raining from the skies (or snowing in some places) of 5×10^{17} kg. That must also be the annual amount of water evaporated into the atmosphere. Remembering the amount of energy needed to boil a kettle containing 1 kg of water, that represents a lot of energy!

85% of atmospheric water comes from the sea. Countries and counties nearest the sea are therefore in line for the most rainfall. The energy required to produce water vapour is not lost - it appears upon condensation (or deposition) of the water vapour into clouds. Water vapour therefore cycles energy from the Earth's surface to the atmosphere.

The wind transports water and energy far from its source to the land. Precipitation is the next stage, taking water from the atmosphere to the ground. Finally, runoff transports water back to the sea via rivers, with 15% direct contribution to atmospheric water vapour by direct evaporation from land, lakes, etc. + transpiration from plants (plants give off water vapour and oxygen - they humidify rooms and we can all use oxygen). The hydrological cycle is very efficient at circulating both water and energy.

The implication of the usual diagrams of the hydrological cycle is that it is driven by solar evaporation. There is a very important twist in the tail to this story that is becoming

increasingly appreciated in the 21st century. The ingredient not explicitly drawn into the diagram is vegetation, particularly trees. One sizeable tree pumps litres of water into the atmosphere per day, winter excluded. Forests repeat this on a grand scale. Of course, it is the Sun that powers this evaporation. Vegetation recycles water into the atmosphere that originally came from seas, rivers and lakes, increasing the humidity and the likelihood of rain downwind. Without vegetation, rainfall generated from open water would soak into the soil or just run-off. Without vegetation, most land more than a few hundred kilometres downwind from open water would not get much rain. The influence of extensive forested areas extends to countries far away from a forest's borders. Cut down a large enough area of forest and climate is affected downwind, reducing rainfall in areas that have little upwind open water. As always, the importance of the effect depends on the numbers involved. Who has the moral right to clear forests? Clearly not just the owners of the trees. A very twisted tail.

Measuring Water Vapour

The amount of water vapour in the atmosphere is called its **humidity**. Humidity can be measured in several different ways. We shall mention only two, called *specific humidity* and *relative humidity*.

$$\text{Specific humidity} = (\text{mass water vapour})/(\text{total mass of air}).$$

The word 'specific' is frequently used in physics to mean 'per unit mass' i.e. for one kg in the mks system of units. Thus *specific humidity* is measured in g kg⁻¹.

In meteorology, we often look at what happens to particular masses of air that move around approximately as a whole, perhaps brought in by the wind, perhaps on a smaller scale heated by the ground in one small area, perhaps confined in a valley by hills and so on. These air masses are called **parcels of air** (or packets of air in some books). They are not completely separated, of course, from neighbouring air but the underlying idea is that most of the molecules of air in a parcel remain within it while something happens to the parcel as a whole. It may just stay fixed in position and cool or heat, or it may get moved around or up and down. What happens at the boundary doesn't affect most of the air in the parcel. The specific humidity of a parcel of air stays constant.

Average Specific Humidity

Looking over the Earth as a whole, average specific humidity decreases as you move from equator to pole. There are two reasons for this:

- Solar energy heats equatorial water more, evaporating more water than nearer the poles.
- Secondly, air at cooler temperatures further north is saturated at lower water vapour concentrations and hence we would expect fewer g kg⁻¹ of water vapour the further north we look. In reality, the specific humidity doesn't depend just on latitude, because of the distribution of land and sea around the globe.

Vapour Pressure

The water in the atmosphere exerts its own pressure, known as **water vapour pressure**. *Each molecular species exerts its own contribution* to atmospheric pressure. In a given parcel of air, the *pressure exerted* by gas molecules depends only on the temperature and the *number*

of molecules of each type. You might think that the mass of each molecule was important, more massive molecules exerting more force per unit area when they collide and bounce off whatever the gas is next to. Well, they do but more massive molecules travel more slowly at a given temperature and hence fewer strike unit area per second. The two effects cancel out, making the pressure contribution independent of the kind of molecule and dependent only on the number of molecules present. [Possible digression on James Clerk Maxwell and kinetic theory of gases].

e.g. if the atmospheric pressure is 1000 mb and 1% of atmospheric air is water vapour (by counting the number of molecules), then the vapour pressure of the water is 10 mb.

Saturation Vapour Pressure

[Alternative name: *saturated vapour pressure*] Saturation Vapour Pressure is the maximum vapour pressure of water at a given temperature. If you left your water in the bath, went away and didn't come back for a day, you wouldn't be surprised to find the water still there. You don't need a bath full of water to try this experiment. We've all experienced the debris of the morning after a party. Abandoned drinks glasses appear just as full as when they were left the previous night. Doesn't water evaporate? Well, it does to begin with but after a while the air in the room will become saturated. When this happens, no more water will evaporate. At 20 °C, saturation vapour pressure is just over 20 mb, i.e. when some 2% of the molecules are water vapour. That's only a few hundred grammes of water vapour in a room of volume 20 m³. As with your room, so with the outside world, only much bigger quantities of water are involved.

Notes:

- Saturation vapour pressure increases sharply (exponentially) with temperature. Many more molecules escape from the liquid at higher temperature. If the computing class is running this year you will use an Excel spreadsheet to calculate the saturation vapour pressure over the range of temperatures typical of our weather. In fact it doubles for every 10 degrees Celsius rise in temperature.
- Saturation vapour pressure is not zero at 0°C, as has been said already. There is vapour above ice at a pressure of about 6 mb at 0°C. We will see later how to make calculations of the humidity of air using a table of saturation vapour pressures. Ice has a lower vapour pressure than water at same temperature (as you might expect if you think about it). It is because of this that food tends to dry out when kept in a deep freeze. When first put into the freezer, water evaporates from the food and re-condenses on the inside of the containing bag as ice crystals. These don't evaporate as readily so water is lost from your peas, beans, meat, bread, etc.

In the atmosphere, if the water vapour content is reduced below saturation, evaporation takes place. *e.g.* cumulus clouds that appear over land on a sunny summer day, due to evaporation of water from the land. The clouds themselves evaporate in the evening when the source of water vapour feeding them is reduced.

Relative Humidity

Relative humidity measures:

(the water vapour content)/(capacity of air to hold water vapour), expressed as a %.

As long as content and capacity are measured in the same way, it doesn't matter how they are measured. Relative humidity is conveniently defined as the ratio of vapour pressures, namely:

$$\text{Relative humidity} = (\text{actual water vapour pressure})/(\text{saturation vapour pressure}) \times 100\%.$$

Relative humidity is what we tend to be aware of. When the relative humidity is high, sweat does not evaporate easily and the atmosphere 'feels' humid. Relative humidity rises steadily before rain. If it is too dry, on the other hand, our skin loses moisture easily, lips dry out and so on. We can also feel uncomfortable. Control of humidity in buildings is almost as relevant as control of temperature - perhaps even more so to preserve the contents of buildings. In the long term, a building with high relative humidity encourages fungal growth and condensation; one with very low relative humidity, drying out and cracking of timber, warping of furniture, embrittlement of documents and so on. At a cost, building humidity can be controlled. Weather can't. Whether applying the idea to rooms or outside, if a packet of air cools its relative humidity increases, because the saturation vapour pressure decreases, and of course *vice - versa*.

In our climate it's pretty common to find the relative humidity is more than 75%, yet the relative humidity in a room at 20°C may well be less than 50%. This is simply because the ventilating air from outside is usually a lot cooler than 20°C so when it is heated within the room its humidity naturally falls, without any effort on our part. If you take figures from the table of saturation vapour pressure for water at various temperatures given in Ahrens' textbook, you'll find that when air at 12°C that has a relative humidity of 85% (a pretty damp feeling day outside) it has a water vapour pressure of 14 mb. When this air is heated to 20°C, then its relative humidity will fall to 60%, because 14 mb is only about 60% of saturation vapour pressure at 20°C.

Put another way, it takes more water vapour to saturate air when it is hot than when it is cool. For example, when the temperature is 30°C, about 4% of the air needs to be water molecules for the humidity to reach 100%. At 20°C, 100% humidity is reached when just over 2% of the air is water. Without looking at tables, the supplement piece on our web page on '*ideal gas meteorology*' shows that if the temperature of a parcel of air rises by 10°C then the relative humidity halves. For example, if you wake up in the morning in your flat and the temperature has fallen to 9°C and the relative humidity is 90%, then upon heating the room to 19°C the humidity will fall to 45% in round figures, if your activity doesn't add much in the way of new water vapour.

In daily life we expect the atmosphere to be dry at times. Low relative humidity is needed to make hay and dry off ripening corn, for example. We need reduced humidity to dry washing hung on the line. In winter when it's cold, roads that have become damp with overnight condensation or even rain take a long time to dry. Light spray is kicked up by traffic until well into the day, simply because with low temperatures the amount of moisture that is evaporated before the air becomes saturated is relatively small. In fact in typical December weather in these parts when the temperature is 5°C or less, there is often a general dampness around on roads, paths, grass and pretty well everywhere for days after it has rained. To say the same thing in other words, when it is very cold it takes only a little moisture in the air to make the humidity high. For example, with the temperature at 0°C, then if water vapour pressure is 6 mb the relative humidity will be 100%. 6 mb occurs when only about 0.6% of the atmosphere is water vapour. It's for this reason that Arctic or Antarctic explorers can find

it very difficult to dry damp clothes. It's so cold outside that you can't properly ventilate your cabin, tent or ice house. There is water all around in the form of snow, ice or condensation and when the air is cold it takes very little water vapour to create 100% humidity. Under these conditions, clothes won't dry.

Although relative humidity is a nice concept, related to how we experience the atmosphere, it's not such an easy concept to measure directly. How can you find directly the vapour pressure due to water molecules alone? In practice you don't. You have to deduce relative humidity from indirect measurements. We'll see how, soon.

Dew Point

Dew point is one of the most useful figures describing water vapour in the atmosphere. Dew point can be directly measured. It is the temperature to which a parcel of air has to be cooled for water vapour saturation to occur. If the dew point is close to the air temperature, it means that dew, fog or cloud is near to forming. If dew point is much below air temperature, then the amount of water vapour in the atmosphere is low for that air temperature, relative humidity is low and fog or cloud will not form. If water vapour pressure is less than 6 mb, then we tend to talk about the *frost point* and compare with the vapour pressure of ice.

Ahrens points out how 'dry' desert air at 35°C at a relative humidity of only 15%, has a dew point of 4°C. It therefore contains more water vapour than saturated air at 0°C during a snowstorm. The water vapour, though, is inaccessible to plant and animal life. [Fish can extract small amounts of oxygen dissolved in water - animals can't extract small amounts of water in atmospheric oxygen!].

Another useful statement concerning dew point is that the difference between air temperature and dew point is a measure of relative humidity. E.g. If the dew point is 15° below air temperature, the relative humidity is less than if it is 8° below air temperature.

Measuring Humidity

Hygrometers measure humidity.

- We have met the modern electrical sensor: two charged electrodes are separated by a narrow gap. Moisture in the gap changes the electric resistance and the electrical capacitance of the gap and hence alters the current passed between the electrodes. When the moisture content is measured at the same time as temperature, relative humidity can be deduced.
- Infra-red remote sensing detects the amount of water vapour in the line of sight between the IR source (which can be the Earth) and the sensor. [Ahrens shows IR absorption profiles] 5-8 μm is the strong water vapour absorption band.
- Hair-hygrometer - Wash a lock of hair in alcohol to remove its oil; stretch it between a fixed anchor point and a moveable lever. The idea is over 200 years old. Hair becomes longer with moisture. This is the basis of Dutch weather house in which a twisted hair controls whether the man or lady comes out. Seaweed is another traditional hygroscopic material.
- Cool air to its dew point - e.g. Daniel's hygrometer is based on this measurement.

Wet and Dry Bulb psychrometer

The working is explained on the slide.

This common device is based on cooling brought on by evaporation - the same effect that makes perspiration so useful to us. The evaporating surface, the bulb of a thermometer covered by a wick dipped in water, does *not* cool to the dew point but cools by an amount that depends on the difference between air temperature and the dew point. Basically, it cools a certain fraction of the way to the dew point and that fraction can be found from a look up table (Ahrens appendix D). The amount of cooling is called the *depression of the wet bulb*.

The cooling does depend a bit on the ventilation of the psychrometer, being greater for good ventilation compared with still air. Psychrometers tend to be one of 2 types: the *sling psychrometer* (fig 5.18) or Assman's *whirling psychrometer*. You can sometimes see the University Estates officials about the campus using a sling psychrometer to measure relative humidity.

The slide shows an example of readings taken with a psychrometer and the use of appendix D to deduce relative humidity (and the use of numbers in meteorology!).

The wet bulb temperature becomes an issue of life or death if it rises to 35° C or higher. In hot weather our bodies cool by perspiration but if the wet bulb temperature is 35° C or higher then we can't keep our core temperature at the 37° C or so needed for life. Humans are very adaptable creatures in many respects but not so in relation to our core operating temperature. Six hours or so at higher temperatures is all it takes, apparently, for an unpleasant death. Air temperatures of 40° C or even 45° C are quite tolerable, so long as the humidity is low enough to make the web bulb temperature less than 35° C. In short, heat plus humidity is a deadly combination. A place may have a liveable climate 360 days of the year but if for 5 days in the year the wet bulb temperature is above 35° C, then unless there is access to some form of cooling, the place is unliveable. This is one reason why global warming is likely to have a bigger impact than we might at first think, especially those of us who live in a cool climate who never have to worry about temperatures over 30° C.

Relative Humidity Calculations

See slide on the use of Ahrens' Table 2.

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