Condensation, atmospheric motion, and cold beer

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The latent heat released when water condenses is an important driver of weather phenomena. And as a simple experiment shows, it also makes it tough to enjoy a frosty one in the summertime.

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Weather occurs as the atmosphere transfers heat from places that absorb lots of sunlight to those that absorb less. One major avenue for such transfer runs vertically and involves exchanges between air at Earth's surface and the air aloft. A second major avenue is horizontal; along it, heat flows from the tropics toward the poles.

Latent heat, exchanged when water changes phase, is important for those energy transfers. Most of us are familiar with evaporative cooling: We cool our skin by sweating; when our skin is wet, we feel cold standing in the wind; some of us try to beat the heat with swamp coolers. Yet we have little personal experience with the flip side of that energy exchange: the warming that occurs as water vapor condenses to form liquid droplets. To improve our intuition about the power of condensational heating, the two of us teamed up with a pair of students to investigate the warming of cold drinks as water condenses on the outside of an aluminum can. Before turning to those experiments, we briefly summarize some of the important ways in which latent heating influences weather.

Latent heating in the atmosphere

Meteorologically significant heating in the atmosphere occurs at essentially constant pressure and increases the enthalpy, which sums the energy contributions from changes in air temperature T and the amount of water vapor but does not include pressure–volume work. The water-vapor content of a sample of air may be expressed as the mixing ratio q of the mass of water vapor to the mass of dry air. The enthalpy per unit mass of moist air is well approximated as $c_pT + Lq$, where c_p is the specific heat of dry air at constant pressure and L is the latent heat released per unit mass when water changes phase from a gas to a liquid.

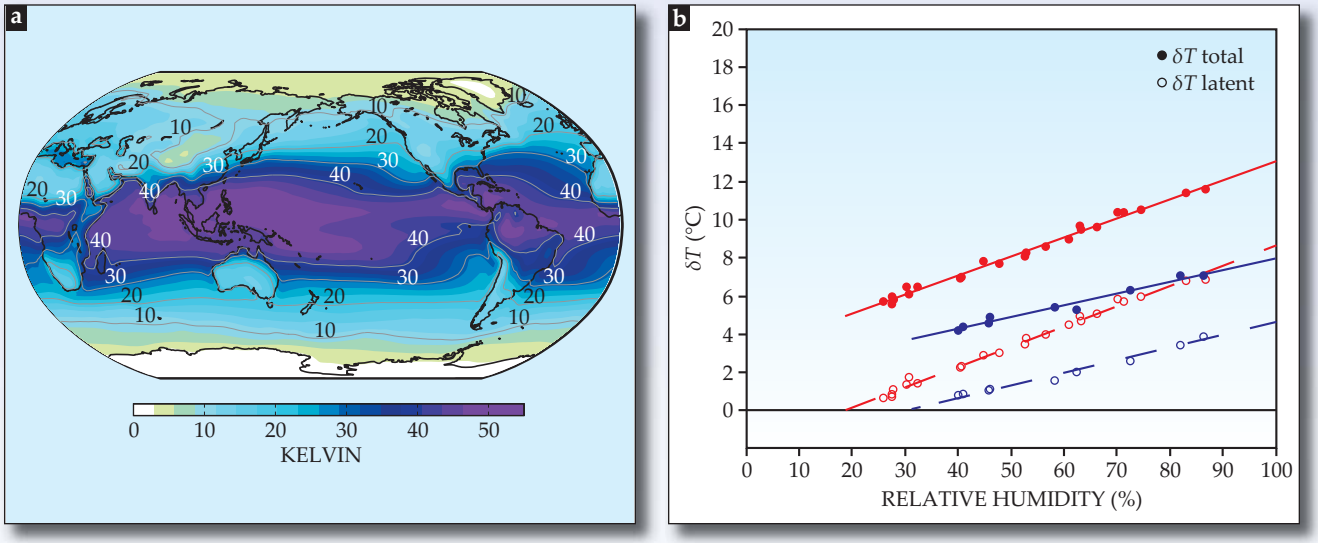
The importance of atmospheric moisture for horizontal heat transport is illustrated in panel a of the figure, a contour plot of q at Earth's surface multiplied by the factor L/c_p. That scaling expresses the water-vapor contribution to the enthalpy in kelvin and allows a direct comparison between the thermodynamic importance of variations in temperature and water vapor. The annual mean equator-to-pole contrast in enthalpy at the surface is about equally divided between contributions resulting from gradients in temperature and those from moisture; each gives about a 50-K difference between the equator and the poles. Consistent with that 50-50 split, moist processes account for roughly half of the total heat transport between the tropics and high latitudes.

Vertical heat transfer by latent-heat release occurs, for example, in a thunderstorm's updraft core. Like hot-air balloons, the updrafts are warmer than their environment and their ascent is powered by upward buoyancy forces. Rising blobs of air experience a drop in the surrounding atmospheric pressure and cool through adiabatic expansion. Consider a hypothetical blob of air rising from an elevation of 1 km, typical of the level at which clouds might form in air rising over the tropical oceans, to a height in the cloud of 8 km, where most of the water vapor would have condensed to form liquid droplets. If the air in the blob were completely dry and did not mix with its surroundings, its temperature would decrease by 69 K as it rose. That substantial cooling would be largely offset in a rising blob of moist tropical air that becomes saturated at a height of 1 km, because latent heat would be released during the blob's ascent as water vapor condensed to form cloud droplets. When the moist blob reaches the 8-km level, the latent heat released could make it more than 30 K warmer than the dry blob would be.

Without the enormous boost from latent heating, updraft cores would not be able to stay warmer than the air they penetrate, and thunderstorms would never grow to such great heights. But even with that boost, thunderstorm updrafts are only slightly warmer than their environment; that is because moist processes play a dominant role in setting the vertical temperature gradient throughout the entire lowest 15 km of the tropical atmosphere. If the atmosphere were completely dry, the vertical temperature differences throughout the lowest 10–15 km of the atmosphere would be much larger than is actually observed, as would be the horizontal temperature differences between the equator and the poles.

Condensation warms your drink

On a hot, humid day, a can of your favorite cold beverage quickly becomes covered with condensation. Suppose your drink comes in a 12-fluid-oz aluminum can and that over some period of time the condensed water forms a layer averaging 0.1-mm thick. It's easy to estimate an upper limit for the temperature rise produced by the condensation during that time, assuming that your drink is mostly water. The surface area of the can (not counting its bottom) is about 290 cm^2, which implies that 2.9 g of water condensed. The latent heat of condensation for water near 0 °C is 600 cal/g. Therefore, if all the latent heat of condensation is transferred to the 350 g of water inside a 12-oz can, the average water temperature would rise 4.9 °C.



Water, water everywhere. (a) The illustration shows the water-vapor mixing ratio at Earth's surface expressed in kelvin as described in the text. The temperature units allow thermodynamic effects resulting from differences in water-vapor content to be compared with those resulting from temperature gradients. **(b)** The temperature rise *(δT)* of water in a 12-fluid-oz can depends on relative humidity and ambient temperature. In this plot, each filled circle represents the change in temperature, after five minutes, of water initially near 0 °C for ambient temperatures of 25 °C (blue) and 35 °C (red). Open circles show the portion of the temperature change due to latent heating. The straight lines are least-squares fits to the data points.

The preceding estimate suggests that condensation might significantly affect the temperature of your drink, but how do the can's contents actually respond as a function of air temperature and humidity? How important is latent heating compared with the heat transferred from the surrounding dry air?

Undergraduates Stella Choi and Steven Brey helped us answer those questions using the experimental procedure detailed in the online supplement to this Quick Study (which includes additional data not reported here). Panel b of the figure is a plot summarizing our results for environmental temperatures of 25 °C and 35 °C. It shows, as a function of relative humidity and over a five-minute period, the increase in temperature of a can filled with 12 oz of water; initially, the temperature of the system was slightly above 0 °C. The plot also indicates how the mass of the collected condensation varies with relative humidity. As presented, the mass is multiplied by the latent heat of condensation and divided by the heat capacity of the water in the can; the scaled mass represents the temperature rise that would be produced if all the latent heat were transferred to the contents of the can. Assuming that the heat provided by the dry air is independent of the relative humidity, one can establish that the presumed complete transfer is essentially realized by noting that the total-temperature-rise line and rise-from-latent-heating line are parallel. In contrast, suppose that only 80% of the latent heat released was transferred to the can's contents. Then the slope of the total-temperature-rise line would be shallower than that of the corresponding rise-from-latent-heating line by a factor of 0.8.

The plot shows that the temperature rise due to latent heating increases dramatically with relative humidity. Moreover, the increase is much larger at 35 °C than at 25 °C, because of the approximately exponential dependence of the water-vapor content of saturated air on temperature. At 35 °C and a relative humidity greater than 60%, the temperature rise due to latent heating exceeds that due to heat transfer from dry air: Latent heating is the dominant factor warming your cold beer. The rate of latent heating decreases as the outside of the can warms, and the heating ceases completely once the can's surface temperature exceeds the dew point (the temperature to which air with a given water-vapor content must be cooled to become saturated) and water no longer condenses on it.

Where in the world will latent heating warm your drink most rapidly? The hottest and most humid conditions occur in coastal areas along the Persian Gulf and the Red Sea. On 8 July 2003, a probable world-record dew point of 35 °C was observed in Dhahran, Saudi Arabia; the air temperature was 43 °C. Our experiments suggest that under those conditions, the condensation deposited in five minutes on a can of beer initially near 0 °C would warm the beer by about 9 °C.

Radiation and precipitation

In this Quick Study, we have focused on latent heat exchanges associated with water condensation, but water also significantly influences atmospheric temperatures through its radiative properties. The globally averaged absorption of outgoing IR radiation by water vapor exceeds that from all other greenhouse gases combined. Clouds are even better absorbers of IR radiation, but they also scatter solar radiation, so depending on their elevation and structure, they can have a warming or a cooling influence. Yet water's role in energy transfer is secondary to an even more important process: Precipitation is crucial for human civilization and most terrestrial life. Not surprisingly, the study of water in Earth's atmosphere continues to be one of the main challenges in atmospheric science.

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