METR 4553 | **Final Exam** | 10:30 am Thursday May 11, 2017

Instructions: CALCULATORS allowed. Use the distributed BLUE BOOK for submitting your answers. *Print your name, and sign your legal signature on the front of the blue book. Print your name on the back of the blue book.* Answer question 1. Then answer 2 of the 3 questions in each of the remaining 3 sections (and please indicate on the front of the blue book which questions you want graded in those 3 sections).

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1 ha $= 10^4$ m^2 1 t $= 10^3$ kg 1 m$^3 = 10^3$ ℓ 1 mi $= 1610$ m 1 bbl $= 159$ ℓ

1 quad $= 10^{18}$ J 1 MJ $= 10^6$ J 1 GW $= 10^9$ W 1 kWh $= 3.6$ MJ 1 cal $= 4.2$ J

1 toe $= 42$ GJ 1 TW $= 10^{12}$ W

$\rho_w = 1000$ kg m^{-3} $c_w = 4186$ J kg^{-1} K^{-1} $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}

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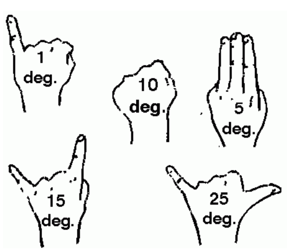
1. REQUIRED. Answer 10 of the 12 questions. (1 pt each)

(a) 

A geological claim that "radiometric dating shows these rocks to be 135 millions years old" means: (a) the elements in the rock formed at that time (b) the crystals in the rock formed at that time (c) the rock broke off from bedrock at that time (d) none of the above, "radiometric dating" is a social protocol for humans.

(b) 

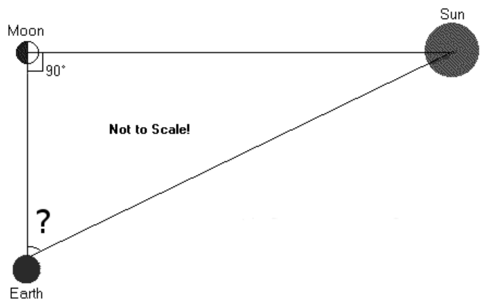
Make a sketch of the conventional incandescent light bulb with a battery and a wire that shows how the light bulb can be made to glow.

(c) 

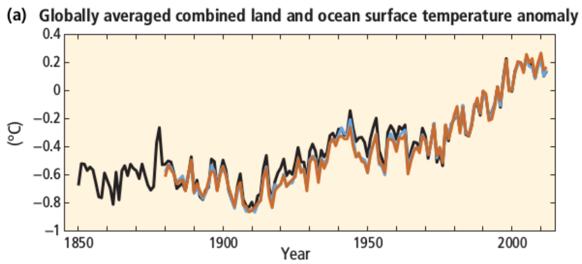
Using an outstretched arm, it is possible to measure the angular size of astronomical objects. Of those indicated, what is the smallest size that could cover a full moon?

(d) 

Where do trees acquire most of their mass? (a) sunlight (b) water (c) soil (d) air

(e) 

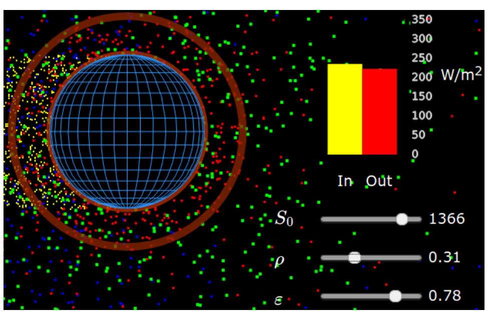
This schematic is not to scale, and the angle for **?** may or may not be appropriate. During a half moon event, the angle at **?** is closest to: (a)60° (b) 70° (c) 80° (d)90°

(f) 

Suppose the theory for global warming is that $\Delta T = \Delta T_{\text{dbl}} \log_2(x)$ where x is the ratio of carbon dioxide concentration to value it was in 1950, which was about 300 ppm. Currently the concentration is approximately 400 ppm. Using $\Delta T_{\text{now}} = \Delta T_{\text{dbl}} \log_2(x_{\text{now}})$, infer ΔT_{dbl} from what you see in the data. Note: $r = \log_2(x) \implies 2^r = x$. Hint: $2^{0.42} = \frac{4}{3}$.

(g) Using the theory and result of the previous question, what will be ΔT in units of C if the concentration of carbon dioxide reaches 1200 ppm?

(h) Match the number for the top-of-the-atmosphere phenomena with the letter for the quantity of W m^{-2}: (1) Global radiative forcing for double CO_2. (2) Global radiative forcing for the 11-year sunspot cycle (3) seasonal radiative forcing at the latitude of Norman (4) Ice age radiative forcing at the summer solstice at 65° North latitude. (a) 200 (b) 50 (c) 4 (d) 0.25

(i) 

This is a screenshot from an applet we used in class (the predicted average surface temperature T_s is clipped). Is this situation in equilibrium or disequilibrium? Is T_s rising or falling?

(j) 

How old are the channeled scablands? How did they form?

(k) 

Evidence exists in the south Libya desert for human settlement engaged in agriculture 7000 years ago. How was seasonal insolation different at that time, as compared with today? Why did that effect rainfall?

(l) 

Why is methane release from tundra claimed to be a *positive feedback* process in global warming?

1 Test 1 material, answer 2 questions

2. Human civilization consumes about 100 million barrels of oil per day, or 10^8 bbl d^{-1}.

   (a) (2 pt) Calculate that volume rate in units of bbl s^{-1} (barrels per second).

   (b) (2 pt) Calculate that volume rate in units of mi^3 y^{-1} (cubic miles per year).

   (c) (2 pt) Calculate the power provided by that volume rate in units of TW. Assume the energy content of crude oil is the same as for gasoline: 32 MJ ℓ^{-1}.

   (d) (2 pt) Calculate the power provided by that volume rate in units of quad y^{-1}.

   (e) (2 pt) Calculate the power provided per capita on Earth (per human on Earth) in units of watts.

3. Assume the area of the arable land in the USA is about 1.5×10^8 ha.

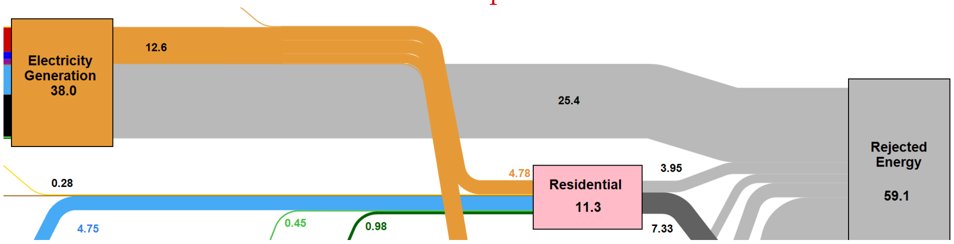
   (a) (1 pt) If this area were to be shaped into a square, what would be the length of one of the sides, in units of mi (miles)?

   (b) (2 pt) If this area were equally distributed among the approximately 300 million humans in the USA, what would be the area available to each human in the USA? Give the answer in units of m^2.

   (c) (1 pt) If this individual area was shaped as a square, what would be the length of one of the sides, in units of m?

   (d) (6 pt) Annual energy consumption in the USA is about 100 quad. Suppose sugar beet can be produced at 50 t ha^{-1} y^{-1}. One ton of sugar beet can produce 100 ℓ of ethanol, which has an energy content of 22 MJ ℓ^{-1}. If the entire allotment of an American's arable land were devoted to ethanol production from sugar beets, what fraction of the American's energy needs could be supplied?

4. Here is a portion of the LLNL Sankey diagram for energy consumption in the USA, in year 2015. The numbers are in units of quad.



   (a) (5 pt) Look at the electrical power consumed as "Residential". (Hint: 4.78. The 11.3 includes heating by natural gas). What is the average electrical power in watts consumed **per person** in the USA?

   (b) (5 pt) How many kWh per month is that? If electricity costs 0.15 $\$\ \mathrm{kWh}^{-1}$? What is the average residential electricity cost **per person** in the USA , in units of \$ per month?

2 Test 2 material, answer 2 questions

5. Suppose house insulation is marked R-17. So, in units useful for us, $R = 3\ \mathrm{m}^2\ \mathrm{K}\ \mathrm{W}^{-1}$. Suppose the temperature inside is 295 K and the temperature outside is 265 K. Suppose the house has a floor size of 10 by 20 meters and the walls are 3 meters tall. Assume, the floor is perfectly insulated (or, alternatively, the soil temperature beneath the slab is the same as the inside temperature)

   (a) (2 pt) How many $\mathrm{W}\ \mathrm{m}^{-2}$ are escaping the house?

   (b) (2 pt) How many W are escaping the house?

   (c) (2 pt) Suppose the house is heated at that rate with electrical heaters. How many kWh per month are required? How much would that cost, approximately? Assume the price of electricity is 0.15 $\$\ \mathrm{kWh}^{-1}$.

   (d) (2 pt) Suppose you heat the house with natural gas. ONG will charge about \$4 per GJ (or dekatherm). What is that price in units of $\$\ \mathrm{kWh}^{-1}$?

   (e) (2 pt) If the house were heated by natural gas, what would be the monthly cost for the natural gas?

6. *Similar* to the TED talk of David MacKay, consider one lane of cars in a hypothetical roadway.

   - 60 miles per hour
   - 30 miles per gallon
   - 2000 liters of biofuel per hectare per year
   - 200 meters car spacing

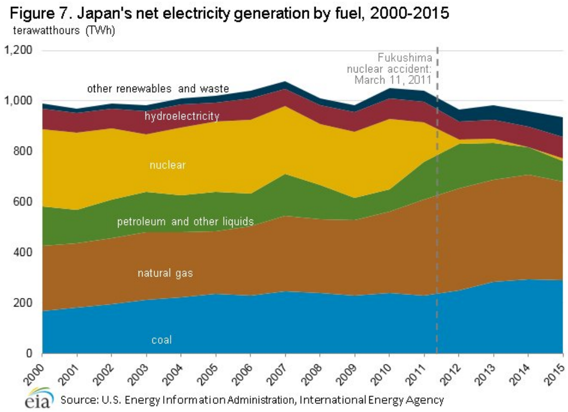
   (a) (1 pt) What is the rate of fuel consumption in a car, in units of $\ell\ \mathrm{hr}^{-1}$?

   (b) (2 pt) What is the rate of biofuel production in units of $\ell\ \mathrm{hr}^{-1}\ \mathrm{m}^{-2}$.

   (c) (5 pt) If the biofuel is grown in a plantation stretching along the border of the highway, how wide would it need to be to supply the fuel for the cars?

   (d) (2 pt) Assume the biofuel has an energy density of 22 $\mathrm{MJ}\ \ell^{-1}$. What is the power density of fuel production in units of $\mathrm{W}\ \mathrm{m}^{-2}$?

7.



In the Wikipedia we can see plots that show, in year 2015, the annual U.S. wind energy generation was 190,027,000 MWh, and the U.S. wind generation capacity was 82,183 megawatts. The plot to the left is labeled "terawatthours (TWh)". But, for clarity, it could be TWh y^{-1}. The "tera" prefix, or T, means 10^{12}.

(a) (2 pt) On average, how many gigawatts of wind power was being produced in the U.S. in 2015?

(b) (2 pt) How many nuclear power plants is that equivalent to?

(c) (3 pt) What was the average *capacity factor of US wind* installations?

(d) (3 pt) How did the U.S. wind power production compare with power lost from nuclear power plants in Japan?

3 Test 3 material, answer 2 questions

8.

You may need these numbers:

T (K)	σT^4 (W m^{-2})
242	194.47
288	390.80
243	197.70
289	395.53

In the image for the previous question, the infrared radiation coming out the top of atmosphere is a blend of radiation streams from layers of various temperature. To model the effect of increased greenhouse gases on global warming, we postulate two layers, a warmer surface of temperature T_s and a cooler upper atmosphere of temperature T_a. A simple model of the blending is

$$F\uparrow = (1-\epsilon)\sigma T_s^4 + \epsilon\sigma T_a^4$$

To model pre-industrial conditions we take $T_s = 288$ K, $T_a = 242$ K, and $\epsilon = .78$.

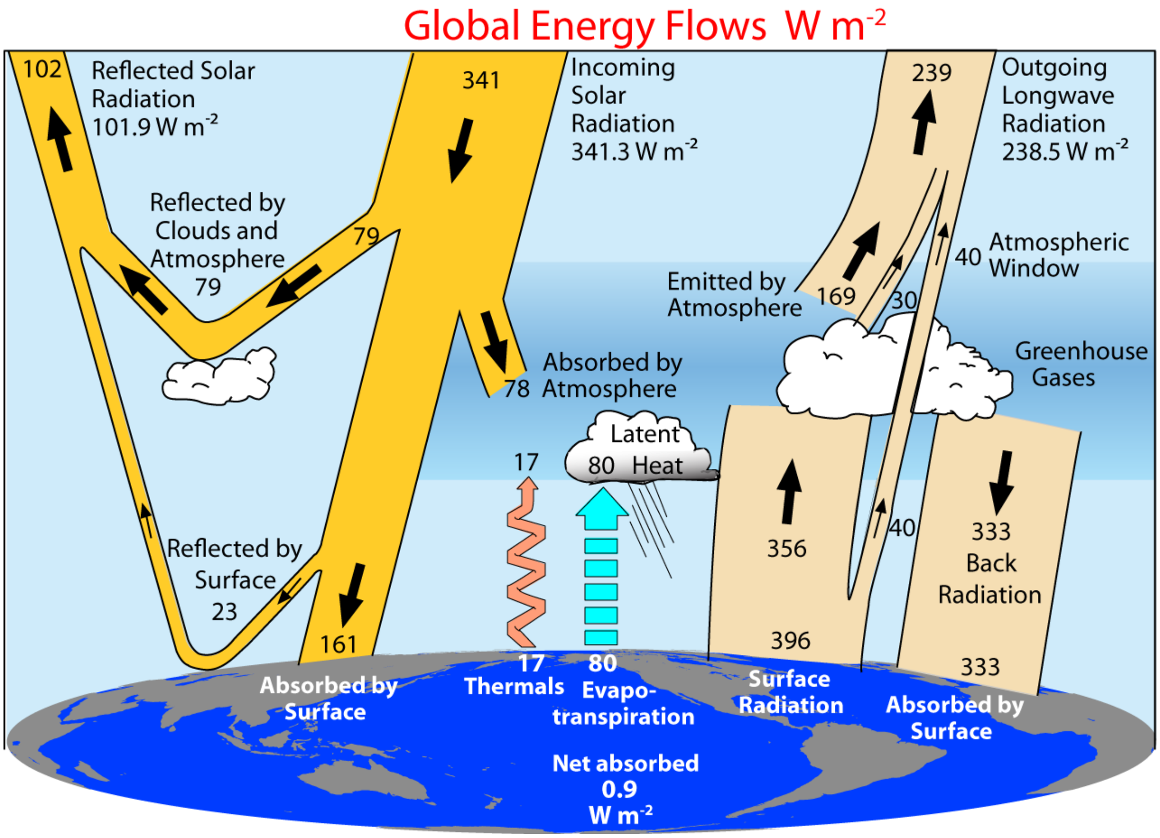
(a) (2 pt) Calculate $F\uparrow$ in pre-industrial conditions. *This number will be assumed to be in radiative equilibrium with the net incoming solar radiation.*

(b) (2 pt) If both T_a and T_s increase by 1 K from the pre-industrial values, by how much does $F\uparrow$ increase? The number you get will have units of W m^{-2} K^{-1}.

(c) (2 pt) It is claimed that a **octupling** of CO_2 would change ϵ to 0.84. Suppose this was done instantly, with no change in T_s or T_a from the pre-industrial values. What would be the value of $F\uparrow$?

(d) (4 pt) Use your answers in (a), (b) and (c) to estimate what the new radiative equilibrium temperatures would be for T_a and T_s, after the atmosphere and surface warm up in response to the increase of CO_2.

9.



(a) (2 pt) If the 239 W m^{-2} of outward infrared (or longwave) radiation is consistent with $F = \sigma T^4$ where T is some sort of average temperature of all the atmospheric layers and surface, what is the temperature T in degrees K, C and F?

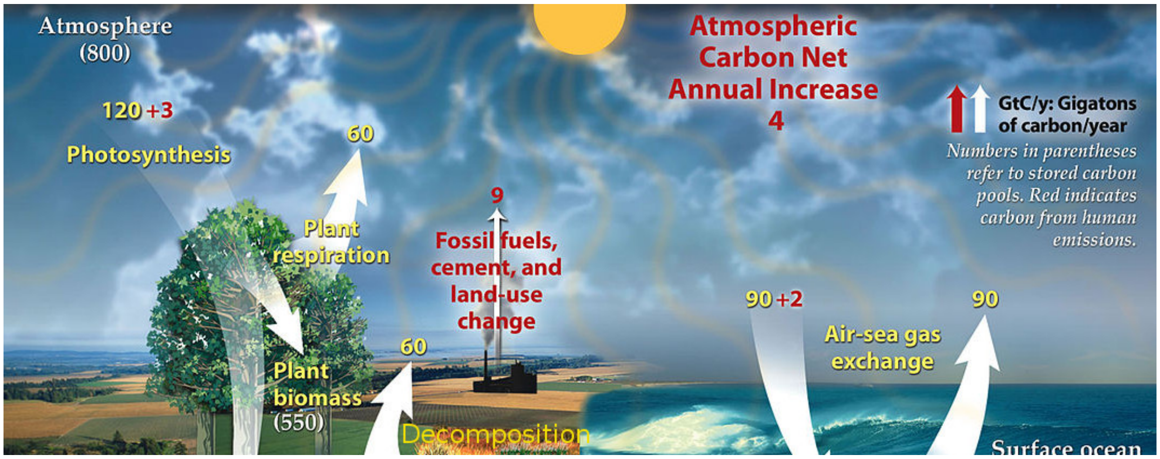
(b) (2 pt) If the 396 W m^{-2} of Surface Radiation is consistent with $F = \sigma T^4$ where T is the surface temperature, what is this temperature T in degrees K?

(c) (2 pt) If the Surface Radiation increased to 397 W m^{-2}, the ocean could be in thermal equilibrium. What would be the surface temperature T in degrees K?

(d) (2 pt) Suppose still more CO_2 is added to the atmosphere, and the Earth surface comes into radiative equilibrium after the oceans and surface warm up. In the new equilibrium suppose "Back Radiation" is 337, and "Evapotranspiration" is 81, "Thermals" is 17 and "Absorbed by Surface" is 161. What would the value of "Surface Radiation" be?

(e) (2 pt) Suppose a global observing program frequently samples temperature in the oceans to a depth of 2000 m. By looking at the temperature changes, it is deduced that the ocean heat content is increasing at 10^{22} J y^{-1}. Calculate the average W m^{-2} into oceans that could cause this temperature increase.

10.



(a) (1 pt) If current trends continue how many more years elapse before there would be **1600** GtC in the atmosphere?

(b) (1 pt) In a *Keeling curve*, the concentration of CO_2 in the atmosphere is measured in "parts per million", or ppm. The current concentration of CO_2 is 400 ppm. Inferring (or scaling) from this diagram, by how many ppm is CO_2 increasing every year?

(c) (1 pt) If all emitted CO_2 were remaining in the atmosphere, by how many ppm would CO_2 be increasing every year?

(d) (1 pt) From a number in this diagram, calculate how many kilograms of C are above every square meter of Earth. The area of Earth is 5×10^{14} m^2.

(e) (1 pt) From the previous answer, and the amu values for carbon and oxygen, how many kilograms of CO_2 are above every square meter of Earth?

(f) (3 pt) Suppose 1 ton of carbon from the atmosphere can make 1.16 ton of oil equivalent (toe), as woody biomass (which might weigh 2 tons, BTW). How many quad of energy is being stored by 63 GtC of photosynthesis every year? Compare that number with the quad used annually by the USA.

(g) (2 pt) Combusting biofuels for energy, rather then coal, is claimed not to increase CO_2 in the atmosphere. Why?