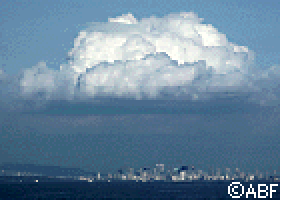

Question 1 - Correct

Clouds can form in the atmosphere because cold air cannot hold as much moisture (water vapor) as warm air can hold.
True. False.

Alas, this is perhaps the most widely offered fallacy in all of meteorology! It just is not true, despite a legion of teachers and on-air forecasters glibly asserting its veracity: air does not have a holding capacity for water vapor which varies with temperature (or anything else).

A discussion of both the falsehood and what is really happening can be found at Bad Clouds. Suffice to say here, you should never allow anyone to claim that the statement (as offered in the question, above) is acceptable, even as a simplification for the sake of clarity; it is not a simplification; it is categorically wrong, and has no place in the explanatory arsenal of teachers or meteorologists. Treat anyone offering it with pity.

The reason clouds form when air cools is because cold air cannot hold as much water vapor as warm air.
When moist air cools, a cloud can form. This much is true. The process is responsible for the cumulus cloud over Vancouver and the cap cloud over Rainier, shown to the right. Ascending air always cools. The cumulus cloud formed when air over the sun-warmed ground became buoyant and rose; the cap cloud, when the wind (coming from the right) blew against the sloping side of the mountain and was forced up.
But did the clouds form because the colder air had a lower holding capacity for water vapor than the warm air? If you believe a legion of teachers (from grade school to university), TV weather broadcasters, and endless textbook writers, this is the reason. They speak of the air being saturated and one even published an illustration of the air being wrung out like a sponge as the temperature dropped (sigh...). Unfortunately, it is not true. Sure, a cloud may form as the temperature drops, but not because some mystical holding capacity of the air has decreased.

To claim that a temperature-dependent holding capacity of the air caused the cloud to form in cold air is to get (approximately) the right answer for the wrong reason. It is like trying to reduce the fraction, 19/95, by imagining that you can cancel the 9s. The right answer ensues, but for the wrong reason. And, if the process was wrong, it is unlikely to work the next time you try it in a slightly different situation.

The air (mainly nitrogen and oxygen) no more has a holding capacity for water vapor, than, say, water vapor has for nitrogen. The atmosphere is a mixture of gases. While saturation (which involves bonds between different molecules) is a real phenomenon in liquids it does not describe the interaction of atmospheric constituents.

So, what is going on?

Water molecules are constantly coursing back and forth between phases (another word for the three states: vapor, liquid, and solid). If more molecules are leaving a liquid surface than arriving, there is a net evaporation; if more arrive than leave, a net condensation. It is these relative flows of molecules which determine whether a cloud forms or evaporates, not some imaginary holding capacity that nitrogen or oxygen have for water vapor.

The rate at which vapor molecules arrive at a surface of liquid (cloud drop) or solid (ice crystal) depends upon the vapor pressure.

The rate at which vapor molecules leave the surface depends upon the characteristics of the surface. The number escaping varies with:

1. the phases involved --- molecules can escape from liquid more readily than from the solid (ice);
2. the shape of the boundary --- molecules escape more readily from highly curved (small) drops or ice crystals (convex);
3. the purity of the boundary --- foreign substances dissolved in the liquid or ice diminish the number of water molecules which can escape;

4. the temperature of the boundary --- at higher temperatures the molecules have more energy and can more readily escape.

And therein lies the origin of the myth. The temperature of a cloud droplet or ice crystal will be (nearly) the same as that of the air, so people imagine that somehow the air was to blame. But, if the (other gases of the) air were removed, leaving everything else the same, condensation and evaporation would proceed as before (the air was irrelevant to the behavior). To assign the behavior of water to an invented holding capacity of the air is like assigning your life's fortunes to an invented influence of the constellations (and as we all know, nobody does that anymore).

So, what do you tell your students?

What appears to be cloud-free air (virtually) always contains sub microscopic drops, but as evaporation exceeds condensation, the drops do not survive long after an initial chance clumping of molecules. As air is cooled, the evaporation rate decreases more rapidly than does the condensation rate with the result that there comes a temperature (the dew point temperature) where the evaporation is less than the condensation and a droplet can grow into a cloud drop.

Evaporation increases with temperature, not because the holding capacity of the air changes, but because the more energetic molecules can evaporate more readily (with, of course, the caveat that evaporation is also influenced by things other than temperature, as described above).

If that explanation is not simple enough for your students, just present the facts: when the temperature drops below the dew-point temperature, there is a net condensation and a cloud forms.

But don't ever teach nonsense by claiming that the air has a temperature-dependent holding capacity for water vapor.

A little history

The idea that it is the air which determines the amount of water vapor which can be present through some sort of holding capacity is an eighteenth century idea which was shown to be false both empirically and theoretically about two hundred years ago! The fact that it is still taught in our schools and defended by teachers and (gulp) professors, is a testimony to the mindless persistence of myth. A discussion of some of the history of this bankrupt idea is offered by Steven M. Babin .

Preamble

This FAQ (Frequently Asked Questions) is written by Alistair B. Fraser. It is in response to questions posed over the years by readers of the Bad Meteorology pages. If you have arived on this page without having read those pages or the other Bad Science pages, then what follows, will probably make little sense.

Although the questions presented here are often ones asked by a specific person, each is chosen to characterize a group of similar questions which have been asked about the topic.
Issues discussed below (arising out of the Bad Clouds page)

- **Air is a sponge**
- **But, air does have a holding capacity for water vapor**
- **A correct prediction implies a correct reasoning**
- **The air-holding water explanation is just a simplification**
- **But, what about the relative humidity?**
- **What about boiling? It clearly depends upon the air pressure.**

Questions arising out of Bad Clouds:

☞Air is a sponge

Question:

When I was taught about the formation of clouds, I was given a physical reason for why the cold air cannot hold as much water vapor. I was taught that with decreasing temperature, there is not as much room between the air molecules and so the water vapor gets squeezed out (like water in a sponge). This makes sense to me. How can you say that the air is irrelevant when we actually know how the air squeezes the water vapor out?

Answer:

This sponge analogy is an attempt to provide a physical explanation for something which does not actually occur. The distance between the molecules in the air is very large. There is far more than adequate room for lots more water vapor or anything else for that matter. As Dalton pointed out in the nineteenth century, the gases behave independently of one another: one does not squeeze out the other.

Yet, there is a simple way to convince yourself of this without even making recourse to books: just watch the formation of cumulus clouds. These are the puffy white clouds which form on a summer's day over the Sun-warmed ground. The clouds form at the top of rising columns of air. As the air rises to a region of lower pressure, its density drops (the molecules get farther apart) and yet that is where the cloud forms. If you were to believe the silly explanation of the water being squeezed out because the molecules were getting closer together, then you should also expect that the clouds would have formed, not in the rising air, but in the sinking air, because it is there that the air density is increasing.

So, casual observation of the formation of many clouds shows that the issue is not one of air density (the closeness of the air molecules) but one of temperature, and not the temperature of the air, but of the water, itself.

But, air does have a holding capacity for water vapor

Question:

You criticise the phrase, "The reason clouds form when air cools is because cold air cannot hold as much water vapor as warm air." Yet, contrary to what you say, this phrase states the issue correctly. The fact that, as you argue, the temperature dependence of condensaton results from an intrinsic property of water, and not of air, does not prevent the phrase to be logically true.

Answer:

Yikes! Well here we really part company. The phrase is categorical nonsense. Heck, even Dalton knew better when he

pointed out that the gases are independent. The idea that air has a holding capacity is an eighteenth century speculation that likened water vapor in air to salt in water. Air is not holding the water vapor in any sense. Further, if all the air is removed, the relationship between the equilibrium vapor pressure and temperature remains the same. Empirically, the air is irrelevant. So, how can you justify telling folks that something which has no bearing on the issue (because in its absence the system behaves the same way) is the causative agent.

A correct prediction implies a correct reasoning

Question:

The fact that one gets the correct physical behavior (a cloud forms when air is cooled) from an application of the idea of air having a temperature-dependent holding capacity for water vapor is sufficient proof that the explanation is, in fact, also correct.

Answer:

Your suggestion is specious on two counts: the fact that you sometimes will get the correct answer from applying the reasoning is not a vindication of the logic; the reasoning often produces the wrong answer (that is, a result not in accord with experiment).

A simple illustration of the first problem was given on the Bad Clouds page itself: just because you get the correct answer by trying to reduce the fraction 16/64 by canceling the 6s does not vindicate the technique or assure one that it will work under other circumstances. In short, it is so easy to get the right answer for the wrong reason, that one should always be skeptical of any assertion that a correct result implies that the process by which it was attained was also correct.

Examples of the second problem abound. The observed behavior of all manner of natural phenomena refute it: the transformation of a water cloud into an ice cloud, the formation of haze, the metamorphism of a snow pack,the formation of steam fog, etc. Indeed, so many are the examples that we sometimes pose a problem for our students: describe the

behavior of the weather in a world in which the physical processes actually behaved as that described by the air-holding-water myth. Most meteorology students have no difficulty in covering many sheets of paper with descriptions of how different would be the weather in this fantasy world.

The air-holding water explanation is just a simplification

Question:

But, describing the process in terms of the air is merely a simplification to make it easier for the student to understand. How can you object to simplifications?

Answer:

I don't object to simplifications. However, you must make a distinction between something which has been made simple (stripped to its essence), and something which has been made simplistic (stripped of its essence). The explanation which attributes the formation of clouds to the inability of the air to hold as much water vapor at lower temperatures is not a simplification, it is categorically wrong! It bears no more correspondence to the behavior of nature than if I were to explain the process as one in which the water molecules were held in the arms of angels who, upon being chilled, begin to shiver and drop them. Just because the former explanation has the patina of science (rather than religion) does not make it correct.

I am not in favor of telling lies to students, nor will I accept the justification that lies are acceptable if they seem easier to grasp than the truth. One is not obliged to provide an explanation (you could merely state what happens rather than why it happens), but if you do provide an explanation, you are obliged to get it right.

The amazing thing is that this is an issue which was settled in the nineteenth century and is handled correctly in virtually every thermodynamics textbook in the world and yet nearly two centuries later, a disproved eighteenth century speculation continues to be presented as fact in school text books and by teachers.

But what about the relative humidity?

Question:

Based on your explanation, how is relative humidity explained? Everything I have read describes it as being the amount of water vapor in the air compared to the amount of water vapor the air at that temperature could hold.

Answer:

The relative humidity is a useful measure of some aspects of water vapor. The flaw is not in the concept, but in the way some incompetent authors present it to their readers as a percentage of the air's holding capacity. The relative humidity is the vapor pressure divided by the equilibrium vapor pressure (times 100%). The equilibrium vapor pressure occurs when there is an equal (thus the word equilibrium) flow of water molecules arriving and leaving the condensed phase (the liquid or ice). Thus there is no net condensation or evaporation. If the vapor pressure is greater than the equilibrium value, there is a net condensation. And that is not because the air cannot hold the water, but merely because there is a greater flow into the condensed phase than out of it.

What about boiling? It clearly depends upon the air pressure.

Question:

You list four things that affect the rate at which water molecules leave the surface. I understand Dalton's law of partial pressures (I think) but I have also seen water boil as the container around it is evacuated. How is this reconciled?

Answer:

When I was in grade school, I was taught that water freezes if its temperature is below 32 F and evaporates if it is above 212 F. Between those temperatures, it remains a liquid. This was all patent nonsense.

The evaporation rate of water is a continuously varying function of the temperature of the water. It does not have an abrupt transition at the boiling point, say, going from zero to some very high value. This might seem like an odd statement given that we

all apparently have seen the evaporation increase abruptly at the boiling point, but let me explain.

By evaporation rate, I mean (what is normally meant), the number of molecules leaving a unit area of the water surface in a unit time. And this evaporation rate changes slowly and smoothly through the boiling point (as it does for every other temperature value). However, when boiling begins, the surface area of the liquid increases discontinuously. This leads to a vastly greater loss of molecules from the liquid, but not because the loss per unit area has increased. Boiling just means bubbling: vapor bubbles can now survive inside the liquid. This, of course, happens when the vapor pressure (from the evaporating molecules) becomes greater than the pressure which would collapse the bubble. At lower temperatures and vapor pressures, any incipient bubbles which form in the liquid are immediately crushed by the surrounding pressure (which will be slightly higher than the pressure on the liquid itself --- often caused by the atmosphere). At higher temperatures and vapor pressures, a bubble survives, grows, rises to the top, breaks, and releases its vapor.

The supposed upper limit of the temperature of the liquid sometimes attributed to the boiling point is merely an approximate consequence of the increased loss of vapor and so latent heat cooling. When the cooling from this increased evaporation matches the heating from, say, the stove, then the temperature does not rise any further. But, there is no actual temperature bound; it merely takes greater heating to keep up with the latent heat loss.

If one places water in a container and lowers the pressure, then the temperature at which boiling takes place is also lowered. However, the evaporation rate (that is molecules leaving per unit time per unit area) is just as it would have been outside the chamber. But now bubbles survive.

But, none of this has anything in particular to do with the formation of clouds other than the fact that the relationship

between temperature and vapor pressure is of interest in both processes.

Question 2

The air flowing around the low pressure center of a large storm rotates

- a) cyclonically in both hemispheres.
- b) anti-cyclonically in both hemispheres.
- c) cyclonically in the northern hemispheres and anti-cyclonically in the southern hemisphere.
- d) anti-cyclonically in the northern hemisphere and cyclonically in the southern hemisphere.

The adjective cyclonic is used in the geosciences to mean that the fluid (atmosphere or ocean) is rotating in the same sense as the surface under it. Thus cyclonic rotation is, like the earth, counter-clockwise in the northern hemisphere and clockwise in the southern hemisphere. Thus, although the direction of rotation around a large low pressure area changes from one hemisphere to the other, in each case it is described as cyclonic because the direction of rotation of the underlying earth changes in the same way.

Question 3

The greenhouse effect causes the surface of the earth to be warmer than it would have been in the absence of an atmosphere, because

- a) the atmosphere behaves like a greenhouse.
- b) the atmosphere works like a blanket.
- c) the greenhouse gases trap heat.
- d) the surface is warmed by radiation from both the air and the sun.

Most of the explanations of the greenhouse effect which are offered by the popular press are at best bad metaphors and at worse just wrong. The issue is further muddied by an unfortunate confusion between the greenhouse effect and global

warming. A discussion of this can be found on the page Bad Greenhouse.

Suffice to say here, the basic explanation is as simple and understandable as that of a person being warmer if exposed to two, rather than one, sources of energy. In this case the two sources are the sun and the earth's atmosphere, which, surprisingly, sends more radiation to the surface of the earth than does the sun itself. As a digression, I note that the greenhouse effect is a misnomer: greenhouses are not kept warm by the greenhouse effect.

Question 4

The basic cause of the greenhouse effect is

- **a) the burning of fossil fuels.**
- **b) forest clearing in the Amazon.**
- **c) both of the above.**
- **d) none of the above.**

If you got this one wrong, I have succeeded in trapping you in the popular confusion between the greenhouse effect and global warming. It may be that global warming is attributable to things such as the burning of fossil fuels and forest clearing, but the greenhouse effect, which the earth has enjoyed for millions of years, is not.

The greenhouse effect is the (unfortunate) name applied to the effect which causes the surface of the earth to be warmer than it would have been in the absence of an atmosphere. Global warming is the name applied to the change in magnitude, or the augmentation, of the greenhouse effect which is expected to further increase the average temperature of the earth's surface.

Question 5

What is stability of a parcel of air which is buoyant?

a) stable
b) unstable
c) neutral
d) undefined

The words stable and unstable are adjectives; the noun they implicitly modify is equilibrium. The stability of something which is not in equilibrium is undefined for the simple reason that it is supremely irrelevant.

If, for example, a parcel is buoyant, one knows what will happen: there is a net force on the parcel and it will (in this case) rise. Thus, buoyant parcels of air in a cumulus cloud are not unstable, despite the callow beliefs of a myriad meteorological students. It may be that the cumulus formed in air which was originally in an unstable equilibrium, but once the cumulus is growing, the air in it is hardly in equilibrium and so not in need of any adjudication on its stability.

Question 6

If you were looking down at earth from a weather satellite and your eyes could see in the infrared portion of the spectrum (say, from 8 - 12 micrometer wavelength), then the warmest things (earth's surface) would appear brightest (white), and the coldest things (high clouds) would appear darkest (black).

True. False

If one were to judge by the infrared satellite pictures (such as the scene in the upper right) which are offered by NOAA and are widely available on the internet and seen on TV, the answer to this question would have to be false. They show bright clouds and dark ground, and students are taught, the darker the hotter.

(This particular scene is over eastern North America and extends from Lake Superior in the upper left to Florida in the bottom center. A cyclone has moved off the east coast.)

The trouble is that these pictures are negatives: their tonal range has been inverted from the way the eye would (and satellite cameras do) see the scene. Either theory, or experiment, reveals

that the hotter, the brighter. Turn on the element on a stove sometime and watch it get brighter as its temperature rises. The infrared sensitive eye would see the scene as in the picture in the lower right.

So why is this sham (upper picture) perpetrated? So, the images will look something like photographs taken in the visible; white clouds, dark ground and all that. Apparently, it was thought that neither the professionals nor the public was prepared to handle the idea of clouds and snow looking darker than warm ground. Yet, that is what the world is like in the infrared. One bizarre consequence of this silly game is that space, which is dark in both the visible and the infrared, now appears white. Yuk.

Question 7 - Correct

The blue of the sky is caused when sunlight is scattered primarily by

a) dust
b) nitrogen and oxygen.
c) water vapor
d) ozone

The blue of the sky is caused because light with shorter wavelengths are preferentially scattered by the molecules which make up our atmosphere: mainly nitrogen and oxygen.

Some people hold the erroneous belief that scattering from water molecules is the primary cause of the blue sky. While it is true that the water vapor molecule does preferentially scatter blue, there are two reasons that it is of vanishing importance. First, there are relatively so few water molecules that their contribution is very small, indeed. Second, the water does not do as good a job of the scattering as does the nitrogen and oxygen. Thus, if the, admittedly few, water molecules were replaced by the other major gasses, the sky would be a brighter blue.

Question 8 - Correct

Water draining from a bathtub or sink rotates

a) clockwise in the northern and counter-clockwise in the southern hemisphere.
b) counter-clockwise in the northern and clockwise in the southern hemisphere.
c) cyclonically in both hemispheres.
d) in a direction unrelated to the hemisphere.

The Coriolis force, which causes air in a large low pressure area to circulate in a cyclonic direction, is a very, very small force. It must act for a long time without major competition from other forces for it have a perceptible effect. On the short time scale of filling and emptying domestic basins, residual motions from filling the basin, subsequently introduced swirling motions, or friction between the liquid and the non-curricular basin, all trounce the Coriolis force. The direction of rotation of the draining liquid is unrelated to the rotation of the earth.

This is true, notwithstanding the fakery of some equatorial residents who claim to be able to demonstrate the consequences of the Coriolis force by causing water draining from a basin to rotate in opposite directions within a few meters to either side of the line. There is a discussion of this on the page Bad Coriolis.

Question 9

A mirage is an optical illusion.

True. False

My American Heritage Dictionary says a mirage is

> **"An optical phenomenon that creates the illusion of water, often with inverted reflections of distant objects, and results from distortion of light by alternate layers of hot and cool air. Also called fata morgana."**

After the first three words the AHD degenerates into unmitigated blather. A mirage is an image formed when the atmosphere behaves as a lens. It is no more illusory than any of the other

images one sees around one: the view through the lenses of eye glasses and binoculars, or the view of a newscaster on a television. If, for example, you actually believe that a real newscaster is inside that squat box in your living room (as opposed to merely his image) then you are deluded. Similarly, in the case of the mirage, if you believe you see water, you are deluded. Real illusions exist, but a mirage is not one of them.

The silly AHD entry (let's not grace it with the word, definition) further claims the phenomenon is caused by reflection, requires alternate layers of hot and cool air, and is a synonym for fata morgana --- none of which is true.

The mirage shown here of two lads apparently walking on the waters of Puget Sound is explicable by atmospheric refraction (not reflection). Further, the water is real (not illusory), as are the lads and the boat. If one assumed that the physical arrangement of the objects in the image had to obey the laws for objects, one might be tempted to believe in miracles.

Sigh..., don't turn to a dictionary for science, certainly not the American Heritage Dictionary.

Question 10

On the (primary) rainbow, red is seen

a) on the inside of the bow.
b) on the outside of the bow.
c) in the middle (between the other colors) of the bow.
d) it varies from storm to storm.

One of my favorite documents is a coloring book which instructs children on the proper colors to render an illustration of Noah leaving the Ark. Carefully specified are the important (but in truth, unknown) colors of Noah's and his wife's robes, but when it comes to the natural world, the children are instructed to "Color the rainbow to suit yourself." In this way, worlds are revealed about just what it is that is important for children to know --- and the winner is clearly not the natural world.

Red is on the outside of the (primary) rainbow; nature is not capricious on this point (although artists and authors certainly are).

Incidentally, rainbows in nature do not have the poster-paint purity of those rendered by either children or graphic artists.
