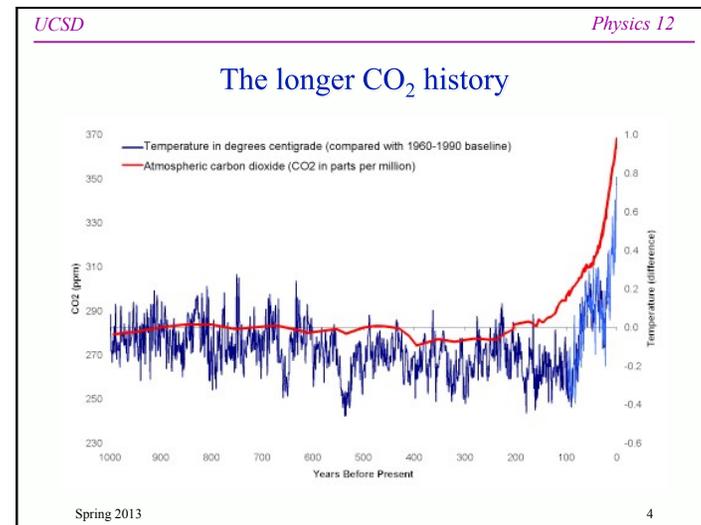
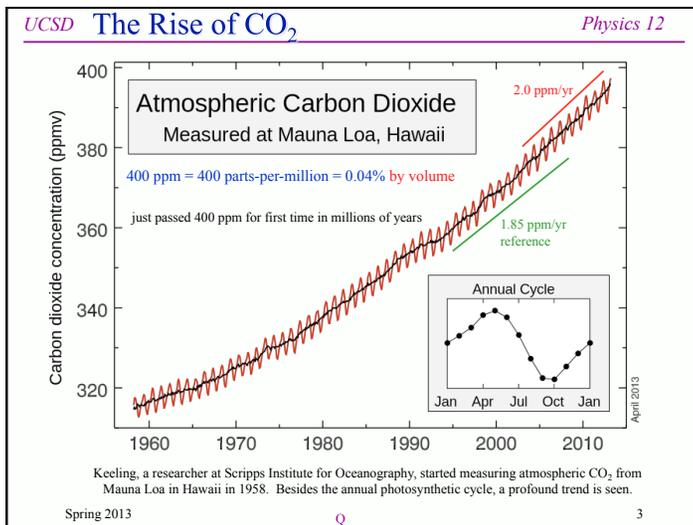


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Science vs. Influence

- Scientists have seen direct signs of climate change for decades
 - confidence has grown based on loads of *data*, often collected by scientists who are themselves skeptical about climate change
- Scientific consensus is not as easy as you may think
 - practiced by humans, each interested in making a mark
 - scientists are by nature skeptical, and eager to tear holes in shoddy ideas
 - but in the end, driven by *evidence*, not emotion, authority, or pet ideas
- Long after scientific consensus, waters were still muddied
 - overt influences by financial powers emphasized controversy and “lack of consensus”
 - and had a bigger bullhorn: popular media ran the controversy over the consensus, which has had a damaging delay-effect
 - fantastic article about conflict between capitalism and climate change:
 - <http://www.thenation.com/article/164497/capitalism-vs-climate?page=full>

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What's the Problem?

- Adding CO₂ to the atmosphere changes the radiative balance on earth
 - CO₂ absorbs infrared light, so more of the thermal emission trying to escape from earth is absorbed in the atmosphere, causing earth to warm
 - it's like the glass sheet over the solar hot water collector: like a greenhouse
 - eventually, a hotter earth radiates more prodigiously (according to σT^4 law), and balance is re-established

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H₂O and CO₂: major greenhouse gases

Figure 4.1 The wavelength distribution of solar radiation above the atmosphere (dashed line) and at the earth's surface (solid line). The Solar Constant is given by the area under the dashed curve. The sharp dips in the solid line are due to absorption of certain wavelengths by various atmospheric gases, including water vapor and carbon dioxide. (Adapted from *On the Nature and Distribution of Solar Radiation*, Watt Engineering, Washington, D.C.; U.S. Government Printing Office, Department of Energy HCP/T2552-01, 1978).

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Absorption Bands and Blanket Effect

- The atmosphere is pretty transmissive for visible light (incoming energy)
- But the thermal infrared is significantly absorbed
 - mostly H₂O; some CO₂ and friends
- Effectively absorbs 75% of the IR trying to get out
 - half of this re-radiated up, half back down
- $\sigma T^4 = 390 \text{ W/m}^2$ leaves the surface
 - but 150 W/m² comes back as IR
 - this is the effect of having a blanket
- Would be 255 K (-18°C) without any greenhouse effect
 - but instead a comfy 288 K (15°C)
 - 21°C of 33°C difference is due to H₂O, 7°C due to CO₂, 5°C from "other"

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Is this rise surprising?

- Every gram of fossil fuel used produces 3 grams of CO₂
 - it's straight chemistry: to get the energy out via combustion, the carbon from the hydrocarbon gets attached to oxygen and off it goes
- How much should we expect?
 - global energy budget is $4 \times 10^{20} \text{ J}$; pretend all from fossil fuels
 - average 10 Cal/gram $\rightarrow \sim 40,000 \text{ J/gram} \rightarrow 10^{16} \text{ g/yr F.F.}$
 - so $3 \times 10^{16} \text{ g/yr CO}_2 \rightarrow 3 \times 10^{13} \text{ kg/yr CO}_2$
 - atmosphere has mass = $5.3 \times 10^{18} \text{ kg} \rightarrow \text{CO}_2$ adds 5.7 ppm/yr by mass
 - about 3.7 ppm/yr by volume (CO₂ is 44 g/mol vs. 29 for air)
 - if half goes into ocean, half into atmosphere (as studies show), atmospheric rise is 1.85 ppm/yr, by volume
 - this is darned close to what we see on the "Keeling curve" graph

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Total CO₂ rise

- We can do the same thing for the entire fossil fuel history
 - have gone through 1 trillion barrels of oil → 140 Gtoe
 - Gtoe is gigaton (10⁹ ton) oil equivalent (by energy)
 - used about 160 Gtoe coal worldwide
 - using 40 Gtoe U.S. times four, since U.S. uses 25% of world energy
 - used 1037 tcf natural gas in U.S. → 27 Gtoe, so guess 100 Gtoe worldwide
 - 400 Gtoe of fossil fuels → 1.2×10¹⁵ kg of CO₂ (3× FF mass)
 - 228 ppm of atmosphere by mass; 150 ppm by volume
 - half into atmosphere → 75 ppm increase
 - see 100 ppm increase (280 ppm pre-industrial to 380 ppm)
- So the CO₂ increase is **absolutely expected!**

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Expected Temperature Rise

- If you add to the blanket, **expect** to get warmer
- How much warmer?
 - Historically we have a 7°C effect from CO₂
 - Have gone from 280 to 400 ppm (10/7 times as much, or 3/7 increase)
 - This should translate into 7°C × 3/7 = 3°C change
 - but takes some time because oceans are slow to respond, having *enormous* heat capacity
- Should be **NO SURPRISE** that burning loads of fossil fuels makes us warmer
 - not actually hard to understand!

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Temperature record of the past

Often called the “hockey stick” curve

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Antarctic ice core records span 400,000 years

- Cyclic climate change as we enter and leave ice ages
- Tight correlation between temperature and CO₂
- Never have seen CO₂ levels over 300 ppm
 - until now (400 ppm)!
- Some temperature spikes “briefly” warmer than now
 - but sea level was 15 feet higher in these periods
- Current rate of temperature climb unprecedented in record (not visible here)

Spring 2013 Note: Greenland’s ice sheet is 110,000 years old: melted in last interglacial period. 12

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History of Sea Level

- Over the past four cycles, each lasting about 100,000 years, sea level rose and fell by about 400 feet, with ice ages having lower sea level and warm interglacial periods having higher sea level.
- During the warmest part of the last interglacial period (about 130,000 years ago), global average temperature was 2–3 °F warmer than today and global sea level was 13–20 feet higher.
- During the Middle Pliocene (3 million years ago), global temperature was 3.5–5.5 °F warmer than today and sea level was 80–115 feet higher.
- If emissions of man-made greenhouse gases continue without abatement, the earth could warm by 5.5 °F (3 °C) within the next century.

Spring 2013 from <http://www.pewclimate.org/global-warming-basics/slr.cfm> 13

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Sea Level After the Ice Age

Note: this is a good example of *real* data: lots of measurements from different scientists around the world all pointing to similar (and sensible) results. Note also *error bars*.

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Global Consequences

- The earth’s ocean/atmosphere/ice system is *very* complex
 - it’s difficult to make predictions due to the *interconnectedness*
- Naïve extrapolations say that by the end of this century, the global temperature will be 1.4 to 5.8 °C warmer than today
 - this is a *huge* change!
- Same predictions have oceans rising roughly half-a-meter by 2100, and *several meters* by 2300
- These predictions don’t account for all possible feedback scenarios

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Fidelity of the Model

- When all known influences are treated in a global model, our ability to reproduce the observed temperature record is quite good
 - not perfect, but the major features are captured
- This gives scientists confidence that we can extrapolate to the future
 - unless a “tipping point” is crossed, triggering a dramatic, rapid change

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Feedback Types: Positive can be bad!

- Increasing temperatures could unleash a *runaway* process: **positive feedback**
- Example of **negative feedback** (tendency toward stability)
 - warmer → more clouds → more reflection → cooler
- Examples of **positive feedback**:
 - warmer → less CO₂ absorption by water → more greenhouse gases → gets warmer
 - colder → more ice on planet → more reflection → colder
- Note that feedback type doesn't determine the direction, just whether the behavior **self-reinforces** and runs away
- The open question is which type of feedback will dominate: positive feedback means runaway

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Positive feedback contributors

- Warm water has diminished ability to absorb CO₂
 - already “sharp drop” observed in Pacific CO₂
- Melting Arctic ice → darker water → absorbs more sunlight → warms up → melts ice faster
- Hotter soil means trapped CO₂ is given off
- More stable ocean (hot on top) starves plankton
 - they rely on nutrients swept up from bottom
 - net result: reduced activity means less CO₂ absorbed
- Thawing tundra → wetlands → more methane
 - a powerful greenhouse gas
- Submarine methane-hydrates frozen in place are warmed out

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The consensus view?

- The majority view among climate researchers globally is that positive feedback is likely to dominate over negative feedback
 - but this isn't being explicitly stated (published), as the uncertainties are still too high
 - good lesson of less-than-alarmist science community
- From 1992 IPCC report (a rather conservative body):

“Because natural sources and sinks of greenhouse gases are sensitive to a change in climate, they may substantially modify future concentrations [of greenhouse gases]. ... **It appears likely that, as climate warms, these feedbacks will lead to an overall increase rather than a decrease in natural greenhouse gas abundances.** For this reason, climate change is likely to be **greater** than the estimates we have given.”

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IPCC Assessments

- The Intergovernmental Panel on Climate Change (IPCC) is a body of scientists tasked with providing the most robust analysis on climate change available
 - about 1000 scientists
 - emphasis is on consensus view of the most solid facts/data
 - as a result, the conclusions are very conservative
- Have worked on four major assessments
 - third assessment in 2001; fourth in 2007; fifth in final preparation
 - can see products at: <http://www.ipcc.ch/>
- Explore a variety of scenarios as modifications to our current “business as usual” trend

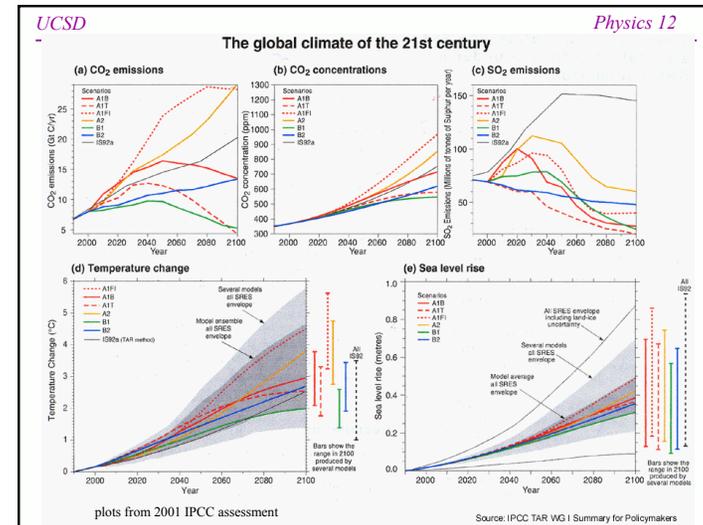
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Predicted Temperature Changes

- The IPCC predicts an increase of 1.1°C to 6.4°C from 1990 to 2100 depending on scenario
- Earth can be slow to respond, due to thermal sink of oceans, and this lag means the temperature will continue to rise *even if we ceased burning fossil fuels today!*
- CO₂ hangs around long enough that we would likely not see the end of changes until ~2300
 - this is under scenario that we **STOP** fossil fuels tomorrow (not going to happen!)
 - sea-level rise is the gift that keeps on giving

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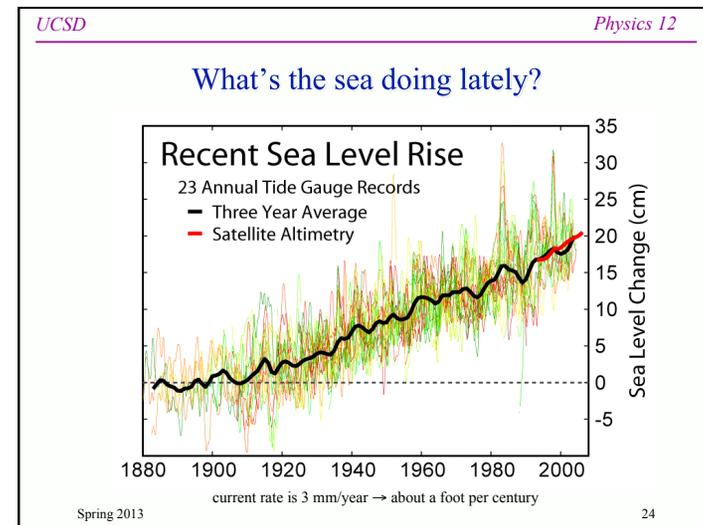


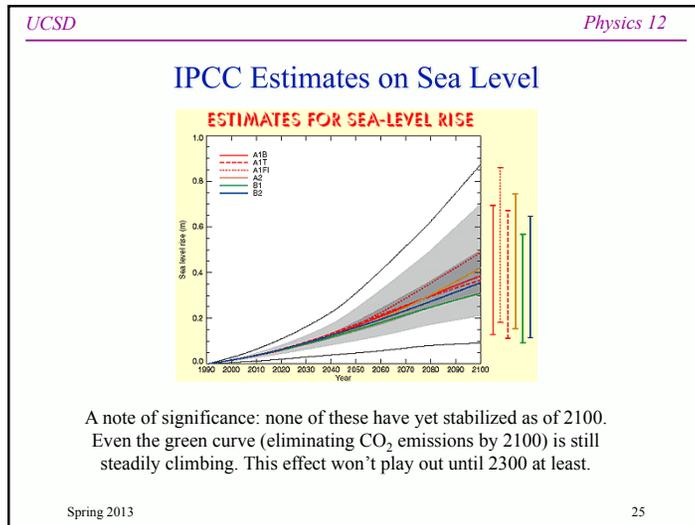
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Sea-level rise

- Thermal expansion of water plus glacial and polar ice-cap melting raise the sea level
- The oceans are predicted to rise something like half-a-meter by 2100, maybe as much as 1 meter
 - goodbye to much of Bangladesh, much of the Nile valley, Louisiana
- Doesn't stop there: it won't stabilize until maybe 2300, by which time the rise could be several meters
 - this is even if we stop the CO₂ production *today*

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How are we responding?

- Globally, the response has been encouraging
- The U.S., however, has been egregiously reluctant to accept the consequences
 - doing so would impact “our blessed way of life”
 - not surprising that the worst offenders/contributors are behaving the least responsibly
- A tragic human epitaph:
 - We wanted to save the world, but our leaders told us it would be too expensive
- Result: Business as Usual

Spring 2013 2xQ 26

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Other observations of global warming

- The earth is slowing down as polar ice melts and redistributes into the oceans
 - like an ice-skater slowing down by holding arms out
- Sea level rise, at rate of 3 mm/year
- Arctic Ice Cap melting faster than most dire predictions
- Glaciers retreating
- Satellite monitoring of global temperature from 1980–1999 (deduce 0.13 °C/decade)
- More erratic weather (hard to quantify, though)
- Species extinctions at an unprecedented rate
- Plant growing season and insect cycles are longer

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Good references on the subject

- http://www.ucsusa.org/global_warming/
 - Union of Concerned Scientists
- lwf.ncdc.noaa.gov/oa/climate/globalwarming.html
 - NOAA: the National Oceanic and Atmospheric Admin.
- <http://epa.gov/climatechange/index.html>
 - Environmental Protection Agency site
- Ten myths about global warming
 - <http://www.sierraclub.ca/national/programs/atmosphere-energy/climate-change/ten-myths.html>
- *Field Notes from a Catastrophe*, by Elizabeth Kolbert
 - well-written overview book on climate change
- Do the Math: 7. [A Recipe for Climate Change](#)

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Reminders

- HW 7 due Friday
- Quiz 8 also on Friday
- Extra Credit (2% of final grade) available on TED
- Will do review session during 10th week
 - exam on Wednesday, 6/12, but I'm out of town after 6/8
 - perhaps another session during finals week, led by Matt
- Final Exam Study Guide posted