ATM 211: Climate and Climate Change – Review for Final

General
Bring a calculator to the final exam
Be able to read and interpret information from graphs (see examples in homeworks)
Format will be the same as the midterm, but somewhat longer.
Class website: http://www.atmos.washington.edu/2003Q4/211/

Weeks 1-5:
See "Review for Midterm" handout. *Final exam covers entire course.* However, the second half of the course will be emphasized. The essay questions and problems will come from the second half of the course.

Week 6: Earth Circulations and Regional Climates
Readings:
Atmospheric circulations: KKC Chap 4(all)
Ocean KKC Chap 5(p79-top82, p85 (last paragraph), p88-95, Key Figs 5-2, 5-3, 5-8, 5-14, 5-16)
Solid Earth: KKC Chap 6(p97-98:Intro/Overview, p116-117:Plate Tectonics driven by radioactive decay, p123-125:Wilson Cycles of continental drift; Key Figs 6-19, 6-21, 6-26, 6-27)

Terms and concepts you are expected to know
Overview... 3 BIG pumps: (i) Atmosphere/Surface-Ocean redistributed solar energy from Tropics to higher latitudes on timescale of weeks to months, (ii) thermohaline circulation (THC) driven by density gradients mixing the deep ocean on a timescale of about 1000 years, (iii) Wilson Cycle of plate tectonics, driven by radioactive decay in the Earth's interior, causes continents to move about, coming together into a super-continent then spreading apart with a timescale of about 500 million years. All three serve to redistribute energy and to mix and recycle material within the Earth system. We focus most attention on (i).
Key concepts for Atmospheric circulations:

Physical Fundamentals	Environmental Phenomena
Cause of vertical motions: - buoyancy (density variations) Cause of horizontal motions: - pressure gradient force then, motion modified by: - friction at the surface - Coriolis force Horizontal motions described by: - convergence/divergence Vertical motions described by: - convection/subsidence Why "circulation"? - Law of Conservation of Mass Evaporation/condensation: - latent heat (lots of energy!) Thermal inertial, thermal lag	Global/seasonal distribution of surface temperature Hadley circulation in tropics: ITCZ tradewinds subtropical deserts Land/Sea breezes and Monsoons Extratopical circulations: pressure waves, fronts prevailing westerlies in midlatitudes warm (tropical) air masses cold (arctic) air masses

Key concepts for Ocean circulations: friction at air/water interface, ocean mixed layer (or surface layer), salinity, thermal expansion of water, density, thermohaline circulation (THC)
Key concepts for Solid Earth circulations: radioactive decay, Wilson cycle, plate tectonics, continental crust, oceanic crust
Layout of the Earth: Know the latitude ranges associated with the Tropics, Extratropics, Subtropics, Midlatitudes, and Polar Regions. Know where on earth to expect Trade Winds and where to expect Westerly winds.

Some selected definitions and explanations:
Land/water contrast: land surface changes temperature quickly (e.g. heats up during the day) while ocean surface changes temperature very slowly (little change even between summer and winter). Why? (Be sure you know.) This sets up temperature differences that drive both land/sea breezes along coasts and drive the tropical monsoons.

Intertropical Convergence Zone (ITCZ): band of deep convection circling the Earth near the equator. Part of the Hadley circulation. A dominant feature of the planet that plays a major role in the transport of moisture and energy.

Surface-Ocean Currents: Wind-driven currents arising from friction of air moving over the water. Follow the mean wind direction except deflected by the Coriolis Force and modified by land boundaries. Important effects of these currents include: warm and cold currents (affect coastal climates); transport of heat energy poleward; turbulent mixing of surface layer of ocean.

Stratosphere: In the context of atmospheric circulations, the stratosphere acts as a lid or upper boundary on deep convection (e.g. the Hadley circulation).

Convection: rising air (favors cloud formation)

Subsidence: sinking air (suppresses cloud formation)

Latent heat: The energy associated with changing liquid water to water vapor. It is huge. For example, it takes 2 Joules of energy to heat 1 gram of liquid water by 1°C, but to convert it to water vapor takes 2500 Joules.

Subtropical dry belt: The Hadley circulation involves convection near the equator – thus massive thunderstorms – and subsidence in the general vicinity of 30° latitude. Subsiding air warms, thus inhibiting the formation of clouds, especially rain clouds. Thus, the major deserts of the world are located in this general vicinity.

Thermal inertia: Ability of a body to resist changes in temperature.

Turbulent mixing: A moving fluid (air or water) frequently contains small, turbulent eddies within it. This is true of winds, especially near the surface and of the surface ocean currents. Turbulent eddies cause mixing. For example, they mix heat from the sun to depths of several 10's of meters in the ocean.

Trade winds: prevailing easterly winds (from the east) in the tropics

Westerlies: prevailing westerly (from the west) winds in midlatitudes

Salinity: concentration of dissolved material in ocean water; main solutes are sodium (Na) and chloride (Cl), which is why ocean water tastes "salty" (table salt is NaCl).

Types of questions to expect:

1. Explain why more solar energy is absorbed at low (i.e. tropical) latitudes than at high (i.e. polar) latitudes. Explain why more longwave (infrared) energy is emitted at low latitudes than at high latitudes.
2. Describe the Hadley circulation and the features of global climate that it explains (long-essay).
3. What is the most important reason that the ocean surface changes temperature much more slowly than the land surface?
4. What does "friction" have to due with the circulation of surface water in the global oceans?
5. What two factors control the density of ocean water. For each factor, state which way it changes in order for water density to go up.
6. (a) What process occurs in the North Atlantic region that is of key importance to the thermohaline circulation (THC)? (b) How might massive glacial melting disrupt this process and shut off the THC?
7. List the types of regions on Earth where the annual temperature range is especially small and especially large? Explain why in terms of two factors.
8. Explain the role of latent heat in how the Hadley circulation redistributes energy.

Selected answers:

1-5. see HW 4 key

6. (a) The North Atlantic is a region where cold, saline (and therefore very dense) water forms. This dense water tends to sink to great depths, initiating the thermohaline circulation. (b) Melting glaciers would constitute an input of fresh water to this region. Fresh water is less dense, so this might keep the surface water from sinking.
7. Annual temperature range is small in tropics, over oceans, along coasts; far greater over the interior of high-latitude continents. Why? Seasonal changes in energy from sun are greater at high latitudes; thermal inertial for land is low but for oceans is very high.
8. Water evaporating from the ocean carries an enormous flux of energy upward in the form of latent heat – far more than is carried up in the form of sensible heat. Recall Fig. 3-19, "thermal" vs "evaporation" terms. Latent heat is released when the water vapor recondenses as cloud droplets. This release of heat increases the buoyancy of the cloud, encouraging it to continue rising. Thus, latent heat is a dominant factor in the creation of deep, convective clouds like the cumulonimbus clouds at the ITCZ. The net effect is to transport energy from the surface high into the atmosphere. Because the upper air motion in the Hadley circulation is poleward, much of this energy is transported from low latitudes to higher latitudes.

Week 7: Ancient Climates

Readings:

Topic (Book Section)	pages	Figures
Introduction/Overview	8:152-153	8-1
Formation of Early Atmosphere	8:158-159	8-7
Faint Young Sun paradox	8:159-161	8-8, 8-9
Long Term Climate Record	8:161-164	8-10, 8-11
Low Latitude Glaciations Box	8:165	
Warm Mesozoic Era	8:167-169	8-15
Cooling During Cenozoic Era	8:169-170	8-17
Modern Controls on Atmos. O2	9:188-189	9-17

also: "Snowball Earth" article (get from class website)

Terms and concepts you are expected to know

eight marker events in Earth history and their dates (to be memorized), Faint Young Sun paradox, Mesozoic Warm Period, Cenozoic cooling, Snowball Earth (Late Proterozoic glaciations), buildup of atmospheric oxygen, fossil record, weathering, calcium carbonate sediments, carbonate and bicaronate ions (dissolved in water)

Types of questions to expect

1. Give the significance of each of the following dates from Earth history [for answers, see 2, below]: 4.6 billion ybp (years before present), ~4 billion ybp, ~2 billion ybp, 600-900 million ybp, 540 million ybp, 65 million ybp, ~3 million ybp, 10,000 ybp
2. When did each of the following major events in Earth history take place [for answers, see 1, above]: formation of planet Earth, origin of life, atmospheric oxygen rises to essentially modern levels, global glaciations of the Late Proterozoic (Snowball Earth), Cambrian explosion of multicellular life and beginning of fossil record, extinction of dinosaurs by asteroid impact, beginning of Pleistocene glaciations, end of the most recent ice-age
3. Consider the following term that might appear in a chemical reaction: $2HCO_3^-$ (a) how many hydrogen atoms are there? (b) how many oxygen atoms are there? (c) how many negative charges are there? (d) what is the chemical species?
4. What are the four lines of geological evidence discussed in the Hoffman and Schrag article that led scientists to propose the "Snowball Earth" hypothesis? Pick one of these lines of evidence and explain it in a few sentences.
5. Explain the Faint-Young Sun paradox, some proposed (but rejected) explanations, and the currently favored explanation. [This would be a long-essay question.]
6. Briefly explain how the Earth's atmosphere came to have such a high concentration of oxygen (21% of the atmosphere, at present).
7. Beyond the overall warmth, what is hard to explain about the distribution of temperatures around the globe during the warm Mesozoic era?

Selected answers:

3. (a) 2 hydrogens, (b) 6 oxygens, (c) 2 negative charges, (d) bicarbonate ion
4. see HW 5 key
5. [read 8:159-161] Points to include in your essay: The paradox is that solar energy was ~30% lower early in Earth's history, which should have caused average surface temperature to be well below freezing, yet there is clear evidence of photosynthetic life, so the surface ocean must not have been frozen. Possible explanations would be lower albedo, enhanced greenhouse effect, or enhanced geothermal energy. Of these, only enhanced greenhouse effect makes sense (explain why). Possible GHGs that might have been enhanced include water vapor, ammonia, and carbon dioxide. Of these, only CO_2 makes sense (explain why). The CO_2 concentration would have had to be MUCH higher than today – around 1000 times higher. Is this plausible? Yes. (explain why)
6. Early earth atmosphere was mostly CO_2 and had almost no oxygen. Photosynthetic life takes in atmospheric CO_2 and emits oxygen as a waste product. The oxygen built up slowly, taking roughly 2 billion years from the origin of life to the attainment of essentially modern levels of O_2 in the atmosphere.
7. [see Fig. 8-15] The equator-to-pole temperature difference was much less than today. That is, the tropics were somewhat warmer, but the high latitudes were far warmer than today. Part of this can be explained by the absence of polar ice caps (which, today, keep the polar regions cold due to their high albedo). But this is not a sufficient explanation. Thus, atmospheric and oceanic circulations must have been much more active and much more efficient at transferring heat from the tropics to the high latitudes. No one knows exactly why.

Week 8: Recent Climates and Climate Variability

Readings:

Topic (Book Section)	pages	Figures
Geological Evidence of glaciations	11:212-215	11-2, 11-3, 11-4
Milankovitch Cycles (orbital theory)	11:215-219	11-5, 11-7, 11-9
Glacial-climate feedbacks	11:219-221	11-10, 11-11
Time Scales of Change	12:229-232	12-1, 12-2
Volcanoes and Climate	12:236-240	12-6
Solar Variability	12:240-242	12-7, 12-8
El Nino-Southern Oscillation	12:244-247	12-10, 12-16

Terms and concepts you are expected to know

evidence of glaciations (glacial striations, erratics, U-shaped valleys, oxygen isotope record in ocean sediments), time scales of major climate or climate-related cycles (ENSO, solar cycle/sunspots, glaciations), orbital parameters (precession, tilt, eccentricity), orbital parameter theory of glaciations ("Milankovitch Cycles" in text)

Types of questions to expect

1. Explain how the following geological phenomena provide evidence of glaciations: glacial striations, erratics, U-shaped valleys.
2. Explain how the concentration of 'heavy' oxygen, ^{18}O, in ocean sediments provides a record of glacial ice volume.
3. Match each climate phenomenon with a time scale [2 pts each]
   Climate phenomena: ENSO, sunspots, ice ages, seasons, a single volcanic eruption
   Time scales: 1 year, 1-2 yrs, 2-10 yrs, 11 yrs, 40 yrs, 1000 yrs, 100,000 yrs
4. Discuss the orbital parameter theory of ice-ages in terms of (a) the proposed mechanism that explains the growth and melting of ice-sheets, (b) the evidence from ocean sediment records that supports this theory, and (c) the main weakness of the theory. [This would be a long essay question.]
5. How do volcanoes affect global climate? Explain why the time scale of the climate perturbation from a single volcanic eruption is 1-2 years. [12:236-240]
6. The following statements are climatic 'lessons' that derive from current knowledge of the Pleistocene glaciations. Briefly expand upon one of them:
   - The current climate is not the only possible one for Earth (indeed, glacial conditions seem to be preferred).
   - A change in global-average surface temperature of about -5C is associated with a massive shift in global climate.
   - Global climate and CO_2 appear to be intimately intertwined.
   - If the orbital parameter theory is right, small climatic triggers can produce major climate changes (at least under some conditions).
   - There are many remaining questions and enigmas concerning the ice-ages.
7. Match each question with the corresponding orbital parameter:
   Questions: (a) Is the earth's orbit nearly circular or highly elliptical? (b) Is there an large or a small difference between summer and winter? (c) Does Northern Hemisphere summer occur when earth is nearest to or farthest from the sun?
   Orbital parameters: obliquity (or, tilt of axis), precession, eccentricity
8. Explain the difference between "noise" and "signal" in a scientific measurement. Give examples illustrating how "noise" in one context can be "signal" in another context.
9. Explain what is meant by "precision" of a measurement.
10. What are the two sources of "noise" in the industrial-era temperature record that make it difficult to detect the "signal" of human-induced global warming? Give an example of each.
11. Justify the following statements: (a) "Correlation does not prove causation." (b) "Lack of correlation is strong evidence against a causal relationship."

Selected answers:

1. <u>glacial striations:</u> long scrapes etched in bedrock by rocks that were frozen into the bottom of a glacier and drug along as the ice flowed over the bedrock. <u>erratics:</u> isolated boulders found far from their source rock. Such boulders fell on top of the glacier and were transported by the moving ice. This is very decisive evidence because no other process (e.g. wind or flowing rivers) could account for the transport of single,

large boulders. U-shaped valleys: Normal weathering and rivers create V-shaped valleys. Advancing glaciers cut away at the sides, widening the valley into a U-shape.

2. [read 11:213-214 and see Fig 11-3] Lighter water (containing less of the heavy isotope, ^{18}O) evaporates more easily and is also transported to the polar regions more easily. Thus, as polar ice caps grow in volume, ocean water becomes progressively heavier (the water left behind has a higher fraction of ^{18}O.) Thus the sediments left by ocean life have more ^{18}O during glacial periods.
3. ENSO 2-10; sunspots 11; ice ages 100,000; seasons 1; volcanic eruption 1-2
4. [see Figure 11-9, surrounding text, and also the orbital parameter handout] Points to cover: (a) Proposed mechanism is a trigger involving the amount of solar energy received in summer in high-latitudes of the N. Hemisphere (where most land is and, therefore, most potential for growing or melting ice sheets). Orbital parameters do cause a change in this quantity and these changes could effect whether the winter snows do or do not last through the summer. This, in turn, could trigger a climate change by triggering the ice-albedo feedback. [Then show you understand the ice-albedo feedback.] (b) Evidence is that orbital parameters change with known frequencies (23 k.y., 41 k.y., 100 k.y.) and these same frequencies can be identified in the long-term record of glacial ice volume from ocean sediments. (c) The big weakness involves variations at the 100 k.y. time scale. This is the orbital parameter (eccentricity) with by far the least power (least change of solar energy to summer, high-latitude N. Hem.) but it accounts for the most variation in glacial ice volume, as evidenced by the ocean sediment record.
7. a: eccentricity; b: obliquity (or, tilt of axis); c: precession
8. Any measurement can be thought of as having two components: "signal", which arises from the phenomenon of interest, and "noise", which arises from anything else. In other words, "noise" is whatever gets in the way of accurate quantification of the thing you are trying to measure. Say you are making detailed measurements of solar energy from the Earth's surface. If you are interested in the Sun, then variations caused by the intervening atmosphere are "noise". But if you are interested in the atmosphere, then these same variations are your "signal" and variations causes by changes in the Sun would constitute "noise".
9. Precision expresses how well a measured or calculated quantity is actually known. The global-annual average surface temperature is known to a precision of about 0.1°C.
10. (i) measurement error (e.g. arising from incomplete global coverage and changing measurement methods), (ii) natural variability (e.g. internal climate variability or forced changes due to volcanoes or solar variations)
11. (a) Two phenomena may be correlated due to (i) pure coincidence or (ii) both are caused by a third, common factor. For example, wearing sunglasses does not cause sunburn, even though the two phenomena are highly correlated. Thus, the mere fact that x and y are correlated does not prove that x is the cause of y. (b) The hypothesis that x causes y can be tested by examining whether changes in x are associated with corresponding changes in y. This is a correlation test. While the existence of correlation does not prove that there is a causal connection, the absence of correlation is strong evidence against it. [This is an example of Karl Popper's point that science advances by disproof - that is, by eliminating erroneous ideas - rather than by positive proof.]

Weeks 9-11: Global Warming Science and Policy

Readings:

Organic Carbon Cycle KKC 7:128-138 (esp. short-term org. carbon cycle 133-138)
Science of Global Warming KKC 13 (all)
IPCC 2001 "Summary for Policymakers" [on website]
Seattle Times Pro/Con debate [on website]
Azar and Rodhe article, "Targets for CO2 Stabilization" [on website]

Terms and concepts you are expected to know

anthropogenic perturbation of the carbon cycle by burning fossil fuels, renewable energy, CO_2-fertilization (of terrestrial biosphere), equilibrium surface warming vs transient response, global climate model (or, general circulation model; GCM), thermal inertia (the text uses "thermal drag"), thermal expansion (of the oceans), GHGs (greenhouse gases), climate forcing by anthropogenic aerosols including their direct and indirect effects, carbon cycling vs permanent removal, major reservoirs of carbon (terrestrial biosphere, atmosphere, surface ocean, deep ocean, lithosphere), global warming vs regional response, climate forcing, climate sensitivity, detection and attribution of climate change, role of forests with respect to atmospheric CO_2

Chemical reactions

photosynthesis: $CO_2 + H_2O \rightarrow CH_2O + O_2$ [requires energy from the sun]
burning or respiration: $CH_2O + O_2 \rightarrow CO_2 + H_2O$ [the reverse; releases energy]

Equations

Residence Time (or Lifetime) of material cycling through a reservoir:

$$\boxed{\text{Residence Time} = \text{Burden / Flux}}$$

where: Burden means the amount of material present in the reservoir
Flux means the rate at which material is removed from the reservoir

Climate forecast equation

$$\boxed{\Delta T = \lambda * \Delta F * \text{lag\_factor}}$$

ΔT change in global average surface temperature at some specific time (e.g. the year 2050). Note that this is different from the long-term, equilibrium temperature change.

λ climate sensitivity

ΔF climate forcing or change in energy balance

lag_factor: a correction factor that converts from long-term, equilibrium temperature change to the actual temperature change at any given time. This can be estimated from "transient simulations" with climate models. For a steadily rising forcing (such as is expected over the coming century), the temperature change expected in a given year is about 0.66 times the equilibrium temperature change associated with the forcing in that year. Therefore, we set the lag_factor to about 0.66.

Types of questions to expect

1. Given the burden of material in one of the carbon reservoirs and the flux out of that reservoir, be able to calculate the residence time of carbon in that reservoir. Be able to compare residence times and discuss implications for atmospheric CO2 concentrations.
2. Name and give the chemical formula for the three major GHGs that are being emitted to the atmosphere by human activities.
3. The lifetime of carbon dioxide in the atmosphere is about 5 years. Why, then, do anthropogenic emissions of CO_2 cause a perturbation in atmospheric concentration that is expected to last for centuries or even thousands of years?
4. Make a climate forecast given values for forcing, climate sensitivity, and lag_factor. Or estimate climate sensitivity given values of forcing, temperature change, and lag_factor.
5. According to global warming predictions by global climate models, what regions of the world are predicted to warm the most?
6. What are the two causes of predicted sea-level rise?
7. GHGs affect the longwave energy budget. What anthropogenic perturbation to the atmosphere is thought to have caused a change in the shortwave energy budget? Explain.
8. What processes (fluxes) couple the following carbon reservoirs [see Fig. 13-1] (a) atmosphere and land, (b) atmosphere and surface-ocean, (c) surface-ocean and deep-ocean, (d) deep-ocean and lithosphere? (e) lithosphere and atmosphere?
9. If increased atmospheric CO_2 causes enhanced forest growth by the carbon fertilization effect, would this constitute a positive or negative feedback on the climate system?
11. What is the amount of change in global- annual-averaged surface temperature (GAAST) associated with (a) an ice age, (b) the past 1000 years, based on proxy records, (c) the past century, based on direct measurements, and (d) the next hundred years, based on the latest IPCC Scientific Assessment?
12. Describe the difference between stabilizing CO_2 emissions to the atmosphere and stabilizing CO_2 concentration in the atmosphere. Discuss in terms of both public policy and global climate change.
15. Give arguments for and against the reality/danger of global warming.
16. List and briefly describe some of the likely impacts of global warming, both in this region and around the world.
18. Distinguish the direct and indirect effects of anthropogenic aerosol particles on climate. Are these positive or negative forcings? Do they operate on the longwave or the shortwave portion of global energy budget?
19. (a) What is the range of projected temperature change by the year 2100 given in the third (2001) IPCC Scientific Assessment? (b) Between the second (1995) and third (2001) assessments, did the projections of warming by the year 2100 get higher or lower? (c) What is the main factor that accounted for this change?

Selected answers:

2. carbon dioxide (CO_2), methane (CH4), nitrous oxide (N_2O). [Note that human activities do not directly perturb the concentration of water vapor (H_2O).]
3. CO_2 cycles between the atmosphere and surface ocean rapidly (e.g. about 5 yr turnover of all CO_2 in atmosphere), but this cycling of carbon does not represent a permanent removal from the atmosphere. New

emissions (from fossil fuel burning) result in higher concentrations that are gradually diluted by mixing with the oceans and, finally, removed by being mixed back into the lithosphere via silicate weathering. Mixing with the deep ocean takes about 1000 years. Mixing back into the lithosphere takes millions of years.

5. High latitudes more than tropics and land areas more than the oceans (Fig 13-9).
6. Thermal expansion of the oceans and melting of continental ice sheets.
7. Anthropogenic aerosols are thought to have changed planetary albedo – that is, they are thought to have increased the amount of solar energy reflected back to space, thereby having a cooling effect that counteracts some portion of GHG warming.
9. CO_2 goes up, which causes enhanced growth of forests, which tends to draw atmospheric CO_2 back down. This is a negative feedback; it tends to dampen (rather than amplify) the climate effect.
11. (a) about -5°C, (b) about +/-0.5°C, (c) +0.6+/-0.2°C, (d) +1.4 to +5.8°C (IPCC, 2001)
12. Stabilizing emissions means stopping the current increase in emissions – that is, the entire world would have to learn to live with the same level of fossil fuel burning that we have right now. But this would result in ever-increasing CO_2 concentrations and continual warming of the climate. Stabilizing CO_2 concentration is the only way to stabilize the climate (even though it may take decades after CO_2 has stabilized for the climate to stabilize). However, stabilizing CO_2 concentration would require massive reductions in CO_2 emissions (e.g. around 80% reduction by the end of the century to stabilize at 2 times the preindustrial level of CO_2.) This would have to be achieved either by switching to non-fossil-fuel energy sources or by figuring out how to sequester and permanently store the CO_2 that results from fossil fuel combustion. [A tough challenge either way, but then, we humans are pretty creative and adaptable.]
18. Anthropogenic aerosols have a direct effect on climate by scattering sunlight back to space. They have an indirect effect by modifying the properties of clouds, causing more and smaller droplets, which also leads to more solar radiation being reflected back to space. In both cases, these are negative climate forcings (tending to cool the planet) that operate on the shortwave portion of the Earth's energy budget.
19. (a) 1.4 to 5.8 K (b) considerably higher (it was 1.0 to 3.5 K previously) (c) lower projected concentrations of sulfate aerosols, which have a cooling effect. The sulfate projections got lower because the previous projections implied deadly pollution levels that would not be tolerated even in poor, developing countries.

A few handy numbers

Key dates in Earth history (ybp=years before present)	
formation of Earth	4.6 billion ybp
life begins	~4 billion ybp
oxygen reaches levels similar to today	~2 billion ybp
global glaciations in Late Proterozoic (Snowball Earth)	600-900 million ybp
Cambrian explosion of multicellular life, beginning of fossil record	540 million ybp
asteroid impact, extinction of dinosaurs	65 million ybp
beginning of modern (Pleistocene) glaciations	3 million ybp
end of last ice-age	10,000 ybp
GAAST: global-annual-average surface temperature (our key climate index) or T_s	
[Note: the following is an update to the numbers given in the midterm review]	
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 +/- 0.2 °C
Predicted change in GAAST by 2100 (IPCC)	+1.4 to +5.8 °C
Change in GAAST associated with ice-age	about –5 °C
Natural changes in GAAST over last 1000 years	about +/-0.5 °C
Sea-level (another global index)	
Predicted change by 2100 (IPCC)	+0.1 to +0.9 m