MET 200: Atmospheric Processes and Phenomena
Fall Semester
Businger   **Homework Assignment #1 Key**

1. (20 pts) The International Space Station has an interior pressure just about equal to that at sea level on Earth, 100 kPa. In building the ISS, the designers want to calculate how many bolts are needed to hold a small door to outer space in place. The door is rectangular with dimensions 2 m high x 1.5 m wide.

(a) What is the pressure on the inside of the door (i.e. the pressure wanting to push the door outwards)? What is the pressure on the outside of the door?

What is the pressure on the inside door? This is given above – 100 kPa
On the outside of the door? This is outer space – There is no air, and therefore no molecules to bang against the door from the outside, and therefore the outside pressure is 0.

(b) What, then, is the force on the inside of the door? What is the force on the outside of the door?

$$\text{Pressure} = \text{Force/Area} \rightarrow \quad \text{Force} = \text{Pressure} * \text{Area}$$

F on inside = Pressure on inside * Area of door = 100×10^3 Pa * (2 m * 1.5 m) = 3×10^5 N
F on outside = Pressure on outside * Area of door = 0 Pa * (2 m * 3 m) = 0 N

(c) If each bolt can hold 30 kN of force before breaking, then what is the minimum number of bolts needed to make sure this door holds?

Number of Bolts = (Total force on door) / (Amount of force each bolt holds)

Number of Bolts = $(3 \times 10^5$ N) / (3.0×10^4 N) = 10 bolts, maybe add an extra one just for safety margin.

(d) Does the answer depend on the orientation of the ISS, i.e. if the door points at Earth, or away from Earth, or in any other direction? Why?

No, fundamentally pressure is isotropic, force/area is distributed equally in all directions. The ISS is a sealed container – no matter which way it points, the pressure differences between the inside and the outside of the container are the same. Gravity does affect the station (this is the reason why the station orbits the Earth). But gravity is not responsible for the pressure force, the molecules on the inside of the space station are, which don't change as a function of the space station orientation.

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2. (20 pts) a. Calculate escape velocity for a satellite launched from Earth. Use the universal law of gravitation.
   G=6.67×10^{-11} Nm^2 kg^{-2} and mass of Earth = 5.98 x 1024 kg, radius = 6.37 x 10^6 m,

Earth escape velocity $\Rightarrow$ Kinetic energy = Gravitational energy
initial = final $\Rightarrow$ $1/2mV_e^2$ - $GmM_E/r = 0+0$ then solve for V_e
V_e = 11,200 m/s

b. Give an example of an <u>active</u> remote sensing instrument carried on a satellite.

An active instrument is one that emits radiation, e.g., radar, lidar, microwave scatterometer, etc.

c. What type of satellite (e.g., orbit) would this type of instrument most likely be flown on? Why?

Radiation from an active instrument must be reflected/scattered from the Earth/Atmosphere back to the satellite to be measured at the satellite. If the satellite is too far from the Earth, these reflected/scattered signals will be too weak to detect. Therefore, active instruments are confined to near-Earth polar orbits.

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3. (20 pts) a. Calculate the height (in km) of a geostationary orbit given:
     angular frequency of the Earth's rotation = 7.29 x 10^{-5} s^{-1},
     mass of Earth = 5.98 x 1024 kg, radius = 6.37 x 10^6 m,
     universal gravitational constant = 6.67 x 10^{-11} Nm^2 kg^{-2}
     Show your work

force of gravity = centrifugal force
$GmM/r^2 = mV/r^2 = \Omega^2 r$
Solve for r and note that $r = R_e + h$, where h is the height of the satellite. h = ~36,000 km

b. What are three practical advantages of a geostationary orbit?

At that distance a large area of the Earth can be monitored continuously (animations).
With a large dish pointed towards the satellite, continuous communication of the data is straightforward.

c. What are two disadvantages of a geostationary orbit?

Resolution of the data is not as high as that available from a near-Earth polar orbit.
Active instruments are not a realistic option.
Coverage is not global. Polar regions are beyond the reach of this type of orbit.

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4. (10 pts) Consider a pot of water that contains 7 L of water at 25°C.
(a) Calculate the amount of energy that is needed to bring this water just to a boil.

Initially the water is at 25°C. We want to bring the water just to a boil, which is a temperature of 100°C. SO we want to raise the temperature of the water by 75°C. (Note: if you are considering a change in temperature, 75°C = 75 K)
Amount of energy needed = (Heat capacity of water) * (change in T) * (mass of water)
Heat Capacity = 4.2 kJ/(kg K) = 4.2x 10^3 J/(kg K)
Change in T = 75 K
Volume of water = 7 L * (1 m^3 / 1000 L) = 7x 10^{-3} m^3
But the density of water = 1000 kg/m^3 (you can look this up).
Therefore, M = ϱ * V → mass of water = density * volume = 1000 kg/m^3 * 7x10^{-3} m^3 = 7 kg
And therefore,
Energy = 4.2x10^3 J/(kg K) * 75 K * 7 kg = $\boxed{2.21x10^6 \text{ J}}$

(b) Find the energy necessary to evaporate all of the liquid.

You need to use the latent heat of evaporation: 2.5x10^6 J/kg
Energy = (latent heat)* (mass of water) = 2.5x10^6 J/kg * 7 kg = $\boxed{1.8x10^7 \text{ J}}$
Note that this is roughly 10 times the value for (a), meaning that the condensation of water vapor releases a lot of energy!

(c) From the time the pot is put on the burner until it is completely dry, find the amount of time required if the burner outputs 2500 W.

First calculate the total amount of energy needed to heat up the water AND evaporate it (i.e., add your answers form part (a) and part (b)) →
Total energy = 0.22x10^7 J + 1.8*10^7 J = 2.0x10^7 J (note significant figures here!)

But Power = energy/time
Power = 2500 W (or J/s)
Therefore,
Time = energy/power = 2.0x10^7 J / 2500 W = 8.0x10^3 s

This turns out to be: $8000s * \dfrac{1\min}{60s} * \dfrac{1hr}{60\min} = 2.2hr \approx$ ⎘2 hr (133 min)⎘

(Note: Your answers may vary somewhat depending on how many digits you used in your calculation).

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5. (10 pts) If the Earth's tilt were 30° rather than 23.5°, discuss whether or not the following would change, how they would change, and why. Draw diagrams for each.
(a) Summertime and wintertime temperatures

If the tilt of the Earth is increased, then the <u>difference</u> between sunlight received by the NH and SH around the winter and summer solstices is <u>increased</u>. This means that summertime temperatures would be warmer (more sun), while wintertime temperatures would be colder (less sun).

(b) Position of the sun during the equinoxes

At the equinox, the sun would remain in exactly the same place (directly overhead the equator).

(c) Length of day during the solstices

At the summer solstice, the length of the day would increase, while at the winter solstice, the length of the day would decrease (by the same amount).

(d) Position of the arctic circle

The position of the Arctic Circle would move towards the equator, and in fact it would be at 90° – 30° = 60°.

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6. (10 pts) As the Earth warms, the amount of permanent ice (such as glaciers and ice sheets) as well as seasonal ice (ground-level snow, much of the Arctic ice cap) decreases. Let's say that if we instantly removed all of this ice and snow from the Earth's surface, the albedo of the Earth would decrease from 0.30 to 0.28. Estimate how much the Earth's average surface temperature would *increase* if this occurred.

There are two ways to approach this problem, with or without a greenhouse layer.
Without a greenhouse layer we can write:
Incoming Energy (visible) = Outgoing Energy (IR)
$S(1-a)\,\pi r^2 = \sigma T_E^4 (4\,\pi r^2)$
$T_E = [S\,(1-a)/4\sigma]^{1/4}$ then plug in for a = .3, and .28 and find the difference (~1.8 K)
*Where S = solar constant = 1379 W/m², a = albedo, and σ = 5.67*10^{-8} W/(m²*K⁴).*

With a greenhouse layer we have the following radiation balance at the surface:
Sunlight In + GHG Layer In = Reflected Sunlight out + IR emission out
Now solve for T_{sfc} after modifying the "Reflected sunlight out."
Reflected Sunlight Out = Area * albedo * Sun In = 1 m² * 0.28 * 343 W = 6 W
Therefore,
IR emission out = 343 W + 161 W – 96W = 408 W
Solving, leads to:
$T_{surface} = (P/A\sigma)^{0.25} = (408$ W$/ (1$ m² $* 5.67x10^{-8}$ W/m²K⁴$))^{0.25} = 291.25$ K

Which is a difference of 291.25 K – 290 K = 1.25 K from the original case of $T_{surface}$ = 290 K

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7. (10 pts) What type of radiation (e.g. x-rays, microwaves) is primarily associated with each of the following phenomena. When possible, use Wien's Law to calculate the wavelength of peak radiation emission:

Wein's Law = λ = 2900 μm K / T

(a) Sunlight – visible light (T = 5800 K, λ = 0.5 μm)
(b) Earth's reflected radiation – reflected radiation is Sunlight, so same as (a)
(c) Earth's emitted radiation – infrared (T = 290 K, λ = 10 μm)
(d) Emitted radiation by the greenhouse gas layer – infrared (T = 255 k, λ = 11.4 μm)