Assignment IX, PHYS 459 (Cloud and Precipitation Physics)
Fall 2021 Due 11/23/21

1. The largest difference between the saturation vapor pressure of liquid water and the saturation vapor pressure of ice occurs near about -14°C. Thus, this is the regime where you would expect supersaturations with respect to ice to be largest and you would get most rapid growth of ice crystals by deposition.

   a) If a mixed phase cloud is exposed to a situation where the air is at -14°C and supersaturated with respect to ice but subsaturated with respect to supercooled liquid water (as in the Bergeron process), what sort of ice crystal habit would you expect to find a lot of?

   b) If a mixed phase cloud is exposed to a situation where the air is at -14°C and supersaturated with respect to both ice and supercooled liquid water, what sort of ice crystal habit would you expect to find a lot of?

   c) What ice crystal habit would you expect in cirrus clouds that somehow have lots of water vapor?

2. This problem makes sure you have developed a sense of scale for cloud droplets.

   a) Assuming a "mature" cloud droplet has a diameter of 20 micrometers and assuming that there are about approximately 100 cloud drops per cubic centimeter in a cloud, what is a realistic "liquid water content" for a cloud? (Report your answer in grams of liquid water per kg of air). You should assume the cloud is close to the surface of the Earth.

   b) Our electronics and optics lab has a volume of around 190 m^3 (I measured). Based on the same properties of a cloud used in part (a), how many liters of liquid water would be in a typical cloud in that room? (You might be surprised.)

3. We may or may not have time to cover this in great detail, but light intensity can be obscured by cloud droplets. (Duh.) The amount of light passing through a random medium (like a cloud) is given by the Beer-Lambert-Bouguer Law, and is generally written something like $I(z) = I_\circ \exp(-\tau)$ where τ is the so-called "optical depth" of the medium. When $\tau = 1$, this means that 1 "e-th" of the initial light intensity makes its way through the cloud. (Note that τ is unitless; it is not a characteristic time here. I'm sorry – the choice of variables is traditional).
   For a warm cloud with a narrow drop size distribution and assuming the cloud drops are much larger than the wavelength of the sunlight traveling through the cloud, you can estimate $\tau \approx 2\pi h r_e^2 n$ where h is the cloud depth, n is the number concentration of drops (in drops per cubic meter), and r_e is the mean (effective) cloud drop radius.

   a) Derive an expression for the cloud liquid water content (in kilograms per cubic meter) in terms of r_e, n, and the density of water ρ_ℓ.

   b) Derive an expression for the total liquid volume in the cloud in terms of only r_e, τ, and A (the horizontal area of the cloud). You may assume the cloud is box-shaped.

   c) Let cloud 1 have mean droplet radius R and optical depth τ_1 and let cloud 2 has mean droplet radius $3R/4$ but the same spatial extent and total liquid water volume as cloud 1. What would the optical depth of cloud 2 be (in terms of τ_1)? Your answer to part (b) might be valuable here – and, just so you don't think this question is merely academic – the idea behind this is relevant to something known as the aerosol indirect effect.

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Remainder of Assignment
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The rest of this homework is going to be a little unfamiliar. There's only one more question, and it is an essay. I am looking for you to construct a well thought out and complete narrative. I'm still expecting you to spend a substantial amount of time with this part of this homework assignment. Please type your response, and spend some serious time crafting this; just giving me a bunch of facts and ideas loosely connected together won't be enough to earn substantial credit. It may be worth developing an outline and doing some pre-writing before trying to tackle this, because the task I ask isn't easy. That's also why you are getting a bit more than a week for this homework assignment. You also won't be getting an answer key to this part of the homework assignment, since it really would just be an exercise in me recapping the last month of the semester, and – although important – we've already done this, and I'm interested in seeing how *you* weave the narrative together.

4. We have been studying the mechanisms by which airborne cloud drops and ice crystals grow for quite a few weeks now and – whenever a class spends that long on a topic – it is sometimes hard to make sure you have an appropriate understanding of the "big picture." I've tried to emphasize this where I can through the process, and I've even given you a big flow-chart of the full process, but keeping any narrative thread through weeks of lecture and discussion is always a challenge.

   The average middle-school level understanding of precipitation development goes something like this: water evaporates from the ocean surface, then condenses into clouds, and finally falls back down as rain or snow. We now can say a whole lot more about all parts of this process.

   Describe – in detail – the different processes that occur starting from surface evaporation and continuing all the way through the arrival of a fully grown raindrop on the ground.

   Although there is no formal required page length for this problem, a 3-5 page typed answer would be appropriate.

   Your intended audience for your essay would be someone who has a degree in Physics, but no background in atmospheric stuff. (Think of your professors that are really smart people, but don't likely know much of anything about atmospheric science – or your classmates in your Physics classes who are constantly getting "A" grades in their classes, but haven't shown an interest in atmospheric science or meteorology so far.) Give a concise but complete explanation (with that audience in mind) of what you've learned in the last month or so.

   Your essay should include a discussion of all of the following topics: homogeneous and heterogeneous nucleation of liquid water and ice, Köhler Theory, deliquescence, condensational growth of liquid water and ice, coagulation (perhaps in a variety of contexts), the Wegener-Bergeron-Findeisen process, and Saffman-Turner theory. The essay *should not* just be a collection of defining these different phenomena. You are trying to tell a coherent story about the processes water goes through as it grows in the atmosphere.

   Incidentally, CofC is well known for its liberal arts tradition. We expect our students to be more accomplished writers than your average college student. It is also possible that many of you will someday ask me for a letter of recommendation for graduate school or a job; the best recommendation letters are able to draw on significant events or stories that clearly convey a strength in your portfolio that may not exist in your GRE scores and/or your grades. This essay is a chance to impress me. If you do a good job on this, I'll remember.