Geosci 232 Take-Home Final Exam
Fall Quarter 2009

December 3, 2009

Instructions: This exam is open book and open notes, and you may also use any computer resources, including web searches and Python scripts distributed as part of the class or problem set solutions. You should not consult with any humans or other sentient sources, though. Turning in this exam constitutes your agreement to the statement: *I will not discuss the contents of this exam with any person, nor solicit advice from any person as to methods of solution, until after the end of the University's exam period. I will turn in my answers to this exam within 48 hours of the time I begin work on the problems.*

Further instructions: Feel free to use Python to help you compute things when you reach the point that algebra won't get you further or will take too long (this point will vary from one person to another). Thermodynamic constants you may need can be found in the table in Chapter 2; they are also in `phys.py`. Don't panic! There will be lots of partial credit. If you get this exam even half right you are doing adequately, provided you have made a reasonable effort on the problem sets. We want to see how much you've learned about how to think about the climate of planets. If you need to make a choice, it's better to do a few problems thoroughly than all problems poorly. Remember to justify your answers. We need to be able to understand your reasoning. Be sure to explain what your reasoning is as you do the problem, and justify your answers. If you can't get an answer all the way, you can still get significant credit by explaining clearly what you would need to know in order to calculate the answer, and what steps you are hung up on.

Each problem counts for the same number of points, even though some are harder than others. It is to your advantage to spot the problems which are easiest for you.

Some useful constants (mks units): $R^* = 8314\ J/Mole{\cdot}K = 8.314 J/mole{\cdot}K$ (1 $Mole$ = 1000 $moles$); Planck's Constant = 6.626e-34 $Jsec$; speed of light $= 3 \cdot 10^8 m/s$; Radius of Earth = 6371 km; Radius of Moon = 1737km. Specific heat of liquid water is 4218 $J/(kg \cdot K)$

	H_2O	CH_4	CO_2	N_2	O_2	H_2	He	NH_3
Triple point T	273.15	90.67	216.54	63.14	54.3	13.95	2.17	195.4
Triple point p	611.	.117e5	5.185e5	.1253e5	.0015e5	.072e5	.0507e5	.061e5
L vap(b.p.)	22.55e5	5.1e5	–	1.98e5	2.13e5	4.54e5	.203e5	13.71e5
L vap(t.p.)	24.93e5	5.36e5	3.97e5	2.18e5	2.42e5	??	??	16.58e5
L fusion	3.34e5	.5868e5	1.96e5	.2573e5	.139e5	.582e5	??	3.314e5
L sublimation	28.4e5	5.95e5	5.93e5	2.437e5	2.56e5	??	??	19.89e5
c_p(0C/1bar)	1847.	2195.	820.	1037.	916.	14230.	5196.	2060.
ρ liq kg/m^3	958.4	450.2	1032.	808.6	1141.	70.97	124.96	682.
ρ sol kg/m^3	917.	509.3	1562.	1026.	1351.	88.	200.	822.6
$\gamma(c_p/c_v)$	1.331	1.305	1.294	1.403	1.393	1.384	1.664	1.309

CO_2	a_o	a_1	a_2	a_3
10ppmv	258.56	2.5876	-0.0059165	-0.00013402
100ppmv	246.13	2.5056	-0.0034095	-0.00010672
1000ppmv	232.51	2.3815	-0.0015855	-8.3397e-05
10000ppmv	215.74	2.1915	0.00056634	-5.0508e-05
100000ppmv	189.06	1.8554	0.0044094	1.0735e-05

Table 1: Coefficients for polynomial fit $OLR = a_o + a_1 x + a_2 x^2 + a_3 x^3$, where $x = T_g - 275$. Calculation carried out with $rh = .5$.

8 Final Exam Problems

Problem 8.1 Estimate the total power radiated by the Earth at wavelengths equal to or shorter than visible light (about 0.5 microns. For the purposes of this problem, assume that the Earth has a uniform radiating temperature of $255K$.

Problem 8.2 A Pail of Air

This problem is inspired by Fritz Leiber's story, "A Pail of Air." The Earth has a close encounter with a large interplanetary object, and is flung off into the cold night of space far from the Sun. As the Earth gradually cools down the atmosphere begins to condense, until essentially all of the atmosphere is deposited in a condensed layer at the surface of the planet. For the purposes of this problem, you may assume that dry Earth air consists of a mixture of 80% N_2 and just under 20 % O_2 (by mole fraction), with the balance consisting of CO_2 with a mole fraction of $380ppmv$. To keep things simple, we'll ignore atmospheric water vapor, which would quickly snow out and add to the existing surface layer of water ice and snow. The Earth's initial surface pressure is $10^5 Pa$, and the acceleration of gravity is $9.8m/s^2$.

Describe the sequence of events that occurs as the atmosphere cools. Will the atmosphere condense into solid or liquid forms? Will all the components of the atmosphere be mixed together at the surface, or will they occur in layers? Why? How thick would the layer of each substance be, and in what order would the layers occur? For the purposes of this problem, you may assume that any snow (of any substance) that forms becomes so compacted that the density is the same as that of the pure solid.

Problem 8.3 Geoengineering

A civilization is living on a planet in an orbit where the solar constant is $1450W/m^2$. The atmosphere consists of mostly Earthlike air with water vapor at a relative humidity of 50%, with some CO_2 mixed in. At the beginning of their Industrial Revolution, the planet has a CO_2 concentration of $1000ppmv$, and the temperature is a comfortable $280K$.

(a) At this point, what albedo does the planet have? (You may assume that this atmosphere has no high clouds, having been designed with the convenience of climate theorists in mind).

(b) A few centuries later, the CO_2 has increased to 10,000$ppmv$ and things are getting too hot. The inhabitants decide to cool things back down to the original temperature by injecting aerosols into the stratosphere so as to increase the albedo. How much do they need to increase the albedo in order to achieve their goal?

Problem 8.4 Ice-albedo and snowball

Consider an ocean-planet whose ocean can freeze over into a perfectly reflective ice with albedo $\alpha = 1$. The ocean liquid is unusually absorbing, so when there is no ice the albedo is zero. The planet is completely frozen over for temperatures below $260K$, and is completely ice-free for temperatures above $300K$. Between these values, the albedo varies linearly. The atmosphere of the planet satisfies the conditions necessary for the polynomial fit in the accompanying table to be used. Assume the CO_2 concentration is 100,000 ppmv.

Plot the incoming and outgoing fluxes. Experiment with turning the solar constant up and down. (It would be $1370W/m^2$ on Earth, but here you can set it.) For what range of solar constant are there three equilibrium solutions? Provide graphs at several values of the solar constant, showing the location of the solutions.

Can the Snowball state ever be eliminated in this problem?

Problem 8.5 Compute the equilibrium temperature at the subsolar point of Europa, which is in orbit around Jupiter and therefore has the same solar constant as that planet. The greenhouse effect of Europa's tenuous atmosphere can be neglected. For the purposes of this problem, you may assume that the albedo of Europa is .67 . Assuming Europa to have a water-ice surface, what would be the saturation vapor pressure of the water vapor atmosphere immediately above the subsolar point? Suppose that there is some methane, carbon dioxide and ammonia mixed in with the ice. What would be the partial pressures of these gases?

Problem 8.6 A typical well-fed human in a resting state consumes energy in the form of food at a rate of $100W$, essentially all of which is put back into the surroundings in the form of heat. An astronaut is in a spherical escape pod of radius r, far beyond the orbit of Pluto, so that it receives essentially no energy from sunlight. The air in the escape pod is isothermal. The skin of the escape pod is a good conductor of heat, so that the surface temperature of the sphere is identical to the interior temperature. The surface radiates like an ideal blackbody.

Find an expression for the temperature in terms of r, and evaluate it for a few reasonable values. Is it better to have a bigger pod or a smaller pod? In designing such an escape pod, should you include an additional source of heat if you want to keep the astronaut comfortable?

How would your answer change if the pod were cylindrical instead of spherical? If the pod were cubical?

Problem 8.7 For Jupiter, the observed OLR is $14.3W/m^2$. Compute the effective radiating temperature. Referring to the Jupiter temperature profile given in Chapter 3, estimate the effective radiating pressure of Jupiter. Is there more than one possible value? Which of these do you consider more likely?

Problem 8.8 Venus has a surface pressure of $92bar$, and a surface gravity of $8.87m/s^2$. 3.5% of the atmosphere (by mole fraction) consists of N_2. Compute the mass of N_2 per unit surface area of Venus, and compare with the corresponding number for Earth's atmosphere.

Problem 8.9 The atmosphere of Jupiter is predominantly H_2. A space probe determines that the temperature is $150K$ at a pressure of $10^5 Pa$. At what pressure does the temperature reach $300K$ if the atmosphere is well mixed and there is no condensation of any substance? Compare your results with the observed temperature profile for Jupiter given in the text.

Problem 8.10 According to some interpretations of geologic data from the Neoproterozoic (about 600 million years ago), the Earth went through one or more episodes of global glaciation. The phenomenon is known as "Snowball Earth." The general thinking has it that the Earth would exit from a Snowball state after sufficient CO_2 has built up in the atmosphere to warm the planet to the point where it deglaciates.

In the Snowball state, the planet becomes very cold, because an ice surface reflects a great deal of solar radiation. Simulations show that the surface temperature at the Winter pole can drop to $160K$, though it warms to about $240K$ in the balmy polar summer. Under these circumstances, how high would the CO_2 partial pressure have to rise before CO_2 condensation sets in at the winter polar surface? Based on a 1 bar surface pressure for the non-CO_2 part of the air what would the molar mixing ratio and molar concentration of CO_2 have to be to cause condensation? How do your answers change if the surface temperature is increased to $200K$? What do you think condensation would do to the global CO_2 concentration?

Problem 8.11 Consider a planet whose atmosphere has a mixture of $1bar$ of N_2 (measured by surface partial pressure) with CO_2 in saturation. Find the slope of the moist adiabat $(-d\ln T/d\ln p)$ at the surface, assuming that the mixing ratio of CO_2 is small, and compare to the dry adiabatic slope. Consider temperatures in the range $150K$ to $300K$. For what temperatures does the dilute approximation break down?