How do Tornadoes Work? An Introduction to Experimental Fluid Dynamics

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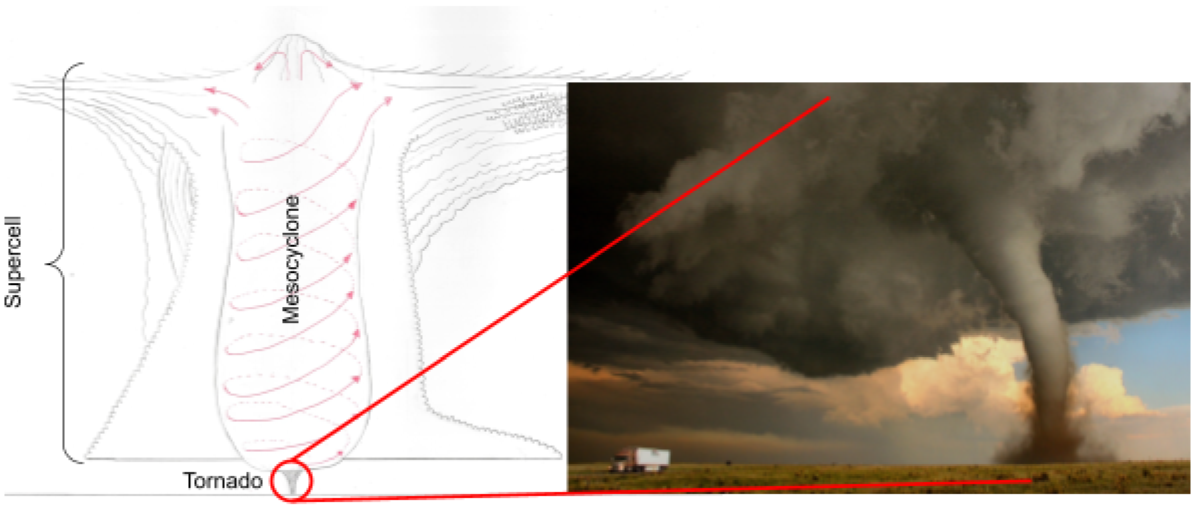
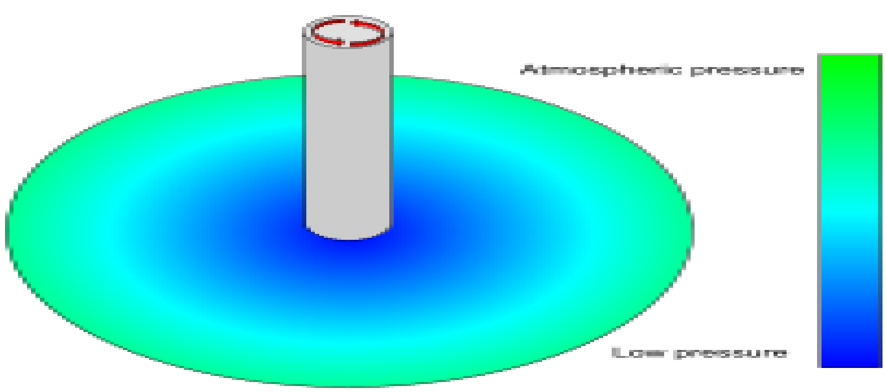
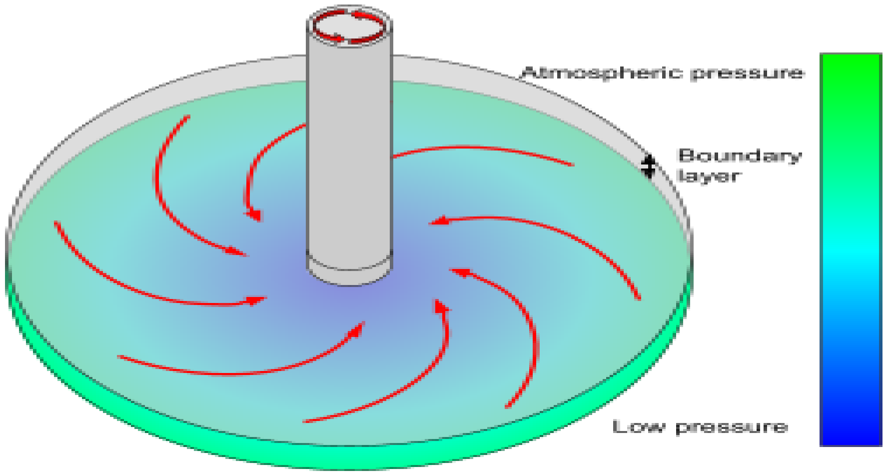
Tornados are one of the world's most powerful weather phenomena. They can be up to 100m in diameter and over a kilometre tall with wind speeds exceeding 400 mph. This makes them very violent and damaging in areas of the world where they form. What's really exciting about them is they bring you right to the edge of human understanding. We really don't understand much about them because they are very difficult to measure without destroying your equipment and they have a very complicated flow structure. We're going to use two engineering tools to help us think about them: experimentation and comparison (to other things that we understand better). Nevertheless, here's what we do know: we know they form under big storm clouds called supercells with rotating cores. These are called mesocyclones which are up to 20 km high (2x the altitude of an airliner).



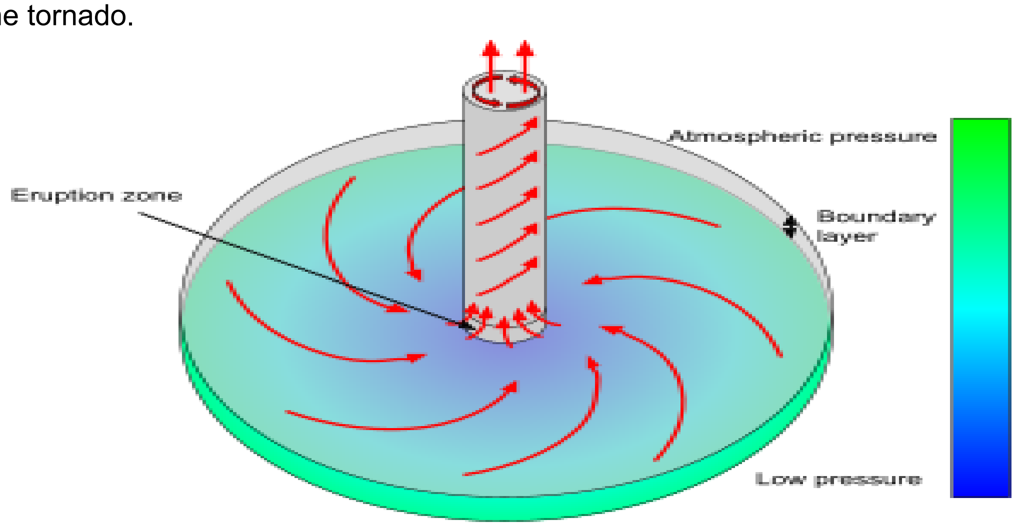
The core of a tornado is effectively a rotating tube of air. What's interesting is that the air nearby also circulates around the spinning core because the core drags the surrounding air along with it. In physics you'll learn that rotating things need a force toward the centre of their rotation to stay moving in a circle and this is true here too. This is the same as the sideways force a car seat exerts on you when you're going round a corner. In fluid dynamics, forces look like (static) pressure differences so what we see is low pressure in the core and atmospheric pressure far from the core.



So, we have a rotating column of air (the core) with a big pressure difference keeping everything in rotation - low pressure in the core, atmospheric pressure far from the core. So far so good. Unfortunately this is the moment we need to acknowledge friction exists. The ground provides friction against all this rotation - enough so right at the ground the air isn't moving at all (think of some air molecule trapped between blades of grass in our hypothetical field in Kansas). This gives us a layer of air which is circulating slower than it's supposed to. This is called the boundary layer and will be roughly as thick as the tornado is wide - ~100m. This is interesting because the boundary layer experiences the same pressure difference as the rest of the flow but, since it is moving much slower, the force it feels is way more than is needed to keep the slower moving air going in a circle. This drives the air in the boundary layer radially inwards.

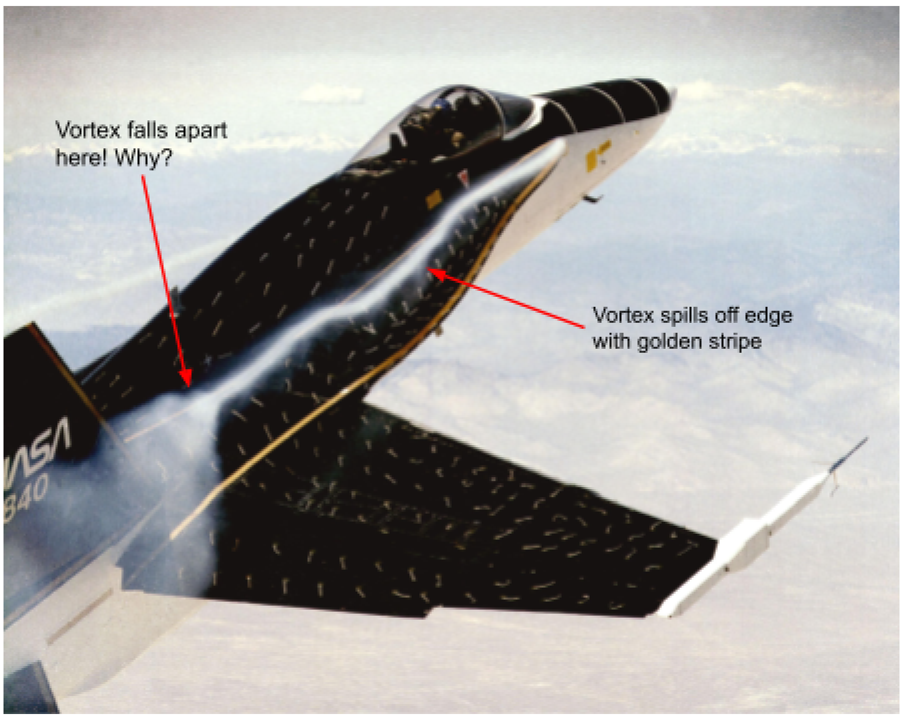


Right. So now we've acknowledged friction exists, we have a rotating column of air, a pressure gradient from high to low at the core and now a boundary layer with slower moving air, spiralling towards the centre of the tornado. But that air can't just disappear…where does it go when it spirals to the centre? It has nowhere to go but upwards. We get a so-called "eruption zone" where all of this inward spiralling air crashes into itself and turns a corner to flow vertically up the core of the tornado.



Our full structure therefore is: spinning core with a big vertical updraft being driven by the low pressure at the core caused by circulating surrounding air acting on the slower moving air in the boundary layer. That's a really complicated setup to start exploring. Well done for following that logic through. Unfortunately this is where we get somewhat stuck. Nobody really understands that boundary layer, nobody's measured the core of a real tornado properly, and we can't even figure out how they form in the first place, we just know they happen under those big rotating supercell clouds. Not much to work off.

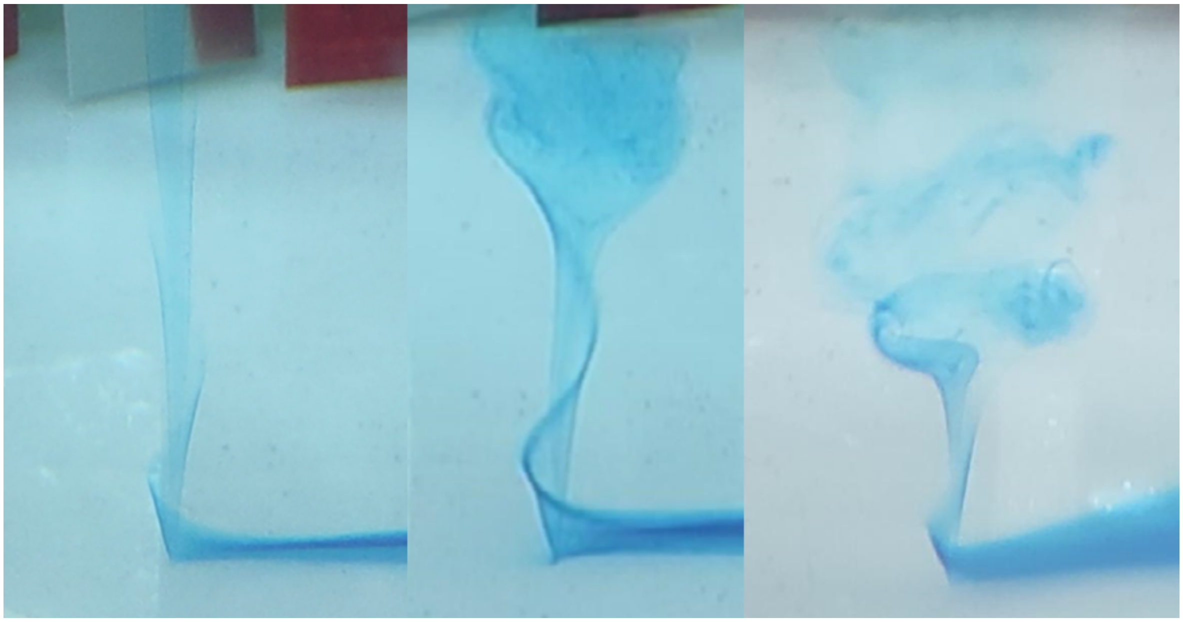
Here's where we're going to use the first of our big engineering tools: comparison to better understood phenomena. Engineers first started playing with tubes of rotating air with an axial flow component in the 1950's when the US air force had a problem with fighter jets falling out of the sky. The terminology for that tube of air is a "vortex", plural "vortices". It turns out that if you have a triangular wing like those planes did, the lift is dominated by a big vortex that spills off the front facing edge. Here's what we saw.



When the pilots pushed the aircraft hard, the leading edge vortex sort of fell apart half way down the wing. We call this "vortex breakdown". Excitingly, we're once again at the limit of human understanding. Nobody can agree why they do this but we can sort of agree on when they are likely to. We found that breakdown occurs when the axial flow velocity matches closely to the rotational velocity. It also helps when the pressure gradient is pushing the air backwards, slowing it down. This helped us figure out how to design better fighter jets but also has given us a window into our mysterious tornado vortex.

Remember the boundary layer gave our tornado vortex a big updraft. It turns out that updraft does tend to match the rotational velocity fairly well. A bit of engineering intuition therefore says that we might expect vortex breakdown to be at play in tornados too. This is what my project is all about: does vortex breakdown happen in a tornado-like vortex?

Here’s where we start using our other big engineering tool: experimentation. It’s useful because we can design our experiments to produce simpler versions of real world phenomena which are then easier to measure and understand. Here I’ve made a rig which can make a tornado but allows us to ignore complex things like the supercell cloud, obstructions like trees and houses and other random crosswinds you get in the real world. I’m working with water rather than air here because it’s easier to see what’s happening with just a bit of dye. Here’s three pictures of what I saw, in increasing order of flow speed (how fast the water is moving).



Left: Normal tornado. Does all the things we talked about earlier with the boundary layer and the eruption zone. Happy days. Middle: Vortex breakdown! This was very exciting to see. It looks just like our fighter jet picture. Right: A new type of breakdown we haven’t met yet. This is called spiral breakdown. It looks like we’ve answered our question: certainly in this experiment we do see vortex breakdown in a tornado-like vortex.

So to recap: we started with a very complex problem which we understood very little of, recognised its similarity to a better understood problem then used that to ask a better question: do we see vortex breakdown in tornadoes? Then we could use a carefully designed experiment to make a clean, simple tornado free from the complexity of the real world to start making some observations. Now all there is left to do is to try to link the experiment back to the real world tornado to see if it helps us understand more of how they work. This is often the hardest bit about experimental engineering, but our results show us that looking for vortex breakdown in real world tornadoes is a sensible next move. Teams of engineers in the USA are working on exactly this right now.