ATM 211: Climate and Climate Change – Review for Midterm (Weeks 1-5)

General

Bring a calculator to the exam.
Be able to read and interpret information from graphs (see examples in homeworks)

Week 1: Earth System and Global Change

Readings: KKC Chap 1 (all), Popper article
Terms and concepts you are expected to know

anthropogenic vs natural, atmosphere/biosphere/hydrosphere/lithosphere (components of Earth system), carbon dioxide (CO2), climate vs weather (the former is the average weather over decades or more), critical rationalism (Popper's theory that all knowledge is merely a guess at the truth and that our understanding advances only through criticism and testing of existing knowledge), Earth system science (studying the earth as a coupled system), forcing a coupled system (vs simple cause-effect), fossil fuels, Gaia hypothesis, GAAST (global-annual-average surface temperature), glacial period vs interglacial period (hint: we are presently in an interglacial period), global warming vs greenhouse effect, greenhouse gases (GHGs), ozone (O_3), ozone hole, ozone layer, photosynthesis, solar luminosity, weather vs climate

Types of questions to expect

1. Burning fossil fuels transfers carbon between what two reservoirs and what two chemical forms?
2. Name three global-scale changes in the Earth system that occurred before humans.
3. Name three global-scale, environmental problems of modern times that appear to result from human activities. What is the timescale associated with recovering from each of these problems?
4. Even though thermometers have been used to make regular temperature measurements for more that 150 years, give three reasons why it is difficult to determine accurately the long-term temperature trend for the globe.
5. Why did the TOMS satellite, which was launched in 1979 to monitor stratospheric ozone, fail to detect the ozone hole that developed over Antarctica in the early 1980's?
6. In Popper's view, some sources of knowledge have *greater* authority than others (for example, our course textbook compared to a tabloid newpaper), but no source of knowledge has *ultimate* authority. Explain what he means by this.
7. How do we know that atmospheric CO_2 is increasing and that this increase is almost certainly due to human activity?
8. How do we know that the atmospheric concentration of CO_2 changes between glacial and interglacial eras? Is CO_2 lower or higher during glacial eras?
9. Distinguish "a change in weather" from "a change in climate". Mention at least three observable properties that are involved in both. Discuss the ease or difficulty of knowing if you have observed a change.

Selected answers:

1. Fossil fuel burning transfers organic carbon from the lithosphere (rocks) to carbon dioxide gas in the atmosphere.
2. Chapter 1 discusses (i) ice-ages, (ii) mass extinction events, (iii) increase of solar luminosity by about 30% over the past 4 billion years. (Each of these show that global change - even drastic change - is natural for the Earth system.)

Week 2: Earth-System Example - Stratospheric Ozone and CFC's

Readings: KKC Chap 14 (all)

Terms and concepts you are expected to know

atmospheric lifetime (or residence time), catalyst, column ozone depth, Dobson unit (DU), dynamic equilibrium, CFCs (or freons), heterogeneous reaction, Montreal Protocol (1987) , odd oxygen ($O_X = O3 + O$), photolysis, polar vortex, polar stratospheric clouds, ultraviolet (UV) radiation (especially UVB)

Chemical reactions

oxygen-only cycle (4 reactions, Table 14-2)
chlorine catalytic cycle (2 reactions, p.285)
Note: You do not need to memorize these reactions, but you should recognize and understand them. Also, you should know how to add reactions to calculate the net reaction

Types of questions to expect

1. Why does temperature increase with height in the stratosphere? What consequence does this have for vertical stability in the stratosphere?
2. On a clear day, what two factors control the flux of UVB radiation reaching the surface?
3. What latitude region has the lowest column ozone depth on average?
4. Why does the photolysis of O_2 represent a source of ozone, even though no ozone is directly created? (Your answer should discuss odd-oxygen.)
5. List the three species that cause catalytic ozone destruction in the stratosphere.
6. Describe the anthropogenic sources of these catalysts, giving both the chemical form of the source species in the troposphere and the human activity that leads to the creation of this source material.
7. CFCs are extremely inert and stable in the troposphere. What process breaks these molecules apart in the stratosphere, thereby liberating reactive Cl?
8. What is the connection between polar stratospheric clouds and heterogeneous reactions?
9. Briefly describe the significance of the Montreal Protocol. What year was it signed? What atmospheric discovery occurred just two years earlier?
10. Why is it difficult to detect trends in global ozone column depth at mid-latitudes?
11. Why is it logical that solar brightness changes might cause stratospheric ozone to change?
12. Consider the oxygen-only reactions from Table 14-2. Which reactions are fast and which are slow? Which reaction represents the production of odd-oxygen? Which reaction is primarily responsible for protecting the Earth's surface from UVB radiation? Which reaction can be catalyzed by the presence of reactive chlorine?
13. Why does a strong polar vortex form over the Antarctica in the winter while the winter polar vortex over the Arctic is much weaker?
14. Identify which of the following chemical species are highly stable in the atmosphere and which are highly reactive or unstable: O, O_2, O_3, NO, N_2
15. Identify which of the following chlorine species are highly reactive, representing a threat to stratospheric ozone, and which are relatively inert? HCl, ClO, Cl, $ClONO_2$
16. What is the atmospheric lifetime of CFC-12? How is this man-made species eventually removed from the atmosphere?

17. True or false: The longer the atmospheric lifetime of a species, the more quickly it will respond to a reduction in emissions.
18. Calculations in the 1970's predicted that chlorine in the stratosphere from CFC's would cause only a modest loss of ozone. These calculations failed to consider heterogeneous reactions. Explain the role that heterogeneous reactions play in creating the ozone hole over Antarctica. Be sure to discuss the reactive and unreactive forms of chlorine.
19. Explain how ozone in the stratosphere makes it possible for there to be life on land.

Selected answers:

5. chlorine (Cl), bromine (Br), odd-nitrogen (NO)
6. The source for Cl is freons or CFCs that are used as refrigerants and blowing agents. The source for Br is halons that are used in fire extinguishers. The source for odd nitrogen is nitrous oxide, N_2O, that results from nitrate fertilization.
8. PSCs provide a surface on which heterogeous reactions can take place.
10. because of the large seasonal cycle in ozone column depth at mid-latitudes
11. Ozone equilibrium is maintained by a series of reactions which are largely driven by photolysis, or the breaking apart of molecules by UV radiation from the sun. Thus, if UV flux were to change, it is logical that ozone concentration would change.
16. Approximately 100 years. Destroyed by photolysis in the stratosphere.
17. False.

Week 3: The Science of Systems

Readings: KKC Chap 2 (all), Mann and Jones (2003) article

Terms and concepts you are expected to know

albedo, component (of a system), coupling (positive or negative), dependent variable, equilibrium (stable or unstable), feedback loop (positive or negative), forcing, GAAST, independent variable, perturbation, state (of a system), system diagram

Equations

Note: Equations with a box around them should be memorized. You should understand and be able to use the others, but do not need to memorize them.

Albedo

The fraction of light reflected by a surface. In terms of a planet, the albedo is the fraction of sunlight (or solar energy) that is reflected back out to space – i.e. that is not absorbed by the planet.

$$\boxed{A = \frac{E_{reflected}}{E_{total}}} \quad \text{so} \quad \boxed{(1 - A) = \frac{E_{absorbed}}{E_{total}}}$$

where E_{total} is the total light impinging upon the surface or planet.

Global Energy Balance

for a planet which is neither warming nor cooling

$$\boxed{E_{IN} = E_{OUT}}$$

where, E_{IN} is the shortwave, solar radiation (a form of energy) absorbed and E_{OUT} is the longwave, infrared radiation emitted by the planet (both in units of W/m^2)

Functions

$y = f(x)$, here x is the independent variable and y is the dependent variable (in words, we would say, "y is a function of x" or "y depends upon x")

Types of questions to expect

1. Name three ways that global climate could change without changing GAAST.
2. The basic energy balance equation for a planet is $E_{IN} = E_{OUT}$. Does the albedo of a planet relate to the E_{IN} term or the E_{OUT} term?
3. How does the biosphere of Daisyworld affect global climate? How does the climate of Daisyworld affect the biosphere?
4. Explain how the Daisyworld example illustrates a planet with a self-regulating climate. Are there limits to its capacity for self-regulation?
5. Be able to draw and interpret system diagrams.
6. The albedo of a planet is 0.07. What fraction of incoming light energy is absorbed by this planet?

Selected answers:

1. (i) geographical distribution of temperature could change - e.g. the Southern Hemisphere warms and the Northern Hemisphere cools, land gets warmer and oceans get cooler, (ii) temporal distribution of temperature could change - e.g. days get warmer and nights get cooler, summers get warmer and winters get cooler, (iii) a climate variable other than temperature could change - e.g. rainfall or windiness or frequency of intense storms.

<u>Week 4-5: Greenhouse Effect, Climate Change, Climate Modeling</u>

Readings: KKC Chap 3 (all), Lorius et al. (1990) article, Modeling Chap from KKC 2003

Terms and concepts you are expected to know

absorption, reflection, transmission of radiation

albedo: fraction of incoming radiation that is reflected (see Week 3)

blackbody radiation: a "blackbody" is an ideal case. It emits radiation exactly according to the Stephan-Boltzmann Law (see Equations). Thus, the S-B Law is an approximation for real objects, but a very good one in most cases.

climate forcing: an imposed change in planetary energy balance (W/m^2)

climate feedback, feedback factor, climate sensitivity: (see Equations) Main feedbacks for Earth are those associated with water vapor, ice-albedo, and clouds

climate model: a mathematical representation of the present state of the Earth-atmosphere-ocean system and of the processes that govern how it changes over time or how it changes in response to a *climate forcing*. Climate models range in complexity from simple box models (e.g. Daisyworld) to full-blown 3-dimensional models, often called *General Circulation Models* (GCMs).

effective radiating temperature of Earth, T_e: temperature that an ideal blackbody would have if it emitted the same amount of infrared energy as the Earth

Kelvin temperature scale (absolute temperature scale)

clouds, local energy balance, and cloud feedback: Clouds affect both SW energy (cooling effect) and LW energy (heat-trapping or warming effect). They have a net heating or cooling effect depending on which dominates. In general, high-altitude clouds warm and and low-altitude clouds cool. Thus, the cloud feedback depends largely on whether the mix of high and low clouds will change in a warmer world.

molecular absorption bands: Why certain molecules are able to absorb infrared radiation. Involves molecular symmetry. If the molecule can vibrate or rotate in a way that moves electrical charges about, then it can absorb energy from the electromagnetic waves. Key examples are the 15-µm CO_2 vibrational absorption band and the 12-µm H_2O rotational absorption band. (µm: 1 millionth of a meter)

shortwave vs longwave (or infrared) radiation

atmospheric structure: *lapse rate, troposphere, stratosphere, pressure* (weight of air overhead)

atmospheric composition: *major constituents, trace constituents, greenhouse gases, water vapor and relative humidity*

visible vs infrared satellite images

Equations

Note: Equations with a box around them should be memorized. You should understand and be able to use the others, but do not need to memorize them. [You do not need to memorize the Stefan-Boltzmann constant, 5.67e-8.]

Kelvin Temperature (absolute temperature scale):

$$\boxed{T\,(K) = T(^\circ C) + 273}$$

Solar energy absorbed by Earth-atmosphere system (cf text p 41-42)

First, energy per unit surface area (or flux) is

$$E\,(W/m^2) = \frac{\text{total energy (Watts)}}{\text{surface area (meters squared)}}$$

Then, the solar energy absorbed per unit Earth surface area is,

$$\boxed{E_{IN} = \frac{S_0}{4}(1 - A) = \frac{1370}{4}(1 - 0.30) = 240\,(W/m^2)}$$

where, S_0 is the solar constant (1370 W/m^2), 4 is a geometrical factor to convert from the area of a circle to the surface area of a sphere, and A is the planetary albedo (fraction of sunlight reflected to space – about 0.30 for the Earth).

Note: This quantity (240 W/m^2) is the average energy flux into and out of the Earth-Atmosphere system. It is a key property of the planet. (For some reason, the text never quantifies it.)

Energy emitted by a blackbody: Stephan-Boltzmann Law

$$\boxed{E = \sigma T^4}$$

where E is the energy emitted in W/m^2, T is the temperature of the body in degrees Kelvin (K) and σ is the Stephan-Boltzmann constant (5.67×10^{-8})

Demonstration and Quantification of the Greenhouse Effect (cf text p. 41-42)

Now we can calculate the *effective radiating temperature* of the Earth, T_e – that is, the temperature of a blackbody that would produce the amount of energy radiated by Earth. According to the S-B Law, the energy emitted by the Earth-atmosphere system is,

$$E_{OUT} = \sigma T_e^4$$

and, by energy balance (that is, E_{OUT} must equal E_{IN} at equilibrium):

$$E_{OUT} = E_{IN} = 240\,(W/m^2)$$

Allowing us to solve for the T_e (using a bit of algebra):

$$T_e = \left(\frac{E_{IN}}{\sigma}\right)^{1/4} = \left(\frac{240}{5.67 \times 10^{-8}}\right)^{0.25} = 255.1\,(K)$$

This effective radiating temperature (255 Kelvin or -18°C, well below freezing) is a real property of the planet, but is obviously not the same as the average surface temperature, T_s (15°C, well above freezing). The greenhouse effect can be quantified as, ΔT_g:

$$\boxed{\Delta T_g = T_s - T_e} \qquad [\Delta T_g = 33K \text{ for Earth}]$$

The fact that the global-annual average surface temperature is 33K warmer than the planetary equilibrium temperature demonstrates significant heat-trapping by greenhouse gases in the Earth's atmosphere.

Climate sensitivity and the *feedback factor* (supplements text discussion of feedbacks):

The *feedback factor*, f, and *climate sensitivity*, λ, are equivalent ways of talking about how much the Earth's surface temperature will change for a given amount of *climate forcing*. The feedback factor is somewhat simpler and provides a better intuitive grasp (which is why the text uses this concept) but climate sensitivity is the term used in most of the scientific literature.

The *feedback factor* is defined by,

$$\boxed{f = \Delta T_{eq} / \Delta T_0}$$

or, equivalently,

$$\boxed{\Delta T_{eq} = f \; \Delta T_0} \qquad \text{(cf equation on p. 51 of text)}$$

where ΔT_0 is the initial temperature change that follows from the Stefan-Boltzmann Law and ΔT_{eq} is the eventual temperature change that occurs once all the Earth's feedbacks have played themselves out. Note that $f = 1$ for the case of no-feedbacks, $f < 1$ for the case of negative feedbacks (the system acts to dampen the initial temperature change), and $f > 1$ for the case of positive feedbacks (the system acts to amplify the initial temperature change.)

The *climate sensitivity* parameter, λ, is defined by,

$$\boxed{\Delta T_{eq} = \lambda \; \Delta F}$$

which is the fundamental equation relating climate forcing, ΔF (W/m^2), to climate response, ΔT_{eq} (K). We will be using this in our prediction of global temperature for the year 2050.

For doubled CO_2, we have said that the forcing, ΔF, is 4 W/m^2 and the initial, no-feedback temperature change, ΔT_0, is 1.2K. From this we can calculate climate sensitivity for the no-feedback case, which we can label, λ_0:

$$\lambda_0 = \Delta T_0 / \Delta F = 1.2K / 4W/m^2 = 0.3 \; \{K/(W/m^2)\}$$

That is, if the Earth behaved as a simple blackbody, we could expect a temperature change of 0.3K for every $1W/m^2$ of forcing.

Types of questions to expect

1. Give two practical reasons why T_s (the average surface temperature of Earth) is of more concern than T_e (the effective radiating temperature of Earth)?
2. How can high and low clouds be distinguished on an infrared satellite image?
3. What are the three main feedbacks at play in the Earth's climate system? For each one, state whether it involves primarily SW energy, LW energy, or both.
4. What are the four ways that radiation and matter interact?
5. Draw a system diagram for the ice-albedo feedback.
6. The average temperature of the Earth is 15°C. Express this in degrees-Kelvin. How much energy per square meter is emitted by the Earth's surface? (Hint: the Stefan-Boltzmann constant is 5.67e-8.)

7. What is the major greenhouse gas in the Earth's atmosphere? Is the Earth's greenhouse effect entirely due to gases? If not, what other constituent of the atmosphere is involved?
8. Which has more heat-trapping capacity: a high-altitude thin cloud or a low-altitude thick cloud? Which of these has a larger effect on the SW energy budget?
9. From a graph of the temperature structure of the atmosphere (e.g. Fig 3-9b), label the troposphere and the stratosphere. State which one has more vertical stability and explain why.
10. From a graph of atmospheric pressure vs height (e.g. Fig 3-9a), state the altitude at which you would be above 90% of the mass of the atmosphere?
11. What two gases comprise 99% of the dry mass of the atmosphere? Which of these two gases (if either) contributes to the Earth's greenhouse effect?
12. True or false: A low-altitude, thick cloud has a net warming effect on the local energy budget.
13. Explain why the water-vapor feedback is thought to be positive.
14. Explain why the cloud-feedback is extremely uncertain. Discuss high clouds, low clouds, LW effects, SW effects, and climate models. [This could be an essay question.]
15. Say that a climate model predicts that the equilibrium change in surface temperature, ΔT_{eq}, for doubled CO_2 is 0.6 K. We know that the initial, no-feedback response for doubled CO_2, ΔT_0, is 1.2 K. What is the feedback factor for this climate model? For this model, does the Earth's climate system constitute an overall positive or negative feedback loop?

Selected answers:

1. (i) Almost all life exists at the surface and experiences the temperature at the surface. (ii) The surface temperature controls many important physical aspects of the climate, such as the rate of evaporation from the ocean and the amount of snow cover and sea-ice cover.
2. Emission depends on temperature at top of cloud. High clouds are colder and so emit much less than low clouds. The shading on an infrared satellite image is such that warm surfaces are darker and cold surfaces are whiter. The ocean surface shows up almost black, low clouds are dark grey, and high clouds are bright white.
6. 15°C = 288K. Emission = $5.67e{-8} * 288^4 = 390$ W/m^2
10. You are above 90% of the mass of the atmosphere when pressure has dropped to 10% of its sea-level value. This occurs at about 15 km.
13. If the surface warms (especially, the surface of the ocean), this will cause more evaporation and thus more water vapor in the atmosphere. Water vapor is a powerful greenhouse gas. Therefore, this will cause the greenhouse effect to be increased, which will cause further warming of the surface. Thus, the initial warming will be amplified.
15. f = 0.5. overall feedback loop is negative (dampens the initial temperature change)

A few handy numbers

Properties of water

freezing point	273K or 0°C
boiling point	373K or 100°C

GAAST: global-annual-average surface temperature (our key climate index) or T_s

Present value	288K or 15°C

The natural greenhouse effect causes GAAST to be 33°C warmer than it would be without an atmosphere.

Observed change in GAAST over last century	+0.6°C
Predicted change in GAAST over this century	+1.5 to +4.5°C
Change in GAAST associated with ice-age	about –5°C

Energy flowing through the Earth Climate System ($E_{IN} = E_{OUT}$ at equilibrium)

Energy flux at present	240 W/m^2
Doubled-CO_2 is an imposed change (forcing) of [equivalent to turning up the sun by ~2%]	4 W/m^2 (or ~2% change)