7 Water Vapour

Learning Goals

After studying this chapter, students should be able to:

1. account for the relationship between saturation and temperature (pp. 149–151);
2. distinguish between the various measures of atmospheric water vapour (pp. 156–165);
3. explain how atmospheric humidity can be measured (pp. 165–169); and
4. describe the relationship between human comfort and atmospheric humidity (pp. 169–170).

Summary

1. Water vapour enters the atmosphere by **evaporation** and leaves by **condensation**. Whereas evaporation is a cooling process that absorbs energy, condensation is a warming process that releases energy.

2. There is a limit to how much water vapour can exist in the air at a given temperature. At this limit, the rate of evaporation is equal to the rate of condensation, and the vapour pressure is the saturation vapour pressure. As temperature increases, saturation vapour pressure increases. This relationship is an exponential one.
3. Once saturation is reached, condensation can occur. **Saturation** can be reached by cooling the air, adding water vapour to it, or mixing together two air parcels that are close to saturation. The most common process for producing condensation in the atmosphere is cooling, which is responsible for the formation of most clouds and fogs.
4. We use many methods to express the amount of water vapour in the air. The absolute measures include **vapour pressure**, **absolute humidity**, **mixing ratio**, **specific humidity**, and **dew-point temperature**. The relative measures are derived from the absolute ones and include **relative humidity**, **vapour pressure deficit, dew-point depression**, and **wet-bulb temperature**.
5. We can measure **absolute humidity** and **dew-point temperature** directly. With a **psychrometer**, we can measure **wet-bulb temperature**. Evaporation lowers the wet-bulb temperature so that the less water vapour there is in the air, the greater is the difference between the wet-bulb temperature and the dry-bulb (air) temperature. We can use this difference to determine other humidity measures.
6. Certain combinations of heat and humidity can cause heat stress. In Canada, an index known as the **humidex** has been developed to make people aware of potentially stressful conditions.

Key Terms

Absolute humidity The mass of water vapour in a unit volume of air. (p. 156)

Depression of the wet bulb The difference between the dry-bulb temperature and the wet-bulb temperature. (p. 166)

Dew-point depression The difference between the air temperature and the dew-point temperature. (p. 164)

Dew-point temperature The temperature to which the air must be cooled, at constant pressure, to reach saturation. (p. 159)

Dry-bulb thermometer The thermometer in a psychrometer that is used to measure air temperature. (p. 166)

Heat capacity The amount of heat required to raise a unit volume of a substance by 1 K. (p. 168)

Humidex An index used in Canada to provide a measure of how warm it feels due to a combination of high temperature and high humidity. (p. 169)

Humidity The amount of water vapour in a quantity of air. (p. 148)

Hygrometer An instrument used to directly measure the amount of water vapour in the air, based on a variety of different methods. (p. 165)

Mixing ratio The ratio of the mass of water vapour to the mass of dry air. (p. 158)

Partial pressure The pressure contributed by a single gas in a mixture of gases. (p. 148)

Psychrometer An instrument used to measure the amount of water vapour in the air, based on the cooling produced by evaporation. (p. 166)

Relative humidity The ratio of the actual amount of water vapour in the air to the saturation value at the air's temperature. (p. 161)

Saturation The maximum amount of water vapour that can exist at a given temperature. (p. 148)

Saturation vapour pressure The maximum water vapour pressure that can exist at a given temperature. (p. 150)

Specific humidity The ratio of the mass of water vapour to the total mass of air. (p. 158)

Supercooled Cooled below the temperature at which a substance would normally freeze, while remaining in a liquid state. (p. 151)

Supersaturated The condition that occurs when the amount of water vapour in the air is higher than the saturation value. (p. 155)

Unsaturated The condition that occurs when the amount of water vapour in the air is lower than the saturation value. (p. 155)

Vapour pressure Partial pressure exerted by water vapour. (p. 148)

Vapour pressure deficit The difference between the saturation vapour pressure and the actual vapour pressure. (p. 163)

Wet-bulb temperature The temperature to which air will cool by evaporating water into it. (p. 166)

Wet-bulb thermometer The thermometer in a psychrometer that is used to measure the wet-bulb temperature. (p. 166)

Wind chill A measure of how cold it feels due to a combination of low temperature and high wind. (p. 169)

Key Equations

Absolute humidity

$$\rho_v = \frac{e}{R_v T}$$

Mixing ratio

$$r = \varepsilon \left(\frac{e}{P - e}\right)$$

Specific humidity

$$q = \varepsilon \left(\frac{e}{P}\right)$$

Mixing ratio for water vapour

$$e = P \left(\frac{r}{\varepsilon + r}\right)$$

Answers to Selected Review Questions (p. 171)

1. **What is vapour pressure? Why does it change with vertical motion?**

   Vapour pressure is the partial atmospheric pressure exerted by atmospheric water vapour. It changes with vertical motion because as an air parcel rises or sinks in the atmosphere, its vapour pressure will change as it adjusts to the surrounding pressure.

3. **What factors influence evaporation? Provide an example for each.**

   The curvature of the surface and impurities in the water are factors that influence evaporation. It is easier for water to evaporate from a curved surface. It is harder for water to evaporate when there are impurities in the water.

5. **What are the three processes by which air can reach saturation? Which is most common in the atmosphere?**

   The three processes by which air can reach saturation are by cooling, adding water vapour, or mixing two air parcels that are both close to saturation. Cooling is the most common.

7. **What are mixing ratio and specific humidity? Why are they almost the same in the atmosphere?**

   Mixing ratio is the ratio of the mass of water vapour to the mass of dry air. Specific humidity is the ratio of the mass of water vapour to the total mass of air. They are almost the same in the atmosphere because vapour pressure is so small compared to total atmospheric pressure.

9. **What is dew-point temperature? How can dew-point temperature increase?**

   Dew-point temperature is the temperature to which the air must be cooled, at constant pressure, to reach saturation. Dew-point temperature can increase when water evaporates.

11. **Why would it be very unlikely for the relative humidity to be 90 per cent if the temperature was 34ºC?**

    The saturation vapour pressure at 34°C is 5.32 kPa. For the relative humidity to be 90 per cent at that temperature, an extremely high (and unlikely) amount of water vapour would be likely.

13. **What does vapour pressure deficit tell us? What does dew-point depression tell us?**

    Vapour pressure deficit tells us the difference between the saturation vapour pressure and the actual vapour pressure. Dew-point depression tells us the difference between the air temperature and the dew-point temperature.

15. **When it is hot, why do we *feel* much hotter if it is also humid?**

When humidity is high, it is more difficult for our bodies to regulate our internal temperature because our sweat will not evaporate.

Answers to Selected Problems (p. 172)

1. **The temperature is 24°C, the air pressure is 101.3 kPa, and the vapour pressure is 2.4 kPa.**
   a) What is the dew-point temperature?
   b) What is the relative humidity?
   c) What is the absolute humidity?
   d) What is the mixing ratio?
   e) What is the saturation mixing ratio?
   f) Use your answers to d) and e) to recalculate the relative humidity.

   a) The dew-point temperature (Td) is 20.5°C (from Table 7.1).

   The saturation vapour pressure (es) at 24°C is 2.983 kPa (from Table 7.1).

   b) $$RH = \frac{e}{e_s} \times 100\%$$

   $$= \frac{2.4\,\text{kPa}}{2.93\,\text{kPa}} \times 100\%$$

   $$= 81.9\%$$

   c) $$\rho_v = \frac{e}{R_v T}$$

   $$= \frac{2400\,\text{kg m}^{-1}\,\text{s}^{-2}}{461.5\,\text{J kg}^{-1}\,\text{K}^{-1} \times 296\,\text{K}}$$

   $$= 0.018\ \text{kg m}^{-3}$$

   $$= 18\ \text{g/m}^3$$

   d) $$r = \varepsilon\left(\frac{e}{P - e}\right)$$

$$= 0.622\left(\frac{2.4\,\text{kPa}}{101.3\,\text{kPa} - 2.4\,\text{kPa}}\right)$$

$= 0.015$ g/g

$= 15$ g/kg

e) $r_s = \varepsilon\left(\frac{e_s}{P - e_s}\right)$

$$= 0.622\left(\frac{2.93\,\text{kPa}}{101.3\,\text{kPa} - 2.93\,\text{kPa}}\right)$$

$= 0.019$ g/g

$= 19$ g/kg

f) $RH = \frac{r}{r_s} \times 100\%$

$$= \frac{15\,\text{g/kg}}{19\,\text{g/kg}} \times 100\%$$

$= 78.9\%$

3. **Use the psychrometric equation to determine the vapour pressure, relative humidity, and dew-point temperature for each of the following sets of observations. (Compare the calculated relative humidity in each case to that found in Table 7.3 or estimated from Figure 7.16.)**
   a) T = 30°C, Tw = 20°C
   b) T = 14°C, Tw = 12°C
   What do you notice about the relationship between T, T_w, and T_d?

a) $e = e_{ws} - \gamma(T - T_w)$

The saturation vapour pressure of the wet-bulb temperature (e_{ws}) is 2.337 kPa (from Table 7.1).

$e = 2.337\text{ kPa} - 0.065\text{ kPa K}^{-1}(303\text{ K} - 293\text{ K})$

$= 1.687$ kPa

The saturation vapour pressure (e_s) is 4.243 kPa (from Table 7.1).

$$RH = \left(\frac{e}{e_s}\right) \times 100\%$$

$$= \left(\frac{1.687\,kPa}{4.243\,kPa}\right) \times 100\%$$

$$= 39.8\%$$

The dew-point temperature (T_d) is 15°C (from Table 7.1).

b) $e = e_{ws} - \gamma(T - T_w)$

e_{ws} = 1.401 kPa (from Table 7.1)

e = 1.401 kPa – 0.065 kPa K^{-1}(287 K – 285 K)

= 1.271 kPa

The saturation vapour pressure (e_s) is 1.598 kPa (from Table 7.1).

$$RH = \left(\frac{e}{e_s}\right) \times 100\%$$

$$= \left(\frac{1.271\,kPa}{1.598\,kPa}\right) \times 100\%$$

$$= 79.5\%$$

The dew-point temperature (T_d) is 10.5°C (from Table 7.1).

T_w is higher than T_d.

5. **Find the saturation vapour pressure and the saturation mixing ratio for the following parcels of air.**
   a) T = 17°C, P = 100 kPa
   b) T = 17°C, P = 80 kPa
   Comment on your findings.

a) $e_s = e_o \exp\left[\frac{L}{R_v}\left(\frac{1}{T_o} - \frac{1}{T}\right)\right]$

$$= 0.611 \exp\left[\left(\frac{2.5\times10^{6}\ \text{J/kg}}{461.5\,\text{J kg}^{-1}\,\text{K}^{-1}}\right)\left(\frac{1}{273\,\text{K}} - \frac{1}{290\,\text{K}}\right)\right]$$

$= 1.96$ kPa

$$r_s = \left(\frac{e_s}{P - e_s}\right)$$

$$= 0.622\left(\frac{1.96\,\text{kPa}}{100\,\text{kPa} - 1.96\,\text{kPa}}\right)$$

$= 12.4$ g/kg

b) $$e_s = e_o \exp\left[\frac{L}{R_v}\left(\frac{1}{T_o} - \frac{1}{T}\right)\right]$$

$$= 0.611 \exp\left[\left(\frac{2.5\times10^{6}\ \text{J/kg}}{461.5\,\text{J kg}^{-1}\,\text{K}^{-1}}\right)\left(\frac{1}{273\,\text{K}} - \frac{1}{290\,\text{K}}\right)\right]$$

$= 1.96$ kPa

$$r_s = \left(\frac{e_s}{P - e_s}\right)$$

$$= 0.622\left(\frac{1.96\,\text{kPa}}{80\,\text{kPa} - 1.96\,\text{kPa}}\right)$$

$= 15.6$ g/kg

Saturation vapour pressure does not vary with pressure but saturation mixing ratio does vary with pressure (saturation mixing ratio increases as pressure decreases).

7. **a) Assume your breath has a temperature of 32°C and a dew-point temperature of 29°C. If the outside air temperature is 2°C with a dew-point temperature of 0°C, will your breath form a "cloud" when you exhale? Assume that your breath mixes in equal proportions with the outside air.**
   b) Do some calculations to determine the importance of the outside air temperature and dew-point temperature in influencing whether or not your breath will form a cloud.

a) $$T = \frac{32°\text{C} + 2°\text{C}}{2}$$

$= 17°C$

The vapour pressure (e) is 4.006 kPa when Td is 29°C (from Table 7.1).

The vapour pressure (e) is 0.611 kPa when Td is 0°C (from Table 7.1).

$$e = \frac{4.006 \text{ kPa} + 0.611 \text{ kPa}}{2}$$

$= 2.31$ kPa

Since the saturation vapour pressure for 17°C is 1.937 kPa, your breath will form a cloud.

b) If the air temperature was at least 8°C (and the dew-point temperature remained at 0°C) then a cloud would not form.

Study Questions

For suggested answers, see below.

1. Why is the usefulness of vapour pressure in meteorology limited?

2. Why does the rate of evaporation tend to increase as temperature increases?

3. What is the curvature effect? Explain its influence on saturation vapour pressure.

4. Why isn't relative humidity a good measure to determine the actual amount of water vapour in the air?

5. Why is the dew-point depression often plotted on 700 hPa charts?

Additional Problems

For answers, see below.

1. One air parcel has a temperature of 8°C and a vapour pressure of 1.07 kPa. A second air parcel, with the same mass as the first has a temperature of –12°C and a vapour pressure of 0.22 kPa. If these two air parcels are mixed together, will the newly formed air parcel be saturated?

2. What is the absolute humidity for a vapour pressure of 2.4 kPa and a temperature of 29°C?

3. For a vapour pressure of 1.7 kPa and a pressure of 100.8 kPa, calculate the following:
   a) mixing ratio
   b) specific humidity

4. For a temperature of 16°C and a pressure of 85 kPa, calculate the following:
   a) saturation vapour pressure
   b) saturation absolute humidity
   c) saturation mixing ratio

5. Calculate the relative humidity for air that has a temperature of 25°C and a vapour pressure of 1.2 kPa.

6. If the temperature of a bottle containing a cold liquid is 7°C and the air temperature is 29°C, calculate the highest possible relative humidity that can occur before condensation will form on the bottle.

7. Air has a temperature of –3°C and a relative humidity of 73 per cent. If the temperature of the air is increased to 20°C, how much is its drying power increased?

8. The temperature is –13°C, the air pressure is 77 kPa, and the vapour pressure is 0.16 kPa. Calculate the following:
   a) dew-point temperature
   b) relative humidity
   c) absolute humidity
   d) mixing ratio
   e) saturated mixing ratio

9. A psychrometer reading gives a dry-bulb temperature of 27°C and a wet-bulb temperature of 15°C. Calculate the following:
   a) vapour pressure
   b) relative humidity
   c) dew-point temperature

Answers to Study Questions

1. As an air parcel rises or sinks in the atmosphere, its vapour pressure will change as it adjusts to the surrounding pressure. This is misleading because, although vapour pressure is changing, the air parcel's actual water vapour content may or may not be changing. (p. 148)

2. Temperature is a measure of the average kinetic energy of the molecules. Thus, at any given temperature, the molecules will not all have the same amount of energy. As temperature increases, more and more liquid molecules will have enough energy to become vapour. (pp. 148–149)

3. It is easier for water to evaporate from a curved surface because water molecules are not held as tightly to a curved surface as they are to a flat surface. This is known as the curvature effect. The saturation vapour pressure above a curved surface is higher than it would be above a flat surface at the same temperature. (p. 153)

4. Relative humidity is dependent on both water vapour content and temperature. An increase in temperature will cause the relative humidity to decrease even if the water vapour content remains the same. (p. 161)

5. It is plotted on 700 hPa charts because areas with dew-point depressions of less than 5°C are likely to be cloudy. The 700 hPa chart is used because it represents the average height of most cloud cover. (p. 164)

Answers to Additional Problems

1. $$T = \frac{8°C + (-12°C)}{2}$$

   $$= -2°C$$

   $$e = \frac{1.07\,\text{kPa} + 0.22\,\text{kPa}}{2}$$

   $$= 0.645\ \text{kPa}$$

   Since the saturation vapour pressure for -2°C is 0.517 kPa, this new air parcel will be saturated.

2. Convert 2.4 kPa to 2400 Pa, and 29°C to 302 K.

   $$\rho_v = \frac{2400\,\text{kg}\,\text{m}^{-1}\,\text{s}^{-2}}{461.5\,\text{J}\,\text{kg}^{-1}\,\text{K}^{-1} \times 302\,\text{K}}$$

   $$= 0.017\ \text{kg/m}^3$$

$= 17\ \text{g/m}^3$

3. a) $r = 0.622\left(\frac{1.7\,\text{kPa}}{100.8\,\text{kPa} - 1.7\,\text{kPa}}\right)$

$= 0.01067\ \text{g/g}$

$= 10.67\ \text{g/kg}$

b) $q = 0.622\left(\frac{1.7\,\text{kPa}}{100.8\,\text{kPa}}\right)$

$= 0.01049\ \text{g/g}$

$= 10.49\ \text{g/kg}$

4. a) $e_s = e_o \exp\left[\frac{L}{R_v}\left(\frac{1}{T_o} - \frac{1}{T}\right)\right]$

$= 0.611\ \exp\left[\left(\frac{2.5\times10^6\ \text{J/kg}}{461.5\,\text{J kg}^{-1}\ \text{K}^{-1}}\right)\left(\frac{1}{273\,\text{K}} - \frac{1}{289\,\text{K}}\right)\right]$

$= 1.83\ \text{kPa}$

b) $\rho_{vs} = \frac{e_s}{R_v T}$

$= \frac{1830\,\text{Pa}}{461.5\,\text{J kg}^{-1}\ \text{K}^{-1} \times 289\,\text{K}}$

$= 0.0137\ \text{kg/m}^3$

c) $r_s = \left(\frac{e_s}{P - e_s}\right)$

$= 0.622\left(\frac{1.83\,\text{kPa}}{85\,\text{kPa} - 1.83\,\text{kPa}}\right)$

$= 13.7\ \text{g/kg}$

5. $$RH = \frac{e}{e_s} \times 100\%$$

The saturation vapour pressure (e_s) at 25°C is 3.167 kPa (from Table 7.1).

$$RH = \frac{1.2\,kPa}{3.167\,kPa} \times 100\%$$

$$= 37.9\%$$

6. The saturation vapour pressure (e_s) for the glass at 7°C is 1.001 kPa (from Table 7.1).

Condensation will form on the glass when the vapour pressure (e) for the air is 1.001 kPa.

The saturation vapour pressure (e_s) for the air at 29°C is 4.006 kPa (from Table 7.1).

$$RH = \frac{1.001\,kPa}{4.006\,kPa} \times 100\%$$

$$= 25\%$$

The highest possible RH that can occur before condensation will form on the glass is 25%.

7. The saturation vapour pressure (e_s) for the air at -3°C is 0.476 kPa and for the air at 20°C is 2.337 kPa (from Table 7.1).

$$RH = \frac{e}{e_s} \times 100\%$$

$$e = \frac{RH\,e_s}{100}$$

$$= \frac{73(0.476)}{100}$$

$$= 0.35\ kPa$$

Calculate the vapour pressure deficit of this air:

$$VPD = 0.476\ kPa - 0.35\ kPa$$

$$= 0.126\ kPa$$

Calculate the vapour pressure deficit of the warmer air:

VPD = 2.337 kPa – 0.35 kPa

= 1.987 kPa

Calculate the change in the drying power of the air:

1.987 kPa – 0.126 kPa = 1.861 kPa

8. a) The dew-point temperature (T_d) is –15°C (from Table 7.1).

The saturation vapour pressure (e_s) for the air at -13°C is 0.198 kPa (from Table 7.1).

b) $$RH = \frac{e}{e_s} \times 100\%$$

$$= \frac{0.16 \text{ kPa}}{0.198 \text{ kPa}} \times 100\%$$

= 80.8%

c) $$\rho_v = \frac{e}{R_v T}$$

$$= \frac{160 \,\text{kg m}^{-1}\text{s}^{-2}}{461.5 \,\text{J kg}^{-1}\text{K}^{-1} \times 260 \,\text{K}}$$

= 0.0013 kg m^{-3}

= 1.3 g/m^3

d) $$r = \varepsilon\left(\frac{e}{P - e}\right)$$

$$= 0.622\left(\frac{0.16 \,\text{kPa}}{77 \,\text{kPa} - 0.16 \,\text{kPa}}\right)$$

= 0.0013 g/g

= 1.3 g/kg

e) $r_s = \varepsilon\left(\frac{e_s}{P - e_s}\right)$

$$= 0.622\left(\frac{0.198\,\text{kPa}}{85\,\text{kPa} - 0.198\,\text{kPa}}\right)$$

$= 0.0015$ g/g

$= 1.5$ g/kg

9. $e = e_{ws} - \gamma(T - T_w)$

The saturation vapour pressure for the wet-bulb temperature (e_{ws}) is 1.704 kPa (from Table 7.1).

$e = 1704$ Pa – 65 Pa/K (300 K – 288 K)

$= 924$ Pa

$= 0.92$ kPa

The saturation vapour pressure (e_s) is 3.565 kPa (from Table 7.1).

$$RH = \left(\frac{e}{e_s}\right) \times 100\%$$

$$RH = \left(\frac{0.92\,\text{kPa}}{3.565\,\text{kPa}}\right) \times 100\%$$

$= 25.8\%$

The dew-point temperature (T_d) is 6°C (from Table 7.1).