

How Fast Does a Plume Rise? Convection Speed and Earth's Layers

Learning target: I can calculate convection speed from a teaching dataset, graph how it depends on the temperature difference, and use real layer thicknesses to see why mantle convection takes millions of years.

Data and graphing About 45 min Individual MS-ESS2-1 · practice data analysis independent practice

Standards connections

MS-ESS2-1 (practice, the flow-of-energy half of the PE): Students quantify the link between a temperature difference and the speed of convection, then scale that idea to the mantle. This gives their energy-flow model a quantitative basis without producing the model itself.

Purpose: practice · **Time:** about 45 minutes · **Format:** individual

Answers with reasoning

Part A: A plume in a tank

Imagine a tall, clear tank of still water 30 cm deep with a small electric warming plate under the center of its base. A thermometer sits on the plate and another sits just under the water surface. The operator sets the plate so that the water at the plate is warmer than the water at the top by a chosen number of degrees, waits two minutes, then releases a drop of dye at the plate and times how long the dye plume takes to rise 20 cm. Each setting was run twice. With the plate switched off (no temperature difference), the dye just spread out slowly on the bottom and no plume formed in 120 seconds.

Time for a dye plume to rise 20 cm (teaching dataset)

Simulated teaching dataset: the numbers are invented to be realistic, not measured.

Temperature difference, plate minus top water (°C)	Trial 1 time (s)	Trial 2 time (s)
0	no plume in 120 s	no plume in 120 s
2	47	49
4	31	33
6	24	26
8	20	22
10	17	19

Simulated data for teaching: realistic for a small water tank, but not measured in a real laboratory.

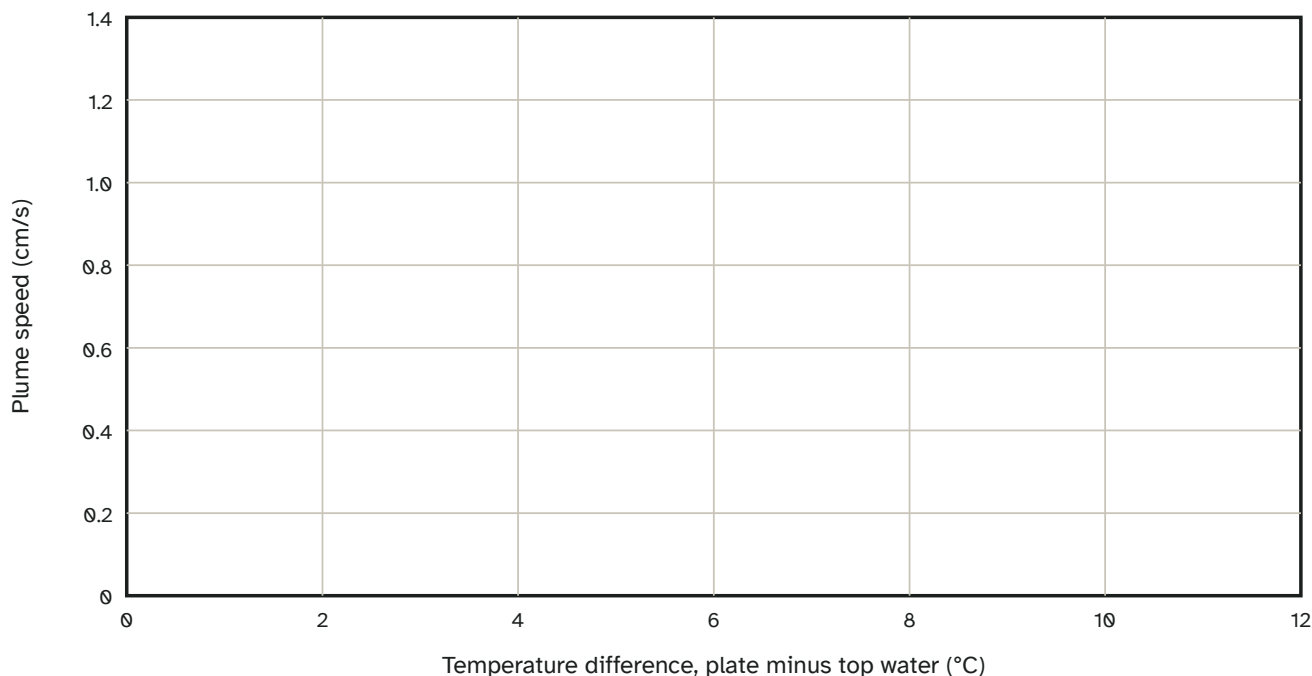
1. Complete the table. Average the two trials, then divide the 20 cm distance by the average time to get the plume speed. Write one full calculation below the table.

Answer: 2 °C: $(47 + 49) \div 2 = 48$ s; $20 \text{ cm} \div 48 \text{ s} = 0.42 \text{ cm/s}$. 4 °C: 32 s; $20 \div 32 = 0.63 \text{ cm/s}$. 6 °C: 25 s; $20 \div 25 = 0.80 \text{ cm/s}$. 8 °C: 21 s; $20 \div 21 = 0.95 \text{ cm/s}$. 10 °C: 18 s; $20 \div 18 = 1.11 \text{ cm/s}$.

Why: Average the two trials, then divide the fixed 20 cm by that average. Rounding to two decimals gives 0.42, 0.63, 0.80, 0.95 and 1.11.

Also acceptable: Accept 0.41 or 0.42 for 2 °C and 0.62 or 0.63 for 4 °C depending on rounding; accept 1.1 for 10 °C.

Plume speed versus temperature difference



2. Describe the shape of your graph in two sentences: what happens to plume speed as the temperature difference grows, and does each extra 2 °C add the same amount of speed, more, or less?

Answer: Speed rises as the temperature difference grows, and the graph rises steeply at first and then more gently. Each extra 2 °C adds a little less speed than the one before (the jumps are about 0.21, 0.17, 0.15 and 0.16 cm/s), so the curve bends over slightly rather than being a straight line.

Why: The pattern is 'more difference, faster flow, with diminishing returns.' A student who calls it roughly straight after 4 °C is reading reasonably; the key point is that speed keeps rising.

Also acceptable: Accept 'nearly a straight line that flattens a bit' with the jumps cited.

- Speed increases with temperature difference
- Notes that the increase per 2 °C shrinks (or that the curve bends)

3. The temperature difference at 10 °C is five times the difference at 2 °C. Calculate how many times faster the plume is at 10 °C than at 2 °C. Is speed growing as fast as the temperature difference?

Answer: $1.11 \text{ cm/s} \div 0.42 \text{ cm/s} \approx 2.6$ times faster. No: the temperature difference grew 5 times, but the speed grew only about 2.6 times, so speed grows more slowly than the difference.

Why: Ratio of the two speeds from q1; the comparison with 5 confirms the bending curve in q2.

Also acceptable: Accept 2.5 to 2.7 depending on rounding.

4. Explain why no plume formed with the plate switched off. Use the word density in your answer.

Answer: With the plate off, the water at the bottom and the top had the same temperature, so there was no density difference. Gravity pulled on every part of the water equally, nothing was denser than its neighbors, so nothing sank and nothing was pushed up. Convection needs a density difference, and a density difference here needs a temperature difference.

Why: The 0 °C row is the control that shows temperature difference, not the dye, is what drives the plume.

Also acceptable: Accept 'the dye was no lighter than the water around it.'

- No temperature difference means no density difference
- Without a density difference gravity cannot sort the water, so no flow

5. Extend your curve to predict the plume speed at a 12 °C difference. Give a value with units and say whether you trust it more or less than the measured points, and why.

Answer: About 1.2 cm/s (accept 1.15 to 1.30 cm/s). It deserves less trust than the measured points because it is an extrapolation beyond the data; the curve might keep flattening, and at larger differences the flow could become turbulent and behave differently.

Why: Extending the trend of 0.95 to 1.11 by one more step of about 0.15 gives roughly 1.25; the exact value depends on the student's curve.

Also acceptable: Any value in the stated range with a reason for lower trust earns full credit.

6. What does this dataset suggest about convection in the ocean or the mantle: what should happen to the speed of a convection loop if the difference between the warm end and the cool end gets bigger? Then name one important way the tank is **not** like the mantle that limits how far you should trust the comparison.

Answer: Model response: The data suggest that a bigger temperature difference between the warm end and the cool end makes convection faster, so an ocean region or mantle with a larger difference should circulate faster, though not in direct proportion. A key limit: the tank holds liquid water, while the mantle is solid rock that creeps only centimeters per year, so the speeds and times in the tank say nothing about the mantle's speeds. Other valid limits: the mantle's heat comes in from a hot core over a huge area, not a small plate; the mantle is thousands of kilometers deep; the tank has no gravity differences or pressure changes to match Earth's.

Why: Full credit requires the general claim (bigger difference, faster loop) and at least one specific, accurate limitation of the tank as a model.

Also acceptable: A student who adds that the ocean's density also depends on salt, which the tank cannot show, has given a valid extra limit.

- Claim: larger temperature difference, faster convection
- Notes the relationship is not proportional
- One accurate difference between tank and mantle

Part B: Scaling up to the geosphere

The thicknesses below are the rounded model values used in this lesson for the geosphere's three main layers. Together they add up to the distance from the surface to Earth's center, about 6,370 km.

Thickness of the geosphere's layers (rounded reference values)

Layer	Thickness (km)
Crust (continental average)	35
Mantle	2865
Core (top of the core to Earth's center)	3470
Total: surface to center	6370

7. Complete the table to find what percent of the distance from the surface to the center each layer takes up. Check that your three percentages add up to about 100.

Answer: Crust: $35 \div 6,370 = 0.0055$, about 0.5% (0.55%). Mantle: $2,865 \div 6,370 = 0.450$, about 45.0%. Core: $3,470 \div 6,370 = 0.545$, about 54.5%. Sum: $0.5 + 45.0 + 54.5 = 100.0\%$.
Why: Each thickness divided by the total, times 100. Students are often surprised that the crust is about half of one percent.
Also acceptable: Accept 0.5% or 0.6% for the crust depending on rounding; accept 45% and 54% or 55% for the others if the sum is near 100.

8. Mantle rock creeps at roughly 3 cm per year. Calculate how many years it would take rock to travel the full 2,865 km thickness of the mantle at that speed. Convert kilometers to centimeters first (1 km = 100,000 cm). Give your answer in millions of years.

Answer: $2,865 \text{ km} \times 100,000 \text{ cm/km} = 286,500,000 \text{ cm}$. $286,500,000 \text{ cm} \div 3 \text{ cm/year} = 95,500,000 \text{ years}$, about 96 million years (roughly 100 million years).
Why: Unit conversion then division; the centimeters cancel and leave years. The 3 cm per year figure is a realistic order of magnitude for mantle flow and plate motion.
Also acceptable: Accept 95 to 96 million years; accept 'about 100 million years' if the work is shown.

9. In the tank, the plume crossed 20 cm in about 20 seconds. Compare that with your answer to q8. Explain why a tank model can show the **pattern** of mantle convection correctly while giving a completely misleading idea of its **speed**.

Answer: The tank plume took about 20 seconds to cross 20 cm; the mantle takes on the order of 100 million years to cross 2,865 km. The tank shows the pattern correctly because the same rule works in both: warm, less dense material rises while cool, denser material sinks under gravity. But the tank uses a liquid that flows easily over a short distance, so its time scale is wrong by an enormous factor. A model can copy the cause and the shape of a process without copying its speed or size, and anyone using the model has to say which parts are meant to match.

Why: This is the model-limitation idea the lesson develops around Biosphere 2 and the tank: models are selective copies.

Also acceptable: Accept 'the tank gets the why right but the how long wrong.'

- Compares the two time scales with numbers
- Explains that the mechanism (density and gravity) is shared
- Explains that the material and distance make the speed completely different

Teacher notes

Part A is simulated. The speeds (0.4 to 1.1 cm/s for differences of 2 to 10 °C) are plausible for a small heated water tank, and the diminishing-returns shape is realistic, but no student should treat these as measured results; Lab 1 produces real observations in a safe warm-water setup. Part B uses the lesson's rounded thicknesses (35 + 2,865 + 3,470 = 6,370 km). Percentages: crust 0.55%, mantle 44.98%, core 54.47%. For q8, $286,500,000 \div 3 = 95,500,000$ years. The 3 cm per year creep rate is a realistic order of magnitude (plate speeds run from about 2 to 10 cm per year); if students ask how it is measured, say satellites can track continents moving a few centimeters each year. Expect unit slips in q8; the scaffold's cancel-the-units routine catches most of them.

Scaffold offered to students: Keeping the units straight

Speed is distance divided by time, so $\text{cm} \div \text{s}$ gives cm/s. In q8 the distance is in kilometers and the speed is in centimeters per year, so convert the distance first: multiply the kilometers by 100,000 to get centimeters. Then divide centimeters by centimeters-per-year; the centimeters cancel and years are left. Write each unit next to each number as you go, and cross out the units that cancel.

Extension: Halve the distance, halve the time?

Suppose the operator repeats the 6 °C run but times the plume over only the first 10 cm and then over the second 10 cm separately. Predict whether the two times would be equal, and explain why a plume might speed up or slow down as it rises (think about what happens to its temperature and density as it moves away from the plate and mixes with cooler water). Then design one more measurement that would test your prediction.