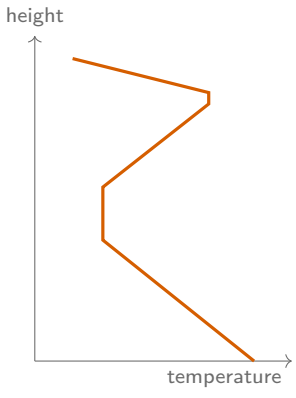
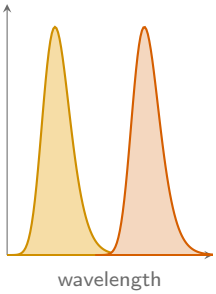
The Atmosphere: Part IV

Density, heat, pressure and buoyancy in the laboratory

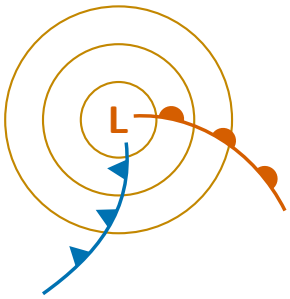
A worked, step-by-step guide to the Weeks 8–11 practicals



Part I



Part II



Part III

Part IV of The Atmosphere

One part of The Atmosphere, with the same numbering as the full book. Every question, data table, figure and worked answer is on the page.

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Chapter 1

How to use this book

1.1 What is in it

This book teaches the atmosphere through questions you work yourself. It has four parts. The first three follow on from each other: Part I describes the structure of the atmosphere, Part II explains how the Sun heats it, and Part III how that uneven heating fills it with moisture and sets it in motion. Part IV goes into the laboratory and tests, by hand, the four physical ideas the others rest on: density, heat, pressure and buoyancy. Everything you need is on the page: every question, data table, map and figure, with its worked answer.

Table 1.1. The four parts of the book.

Part	What it covers	Chapters	Appendix
I	**Vertical structure of the atmosphere.** Pressure and the halving rule, oxygen at altitude, the standard atmosphere, soundings, inversions and the tropopause, lapse rates, stability, climates.	2–10	A
II	**Solar radiation.** The laws of radiation, black bodies and planetary temperatures, the Earth's energy balance and the greenhouse effect, sun angle and the seasons.	11–19	B
III	**Moisture, motion and weather maps.** Humidity and the dew point, the forces that move the air, the geostrophic wind and friction, station models, streamlines, fronts and a full weather-map analysis.	20–30	C
IV	**Density, heat, pressure and buoyancy in the laboratory.** Radiation, conduction and convection, heat flow and latent heat, stratification, Boyle's law and adiabatic cooling, Archimedes' principle, with every activity of the Weeks 8–11 practicals worked through.	31–38	D

Every part opens with a chapter that maps each question to the chapter that answers it, and closes with a chapter that gathers all the answers in one table, a list of mistakes to avoid and a self-test. Its appendix holds the formulas, derivations and symbols. Appendix E lists the shared constants and units, and the references are at the end.

1.2 How each chapter is laid out

1. **The ideas first,** in plain language. Every important equation is numbered, for example (3.4), and followed by a *where* list of its symbols, units and values.
2. **The question**, in a box, with its data beside it.
3. **The method**, one step per line, with every number and unit shown.
4. **The answer**, in a green box, followed by a **check** that it is sensible.
5. **Worked examples**, **key ideas**, points to **take care** over, and **questions that come up**.
6. **Try it yourself**: a practice set, with answers in the green box that follows.
7. **Python**: the equations as functions, which you can run and change. They are also collected in one tested package.

How to get the most out of the book

Cover the green answer box, work the question on paper, then uncover it. If your answer differs, find the step where you diverged before reading on. That step is where the learning is.

1.3 Conventions used throughout

- **Numbering.** "Eq. (4.2)" is equation 2 of Chapter 4; figures and tables are numbered the same way. "§ 4.3" is section 3 of Chapter 4. Appendices are lettered A to D, one per part and one for shared constants.
- **Units** are SI, written as powers: $\mathrm{W\,m^{-2}}$ means watts per square metre, $\mathrm{m\,s^{-1}}$ metres per second. Pressure is in hectopascals, which are the same as millibars ($1\ \mathrm{hPa} = 1\ \mathrm{mb} = 100\ \mathrm{Pa}$). Heights are in metres or kilometres.
- **Temperature.** Temperatures in the data are in degrees Celsius. Any formula in which temperature is multiplied, divided or raised to a power (the gas law, the radiation laws, the potential temperature) needs kelvin: $T_\mathrm{K} = T_{\circ\mathrm{C}} + 273.15$. A *difference* of temperature is the same in both scales, so lapse rates can be written in $^\circ\mathrm{C\,km^{-1}}$ or $\mathrm{K\,km^{-1}}$.
- **Constants.** Each part uses rounded values, stated where they first appear; Appendix E gives precise values and sources.
- **Rounding.** Intermediate results keep at least four significant figures; answers are rounded at the end, usually to three or four.
- **Cross-references between parts** are written in the same way as within a part, with the part named: "Part II, § 17.7".
- **References** to the literature are given as author and year, for example Stull (2017), and listed in full at the end.

1.4 What to have beside you

A calculator with powers, logarithms and trigonometric functions, set to **degrees**; graph paper, a ruler, a soft pencil and three or four coloured pencils, so that each line on a graph has its own colour. Python is optional.

1.5 Acknowledgement

The questions and data in this book grew out of the practicals of EGM305 The Atmosphere at Ulster University, and are reused with the permission of the module staff. The explanations, figures, code and any errors are the author's.

1.6 Reading

Good textbooks for going further are Lutgens et al. (2019) and Ahrens and Henson (2022). A free textbook with worked examples is Stull (2017). For more depth, Wallace and Hobbs (2006) treats the physics at the next level up.

Part IV

Density, heat, pressure and buoyancy in the laboratory

Chapter 31

Part IV at a glance

31.1 What this part covers

Parts I to III worked with numbers on paper: soundings, spectra and weather maps. This part goes into the laboratory. In two sessions (Weeks 8 to 11) you test, with your own hands, the four physical ideas that the rest of the book depends on (EGM305 module team, n.d.):

Density how much mass is packed into a volume, and why warming makes air and water lighter (Chapter 32).

Heat and temperature the difference between them, the three ways heat moves, and the latent heat hidden in melting and evaporation (Chapter 33).

Pressure force spread over an area, why it falls with height, and why gases squeeze while water does not (Chapter 34).

Buoyancy why things lighter than their surroundings rise, the principle behind every rising cloud and every stable or unstable atmosphere (Chapter 35).

Many of the experiments use water instead of air, because water's motions can be seen with a few drops of dye. The physics is identical in both fluids, and every activity ends by carrying the result back into the atmosphere. The activities follow the inquiry-based approach of Karp-Boss et al. (2009); the atmospheric background follows Ahrens and Henson (2022) and Wallace and Hobbs (2006).

Table 31.1. The activities, the ideas they test, and where each is worked through.

Activity	What you do	Ideas	Section
1.1A	black, white and shiny cans under a lamp	radiation, equilibrium	36.1
1.1B	touch wood, metal and cloth at room temperature	conduction	36.2
1.1C	heat one side of a water loop and watch dye	convection, density	36.3
1.2	cold water, then ice, inside hot water	heat flow, latent heat	36.4
1.3A	lift a divider between salt and fresh, hot and cold water	density, stratification	36.5
1.3B	the teabag rocket	buoyancy of hot air	36.6
2.1	balloons, a marshmallow and a cloud under vacuum	pressure, Boyle's law, adiabatic cooling	37.1
2.2	trim the Archimedes ball to neutral buoyancy	Archimedes' principle	37.2
2.3	squeeze the Cartesian diver	pressure, compressibility, buoyancy	37.3

Chapters 32 to 35 build the physics; Chapters 36 and 37 take each activity step by step, answer every question in the handbook, and give worked numbers you can compare with your own; Chapter 38 gathers all the answers, the mistakes to avoid and a self-test. The constants, symbols and corrections to the handbook are in Appendix D. A six-page *lab card* made from the same material is designed to be carried to the bench.

31.2 How the sessions run

You work in a team. Each session has three experiments of 30 to 45 minutes; some are split into two or three short activities. Share the jobs (one person reads the thermometers, one writes, one handles the equipment) and swap round, so everyone tries everything. By the second session your team should run smoothly.

What to record for every experiment

1. **Aim**, hypothesis or question: what you are testing, in one sentence.
2. **Materials and set-up**: a labelled sketch.
3. **Method**: the steps you actually followed.
4. **Predictions**: written *before* you test, each with a reason.
5. **Observations, measurements and calculations**: numbers with units, in a table; a graph where asked.
6. **Conclusion and explanation**: was the prediction right, and which physics explains what you saw?
7. **Examples** in meteorology or oceanography where the same process works.

Writing the prediction first is the heart of the method. Science advances by *predicting*, *asking*, *measuring*, *generalising* and *testing by application*; a prediction that turns out wrong is as useful as one that turns out right, provided you can explain why.

Safety and etiquette

Wear a buttoned lab coat and sensible shoes, tie back long hair, and stand while you work. Bags go under the benches; keep the aisles clear. Report every accident, however small. Keep paper, sleeves and hair away from the spirit lamps, matches and the burning teabag, and use the non-flammable mat. Phones, laptops and tablets stay off and in your bag: anyone seen using one is asked to leave and marked absent. There are no spare parts, so handle the vacuum flasks, thermometers and balls gently. Leave the equipment and bench as clean as you found them, or cleaner, and wash your hands with soap at the end.

Bring: a lab book (squared paper makes graphs easier), a calculator, pencil, ruler and eraser, a tea towel and a lab coat.

31.3 Conventions for this part

The conventions of the whole book are in § 1.3. In this part:

- **Temperatures** are in degrees Celsius unless a formula needs kelvin: $T_{\mathrm{K}} = T_{^\circ\mathrm{C}} + 273.15$.
- **Densities** are in $\mathrm{kg\,m^{-3}}$; in the lab you will often measure $\mathrm{g\,cm^{-3}}$ (multiply by 1000).
- **Worked numbers** use typical classroom values. Your own measurements will differ: compare the *pattern*, not the last digit.

Chapter 32

Density

32.1 What density is

Density measures how compactly matter is packed: the mass in a given volume,

$$\rho = \frac{m}{V}. \tag{32.1}$$

where

ρ	density	$\mathrm{kg\,m^{-3}}$ (or $\mathrm{g\,cm^{-3}}$; $1\ \mathrm{g\,cm^{-3}} = 1000\ \mathrm{kg\,m^{-3}}$)
m	mass	kg or g
V	volume	$\mathrm{m^3}$ or $\mathrm{cm^3}$ ($1\ \mathrm{mL} = 1\ \mathrm{cm^3}$)

Density does not depend on how much material you have: a cup and a bath of the same water have the same density. That is what makes it useful for following air masses and water masses around the globe.

Measuring a density in the lab

Weigh an empty beaker: 52.0 g. Pour in exactly 100 mL of the salt solution and weigh again: 154.5 g. The liquid's mass is $154.5 - 52.0 = 102.5$ g, so

$$\rho = \frac{102.5\ \mathrm{g}}{100\ \mathrm{cm^3}} = 1.025\ \mathrm{g\,cm^{-3}} = 1025\ \mathrm{kg\,m^{-3}}.$$

Check: sea water is 1020 to 1030 $\mathrm{kg\,m^{-3}}$, so a solution of about 35 g of salt per litre is sea-like.

32.2 Air and water compared

Water is about a thousand times denser than air (Table 32.1). Air at sea level and 15°C has a density of about 1.225 $\mathrm{kg\,m^{-3}}$; fresh water at room temperature 998 $\mathrm{kg\,m^{-3}}$; most ocean water 1020 to 1030 $\mathrm{kg\,m^{-3}}$; salt lakes up to about 1250 $\mathrm{kg\,m^{-3}}$.

Table 32.1. Densities met in this practical.

Substance	Density ($\mathrm{kg\,m^{-3}}$)
Air, sea level, 15°C	1.225
Air, sea level, 30°C	1.164
Air at 300°C (in a flame plume)	0.62
Fresh water, 50°C/ 20°C/ 4°C/ 0°C	988.0 / 998.2 / 1000.0 / 999.8
Sea water	1020–1030
Ice	917

32.3 Why warming makes a fluid lighter

Heating makes molecules move faster and push further apart, so a parcel's volume grows while its mass stays the same: by (32.1) its density falls. Cooling does the opposite. For a gas this is the ideal gas law, which links pressure, density and temperature:

$$p = \rho R_d T \qquad \Longleftrightarrow \qquad \rho = \frac{p}{R_d T}. \tag{32.2}$$

where

p	pressure	Pa
R_d	gas constant for dry air	287 $\mathrm{J\,kg^{-1}\,K^{-1}}$
T	temperature	K

It contains three rules worth knowing by heart:

- at **constant volume**, pressure rises with temperature;
- at **constant temperature**, pressure rises with density (squeeze a gas and it pushes back harder);
- at **constant pressure**, density falls as temperature rises: warm air is light air.

Air density at two temperatures

At sea level, $p = 101\,325$ Pa. At 15°C ($T = 288.15$ K): $\rho = 101\,325/(287 \times 288.15) = 1.225$ $\mathrm{kg\,m^{-3}}$. At 30°C ($T = 303.15$ K): $\rho = 101\,325/(287 \times 303.15) = 1.165$ $\mathrm{kg\,m^{-3}}$, about 5 % lighter. At 300°C, inside a flame's plume: $\rho = 101\,325/(287 \times 573.15) = 0.616$ $\mathrm{kg\,m^{-3}}$, half the density of the room air: this is why the teabag rocket flies (§ 36.6).

Water behaves the same way above 4°C, but has a famous quirk: it is densest at about 4°C, and ice (917 $\mathrm{kg\,m^{-3}}$) floats. Figure 32.1 shows both fluids.

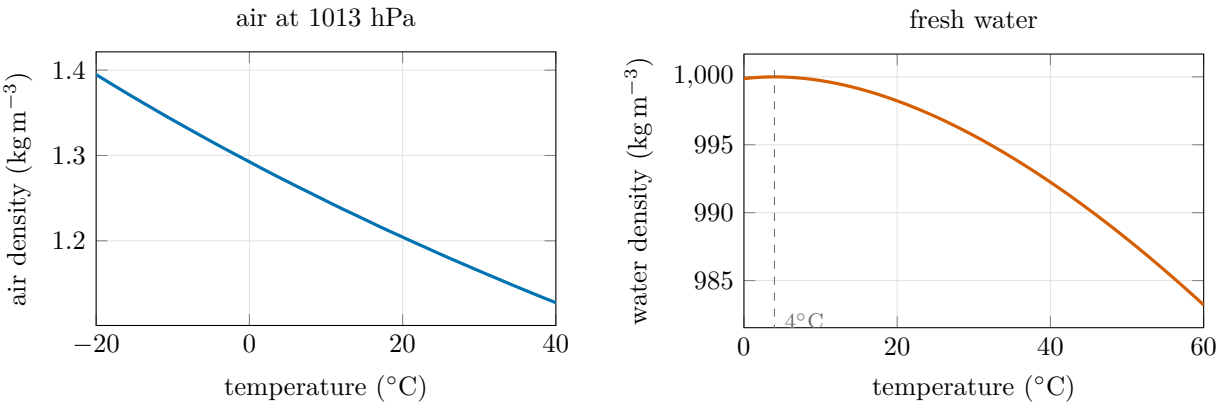


Figure 32.1. Density falls as temperature rises. Left: dry air at sea-level pressure, from the ideal gas law (32.2). Right: fresh water, from a standard empirical fit to measured densities (accurate to about 0.1 $\mathrm{kg\,m^{-3}}$ here); note the maximum near 4°C.

32.4 Stratification, mixing and fronts

When fluids of different density meet, the denser one slides underneath and the lighter one spreads over the top, until they lie in layers ordered by density: **stratification**. A stratified fluid resists vertical mixing, because lifting dense fluid or pushing light fluid down takes work.

In the atmosphere, density falls with height together with pressure, but temperature differences set up *horizontal* density differences too: warm and cold air masses. Where they meet, the colder, denser air wedges underneath and lifts the warmer air (*frontal wedging*). The lifted air expands and cools, and its moisture condenses into cloud and rain (Part III, Chapter 29). In an occlusion, a cold front catches up with a warm front and the warm air is lifted entirely off the ground. In the ocean the same physics, driven by temperature and salinity, sets the layering of the water column and the deep overturning circulation.

Does salt matter in the air?

No: salinity sets the density of sea water, but air has no salt in that sense. In air, density differences come from temperature and, to a smaller extent, humidity (moist air is slightly *lighter* than dry air at the same temperature and pressure, because water vapour molecules are lighter than nitrogen and oxygen). The divided-tank experiment uses salt because it gives a large, steady density difference that is easy to see; the principle carries over.

Chapter 33

Heat and temperature

33.1 Temperature is not heat

Temperature says how warm or cold something is relative to a standard. Physically it measures the average kinetic energy of the molecules' motion. On the Celsius scale water freezes at 0°C and boils at 100°C at sea-level pressure; the Kelvin scale starts at absolute zero, $T_{\mathrm{K}} = T_{^\circ\mathrm{C}} + 273.15$ (the triple point of water is 273.16 K, 0.01°C). Temperature is never measured directly: thermometers read its *effects*, the expansion of a liquid in a bulb thermometer or the change in electrical resistance of a thermistor.

Heat is energy *in transit* from a warmer body to a cooler one, measured in joules (1 calorie = 4.18 J; the food Calorie is 1000 calories). Heat always flows from higher to lower temperature, but that is not the same as from more to less energy: a cup of hot tea has the higher temperature, a cold lake far more internal energy, simply because it is so large. Energy is conserved: what one body loses, the other gains.

33.2 Heat capacity: why the ocean is the climate's flywheel

The **specific heat capacity** c is the heat needed to warm one kilogram by one degree. The heat to change a mass m by ΔT is

$$Q = m\,c\,\Delta T. \tag{33.1}$$

where

Q	heat	J
c	specific heat capacity	water 4186, air 1006 $\mathrm{J\,kg^{-1}\,^\circ C^{-1}}$
ΔT	temperature change	°C (or K: the same size of step)

Water's c is about four times air's. Per *volume* the difference is far larger, because water is about 800 times denser than air:

Heat to warm one cubic metre by 1°C

Water: $998 \times 4186 = 4.18 \times 10^6$ J. Air: $1.225 \times 1006 = 1.23 \times 10^3$ J. Ratio ≈ 3400. So it takes about 3400 times more heat to warm a cubic metre of water than a cubic metre of air by the same amount, and water releases that much more when it cools. (The handbook rounds this to "about 4000".)

Water also stores far more heat than rock or soil. So land warms and cools quickly, the ocean slowly: coastal places have milder days, nights and seasons than inland places; the ocean is a buffer that slows any change in the Earth's temperature; and by carrying warm water poleward (the Gulf Stream) it evens out the difference between equator and poles, which would otherwise be much larger.

33.3 Three ways heat moves

Radiation

Every object emits electromagnetic radiation and absorbs some of what falls on it. If it absorbs faster than it emits, it warms; if it emits faster, it cools; when the two balance it sits at its **equilibrium temperature**. A *black body* absorbs all radiation falling on it; it emits, per square metre and per second,

$$E = \sigma T^4, \qquad \sigma = 5.67 \times 10^{-8}\ \mathrm{W\,m^{-2}\,K^{-4}}, \tag{33.2}$$

so doubling the temperature (in kelvin) multiplies the emission by $2^4 = 16$. The wavelength of peak emission falls as temperature rises (Wien's law):

$$\lambda_{\max} = \frac{2898\ \mu\mathrm{m\,K}}{T}. \tag{33.3}$$

Three emitters

The Sun, about 6000 K: $\lambda_{\max} = 2898/6000 = 0.48\ \mu$m, visible light. A heat lamp's filament, about 2800 K: 1.0 μm, near infrared, felt as warmth. The Earth's surface, 288 K: 10 μm, thermal infrared. At 300 K a black body emits $5.67 \times 10^{-8} \times 300^4 = 459\ \mathrm{W\,m^{-2}}$.

This is the basis of the greenhouse effect: the atmosphere lets most of the short-wave sunlight through but absorbs much of the long-wave infrared the surface emits, and sends part of it back down. Part II works all of this in detail (Chapters 13, 14 and 17).

Conduction

Conduction passes heat between bodies in contact, molecule to molecule: fast-vibrating molecules of the warmer body jostle the slower ones of the cooler. The rate grows with the contact area, with the temperature difference across the material, and with the material's *thermal conductivity*: metals conduct well, wood, cloth and especially still air poorly.

Convection

Convection carries heat by moving the fluid itself, and happens only in liquids and gases. Warmed fluid becomes less dense and buoyant (Chapter 35), rises, and is replaced by cooler fluid, setting up a circulation. It is the main way heat moves in the atmosphere and ocean: from thermals and thunderstorms to the three-cell circulation of the globe.

33.4 Latent heat

Adding heat does one of two things: it raises the temperature, or it changes the state (solid to liquid, liquid to gas) *at constant temperature*. The heat for a change of state is the **latent heat**:

$$Q = m\,L, \qquad L_f = 334\ \mathrm{J\,g^{-1}}\ \text{(melting)}, \quad L_v = 2260\ \mathrm{J\,g^{-1}}\ \text{(evaporating at 100°C)}. \tag{33.4}$$

Going back (condensing, freezing) releases the same heat to the surroundings. Melting 1 g of ice takes as much heat as warming 1 g of water by $334/4.186 = 80$°C.

Latent heat in the climate system

- Water evaporating from the ocean carries latent heat into the atmosphere; it is released where the vapour condenses into cloud, warming the air. This powers thunderstorms and hurricanes, and is a main reason seas are rarely warmer than 28 to 30°C.
- In polar seas, freezing in winter releases heat and melting in summer absorbs it, so surface temperatures there change little through the year. Ice keeps a drink cold until it has all melted.
- Sweating cools us: evaporating water takes its latent heat from the skin. That is why you shiver leaving a pool on a hot day.

Does water have to boil to evaporate?

No. In a liquid, molecules move at a spread of speeds; the fastest can break free at any temperature, which is why puddles and towels dry. Because the fast ones leave, the average energy of those left behind falls: evaporation cools the liquid. Warming the liquid gives more molecules enough energy, so evaporation speeds up. Ice can even evaporate directly (sublimation).

33.5 Thermal expansion

Most substances expand when warmed and contract when cooled, because their molecules vibrate harder and sit further apart. It is why a heated gas fills more volume (and so is less dense), and in the ocean it is a major cause of sea-level rise: estimates put thermal expansion at roughly a quarter to a half of the observed rise, although decadal climate swings make its exact share hard to pin down.

Chapter 34

Pressure

34.1 Force over area

Pressure is a force pressing perpendicularly on a surface, divided by the area it acts on:

$$p = \frac{F}{A}. \tag{34.1}$$

where

p	pressure	Pa ($1\ \text{Pa} = 1\ \text{N}\,\text{m}^{-2} = 1\ \text{kg}\,\text{m}^{-1}\,\text{s}^{-2}$)
F	force	N
A	area	m^2

The same force on a smaller area gives a larger pressure: a sharp knife cuts where a blunt one squashes. Pressure itself has no direction; but when it differs from one side of an object to the other, the object feels a net force from high towards low pressure. That is why air moves from high to low pressure, and how a straw works.

At sea level the atmosphere presses with about 10^5 Pa ($1\ \text{atm} = 101\,325\ \text{Pa} = 1013.25\ \text{hPa}$). We are not crushed because the same pressure acts inside our bodies, so there is no net force. Our senses notice *changes* in pressure, in the air-filled cavities of the ears and sinuses, when we fly or dive.

34.2 Hydrostatic pressure

In a fluid at rest, the pressure at any level is the weight of the fluid above it, per unit area. For a layer of uniform density,

$$p = \rho\, g\, z. \tag{34.2}$$

where

ρ	density of the fluid	$\text{kg}\,\text{m}^{-3}$
g	gravitational acceleration	$9.81\ \text{m}\,\text{s}^{-2}$
z	height of the column above	m

Ten metres of sea water

$p = 1025 \times 9.81 \times 10 = 1.01 \times 10^5$ Pa: one extra atmosphere for every 10 m of depth. A diver at 30 m feels 4 atm: one from the air, three from the water.

In the air, density itself falls with height (air is compressible), so pressure does not fall in a straight line but *exponentially*: each step up of the same size removes the same *fraction* of the pressure,

$$p(z) = p_0\, e^{-z/H}, \qquad H = \frac{R_d\, T}{g}, \qquad z_{1/2} = H \ln 2. \tag{34.3}$$

The height at which pressure halves

With a mean temperature of 250 to 288 K, $H = 287 \times T/9.81$ is 7.3 to 8.4 km, so pressure halves every $0.693\,H = 5.1$ to 5.8 km. The handbook's "about 5.6 km" is in this range; Part I used the same rule (Chapter 7).

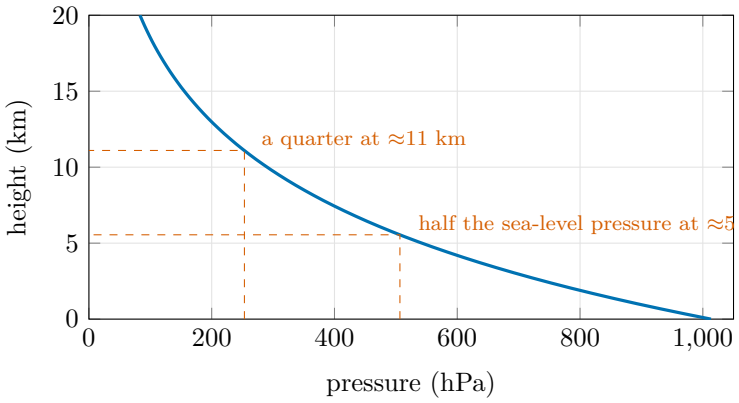


Figure 34.1. Pressure falls exponentially with height (34.3), drawn with $H = 8$ km: every 5.5 km or so it halves.

34.3 Pressure, density and wind

The hydrostatic equation explains why temperature differences make wind. Cold air is dense, so a column of cold air is shorter than a column of warm air holding the same mass. At a given height aloft, the pressure is therefore higher over the warm column than over the cold one: a horizontal pressure gradient that pushes air from the warm side towards the cold side aloft, and so sets up a circulation. Because the Earth rotates, the Coriolis effect turns the moving air to the right in the Northern Hemisphere (left in the Southern) until it flows nearly along the isobars rather than straight across them; near the equator, where the Coriolis effect is weak, winds blow more directly down the pressure gradient (Part III, Chapter 23).

Pressure patterns can shift on large scales: every three to eight years the usual high pressure over the eastern tropical Pacific and low over the western Pacific weaken or reverse (the Southern Oscillation). The trade winds slacken, warm water spreads east, and El Niño affects weather around the world.

34.4 Gases squeeze, water does not

Water is almost incompressible: at 4 km depth, under 400 atm, its volume shrinks by less than 2 %. A gas is very compressible. At constant temperature, the volume of a fixed amount of gas is inversely proportional to its pressure (Boyle's law):

$$p_1 V_1 = p_2 V_2. \tag{34.4}$$

Halve the pressure and the volume doubles; double it and the volume halves. This is why your ears hurt only a few metres down in a pool (the air in them is squeezed) while the rest of your body, mostly water, hardly notices.

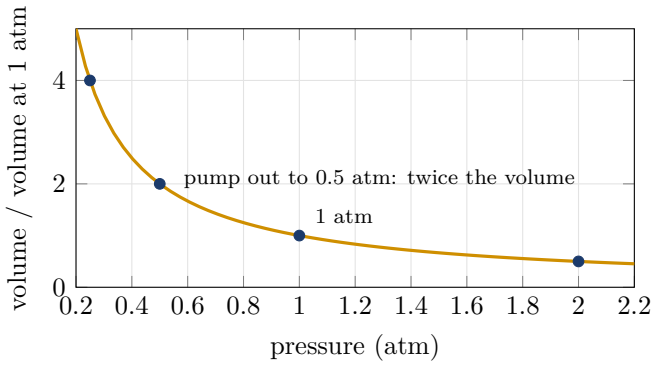


Figure 34.2. Boyle's law (34.4) for air at constant temperature. The balloon under vacuum (§ 37.1) and the Cartesian diver (§ 37.3) both follow this curve.

34.5 Expansion cools: the key to clouds

When a gas expands quickly, without time to exchange heat with its surroundings (*adiabatically*), it does work pushing outwards and so cools; compressed, it warms (a bicycle pump gets hot). For dry air,

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{R_d/c_p} = \left(\frac{p_2}{p_1}\right)^{0.286}. \tag{34.5}$$

Pumping a flask down to half pressure

$T_2 = 293 \times 0.5^{0.286} = 293 \times 0.820 = 240$ K: a fall of more than 50°C if no heat flowed in. In the flask the walls warm the air back within seconds, but the brief chill is enough to make a cloud if the air is moist and has particles to condense on (§ 37.1).

A rising air parcel meets lower pressure, expands and cools the same way, about 10°C per kilometre while it is dry (Part I, Chapter 8). When it cools to its dew point, cloud forms. Almost every cloud in the sky is made this way.

Chapter 35

Buoyancy

35.1 Archimedes' principle

An object put into a fluid pushes some of the fluid aside; fully submerged, it displaces its own volume. Two forces then act on it: its **weight** downwards, and an upward **buoyant force**. The buoyant force exists because pressure increases with depth (34.2): the fluid pushes harder on the bottom of the object than on its top. Its size is the weight of the displaced fluid (Archimedes' principle):

$$F_{\text{buoyancy}} = m_{\text{fluid}}\, g = \rho_{\text{fluid}}\, V_{\text{displaced}}\, g, \tag{35.1}$$

$$F_{\text{gravity}} = m_{\text{object}}\, g = \rho_{\text{object}}\, V_{\text{object}}\, g. \tag{35.2}$$

For a fully submerged object $V_{\text{displaced}} = V_{\text{object}}$, and the net downward force is

$$\Delta F = F_{\text{gravity}} - F_{\text{buoyancy}} = V_{\text{object}}\, g\, (\rho_{\text{object}} - \rho_{\text{fluid}}). \tag{35.3}$$

Sink, float or hover

$\Delta F > 0$: the object is denser than the fluid and **sinks**. $\Delta F < 0$: it is less dense and **rises** (and floats at the surface, displacing just its own weight). $\Delta F = 0$: equal densities, **neutral buoyancy**; it stays at whatever depth it is put. A steel ship floats because its hull, full of air, displaces more water than its own weight.

Why a balloon of hot air rises

A 1 m^3 bag of air at 60°C in a room at 20°C: from (32.2), $\rho_{\text{inside}} = 101\,325/(287 \times 333.15) = 1.060$ and $\rho_{\text{room}} = 101\,325/(287 \times 293.15) = 1.204\ \text{kg m}^{-3}$. Net upward force $= 1 \times 9.81 \times (1.204 - 1.060) = 1.41$ N, enough to lift about 144 g (less the weight of the bag).

35.2 Buoyancy in the atmosphere: stability

In the atmosphere the "object" and the "fluid" are both air: a parcel and the air around it. If the parcel is warmer, it is less dense (32.2) and buoyant; colder, it is denser and sinks back. Per unit mass, the buoyant acceleration is

$$a = g\,\frac{T_{\text{parcel}} - T_{\text{environment}}}{T_{\text{environment}}} \qquad (T \text{ in kelvin}). \tag{35.4}$$

A parcel slightly warmer than its surroundings

A parcel 3°C warmer than air at 290 K: $a = 9.81 \times 3/290 = 0.10\ \text{m s}^{-2}$, a gentle but steady push that can drive a thermal up at several metres per second.

Stability is buoyancy applied to a lifted parcel. Lift a parcel: it expands and cools (34.5). If it ends up colder (denser) than the surrounding air, it sinks back: the air is **stable**. If it ends up

warmer (less dense), it keeps rising: the air is **unstable**, and towering clouds and showers follow. Part I works this through with real soundings (Chapter 8). It is easier to see buoyancy with solids and liquids, which is why the experiments that follow use water.

Chapter 36

Session 1: heat, convection and density

Each activity below follows the same pattern: the set-up and steps from the handbook (EGM305 module team, n.d.), what to predict, the physics, worked answers to every question the handbook asks, what typically goes wrong, and where the same process works in the atmosphere.

36.1 Activity 1.1A: radiation

Set-up and steps

Materials: three cans of the same size, one black, one white and one shiny, each with a thermometer through a hole in its lid; a heat lamp.

1. If the same lamp shines on all three, will the temperatures inside be the same? Why or why not?
2. Record the starting temperatures.
3. Put the cans the same distance from the lamp, switch on and watch the thermometers. What do you see, and how do you explain it? How is heat being transferred?
4. If the lamp stays on for a very long time, will the temperature keep rising? By what mechanisms is heat transferred?
5. How do these principles apply to the absorption of radiation at the Earth's surface and the regulation of its temperature?

The physics. A surface absorbs the part of the incoming radiation it does not reflect. The fraction reflected is its *albedo*. A matt black surface absorbs most visible and near-infrared radiation; white paint reflects most visible light but absorbs much of the infrared; polished metal reflects most of everything. The lamp's filament, near 2800 K, peaks at about 1 μm (33.3), so much of its output is near infrared.

Answers

1. No: the cans receive the same radiation but absorb different amounts. Predict black warmest, then white, then shiny.

3. The black can's thermometer rises fastest, the shiny can's slowest. Heat reaches each can by *radiation*; through the metal wall by *conduction*; inside, the warmed air circulates by *convection* and heats the thermometer.

4. No. As a can warms it loses heat faster: it emits more radiation (σT^4), and conducts and convects more heat to the cooler room air. The temperature levels off at the *equilibrium temperature* where absorbed energy equals lost energy. The black can levels off highest.

5. The Earth does the same: dark ocean and forest absorb, snow, ice and cloud reflect, and the planet settles where absorbed sunlight equals emitted infrared (Chapter 17). Melting ice exposes darker ground or sea, which absorbs more and warms further: the ice–albedo feedback.

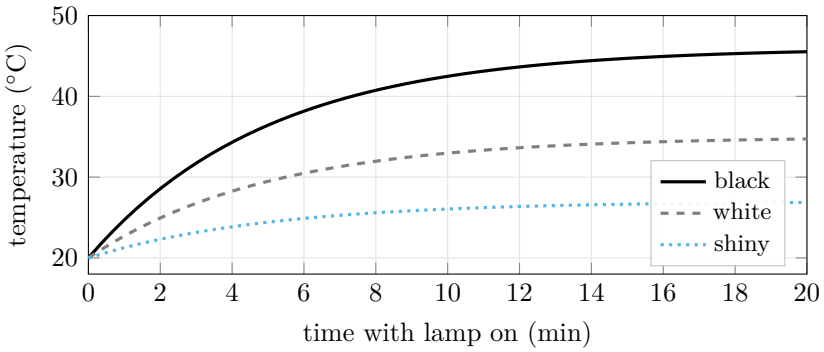


Figure 36.1. The expected shape of the three warming curves (illustrative numbers): each rises quickly at first, then levels off at its equilibrium temperature, highest for the black can.

What goes wrong

Cans at different distances from the lamp (the intensity falls with the square of the distance, so 10 % further means about 20 % less radiation); one can shading another; reading the thermometers from different angles. Keep the lamp at least 30 cm away and do not touch the hot cans.

36.2 Activity 1.1B: conduction

Set-up and steps

Materials: wood, metal and cloth, all at room temperature for some time.

1. Without touching them, predict their temperatures. Will they feel the same?
2. Touch each briefly. Does it match your expectation? Explain, given that all are at room temperature.
3. What does this reveal about how the nervous system senses temperature?
4. When and where does conduction matter in the atmosphere?

Answers

1. All three are at room temperature (say 21°C) because they have exchanged heat with the room for hours.
2. Yet the metal feels cold, the wood cool and the cloth warm. Your skin (about 33°C) is warmer than all three and loses heat to whatever it touches. Metal has a high thermal conductivity, so it carries heat away from your fingers quickly; wood and cloth conduct poorly, and cloth traps air, an excellent insulator.
3. Skin senses the *rate of heat flow*, not temperature. “Cold” means “heat leaving me fast”. Thermometers, not hands, measure temperature.
4. Air is a poor conductor, so conduction matters only in the few millimetres next to a surface: a sunny road heats the air touching it; on a clear night the ground, cooled by radiation, chills the lowest air until fog or frost forms. Above that thin layer, convection and turbulence move the heat.

36.3 Activity 1.1C: convection

Set-up and steps

Materials: the convection apparatus (a rectangular loop of glass tube), food colouring in two colours, a pipette, a spirit lamp, matches.

1. Sketch the set-up.
2. Fill it with water, with no bubbles in the horizontal tubes.
3. If the right column is warmed and the left cooled, which way will water flow through the horizontal tubes?
4. Put the spirit lamp under the right column; wait a minute or two; add a few drops of dye at the top. Does the flow agree with your prediction?
5. Move the lamp to the left side, wait a few minutes, and add the other colour.
6. What atmospheric processes does this demonstrate?

Answers

3. Water warmed on the right expands and becomes less dense (998 $\mathrm{kg\,m^{-3}}$ at 20°C, 988 at 50°C), so it rises; the cooler, denser water on the left sinks. So the flow runs *up* the right column, *right to left* along the top tube, *down* the left column and *left to right* along the bottom tube.
4. The dye is carried round the loop in that direction, slowly at first, faster as the temperature difference grows.
5. With the lamp on the left the loop slows, stops and reverses: the dye of the second colour circulates the other way.
6. A temperature difference makes a density difference, which drives a circulation: sea and land breezes, thunderstorm updrafts, the Hadley cell rising over the hot equator and sinking near 30°, and the ocean's overturning circulation.

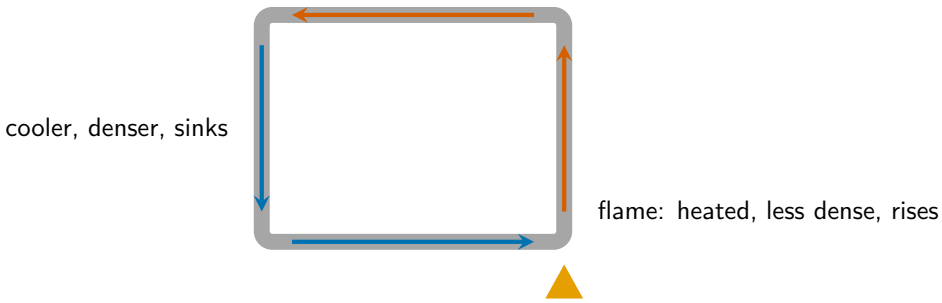


Figure 36.2. The circulation in the convection loop with the lamp under the right column. Moving the lamp to the left reverses every arrow.

36.4 Activity 1.2: heat flow and latent heat

Set-up and steps

Materials: a small plastic container with a lid (a hole for a thermometer) that fits inside nested polystyrene cups, marked so that the cup holds the same volume of water as the container; two digital thermometers; hot tap water, ice-cold water and ice.

1. Draw the set-up with arrows for the direction of heat flow if the container holds ice-cold water (no ice) and the cup hot water. What happens to each temperature?

2. Fill the container with ice-cold water; record its temperature; clamp it.
3. Fill the cup with hot water to the line; record its temperature.
4. Put the container in the cup. Record both temperatures every 30 s for 4 minutes, stirring gently.
5. Plot both against time. Does it agree with your prediction? What will the temperature difference be after a longer time?
6. Predict the result with 60 % ice and 40 % water in the container.
7. Fill the container that way; record its temperature.
8. Repeat steps 4 and 5. Do you see the same trend? Why or why not?

The physics. Heat flows from the hot water to the cold until their temperatures meet. With no losses, heat lost = heat gained (33.1):

$$m_h c\,(T_h - T_f) = m_c c\,(T_f - T_c) \quad \Longrightarrow \quad T_f = \frac{m_h T_h + m_c T_c}{m_h + m_c}, \tag{36.1}$$

which for equal masses is simply the average. The rate of heat flow is proportional to the temperature difference, so the two curves close in quickly at first and then ever more slowly (exponentially).

Run 1: cold water in hot water, 100 g each

$T_h = 50°\text{C}$, $T_c = 5°\text{C}$: $T_f = (50 + 5)/2 = 27.5°\text{C}$. Measured values usually end a degree or two lower, because the cup also loses heat to the room.

Run 2: ice and water in hot water

Container: 60 g ice and 40 g water at 0°C. Cup: 100 g water at 50°C.
Heat the cup can give while cooling to 0°C: $100 \times 4.186 \times 50 = 20\,930$ J.
Heat needed to melt all the ice (33.4): $60 \times 334 = 20\,040$ J.
So almost all of the cup's heat goes into melting. The container stays at 0°C while ice remains; once it is all melted, the remaining $20\,930 - 20\,040 = 890$ J warms all 200 g by $890/(200 \times 4.186) = 1.1°\text{C}$. Final temperature about 1°C, against 27.5°C in Run 1.

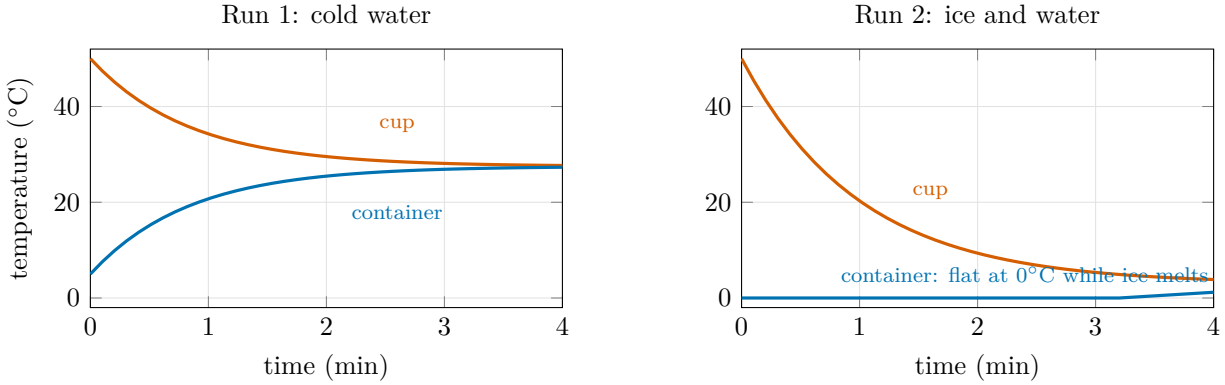


Figure 36.3. Expected curves (illustrative). Left: the two temperatures converge on the average. Right: the melting ice holds the container at 0°C, so the cup keeps cooling towards it and ends far colder than in Run 1.

Answers

1, 5. Heat flows from the cup into the container; the container warms and the cup cools until they meet near the average. After a long time the difference is zero, and both then cool slowly together to room temperature.
6, 8. No, not the same trend: the container's temperature stays flat at 0°C as long as there is ice, because the heat coming in melts ice (latent heat) instead of raising the temperature; the cup cools much further. This is why sea ice holds polar surface waters near freezing all summer, and why ice keeps a drink cold until it is gone.

What goes wrong

Unequal volumes (use the line on the cup); not stirring, so warm water floats on top and the thermometer misreads; letting the hot water stand while you set up, so it starts cooler than recorded. Plot both runs on the same axes to compare them.

36.5 Activity 1.3A: horizontal density differences

Set-up and steps

Materials: a rectangular tank with a removable divider, a bottle of salt solution, food colouring in two colours, ice, beakers, scales.

1. Fill a beaker with tap water.
2. Put tap water in one half of the tank and salt solution in the other, each with its own colour. Predict what happens when the divider is removed, and why.
3. Measure the densities of the tap water and the salt solution.
4. Remove the divider. What happens? Does it agree with your densities?
5. Empty the tank. Fill one beaker with hot tap water and one with ice-cold water, each coloured.
6. Put them in the two halves and repeat steps 3 to 5. After the divider is removed and the tank settles, put your fingertips on the surface and move slowly down. Can you feel the temperature change?
7. How might warming and melting sea ice change the vertical structure of the ocean?

Typical densities, measured as in Chapter 32

Tap water at 20°C: 99.8 g in 100 mL, 0.998 $\mathrm{g\,cm^{-3}}$. Salt solution: 102.5 g in 100 mL, 1.025 $\mathrm{g\,cm^{-3}}$. Hot water at 50°C: 0.988; ice-cold water at 2°C: 1.000 $\mathrm{g\,cm^{-3}}$.
The density difference in the hot–cold tank, $1.000 - 0.988 = 0.012\ \mathrm{g\,cm^{-3}}$, is less than half the salt–fresh difference (0.027): the hot–cold layering forms more gently, and mixes away as the temperatures even out.

Answers

2, 4. The denser salt water slides along the bottom under the fresh water as a wedge-shaped *gravity current*, and the fresh water spreads over the top in the opposite direction. The tank settles into two layers, the coloured salt water below.
6. The same happens with cold water (denser) below and hot water above. Moving your fingertips down you feel a fairly sharp change from warm to cold at the interface (the *thermocline* of the tank).
7. Warming makes surface water lighter, and melting ice adds fresh water, lighter still: both

strengthen stratification. A more stratified ocean mixes less: less heat and oxygen reach the deep water, fewer nutrients reach the surface, and the deep overturning can weaken.

In the atmosphere

A cold front is the tank in the open air: dense cold air undercuts warm air like the salt water, lifting it into cloud. At a warm front the lighter warm air rides up over the cold. Sea breezes and the cold winds that drain down valleys at night (katabatic winds) are density currents too. (Salinity layers water only; in air the density differences come from temperature and humidity.)

36.6 Activity 1.3B: the teabag rocket

Steps

Cut the stapled top off a teabag, tip out the tea, open the bag into a cylinder, stand it on a non-flammable surface and light the top. Watch how it responds. What forces are responsible? Draw a diagram.

Answer

The flame heats the air inside and above the cylinder to a few hundred degrees. That air is far less dense than the room air (about 0.6 against 1.2 $\mathrm{kg\,m^{-3}}$, § 33.3), so it rises as a buoyant plume, and room air is drawn in at the base to replace it. As the paper burns down, the remaining ash ring weighs only a few milligrams. When the upward drag of the rising hot air exceeds the ring's weight, it lifts off and floats up.
Diagram: on the ash ring, weight mg pointing down, and an upward force from the rising plume (drag) larger than it; around the ring, arrows of air flowing in at the bottom and up through the middle.

In the atmosphere

Thermals that gliders and birds ride, cumulus clouds that grow over heated ground, smoke and ash lofted by wildfires (pyrocumulus), and the rising branch of every convective circulation.

Take care

Light the teabag only on the mat, away from paper and hair; let the ash cool before clearing it.

Chapter 37

Session 2: pressure and buoyancy

37.1 Activity 2.1: expanding balloons

Set-up and steps

Materials: three distillation flasks with bungs, a vacuum pump, balloons, water, a marshmallow, a cherry tomato, matches.

1. Put a balloon filled with air into the first flask and one filled with water into the second (how will you do it?). Predict the effect of reduced pressure on each.
2. Pump the air out of the first flask. What happens to the balloon? Remove the vacuum tube to let air back in. What happens now?
3. Repeat with the water balloon. Does pressure affect the two balloons differently? Why?
4. What will happen to the marshmallow and the cherry tomato when the flask is evacuated?
5. Test your prediction.
6. Release the valve and watch the marshmallow. Explain.
7. What would happen to all four objects if you *increased* the pressure with a bicycle pump?
8. What happens to the temperature inside the air-filled balloon as the pressure around it rises or falls?
9. Use what you have learned to make a cloud in the flask. Which ingredients are needed?
10. Take the balloon out of the flask so the next group can struggle to get it in.

Getting a balloon into a flask. Push the deflated balloon in, keep its neck over the mouth, blow it up and tie it off inside; for the water balloon, fill it inside the flask from a tap or a funnel. Both then sit at room pressure.

The physics. Boyle's law (34.4): the air in the balloon keeps pV constant, so when the pressure around it falls it expands until its pressure again matches its surroundings (plus the small extra the stretched rubber adds). Water hardly compresses or expands at all.

How much does the air balloon grow?

A hand pump typically lowers the flask's pressure to about half an atmosphere. At constant temperature $V_2 = V_1\, p_1/p_2 = V_1 \times 1/0.5 = 2V_1$: the balloon tries to double its volume, a $2^{1/3} = 1.26$ times larger diameter. The rubber's tension holds it back somewhat, so it grows a little less.

Answers

1–3. The air balloon swells as the air is pumped out and shrinks back when air is let in. The water balloon does not change visibly: water is almost incompressible (§ 34.4).
4–6. The marshmallow is a foam of tiny air bubbles: it swells under vacuum. When air is let back in it shrinks, and usually ends up *smaller and wrinkled*, because the stretched bubble walls tore while expanded, so some bubbles cannot refill. The cherry tomato is mostly water: little change, perhaps a slight swelling of air pockets near the stalk.
7. With higher pressure everything with gas inside shrinks: the air balloon and the marshmallow are squeezed, while the water balloon and tomato barely change.

8. Expanding air does work and cools; compressed air warms (34.5). Pumped out quickly, the air in the flask cools noticeably for a moment before the glass warms it again.
9. A cloud needs three things: *moisture* (a little water in the flask to humidify the air), *condensation nuclei* (smoke from a blown-out match), and *cooling* (a sudden expansion: pump out quickly, or let a compressed flask release suddenly). The air cools below its dew point and a cloud appears; let the pressure back and the cloud evaporates.

In the atmosphere

A rising air parcel meets lower pressure, expands and cools, about 10°C per kilometre while unsaturated. When it reaches its dew point, cloud forms on the countless dust, salt and smoke particles in the air. Your ears "pop" in a climbing aircraft for the same reason the balloon swells: the air inside them is at a higher pressure than the air outside.

37.2 Activity 2.2: the Archimedes ball

Set-up and steps

Materials: the Archimedes ball (a hollow plastic sphere with a stopper), a 60 mL syringe, tubing, scales, calliper, a container of water and one of an "unknown liquid".

1. Imagine the ball is a submarine. Calculate how much water ballast makes it neutrally buoyant (only the stopper just above the surface). Hint: draw the forces on it.
2. Check your calculation: put the ball in water and draw in water with the syringe. Does the measured volume agree?
3. Put the submarine in the unknown liquid and draw in that liquid until it is neutrally buoyant. What does this say about the liquid's density compared with water's?

The calculation. Measure the ball's mass m on the scales and its diameter d with the calliper; its volume is $V = \frac{4}{3}\pi(d/2)^3$. Neutral buoyancy means weight equals buoyant force: the ball plus its ballast (volume V_b of the same liquid) has the mass of the liquid the whole ball displaces,

$$m + \rho V_b = \rho V \quad \Longrightarrow \quad V_b = V - \frac{m}{\rho} \quad \text{and} \quad \rho = \frac{m}{V - V_b}. \tag{37.1}$$

Worked example

Diameter $d = 7.00$ cm, so $r = 3.50$ cm and $V = \frac{4}{3}\pi(3.50)^3 = 179.6$ cm^3. Mass $m = 60.0$ g.
In water ($\rho = 0.998$ g cm^{-3}): $V_b = 179.6 - 60.0/0.998 = 179.6 - 60.1 = 119.5$ mL.
In the unknown liquid the ball needs $V_b = 125.0$ mL: $\rho = 60.0/(179.6 - 125.0) = 60.0/54.6 = 1.10$ g cm^{-3}, about 10 % denser than water (a strong salt or sugar solution).
Check: the measured ballast in water is usually a few millilitres *less* than calculated, because the stopper stays above the surface and so displaces nothing; subtract its volume from V for a closer match.

Answer to step 3

Read it from (37.1): $\rho = m/(V - V_b)$. The ball's mass m and volume V are fixed, so the *more* ballast it needs (V_b larger), the smaller the denominator and the *denser* the liquid. Needing more of the unknown liquid than of water (125.0 against 119.5 mL in the example) means the liquid is denser than water; needing less would mean it is lighter.

In the atmosphere

A parcel of air is neutrally buoyant when its density matches its surroundings: it neither rises nor sinks. Weather balloons and research floats are trimmed the same way, and submarines flood or blow their ballast tanks to sink or surface.

37.3 Activity 2.3: the Cartesian diver

Steps

Materials: a sealed plastic bottle full of tap water containing a pipette weighted with nuts or washers, with a bubble of air trapped in it.

1. Squeeze the bottle. Why does the half-closed pipette sink? Why does it rise when you let go? Think of the balloons.
2. Explain the diver's behaviour in terms of pressure and Archimedes' principle.

Answers

1. Squeezing raises the pressure everywhere in the water (water passes pressure on but barely compresses). The air bubble in the pipette is compressed (Boyle's law): its volume shrinks and water is pushed up into the pipette. Let go: the pressure falls, the bubble expands and pushes the water out.
2. The diver (glass or plastic, weights and air) displaces less water when its bubble shrinks, while its own mass gains the water that entered: its average density rises above the water's, $\Delta F > 0$ in (35.3), and it sinks. Released, its density falls below the water's and it rises. A carefully held squeeze balances the two, and the diver hovers: neutral buoyancy.

How hard must you squeeze?

Suppose the diver has 2.0 mL of air and just floats, displacing 0.05 mL more than it needs. It sinks once the bubble shrinks by 0.05 mL, to 1.95 mL: by Boyle's law the pressure must rise by a factor $2.0/1.95 = 1.026$, that is by 2.6 %, about 2.6 kPa, a firm squeeze.

In the atmosphere and ocean

The same link between pressure, volume and density decides whether air rises or sinks: atmospheric stability (§ 35.2). Fish adjust their swim bladders, and divers their buoyancy jackets, exactly like the diver's bubble.

Chapter 38

Putting Part IV together

38.1 All the answers in one table

Table 38.1. Every activity, its result and its explanation.

Activity	What you should see	Why
1.1A	black can warms fastest and levels off highest, then white, then shiny	absorption depends on albedo; warming stops at the equilibrium where absorbed = lost energy
1.1B	metal feels coldest, cloth warmest, though all are at room temperature	skin senses the rate of heat flow; metals conduct heat away fast
1.1C	dye rises over the flame, crosses the top, sinks on the cool side; reverses when the lamp moves	warm water is less dense and buoyant: convection
1.2 run 1	curves converge on the average temperature (about 27.5°C from 50 and 5°C)	heat lost = heat gained, $T_f = (m_h T_h + m_c T_c)/(m_h + m_c)$
1.2 run 2	container flat at 0°C while ice remains; ends near 1°C	melting absorbs 334 J g^{-1} without warming: latent heat
1.3A	salt (or cold) water slides under fresh (or hot) water; two layers	the denser fluid sinks beneath the lighter: stratification
1.3B	the teabag's ash lifts off and floats upward	hot air is half as dense as room air; its rising drag beats the ash's weight
2.1	air balloon and marshmallow swell under vacuum; water balloon and tomato do not; marshmallow ends wrinkled	Boyle's law: gases expand as pressure falls, water barely changes
2.1 cloud	a cloud appears on sudden expansion	expansion cools moist air with nuclei below its dew point
2.2	ballast for neutral buoyancy close to $V - m/\rho$ (119.5 mL in the example)	Archimedes: weight = weight of displaced fluid
2.3	diver sinks when squeezed, rises when released	squeezing compresses the bubble, raising the diver's density

38.2 Mistakes to avoid

- Using °C in σT^4, Wien's law, the ideal gas law or the parcel buoyancy formula: these need kelvin.
- Saying "heat" when you mean "temperature": temperature is a state, heat is energy moving because of a temperature difference.

- Thinking metal is colder than wood at the same room temperature: it only feels colder.
- Forgetting that the cup and the container must hold equal volumes in Activity 1.2, or not stirring.
- Calculating the Archimedes ballast with the ball's *mass* in place of its *volume*, or forgetting the stopper above the surface.
- Writing the prediction after the experiment. Predict first, then test; explain the difference.

38.3 Self-test

1. Air at 20°C and 101 325 Pa: what is its density? [1.204 $\mathrm{kg\,m^{-3}}$]
2. How many joules melt 25 g of ice at 0°C? [8350 J]
3. 200 g of water at 60°C is mixed with 100 g at 15°C. Final temperature? [45°C]
4. What extra pressure does a diver feel 25 m below the sea surface? [$\approx 2.5 \times 10^5$ Pa, 2.5 atm]
5. A balloon of 3.0 L at 1 atm is taken to 0.6 atm at the same temperature. New volume? [5.0 L]
6. A ball of volume 200 $\mathrm{cm^3}$ and mass 50 g: how much water ballast for neutral buoyancy? [$\approx$ 150 mL]
7. Why does a coastal town have milder winters than an inland one at the same latitude? [the ocean's large heat capacity]
8. An air parcel is 2°C colder than its surroundings at 280 K. Which way does it accelerate, and how fast? [down, 0.07 $\mathrm{m\,s^{-2}}$]

Appendix D

Part IV: formulas, constants, symbols and corrections

D.1 Formulas

Quantity	Formula	Equation
Density	$\rho = m/V$	(32.1)
Ideal gas law	$p = \rho R_d T$, so $\rho = p/(R_d T)$	(32.2)
Heat to change temperature	$Q = mc\Delta T$	(33.1)
Mixing two masses of water	$T_f = (m_h T_h + m_c T_c)/(m_h + m_c)$	(36.1)
Latent heat	$Q = mL$	(33.4)
Stefan–Boltzmann law	$E = \sigma T^4$	(33.2)
Wien's law	$\lambda_{\max} = 2898\ \mu\text{m K}/T$	(33.3)
Pressure	$p = F/A$	(34.1)
Hydrostatic pressure	$p = \rho g z$	(34.2)
Pressure with height	$p = p_0 e^{-z/H}$, $H = R_d T/g$, halving height $H \ln 2$	(34.3)
Boyle's law	$p_1 V_1 = p_2 V_2$	(34.4)
Adiabatic temperature change	$T_2/T_1 = (p_2/p_1)^{0.286}$	(34.5)
Buoyant force	$F_b = \rho_{\text{fluid}} V g$	(35.1)
Net force on a submerged object	$\Delta F = V g(\rho_{\text{object}} - \rho_{\text{fluid}})$	(35.3)
Parcel buoyancy	$a = g(T_p - T_e)/T_e$	(35.4)
Neutral ballast	$V_b = V - m/\rho$, $\rho = m/(V - V_b)$	(37.1)

D.2 Constants used in this part

Constant	Value	Symbol
Gas constant for dry air	$287\ \text{J kg}^{-1}\text{K}^{-1}$	R_d
Specific heat of water / air (constant pressure)	4186 / $1006\ \text{J kg}^{-1}\text{K}^{-1}$	c, c_p
Latent heat of fusion / vaporisation of water	334 / $2260\ \text{J g}^{-1}$	L_f, L_v
Gravitational acceleration	$9.81\ \text{m s}^{-2}$	g
Standard sea-level pressure	$101\,325\ \text{Pa} = 1\ \text{atm}$	p_0
Stefan–Boltzmann constant	$5.67 \times 10^{-8}\ \text{W m}^{-2}\ \text{K}^{-4}$	σ
Wien's constant	$2898\ \mu\text{m K}$	C
Kelvin offset	273.15	

Precise values and sources for the shared constants are in Appendix E.

D.3 Corrections and clarifications to the handbook

The handbook (EGM305 module team, n.d.) is sound; these points are worth knowing when you read it beside this part.

1. **Kelvin.** It gives $K =^{\circ}\mathrm{C} + 273.16$ and calls 0°C the "freezing (or triple) point". The conversion is +273.15; 273.16 K (0.01°C) is water's triple point. The 0.01 never matters at lab precision.
2. **Stefan–Boltzmann constant.** It gives 5.7×10^{-8}; the value is $5.670 \times 10^{-8}\ \mathrm{W\,m^{-2}\ K^{-4}}$.
3. **"About 4000 times".** Per volume, water needs about 3400 times more heat than air to warm by 1°C (4.18×10^{6} against $1.23 \times 10^{3}\ \mathrm{J\,m^{-3}\,K^{-1}}$, § 33.2); "thousands of times" is the safe statement.
4. **Latent heat of vaporisation.** 2260 $\mathrm{J\,g^{-1}}$ is the value at 100°C; at ocean-surface temperatures it is about 2450 $\mathrm{J\,g^{-1}}$, slightly larger.
5. **Pressure halving height.** "About 5.6 km" corresponds to a scale height of about 8 km; with the real, colder upper air the halving height is 5 to 6 km (§ 34.2).
6. **Activity 1.1C materials:** "Matched" should read "Matches".

D.4 Symbols

Symbol	Meaning	Unit
ρ	density	$\mathrm{kg\,m^{-3}}$
m, V	mass, volume	kg, $\mathrm{m^3}$
p, F, A	pressure, force, area	Pa, N, $\mathrm{m^2}$
T	temperature	K (or °C where stated)
Q, c, L	heat, specific heat capacity, latent heat	J, $\mathrm{J\,kg^{-1}\,K^{-1}}$, $\mathrm{J\,g^{-1}}$
E, $\lambda_{\max}$	emitted energy flux, peak wavelength	$\mathrm{W\,m^{-2}}$, μm
z, H	height or depth, scale height	m, km
g	gravitational acceleration	$\mathrm{m\,s^{-2}}$
V_b	ballast volume	mL
a	buoyant acceleration of a parcel	$\mathrm{m\,s^{-2}}$

Appendix E

Constants, units and conversions

E.1 Constants

Each part works with the rounded values below. The precise values are given for reference.

Table E.1. Constants used in the book.

Quantity	Value used	Precise value	Source	Part
Acceleration due to gravity g	$9.81\,\mathrm{m\,s^{-2}}$	$9.80665\,\mathrm{m\,s^{-2}}$ (standard)	NOAA et al. (1976)	I, III
Gas constant for dry air R_d	$287\,\mathrm{J\,kg^{-1}\,K^{-1}}$	$287.05\,\mathrm{J\,kg^{-1}\,K^{-1}}$	Wallace and Hobbs (2006)	I, III
Specific heat of dry air c_p	$1004\,\mathrm{J\,kg^{-1}\,K^{-1}}$	$1004\,\mathrm{J\,kg^{-1}\,K^{-1}}$	Wallace and Hobbs (2006)	I
Standard sea-level pressure	1000 hPa (Part I)	1013.25 hPa	NOAA et al. (1976)	I
Standard sea-level temperature	15 °C	288.15 K	NOAA et al. (1976)	I
Stefan–Boltzmann constant σ	$5.67 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$	5.670374×10^{-8}	Tiesinga et al. (2021)	II
Wien's constant C	$2898\,\mu\mathrm{m\,K}$	$2897.77\,\mu\mathrm{m\,K}$	Tiesinga et al. (2021)	II
Planck's constant h	–	$6.62607015 \times 10^{-34}\,\mathrm{J\,s}$ (exact)	Tiesinga et al. (2021)	II
Speed of light c	–	$2.99792458 \times 10^{8}\,\mathrm{m\,s^{-1}}$ (exact)	Tiesinga et al. (2021)	II
Boltzmann's constant k_B	–	$1.380649 \times 10^{-23}\,\mathrm{J\,K^{-1}}$ (exact)	Tiesinga et al. (2021)	II
Solar constant S	$1368\,\mathrm{W\,m^{-2}}$	$1361\,\mathrm{W\,m^{-2}}$	Kopp and Lean (2011)	II
Earth's axial tilt	23.5°	23.44°	Stull (2017)	II
Earth's rotation rate Ω	$7.292 \times 10^{-5}\,\mathrm{s^{-1}}$	$7.292 \times 10^{-5}\,\mathrm{s^{-1}}$	Holton and Hakim (2013)	III
Kelvin–Celsius offset	273.15 (273.16 in Part II)	273.15 (exact)	Tiesinga et al. (2021)	all

E.2 Units and conversions

Quantity	**Conversion**
Pressure	1 hPa = 1 mb = 100 Pa; 1 mmHg (torr) = 1.333 hPa
Temperature	$T_{\mathrm{K}} = T_{\circ\mathrm{C}} + 273.15$; $T_{\circ\mathrm{C}} = \frac{5}{9}\,(T_{\circ\mathrm{F}} - 32)$
Temperature difference	1 K = 1 °C = 1.8 °F
Wind speed	$1\ \mathrm{kt} = 0.514\ \mathrm{m\,s^{-1}} = 1.852\ \mathrm{km\,h^{-1}}$
Length	1 km = 1000 m; $1\ \mu\mathrm{m} = 10^{-6}$ m
Power per area	$\mathrm{W\,m^{-2}}$: watts per square metre

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