EGM305 Practical 4: density, heat, pressure and buoyancy

Lab card for Weeks 8 to 11, with step-by-step answers: carry this to the bench

Ahmad Ammar | built from the module's practicals handbook; the full version is Part IV of *The Atmosphere*

How the two sessions run

Two sessions, three experiments each, 30 to 45 minutes per experiment, in teams. Several experiments use water instead of air because it is easier to see; the physics is the same in both. For every experiment write in your lab book:

1. Aim, question or hypothesis	what you are testing, in one sentence
2. Materials and set-up	a labelled sketch (sketches beat words)
3. Method	the steps you actually did
4. Predictions	written *before* you test, with a reason
5. Observations and calculations	numbers with units, a table, a graph where asked
6. Conclusion and explanation	was the prediction right? which physics explains it?
7. Atmosphere or ocean example	where the same process works in the real world

Safety and etiquette

Lab coat buttoned, sensible shoes, long hair tied back, stand while working. Bags under the benches, aisles clear. Report every accident, however small. Spirit lamps, matches and the burning teabag: keep paper and hair away, use the non-flammable mat. Phones, laptops and tablets off and in your bag (using one means leaving the lab, marked absent). There are no spare parts: handle the vacuum flasks, thermometers and balls gently. Clean and return everything; wash your hands with soap at the end. Bring a lab book (squared paper helps), calculator, pencil, ruler, eraser, tea towel and lab coat.

Numbers you will need

Quantity	Value	Note
Density	$\rho = m/V$	$\mathrm{kg\,m^{-3}}$; $1\ \mathrm{g\,cm^{-3}} = 1000\ \mathrm{kg\,m^{-3}}$
Air at sea level, 15°C	$1.225\ \mathrm{kg\,m^{-3}}$	from $\rho = p/(R_d T)$, $R_d = 287\ \mathrm{J\,kg^{-1}\,K^{-1}}$
Fresh water, 20°C/ 4°C/ 50°C	998 / 1000 / 988 $\mathrm{kg\,m^{-3}}$	densest at 4°C
Sea water	1020 to 1030 $\mathrm{kg\,m^{-3}}$	salt adds mass
Specific heat, water / air	4186 / 1006 $\mathrm{J\,kg^{-1}\,°C^{-1}}$	heat to warm 1 kg by 1°C
Latent heat of fusion / vaporisation	334 / 2260 $\mathrm{J\,g^{-1}}$	melting / evaporating, at constant temperature
Kelvin	$T(\mathrm{K}) = T(°\mathrm{C}) + 273.15$	273.16 K is water's triple point
Stefan–Boltzmann	$E = \sigma T^4$, $\sigma = 5.67 \times 10^{-8}$ $\mathrm{W\,m^{-2}\,K^{-4}}$	double $T \rightarrow$ 16 times the energy
Wien	$\lambda_{\max} = 2898\ \mu\mathrm{m\,K}/T$	hotter $\rightarrow$ shorter peak wavelength
Pressure	$p = F/A$; $1\ \mathrm{Pa} = 1\ \mathrm{N\,m^{-2}}$	sea level $\approx 101\,325$ Pa $= 1$ atm
Hydrostatic	$p = \rho g z$, $g = 9.81\ \mathrm{m\,s^{-2}}$	10 m of sea water ≈ 1 atm
Boyle's law	$p_1 V_1 = p_2 V_2$ (fixed T)	halve the pressure, double the volume
Archimedes	$F_b = \rho_{\text{fluid}}\, V_{\text{displaced}}\, g$	sinks if $\rho_{\text{object}} > \rho_{\text{fluid}}$

Session 1, Activity 1.1A: radiation (black, white and shiny cans)

Set-up. Three equal cans (black, white, shiny), a thermometer through each lid, one heat lamp at the *same distance* from all three. Record the start temperatures, switch on, read every minute for about 10 minutes.

Predict before you switch on: will the three cans warm equally? Why?

The physics

A surface absorbs the share of incoming radiation it does not reflect. Black absorbs most, white reflects most visible light, shiny metal reflects most of everything. Every surface also *emits* according to $E = \sigma T^4$, so as a can warms it loses heat faster. The lamp's filament is near 2800 K, so by Wien's law its peak is at $2898/2800 \approx 1.0\ \mu$m, in the near infrared: you feel the warmth.

What you should see, and why

Black warms fastest, then white, then shiny. With the lamp left on, each can levels off at an **equilibrium temperature** where energy absorbed = energy lost (radiation, conduction into the air, convection around the

can). Heat reaches the can by radiation; inside the can it moves by conduction and convection of the air.

Answers, step by step

1. **Same lamp, same temperatures?** No. The lamp delivers the same energy to each can, but each surface absorbs a different share: black absorbs most, white reflects most visible light, shiny metal reflects most of everything.
2. **Start temperatures.** All three should read room temperature (about 20°C) and within 0.5°C of each other; if not, note the difference and compare *rises*, not readings.
3. **What you see.** Black rises fastest, white next, shiny slowest (for example after 10 min: black +12°C, white +7°C, shiny +4°C; use your own numbers). Transfer: lamp to can by **radiation**; can wall to air inside by **conduction**; air inside the can mixes by **convection**.
4. **Lamp on for a long time?** No, each can levels off. As it warms it loses heat faster (emission σT^4, plus conduction and convection to the room). When loss = absorbed gain, the temperature stops rising: **radiative equilibrium**. The black can levels off highest.
5. **The Earth.** Albedo sets how much sunlight is absorbed (snow and cloud reflect, ocean and forest absorb). Earth warms until the infrared it emits balances the sunlight it absorbs, just like the cans. Less ice → darker surface → more absorbed → more melting (ice–albedo feedback).

In the atmosphere

Albedo: snow and cloud reflect, forest and ocean absorb, which is why melting ice speeds warming (ice–albedo feedback). Earth reaches its own equilibrium the same way: absorbed sunlight = emitted infrared. Sun 6000 K peaks at 0.48 μm (visible); Earth 288 K at 10 μm (infrared), which greenhouse gases absorb.

Start temperatures; temperature every minute for each can (table); which levelled off first

Activity 1.1B: conduction (wood, metal, cloth)

Predict the temperature of each object (all have sat in the room for hours). Then touch each briefly.

The physics

All three are at room temperature. Your hand is warmer and loses heat to whatever it touches; skin senses the *rate* of heat flow, not temperature. Metal conducts heat away quickly (high thermal conductivity), so it feels cold; wood and cloth conduct poorly and trap air, so they feel warm.

What you should see, and why

Same temperature, different feel: metal coldest, cloth warmest. Our nerves measure heat flow, not temperature.

Answers, step by step

1. **Prediction.** All three are at room temperature, because they have been in the room for hours. Most people predict they will feel the same.
2. **Touch.** They do not feel the same: metal feels coldest, wood in between, cloth warmest. The reason is that your hand (about 33°C) is warmer than all three. Metal has a high thermal conductivity, so it draws heat from your skin fastest; cloth and wood conduct poorly and trap air.
3. **The nervous system.** Skin senses the *rate of heat flow* out of (or into) it, not temperature itself. So a feeling of cold is not a thermometer reading.
4. **Conduction in the atmosphere.** Air conducts very poorly, so conduction matters only in the few millimetres next to the ground. Hot ground heats the lowest air on sunny afternoons, and cold ground chills it on clear nights (frost, radiation fog). Above that layer, convection carries the heat.

In the atmosphere

Air is a poor conductor, so conduction matters only in the few millimetres next to the ground: hot surfaces warm the lowest air on sunny days, cold ground chills it on clear nights (radiation fog, frost). Above that thin

layer, convection takes over.

Predicted and felt order of warmth; your explanation

Activity 1.1C: convection loop

Set-up. Sketch the apparatus first. Fill with water, no bubbles in the horizontal tubes. Heat the right column with the spirit lamp, wait a minute or two, add dye at the top. Then move the lamp to the left and add the second colour.

Predict which way water flows through the horizontal tubes when the right side is warm.

The physics

Heated water expands, so it is less dense ($\approx 988\ \mathrm{kg\,m^{-3}}$ at 50°C against 998 at 20°C) and buoyant: it rises in the heated column, flows across the top, sinks in the cooler column and returns along the bottom. A density difference drives a circulation: that is convection.

What you should see, and why

The dye rises in the heated column, crosses at the top towards the cool side, sinks there and returns at the bottom. Moving the lamp reverses the loop.

Answers, step by step

1. **Sketch.** A rectangular loop of glass tube: two vertical columns joined by a top and a bottom horizontal tube. Mark the lamp under the right column and the dye entry at the top.
2. **Filling.** Fill slowly and tilt the loop to chase out bubbles: a bubble in a horizontal tube blocks the flow.
3. **Prediction (right warm, left cool).** Heated water expands and becomes less dense (988 against 998 $\mathrm{kg\,m^{-3}}$), so it rises in the right column. It then flows **right to left along the top** tube, sinks in the cool left column, and returns **left to right along the bottom**. The loop runs clockwise when viewed with the lamp on the right.
4. **Dye test.** The dye moves up the right column, across the top to the left, then down. If it does not, check for a bubble or wait longer for the column to warm.
5. **Lamp on the left.** The circulation slows, stops, and then reverses (anticlockwise). The second colour traces the new direction.
6. **Atmospheric processes.** Convection: the sea breeze (and land breeze at night), thunderstorm updrafts, the Hadley cell, and the ocean overturning circulation.

In the atmosphere

Sea breezes (warm land, rising air, cool sea air flowing in near the surface), thunderstorm updrafts, the Hadley cell (rising at the equator, sinking near 30°), and the ocean's overturning circulation.

Sketch with arrows for both runs

Activity 1.2: heat flow and latent heat

Set-up. A small plastic container (thermometer through the lid) sits inside nested polystyrene cups. Equal volumes of water in container and cup (use the line). Read both thermometers every 30 s for 4 minutes, stirring gently.

Run 1: ice-cold water (no ice) in the container, hot tap water in the cup. **Run 2:** container 60 % ice and 40 % water, hot water in the cup.

The physics

Heat flows from hot to cold until temperatures meet. With equal masses of water and no losses, the heat lost by the hot water equals the heat gained by the cold: $mc\,(T_h - T_f) = mc\,(T_f - T_c)$, so $T_f = (T_h + T_c)/2$. Melting ice absorbs latent heat (334 J per gram) *without warming*.

Worked numbers (100 mL each side)

Run 1: hot 50°C, cold 5°C $\Rightarrow T_f = (50+5)/2 = 27.5$°C. In practice a little lower (heat escapes).
Run 2: 60 g ice + 40 g water at 0°C; cup 100 g at 50°C. Heat the cup can give while cooling to 0°C: $100 \times 4.186 \times 50 = 20.9$ kJ. Heat to melt all the ice: $60 \times 334 = 20.0$ kJ. So nearly all the cup's heat goes into melting; the container **stays at about 0**°C while ice remains, and everything ends near $(20.9 - 20.0)\,\text{kJ}/(200 \times 4.186\ \text{J}\,^\circ\text{C}^{-1}) \approx 1$°C.

What you should see, and why

Run 1: two curves that converge on a middle temperature, quickly at first, then slowly (heat flow is proportional to the temperature difference). Run 2: the container's curve stays flat near 0°C until the ice is gone, while the cup cools much further than in Run 1.

Answers, step by step

1. **Arrows and prediction (Run 1).** Heat flows from the hot cup water *into* the cold container. The container warms and the cup cools until they meet near the middle: with equal masses, $T_f = (T_h + T_c)/2$, for example $(50+5)/2 = 27.5$°C.

2–4. **Measuring.** Record the start temperatures, then read both thermometers every 30 s for 4 min, so you have 9 readings each. Stir gently so each thermometer reads the average of its water.

5. **Graph and longer times.** The two curves converge, quickly at first and then more slowly, because the heat flow is proportional to the temperature difference. After a long time the difference tends to **zero**. Both curves then drift slowly to room temperature as heat leaks through the polystyrene.

6. **Prediction with 60 % ice.** The container stays near **0**°C while ice remains, because the heat goes into melting (latent heat, 334 $\text{J}\,\text{g}^{-1}$), not into warming. The cup cools further than in Run 1.

7. **Fill with ice.** The start reading is about 0°C.

8. **Repeat.** The trend is not the same. In numbers, the cup can give $100 \times 4.186 \times 50 = 20.9$ kJ, and melting 60 g of ice needs $60 \times 334 = 20.0$ kJ. So almost all the heat melts ice: the container line stays flat near 0°C, and both end near 1°C. The difference from Run 1 is latent heat.

In the atmosphere

Evaporation takes 2260 J per gram from the ocean and condensation in clouds gives it back to the air: latent heat powers thunderstorms and hurricanes. Melting sea ice holds polar sea temperatures near freezing all summer; ice keeps a drink cold until it has all melted. Water's high heat capacity (by volume about 3400 times that of air) keeps coastal climates mild.

Table: time, $T_{\text{container}}$, T_{cup}, both runs; plot both on one graph

Activity 1.3A: horizontal density differences (the divided tank)

Set-up. Tap water (one colour) on one side of the divider, salt solution (other colour) on the other. Measure each density: weigh an empty beaker, add a measured volume, weigh again, $\rho = m/V$. Predict, then lift the divider. Repeat with hot and ice-cold water.

The physics

The denser fluid slides under the lighter one and the lighter spreads over the top: a horizontal density difference becomes vertical layers (stratification). Salt water at 35 g per litre is about 1025 $\text{kg}\,\text{m}^{-3}$; hot (50°C) water 988; ice-cold (2°C) 1000.

Density from your measurements

Beaker 52.0 g empty, 154.5 g with 100 mL of salt solution: $\rho = (154.5 - 52.0)/100 = 1.025\ \text{g}\,\text{cm}^{-3} = 1025\ \text{kg}\,\text{m}^{-3}$.

What you should see, and why

The salt (or cold) water runs along the bottom as a wedge; the fresh (or hot) water rides over the top. Moving a fingertip down through the hot–cold case you feel the change at a sharp boundary.

Answers, step by step

1. **Beaker of tap water.** It is the reference fluid.
2. **Prediction.** The salt solution is denser. When the divider lifts it will slide underneath the fresh water as a wedge along the bottom, and the fresh water will spread over the top.
3. **Densities.** Use $\rho = (m_{\text{full}} - m_{\text{empty}})/V$. For example, tap water $(151.8 - 52.0)/100 = 0.998\ \text{g cm}^{-3}$, and salt $(154.5 - 52.0)/100 = 1.025\ \text{g cm}^{-3}$.
4. **Divider removed.** The salt colour runs along the bottom and the tap colour rides over it, ending in two layers. This agrees with the measured densities: the denser fluid goes underneath.

5–6. **Hot and cold.** The cold water (about $1000\ \text{kg m}^{-3}$) undercuts the hot water ($988\ \text{kg m}^{-3}$), giving hot on top and cold below. With a fingertip you feel a **sharp change** in temperature at the boundary (the thermocline).

7. **Warming and melting sea ice.** The surface water becomes warmer and fresher, so it is lighter. The ocean becomes **more stratified**, less mixing reaches deep water, and fewer nutrients come up from below.

In the atmosphere

Cold fronts: dense cold air undercuts warm air like the salt water; warm fronts: warm air rides up over cold air. Sea breezes and katabatic winds are density currents. In the ocean, melting ice and warming make the surface lighter, so stratification strengthens and less mixing reaches deep water. (Salt layering is an ocean effect; in air the density differences come from temperature and humidity.)

Masses, volumes and densities; sketch before and after lifting the divider

Activity 1.3B: vertical changes (the teabag rocket)

Method. Cut the stapled top off a teabag, empty the tea, open it into a cylinder, stand it on the mat and light the top. Watch, then draw the forces.

The physics

The flame heats the air inside and above the cylinder; hot air is less dense ($\rho = p/(R_d T)$: at 300°C air is half as dense as at 15°C), so a buoyant plume rises. As the bag burns down, the ash ring weighs only milligrams; when the upward drag of the rising hot air exceeds its weight, it lifts off.

What you should see, and why

The cylinder burns down quietly, then the ash lifts and floats upward. Forces on the ash: weight down, drag from the rising air up. Draw both arrows.

Answers, step by step

1. **What happens.** The cylinder burns down from the top, and when only an ash ring is left it lifts off and rises.
2. **Why.** The flame heats the air, and hot air is less dense ($\rho = p/(R_d T)$: about half as dense at 300°C as at 15°C), so it rises as a plume. The ash weighs only milligrams.
3. **Forces.** Draw the weight mg downwards and the drag of the rising hot air upwards. The ash lifts off when the drag is greater than the weight.
4. **In the atmosphere.** Thermals, convective clouds, and pyrocumulus over fires.

In the atmosphere

Thermals that gliders and birds ride, convective clouds over heated ground, smoke rising from fires (pyrocumulus), and the rise of warm air parcels in an unstable atmosphere.

Session 2, Activity 2.1: balloons, marshmallows and a cloud in a bottle

Set-up. Vacuum flask with bung and pump. Put an air balloon in one flask and a water balloon in another (how will you get them in?). Predict, pump out the air, then let air back in. Then a marshmallow and a cherry tomato.

The physics

Boyle's law: at fixed temperature pV is constant, so a gas expands when the pressure around it falls; liquids are almost incompressible. Halving the outside pressure (to about 50 kPa) lets the air balloon roughly double in volume (less, because the rubber pulls back). Fast expansion also *cools* a gas (it does work pushing outwards): dry air expanding from 100 to 50 kPa without heat exchange would cool from 293 K to $293 \times 0.5^{0.286} \approx 240$ K.

What you should see, and why

Air balloon: swells under vacuum, shrinks back when air returns. Water balloon: no visible change. Marshmallow (full of air bubbles): swells, then collapses and wrinkles smaller than before when air returns (stretched bubble walls tear). Tomato (mostly water): almost no change. With more pressure (a bike pump) the air-filled things shrink instead. The air inside the balloon cools as it expands and warms as it is compressed.

A cloud in a bottle

Three ingredients: **moisture** (a little water in the flask), **condensation nuclei** (smoke from a blown-out match), and **cooling by expansion** (pump out quickly, or compress then release suddenly). The air cools below its dew point and a cloud appears; let pressure back in and it vanishes.

Answers, step by step

1. **Getting the balloons in.** Put the balloon in deflated and inflate it through the neck of the flask, or push in a balloon that is already tied but small, before fitting the bung.
2. **Prediction.** When you pump the air out, the air balloon **swells**, because there is less pressure outside and pV is constant (Boyle). The water balloon **does not change**, because liquids barely compress.
3. **Air back in.** The air balloon shrinks back to its original size. The size of the change: halving the pressure to about 50 kPa roughly doubles the volume ($p_1V_1 = p_2V_2$), and the rubber holds it back a little.
4. **Marshmallow.** It swells, because its air bubbles expand. When air is let back in it collapses *smaller* and wrinkled, because the stretched bubble walls tore. **Tomato:** hardly any change, because it is mostly water.
5. **Temperature.** Fast expansion cools a gas, because the gas does work pushing outwards: $293 \times 0.5^{0.286} \approx 240$ K if the pressure halved with no heat exchange. Compression warms it.
6. **Cloud in a bottle.** You need moisture, nuclei (smoke) and fast expansion. The air cools below its dew point and a cloud forms; when the pressure goes back up the cloud evaporates.

In the atmosphere

A rising air parcel meets lower pressure, expands and cools (about 10°C per km when dry): this adiabatic cooling makes almost every cloud. Ears pop in aircraft for the same reason as the balloon swells. Remove the balloon for the next group.

Predictions and observations for air balloon, water balloon, marshmallow, tomato

Activity 2.2: the Archimedes ball (a submarine)

Aim. Calculate how much water ballast makes the ball neutrally buoyant (stopper just at the surface); test it; then use it to find the density of an unknown liquid.

The physics

Neutral buoyancy: weight = buoyant force, so total mass = mass of displaced fluid. With ball mass m, volume V (from the calliper: $V = \frac{4}{3}\pi r^3$) and ballast drawn from the same liquid, $m + \rho V_b = \rho V$, so

$$V_b = V - \frac{m}{\rho} \qquad \text{and, rearranged,} \qquad \rho = \frac{m}{V - V_b}.$$

Worked example

Diameter 7.00 cm $\Rightarrow r = 3.50$ cm, $V = \frac{4}{3}\pi(3.50)^3 = 179.6$ cm^3. Mass 60.0 g. In water ($\rho = 0.998$ g cm^{-3}): $V_b = 179.6 - 60.0/0.998 = 119.5$ mL of ballast. In an unknown liquid the ball needs $V_b = 125.0$ mL: $\rho = 60.0/(179.6 - 125.0) = 1.10$ g cm^{-3}.

What you should see, and why

The measured ballast is close to the calculation, a little less because the stopper stays above the surface. If the unknown liquid needs *more* ballast than water, it is *denser* than water (salt solution, for example).

Answers, step by step

1. **Volume.** Measure the diameter with the calliper, halve it to get r, then $V = \frac{4}{3}\pi r^3$. For example, 7.00 cm gives 179.6 cm^3.
2. **Mass.** Weigh the empty ball with its stopper, for example 60.0 g.
3. **Ballast in water.** $V_b = V - m/\rho = 179.6 - 60.0/0.998 = 119.5$ mL.
4. **Test.** Add the ballast with the syringe. The ball should float with the stopper just at the surface. The measured value is usually a little *less* than calculated, because the stopper stays out of the water.
5. **Unknown liquid.** Find the ballast that makes the ball neutral, for example 125.0 mL. Then $\rho = m/(V - V_b) = 60.0/(179.6 - 125.0) = 1.10$ g cm^{-3}. More ballast than in water means a denser liquid.

In the atmosphere

An air parcel is neutrally buoyant when it has the same density as its surroundings: it neither rises nor sinks. Weather balloons and submarines are trimmed the same way.

Diameter, V, mass, predicted and measured ballast (water, unknown liquid), ρ of the unknown

Activity 2.3: the Cartesian diver

Method. Squeeze the sealed bottle and watch the weighted pipette; release.

The physics

Squeezing raises the pressure throughout the water (water itself barely compresses). The air bubble trapped in the pipette is compressed (Boyle's law), water is pushed in, the diver's average density rises above the water's and it sinks. Release: the bubble expands, pushes water out, the diver becomes less dense and rises (Archimedes).

What you should see, and why

Squeeze: the water level inside the pipette rises and the diver sinks. Release: it rises. A gentle squeeze can hold it hovering (neutral buoyancy).

Answers, step by step

1. **Squeeze.** The pressure rises everywhere in the water. The air bubble in the pipette shrinks (Boyle), so water enters the pipette. The diver becomes heavier for the same outer volume, so it is denser than the water and **sinks**.
2. **Release.** The bubble expands and pushes water out, so the diver's density falls below the water's and it **rises**.
3. **Hover.** With just the right squeeze, its density equals the water's: neutral buoyancy.
4. **Force diagram.** Draw the weight down and the buoyant force $\rho_w V g$ up. Squeezing increases the weight (more water inside) while the outer volume stays the same.
5. **In the atmosphere.** A parcel's density compared with its surroundings decides whether it rises or sinks: this is stability. A fish's swim bladder works the same way.

In the atmosphere

The same link between pressure, volume and density decides whether an air parcel rises or sinks: atmospheric stability. Fish swim bladders and divers' buoyancy jackets work like the pipette.

What you saw at the pipette's water level; explanation with a force diagram

Putting the four ideas together

Density	warmer → expands → less dense; salt or cold → denser; dense fluid slides underneath (1.1C, 1.3)
Heat	flows hot to cold by radiation, conduction and convection; latent heat changes state without changing temperature (1.1, 1.2)
Pressure	force per area; falls with height; gases compress, water barely does (2.1, 2.3)
Buoyancy	less dense than the surroundings → rises; denser → sinks; equal → neutral (1.3B, 2.2, 2.3)
Atmosphere	warm air rises, expands, cools and makes clouds; cold dense air undercuts warm air at fronts

Based on the EGM305 Weeks 8–11 practicals handbook (Ulster University), after Karp-Boss et al. (2009), Teaching Physical Concepts in Oceanography, The Oceanography Society, and Ahrens (2009), Meteorology Today, 9th edition, Brooks/Cole. Worked numbers are illustrative: use your own measurements.