Why the tropopause temperature minimum occurs at a common pressure near 0.1 bar in thick atmospheres of planets and moons

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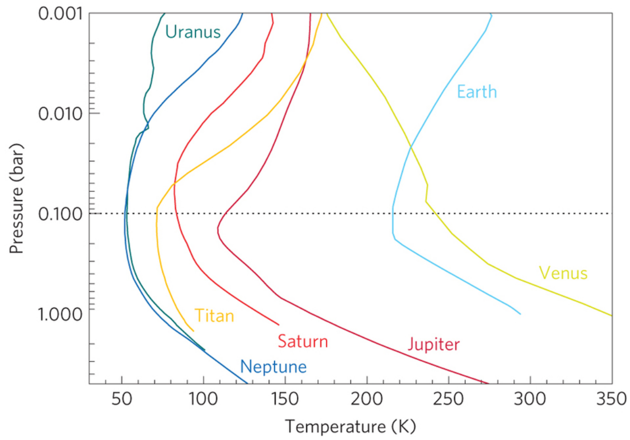
Anyone who has climbed a mountain knows that the atmosphere gets colder and thinner with altitude. But higher still where the air is ten times thinner than at sea level, the atmosphere stops cooling and begins to warm. This altitude is about 30,000 feet (9 kilometers) at the poles and 56,000 feet (17 kilometers) at the equator.

Back in 1902, the scientist Léon Teisserenc de Bort discovered this turnaround level with unmanned balloons. He named it the 'tropopause' and invented the words 'stratosphere' for the atmospheric layer above the tropopause and 'troposphere' for the part below where we live. Little did he know that during the 1980s, various NASA spacecraft would discover a tropopause turnaround in temperature in the atmospheres of Jupiter, Saturn, Uranus, Neptune, and Titan (the largest moon of Saturn). Remarkably, these tropopause turnarounds all appear at roughly the same level in these atmospheres as in Earth's, at a pressure of about 0.1 bar (within a factor of two or three), which can be compared to Earth's surface at a pressure of 1 bar.

At first sight, this common 0.1 bar level is a puzzle because the various celestial bodies have very dissimilar gases in their atmospheres, and their temperatures are all drastically different from each other and from Earth. In a 2014 paper in *Nature Geoscience*, we showed that the physics behind this phenomenon is so general that we can imagine a tropopause around 0.1 bar pressure occurring in billions of planetary atmospheres throughout our galaxy. In fact, this knowledge could be used to extrapolate temperature and pressure conditions from the tropopause down to the surfaces of rocky planets to find if the surface conditions are habitable. So what is the physics?

Above: A view of Earth's atmosphere from the International Space Station. Red-orange colors indicate the troposphere while blue colors indicate the stratosphere and upper atmosphere. Image credit NASA.

Books about planetary atmospheres often start with a graph showing how atmospheric temperatures change with height. These data demonstrate that Earth, Titan, and all the giant planets have a kink in their atmospheric profiles at more or less the same air pressure. But such books give no explanation, so we set out examine why.



Above: Vertical profiles of temperature in the atmospheres of Neptune, Uranus, Saturn, Jupiter, Earth and Venus. With increasing altitude from a pressure level of about 1 bar (which is the pressure at Earth's surface), temperatures in the planetary atmospheres of the giant planets, Titan and Earth decrease with decreasing pressure. But the temperature reaches a turnaround point at the tropopause, and subsequently increases with increasing altitude (or lower pressure) above the tropopause. The tropopause level commonly occurs at a pressure around 0.1 bar, as shown by the dashed horizontal line. Venus does not have a 0.1 bar tropopause in its globally averaged temperature profile because it is dominated by carbon dioxide and doesn't have a distribution of gases or particles that absorb strongly enough in the ultraviolet or visible to cause a temperature inversion at high altitudes.

Our theory is based on the fundamental way that atmospheric gases warm up by absorbing infrared, or heat, radiation. Atmospheres can gain energy by absorbing infrared light emitted from the sunlit surface of a rocky planet or from the deeper, warmer parts of an atmosphere on a planet like Jupiter that has no surface. Where the air is thick it's mostly opaque, and the journey for infrared light through the thicker parts of the atmosphere is impeded, like a car making its way through endless traffic jams in a city center.

The extent that the opaqueness to infrared light increases in atmospheres as you go deeper is roughly similar, whether the air is on Titan, Earth or the giant planets. In general, if you double the atmospheric pressure, you quadruple the opaqueness. This common dependence on pressure arises from a pair of processes that control the amount of infrared absorption. *Pressure broadening* is when molecules such as carbon dioxide or water vapor in Earth's atmosphere gain or lose energy during collisions allowing them to absorb a wider range of infrared light energies. *Collision-induced absorption* is when collisions cause disturbances in the structure of molecules, allowing molecules that otherwise don't absorb infrared light, such as hydrogen on the giant planets, to do so. Although either collision process can operate, they both result in the same pressure dependence in any planetary atmosphere.

Applying this knowledge, we found that it is only at high altitudes above the level where the pressure drops below about 0.1 bar that atmospheres are sufficiently transparent to infrared radiation for the absorption of ultraviolet or visible sunlight to dominate and warm the air, making hot stratospheres and a tropopause temperature turnaround. On Earth, the stratospheric ozone layer absorbs ultraviolet sunlight, whereas on the giant planets and Titan, methane gas and a smog of organic particles absorb both visible, near-infrared and ultraviolet sunlight.

Deeper than the level of 0.1 bar, at somewhat higher pressures, atmospheres are decreasingly transparent to infrared radiation and the temperature increases with depth because the infrared photons have trouble getting through the air. Then, deeper still, atmospheres become so opaque to infrared radiation that the air convects – that is, it churns vertically like water boiling in a pot. So, the reason why tropopauses are all at a similar pressure level is that they share the same two characteristics: the atmosphere at the tropopause needs to be sufficiently transparent to infrared light to allow a temperature turnaround, and that degree of transparency has a common dependence on atmospheric pressure. When you go through the physics, that level always comes out at a pressure of around 0.1 bar, give or take a factor of two to three.

The common physics should apply to any planetary atmosphere of chemically plausible composition, provided that it has stratospheric gases that absorb ultraviolet or visible light, so that a tropopause exists. Obviously, the rule only applies if there's a turnaround in the temperature as you go up. So we hypothesized that a "0.1 bar tropopause" is a sort of rule-of-thumb that should apply to a vast number of atmospheres on exoplanets, i.e., planets orbiting stars outside the solar system.

One broader implication of our "0.1 bar tropopause rule" is that it could help to assess whether some exoplanets are potentially habitable. The key for life as we know it is whether the temperature and pressure conditions on the surface of a rocky planet allows liquid water. In the future, telescopes will be able to obtain detailed spectra of the light given out by exoplanets. But the spectra might not tell us everything we want to know. The spectra might indicate the temperature near the tropopause of an atmosphere but not at the surface. Or the spectra might indicate the temperature at the surface but not the surface pressure. A rule-of-thumb for the expected pressure at the tropopause enables an extrapolation downwards to the surface to work out information that may be missing: either the surface pressure or the surface temperature. Information about both the surface temperature and pressure are required to firmly indicate if liquid water could be stable on the surface of a distant rocky world.

Thus, common physics not only explains what's going on in Solar System atmospheres but also might help with the search for life elsewhere.

References:

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