

Why do clouds tend to form in the afternoon?

A laboratory experiment from the Little Shop of Physics at Colorado State University



Overview

In Colorado, the days usually dawn sunny and clear. But later in the day, clouds often form

You've seen this. And you likely know that clouds form when parcels of air are rising. Why does the air stay put until later in the day, and then start rising?

Theory

Air rises for a simple reason: It warms up. And warm air rises. But there is more to the story.

When the sun rises, it warms the earth. So air near the earth's surface will warm. But it won't go anywhere just yet; we say that the air is *stable*.

Imagine that you did "nudge" a parcel of air, and move it upward. As this rising parcel of air moves upward, it expands. And as it expands, it cools. (The air has to do work to expand, and so its temperature must decrease—the only possible source of energy for the work of the expansion is the thermal energy of the gas. For the large air masses that move in the atmosphere, this is an adiabatic expansion—no thermal energy is transferred from adjacent air.)



How many cases can you stack? Anyone can do 6, but no one can do 10. Try it!

Necessary materials:

- 2" PVC pipe cap
- CD cases (with CDs or not)

The pipe cap is the crucial piece; you can find these at any hardware store. You can use different sizes; they will just require more or fewer cases to make a transition to instability. A 2" cap needs 8 cases. Smaller caps need fewer, larger caps more.

A rising parcel of dry air will cool by about 10°C for each 1000 m that it rises. This is called the *dry adiabatic lapse rate*. So the parcel of air the we "nudge" upward will cool.

Now, suppose you measure how the temperature varies with altitude in the atmosphere. A measurement of the actual change in temperature with height in the atmosphere is the *environmental lapse rate*. This can vary, but a typical value, for the "standard atmosphere" is 6.5°C of cooling for a 1000 m rise in elevation.

This means that a parcel of air that we nudge upward will be cooler than the air it meets—it cools off by 10°C for every 1000 m it rises, but the air only cools off by 6.5°C . This means that the atmosphere will be sta-

ble. The parcel we nudged upward will cool off, be cooler than the air surrounding it, and then fall.

Now suppose you warm up the air near the earth so that the temperature falls more quickly with height. Suppose the temperature drops by 12°C for every 1000 m. Then the air parcel we nudge upward will cool less than the air around it. The air will be warmer than the air around it, so it will keep on rising. A small nudge turns into a runaway rise—the air is unstable!

As the day heats up, this is exactly what happens. The temperature profile changes until the atmosphere becomes unstable, and air masses start to rise, forming clouds as they go.

The actual story is a bit more complicated, but the key element is the transition from stable to unstable. And that's something we can demonstrate in a very nice way with a mechanical system. The end of a 2" PVC pipe cap (a plumbing part) is a section of a sphere with a 3" diameter. If you place a block (or a stack of CDs) that is less than 3" tall on the end of the cap, it is stable; a small nudge will just make it rock, but it will stay put. Anything more than 3" tall is unstable. No matter how hard you try, a stray vibration will cause it to tip, and it won't rock back. The small nudge will grow until it falls off. The transition from stable to unstable occurs at about 8 CDs. (The transition might not be at exactly 3" because the cases can flex a small amount.) Anyone can stack 6 CDs, but no one can stack 10. Try it and see!

Doing the Experiment

Students enjoy this activity as they can have a friendly competition with friends to see who can stack the most CD cases on the cap. Of course, if they each do this carefully, they'll all tie! When they reach a certain number of cases, it is just impossible to stack any more. Here's how it goes:

- Place the PVC cap on a level surface with the rounded side up.
- Take one CD case and carefully balance it horizontally on the rounded top of the cap.
- Give the case a little push with your finger on one of the edges. It should rock a bit, but not fall. This means it's stable.
- Now, add a second CD case. Is it still stable?
- Try stacking more CD cases, giving the stack a nudge each time to test its stability.
- At some point it will be impossible to add any more cases—the stack will be unstable. At this point, any nudge, any little wiggle, will grow. You simply can't balance the stack, no matter how hard you try.
- Have students compare their results with others in the class.

After doing the experiment, discuss the transition between stable and unstable with your students.

Summing Up

This experiment is largely qualitative, but it does make a key point about the transition between stable and unstable situations. There's a tipping point where the behavior changes. And we see the same thing in the atmosphere, which is why a clear day may suddenly give rise to the formation of towering stacks of cumulus clouds!

For More Information

CMMAP, the Center for Multi-Scale Modeling of Atmospheric Processes: <http://cmmap.colostate.edu>

Little Shop of Physics: <http://littleshop.physics.colostate.edu>