Woodrow Wilson School 585b
cross-listed: MAE 580

Living in a Greenhouse: Technology and Policy

Professor: Robert Socolow
AI: Phil Hannam

Robertson Hall 011

Week 1: Wednesday, Sept 11, 2013

A. Introduction to the course

B. Climate science and the IPCC

FIRST MEETING SIGN-UP SHEET

WWS __585b___________FALL 2013
INSTRUCTOR _Robert Socolow
Please fill in the requested information:
NAME **EMAIL** **STATUS (Audit or credit)**

Who Am I? Handout

<u>Personal Data</u>
Name
Position at Princeton (e.g., Chem. Eng. G1, MPP, MPA2)
Princeton address(es)
Princeton phone number(s)
E-mail address:

<u>Why are you here? What do you hope to get from this course?</u>

<u>Special interests? What should I know about you?</u>

Course Scope

The course discusses both the climate change problem and the policies and technologies that facilitate solutions.

Solutions at one level take the form of multiple deep changes in the energy system and in the way we use land. At a deeper level, they engage our values (how we want to live) and our place in nature.

We will discuss future time. Human beings have not thought very hard about the collective multi-generational project which is human life on earth. We need to make distinctions between the next decade, the next 50 years, the rest of this century, and even longer time periods.

The fifty-year time frame

A major focus will be the next 50 years, which is roughly the length of your professional life, as well as the longest time horizon of business strategy and public policy.

I am fifty years older than you. My generation is handing you a nasty problem. What will you be able to say to young adults fifty years from now, when you teach them a course like this one?

Would it be enough if “the climate change problem” that you pass to your grandchildren’s generation is comparably difficult – neither immensely harder nor much easier than the one we are passing to you? Or are you more ambitious?

Balancing acts in the classroom

Lecture	⟷	Participation
Numeracy	⟷	Literacy
Planetary	⟷	Local
Dreams	⟷	Realism

There will be hardly any guest lectures, in favor of coherence and getting to know each other.

I will support your enthusiasms. Your papers should be about issues that you care about.

I would appreciate help “modernizing” our experience via creative use of computer-based tools. We should be able to enhance small-group and full-class projects.

Reschedule the time of the course?

If a significant number of students wish to take this course but have a schedule conflict with Wednesday afternoons, we will see if there is a better time to meet.

Syllabus 2013

<u>Part One, Weeks 1-4: Climate Change, Carbon, and Business-As-Usual</u>

<u>Part Two, Weeks 5-7: Personal, Sub-National, National, and International Initiative</u>

<u>FALL BREAK</u>

<u>Part Three, Weeks 8-12: Technological options and related policy</u>

Story line: Starting only recently, human beings have become aware of the challenge of living on a planet that is small in relation to our collective appetite for experience and acquisitions.

We first explore what it means for Earth to be “small” in relationship to our “appetites.” We then confront the loci of action, from personal to global. We conclude with a tour of “solutions,” all of them problematic.

Syllabus, Part One

<u>Part One, Weeks 1-4: Climate Change, Carbon, and Business-As-Usual</u>

Week 1: Overview. *Sept. 11*

Week 2: The earth's response to human activity. Future targets. *Sept. 18*

Week 3: Abundant fossil fuels. Shale gas, Keystone. Land use and biocarbon. – *Sept 25*

Week 4: The energy system and its policies: grids (oil, natural gas, electricity), sectors (transport, buildings, factories), scales (centralized, decentralized), end uses (transport, heating and cooling, lighting, electronics…), energy and carbon embedded in trade. – *Oct. 2*

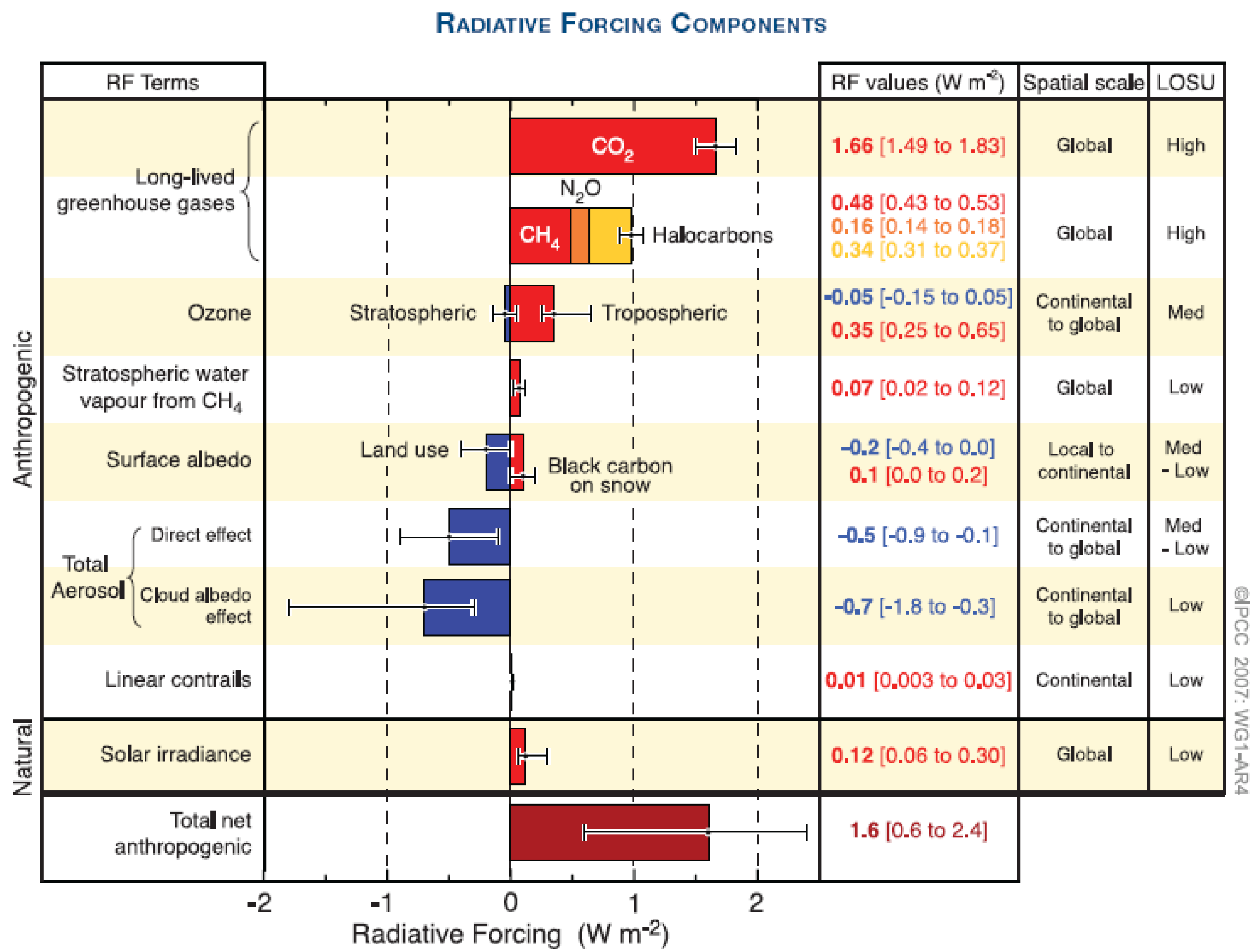


Figure SPM.2. *Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its range are also shown. These require summing asymmetric uncertainty estimates from the component terms, and cannot be obtained by simple addition. Additional forcing factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an additional natural forcing but are not included in this figure due to their episodic nature. The range for linear contrails does not include other possible effects of aviation on cloudiness. {2.9, Figure 2.20}*

Source: 2007 IPCC Summary for Policy Makers

Our “quadrant”: Climate change *is* an urgent matter, *and* fossil fuels *are* hard to displace.

Syllabus, Part Two

<u>Part Two, Weeks 5-7: Personal, Sub-National, National, and International Initiative</u>

Week 5: The student’s carbon footprint, behavior, affluence and poverty, demography. – *Oct. 9*

Week 6: National and sub-national policy. Parallel mitigation campaigns across multiple stabilization wedges. Carbon markets (California). Regulation (EPA and coal). – *Oct 16*

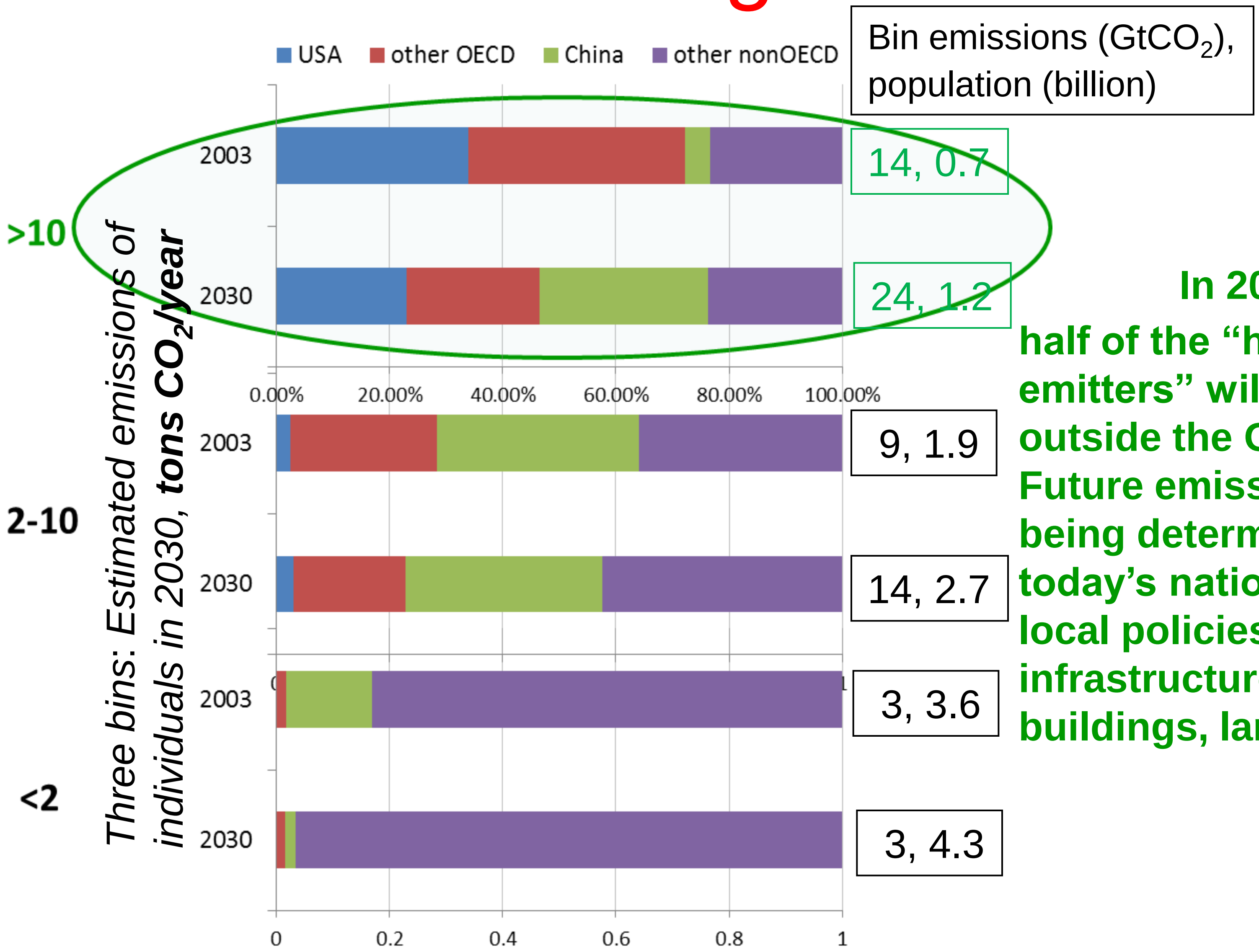
Week 7: International governance and cooperation. [Guest Lecture, Phil Hannam] – *Oct 23*

Four ways to emit 4 ton CO_2/yr (today's global per capita average)

Activity	**Amount producing 4 ton CO_2/yr emissions**
a) Drive	24,000 km/yr, 5 liters/100km (45 mpg)
b) Fly	24,000 km/yr
c) Heat home	Natural gas, average house, average climate
d) Lights	300 kWh/month if all coal-power (1000 gCO_2/kWh) 600 kWh/month, natural-gas-power (500 gCO_2/kWh)

We will discuss the many policies that affect this table, e.g., that affect vehicles, fuels, urbanization and sprawl.

One billion "high-emitters"



In 2030, over half of the "high-emitters" will live outside the OECD. Future emissions are being determined by today's national and local policies on infrastructure, buildings, land use.

Source: http://www.climatescienceandpolicy.eu/2009/11/afocus-on-individuals-can-guide-nations-towards-a-low-carbon-world

Syllabus, Part Three

Part Three, Weeks 8-12: Technological options and related policy

Week 8: Energy efficiency. Electrification and biofuels for transport. – *Nov 8*

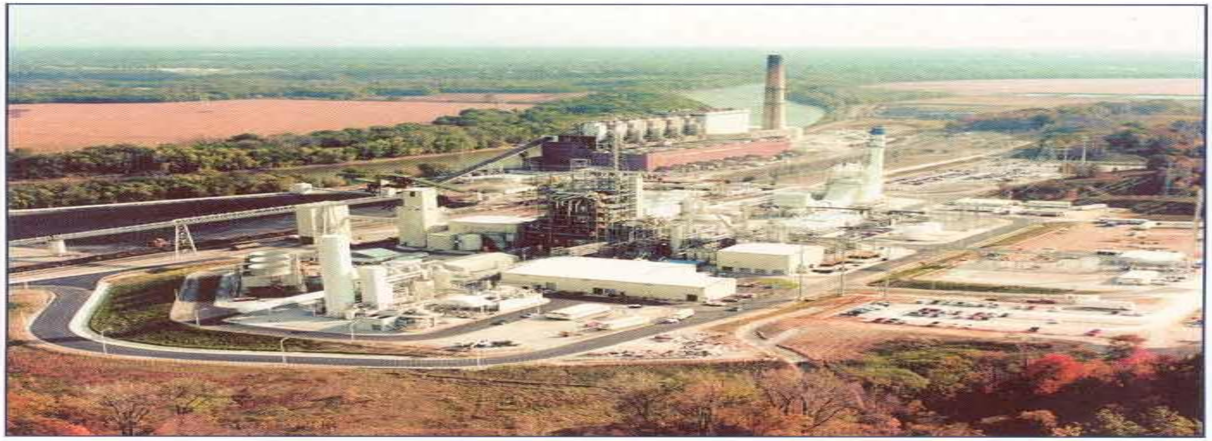
Week 9: Low-carbon fossil-fuel-based energy via CO_2 capture and storage. – *Nov 15*

Week 10: Intermittent and constantly available renewable energy; energy storage. – *Nov. 29*

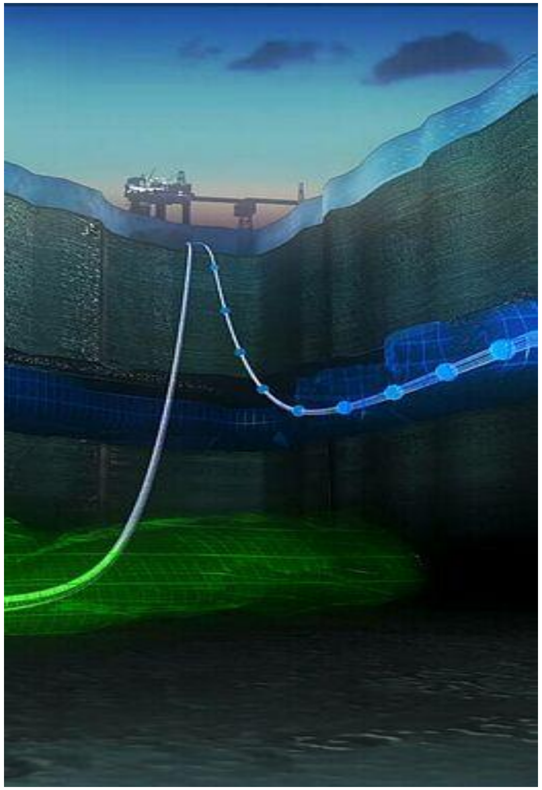
Week 11: Nuclear power. – *Dec 4*

Week 12: Geoengineering. The enduring human project of planetary stewardship. – *Dec 11*

Coal with CO_2 capture and storage



The Wabash coal gasification reprocessing project



Sleipner field, Norway

Graphics courtesy of DOE Office of Fossil Energy and *Statoil ASA*

Geoengineering by imitating volcanoes

On June 15, 1991 (three days after this photo) , Mt. Pinatubo. injected 10 million tons of sulfur into the stratosphere.

The Earth's average surface temperature was 0.5^{o}C cooler six months later, then rebounded.

"Perpetual volcanos" is being discussed: Efficacy, risks, governance.
Motivation: To be able to respond to an emergency.

Every strategy can be implemented well or poorly

Every “solution” has a dark side.

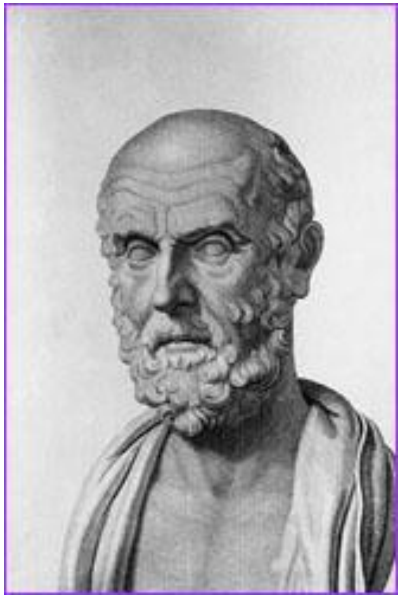
Conservation	Regimentation
Renewables	Competing uses of land
“Clean coal”	Mining: worker and land impacts
Nuclear power	Nuclear war
Geoengineering	Technological hegemony

Risk management: We must trade the risks of disruption from climate change against the risks of disruption from mitigation.

Patient Earth

"I will apply, for the benefit of the sick, all measures that are required, avoiding those twin traps of overtreatment and therapeutic nihilism."

Hippocrates



*** Modern version of the Hippocratic oath, Louis Lasagna, 1964, http://www.pbs.org/wgbh/nova/doctors/oath_modern.html**

Some of the things I do

- I co-direct the University's Carbon Mitigation Initiative (2000-), sponsored by BP (earlier, also by Ford). *Principal areas*: climate science and impacts; CO_2 capture and storage (CCS) and other low-carbon energy strategies; international and domestic climate policy.

- I direct the University's Climate and Energy Challenge (initiation funds for curriculum and student life). Princeton Energy and Climate Scholars (PECS), an honor society for grad students, is one of its programs.

- I participated in two recent National Academy of Sciences studies: *America's Energy Future* and *America's Climate Choices*.

- I co-chaired the study, *Direct Air Capture of CO_2 with Chemicals*," Panel on Public Affairs, American Physical Society.

- I am on the Climate Change Advisory Committee of Deutsche Bank.

- I have many interactions with the major environmental ngo's.

For more details and nearly all papers, see my website: http://www.princeton.edu/mae/people/faculty/socolow/

It’s 1 pm

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INSTRUCTOR _Robert Socolow
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NAME **EMAIL** **STATUS (Audit or credit)**

Who Am I? Handout

<u>Personal Data</u>
Name
Position at Princeton (e.g., Chem. Eng. G1, MPP, MPA2)
Princeton address(es)
Princeton phone number(s)
E-mail address:

<u>Why are you here? What do you hope to get from this course?</u>

<u>Special interests? What should I know about you?</u>

Reschedule the time of the course?

If a significant number of students wish to take this course but have a schedule conflict with Wednesday afternoons, we will see if there is a better time to meet.

Blackboard

I'll post all lecture notes, problem sets, assigned readings on Blackboard.

All readings will have been scanned. Nothing needs to be bought or printed out.

Suggestions of other ways to use Blackboard are welcome.

Suggestions regarding readings and websites are also welcome.

Assignments and deadlines

Unless a class has been rescheduled: 1) the short papers and the interim statements about the term paper are due at midnight on a Tuesday, electronically; 2) problem sets are due at the beginning of class on a Wednesday.

Part One, Weeks 1-4: Climate Change, Carbon, and Business-As-Usual

Sept 25 before class: First Problem Set
Oct 1, midnight: First Short Paper

Part Two, Weeks 5-7: Personal, Sub-National, National, and International Initiative

Oct 8, midnight: First Interim Term-paper Statement – topic, scope, approach
Oct 16, before class: Second Problem Set

Part Three, Weeks 8-12: Technological options and related policy

Nov 12, midnight: Second Interim Term-paper Statement – topic, scope, approach
Nov 19, midnight: Second Short Paper
Dec 11, before class: Third Problem Set

January 14, 2014 (Dean's Day): Term Paper is due.

Weights for grading

Term paper	40%
Two short papers	20%
Problem sets	20%
Participation	20%

I reserve the right to recognize some exceptional performance.

The papers

The two short papers must be submitted electronically to Phil and me before midnight on Tuesday October 1 and Tuesday November 19. For length, think 2000 – 3000 words.

The term paper may be a deeper discussion of the topic of one of your short papers, or it may deal with a completely different topic. It should be about 5000 words and should be submitted electronically before midnight on Tuesday, January 14, 2014 (*Dean's Day*).

You are expected to begin thinking about the term paper right away. You are to submit two interim statements about this paper – "topic, scope, approach." They are due electronically before midnight on Tuesday October 8 and Tuesday November 12.

What makes a good paper?

Each short paper should be sharply focused on a single issue. The term paper can be more ambitious.

All papers should be interesting, focused, imaginative, partially quantitative, and coherent. They should be well written, well argued, and well presented.

An unusual requirement is that each paper should display some quantitative reasoning. For example, this can be a sample calculation that verifies a statement that you have read. You should show an interest in numbers.

It is fine to build on some comparative advantage; for example, you could choose a topic related to something you have done before or involving a country or town that you know.

You are encouraged to discuss all papers with Phil and me electronically, but only well ahead of the deadlines. Experience suggests that we will lead you to people in the Princeton community who may be helpful.

No matter what your topic, you will encounter sales pitches, masquerading as impartial analysis. Learning to deal with biased information is one of the aims of this course.

Sample paper topics

Here are four examples of topics that could lead to papers that are interesting, focused, imaginative, partially quantitative, and coherent.

Report on a personal quest: “I have always wondered why clouds are hard to model…”

Explore impacts: “Flood-plain zoning has much to teach us about adaptation to climate change…”

Address the problem of expert-layperson communication: “Two recent articles on the same subject – one in *Scientific American*, the other in *Esquire* – shed light on the difficulty of explaining science…”

Explore fossil fuels: “The flaring of natural gas in conjunction with the development of new oil reserves in North Dakota is a policy failure.”

Problem sets

One goal of the course is to renew your numeracy and, thereby, to increase your appetite for quantitative reasoning. To this end there will be three problem sets.

Collaboration is encouraged.

The Bradford Seminars

The David Bradford seminars of the Program in Science, Technology, and Environmental Policy (STEP), WWS. Mondays, 12:00 to 1:00. Wallace 300. (Lunch at 11:45.) See: http://www.princeton.edu/step/seminars/current/

Sept 30: Chris Little. Sea level and NYC

Oct 7: Nadine Unger. Air pollution and climate.

Oct 14: James Hansen.

The PIIRS "Communicating Uncertainty" Seminars

A multi-disciplinary study of the communication of uncertainty, with an emphasis on climate change. Five Wednesday afternoon lectures this fall, 4:30 p.m. (4 of 5 in 219 Aaron Burr)

Sept 18: Jonathan Levy, Capitalism and risk in the U.S.

Oct 2: Susan Fiske, Public perception of science

Nov 6: Francis Dennig, Intergenerational climate policy

Nov 20: Michael Oppenheimer (Bowl 1 WWS), IPCC Report

Dec 4: Samuel Scheffler, Ethical import of human continuity

Friday morning, September 27: Special seminar by Amory Lovins

Friday, Sept 27, 10:30 a.m., Robertson 016

Title: Reinventing Fire: The Business-Led Transition Beyond Fossil Fuels.

Who can help you?

Rob Socolow, Guyot 139; x8-5446.
socolow@princeton.edu.

Office hours: By appointment through Caitlin Daley

Caitlin Daley, my assistant: Guyot 132, x 8-5467.
cdreyer@princeton.edu

Phil Hannam, AI, M39 Guyot. May hold precepts.
phannam@princeton.edu

Researchers in the Carbon Mitigation Initiative
(www.princeton.edu/~cmi)

There are a few "energy" books

MacKay, David JC, *Sustainable Energy: Without the Hot Air*, 2009. http://www.withouthotair.com/download.html

*McElroy, Michael B, *Energy: Perspectives, Problems, and Prospects.* Oxford University Press, 2009.

*Richter, Burton, *Beyond Smoke and Mirrors: Climate Change and Energy in the 21st Century*. Cambridge University Press, 2010.

* On reserve in Stokes Library in Wallace

Useful Websites: Energy data

- http://www.iea.org
  - International Energy Agency, Paris, France: OECD/IEA.
    - *World Energy Outlook*.
    - Key World Energy Statistics
- http://www.eia.doe.gov
  - Energy Information Agency, U.S. Department of Energy.
    - *International Energy Outlook*
    - *Annual Energy Review (United States).*
- http://www.bp.com
  - *BP Statistical Review of World Energy.*

Useful Website: Climate

http://www.ipcc.ch

- Intergovernmental Panel on Climate Change, IPCC Fourth Assessment Report: Climate Change 2007**.**

http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_synthesis_report.htm

- Intergovernmental Panel on Climate Change, Technical Reports.

http://www.ipcc.ch/publications_and_data/publications_and_data_technical_papers.htm

Problem Set No. 1, 2012
Rosetta Stone: 7.8 $GtCO_2$ = 1 ppmv
Due before class, Wednesday, Sept 25, 2013

Verify that emitting 7.8 billion tons of CO_2 into the atmosphere (by burning fossil fuels, for example) will add one millionth as many molecules as are there already. Follow these steps:

1. Estimate the mass of the atmosphere (M), in kilograms, using only three quantities: sea level pressure (P), the surface area of the Earth (A), and the acceleration of gravity (g). The relevant equation is $M*g = P*A$. Pressure at sea level is the result of the weight of the atmosphere above.

2. Each 29 grams of atmosphere contains $6*10^{23}$ molecules, since the atmosphere is four-fifths N_2 and one-fifth O_2. Explain. How many molecules are in the atmosphere?

3. Adding 7.8 billion tons of CO_2 (equivalently, 2.1 billion tons carbon in CO_2 – why?) is equivalent to adding how many molecules of CO_2? Verify that this additional CO_2 adds one part per million to the number of molecules already in the atmosphere.

Physical units

Most of the calculations in this course involve numbers which are meaningless unless they are attached to physical units.

Most of the interesting observations involve comparisons of two quantities that are in the same physical units. In these cases, the ratios are dimensionless.

Keeping track of units is a skill that is acquired with practice.

The SI system is helpful, as long as one does not lose track of the G’s, M’s, k’s, m’s, μ’s, and n’s.

Errors can often be caught by asking whether certain ratios are reasonable.

Significant Figures

The computer and hand calculator encourage counterproductive thinking. For many calculations, the most important part of the answer is the exponent – the order of magnitude. Errors of a factor of one million are common in this game, and it takes effort to avoid them.

I find it useful to do a calculation by hand the first time, rounding off all numbers to one significant figure, concentrating on getting the exponent right. Then, I'll do the calculation a second time with my calculator or Excel.

1. What is energy used per week by a 60 Watt bulb operating 30% of the time? The exact number of hours in 30% of a week is 50.4 hours, but for this problem it is clearly better to use 50 hours. Then the answer is three kWh, or maybe 3.0 kWh. Using a calculator one might be tempted to report 3.024 kWh.

2. What are interesting observations about the five-item sum:

$$21{,}874 + 82 + 5{,}677 + 9 + 12?$$

A) The first item is 80% of the sum. B) Three of the five items are negligible. Moreover, the sum itself is interesting only if there is something to compare it to.

3. What is the sum of 14367.29 E+05 and 2676.118 E+04? Lord knows.

BREAK

Readings for Weeks 1 & 2 (1 of 3)

All readings will be posted on Blackboard under “Materials.” See brackets for specific guidance. Please do all required reading before class, in this case meaning before the Week 2 class on Sept. 18. Recommended readings are for the eager student and should also provide useful leads on topics that you pursue for your papers.

I will preview the readings for Week X during the lecture in Week X -1, right after the Break.

<u>Introduction to climate change, consequences, and tools:</u>

World Bank (2012). “Turn down the heat.” [Read Executive summary, and skim Chapters 1-3].

McKinsey & Co (2007). “Reducing U.S. Greenhouse Gas Emissions: How much at what cost?” [Pay particular attention to Exhibit B on page xiii].

D. MacKay (2009). Sustainable Energy – Without the Hot Air. UIT Cambridge Ltd.   [Read Ch.1 “Motivations” pages 2-18].

Readings for Weeks 1 & 2 (2 of 3)

R. Socolow (2012). “Truths we must tell ourselves to manage climate change.” *Vanderbilt Law Review*.

R. Socolow (2011). “Wedges reaffirmed,” released into the blogosphere by Climate Central and the *Bulletin of the Atomic Scientist*, September 2011. [Read the article, and the boxed comments at the end]

<u>Definitions of sustainability:</u>

R. Solow (1991). “Sustainability: An Economist's Perspective.” In Dorfman, R., and Dorfman, N. S., eds, Economics of the Environment, 3d edition. New York: Norton. pp. 179-187.

H. Daly (2005). “Economics in a Full World,” Scientific American, September 2005, Vol. 293 Issue 3, 100-107.

Readings for Weeks 1 & 2 (3 of 3)

<u>The Intergovernmental Panel on Climate Change:</u>

IPCC Special Report (2012) Managing the <u>Risks of Extreme Events and Disasters to Advance Climate Change Adaptati</u>on – Summary for Policy Makers [Skim]

InterAcademy Council (Shapiro, Harold) (2010). *Climate Change Assessments: Review of the Processes and Procedures of the IPCC*. [Read Executive summary (pp. xi-xvi), Ch. 3 on uncertainty (pages 27-41)]

R. Socolow (2011). “High-consequence outcomes and internal disagreements: tell us more, please,” *Climatic Change*.

<u>Recommended for policy background:</u>

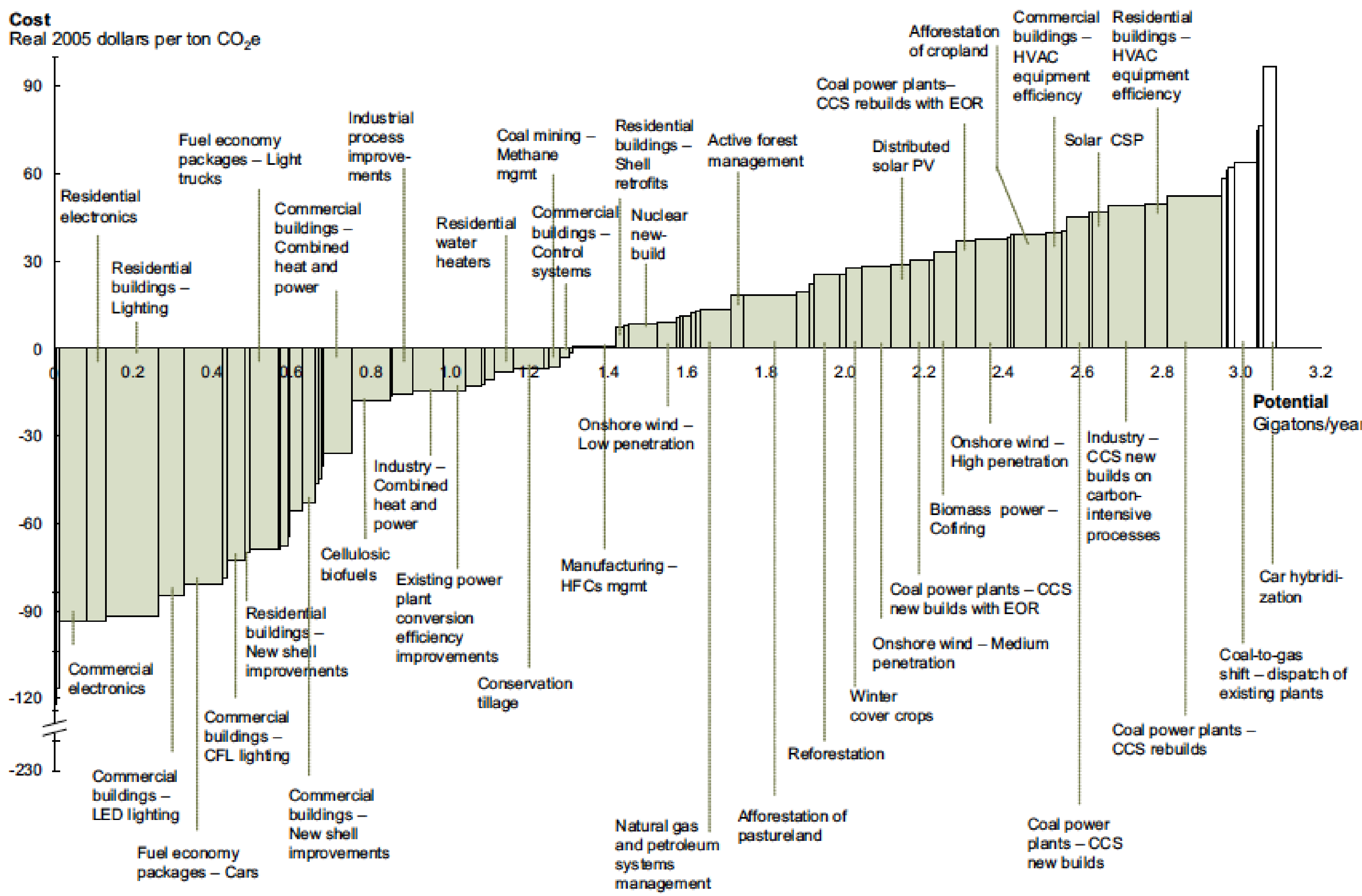
D. Helm (2009) “Climate-change Policy: Why has so Little been Achieved?” [Read pages 9-35], in Dieter Helm and Cameron Hepburn, ed. “Economics and Politics of Climate Change”.

“McKinsey Curve”

Exhibit B

U.S. MID-RANGE ABATEMENT CURVE – 2030

Abatement cost <$50/ton



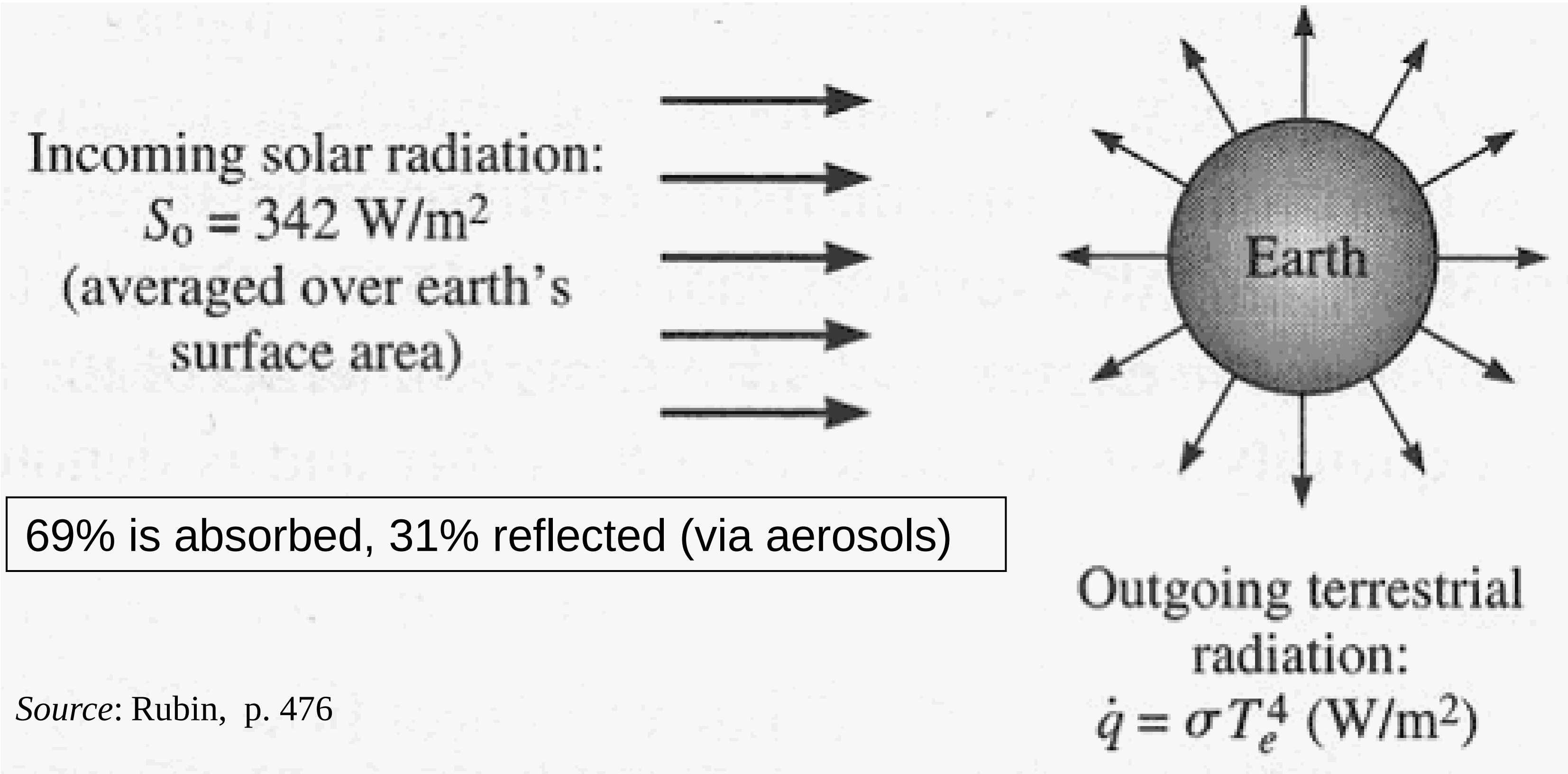
Source: McKinsey analysis

IPCC AR5 WG1 SPM re ECS: coming soon

IPCC: Intergovernmental Panel on Climate Change
AR5: Fifth Assessment Report
WG1: Working Group 1
SPM: Summary for Policy-Makers
ECS: Equilibrium Climate Sensitivity

We will spend the rest of today's class understanding this.

Earth's Energy Balance



69% is absorbed, 31% reflected (via aerosols)

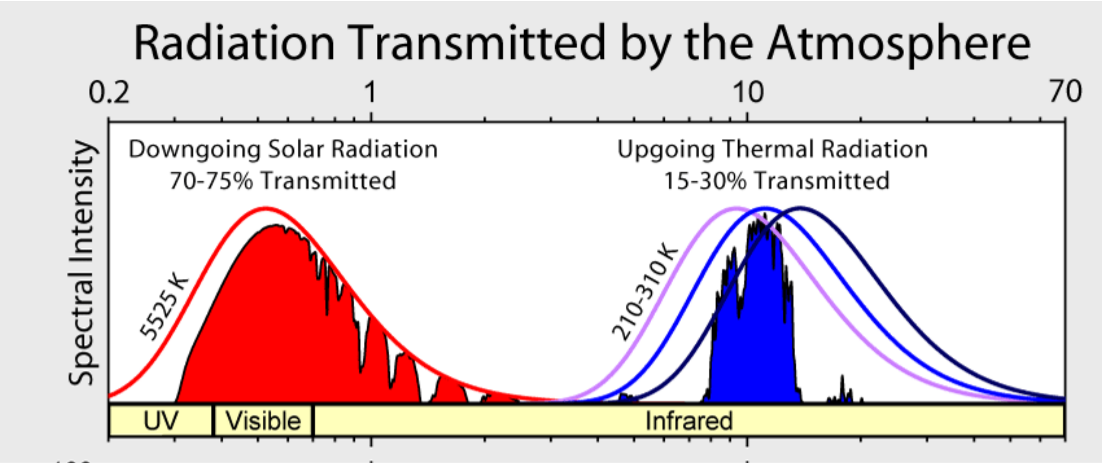
Source: Rubin, p. 476

Solar Input: 120x10^{15} W 0.69 * 342 W/m^2 * [4π * (6370 km)^2]

Human Use: 16x10^{12} W 500 EJ/year , 2 kW/capita

Ratio ≈ 10,000.

The sun and earth are both "black bodies"



Source:
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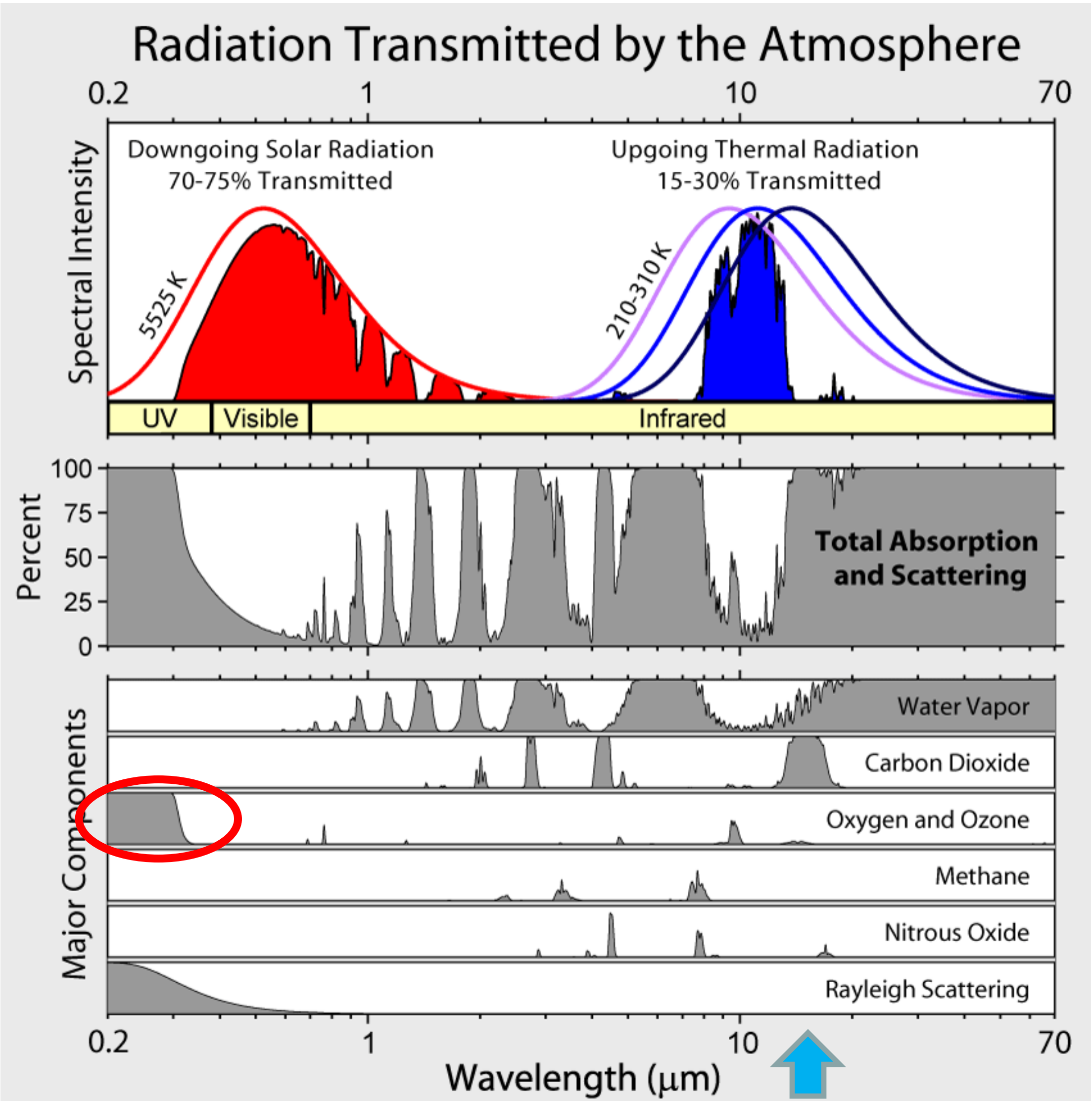
The sun and earth are both "black bodies"



Source:
http://www.google.com/imgres?imgurl=http://milo-scientific.com/pers/essays/figs/Atmospheric_Transmission.png&imgrefurl=http://milo-scientific.com/pers/essays/gw.php&h=857&w=850&sz=75&tbnid=oJSWW8Hq-bIPlM:&tbnh=90&tbnw=89&prev=/search%3Fq%3DCarbon%2Bdioxide%2Binfrared%2Babsorption,%2Bimages%26tbm%3Disch%26tbo%3Du&zoom=1&q=Carbon+dioxide+infrared+absorption,+images&usg=__rWMYx05A2cJa_g8sinD8N-3AlbI=&docid=fC4co5zKk3RuMM&sa=X&ei=kobCT8HHNsbF6gGturWcCg&ved=0CF8Q9QEwBA&dur=3750

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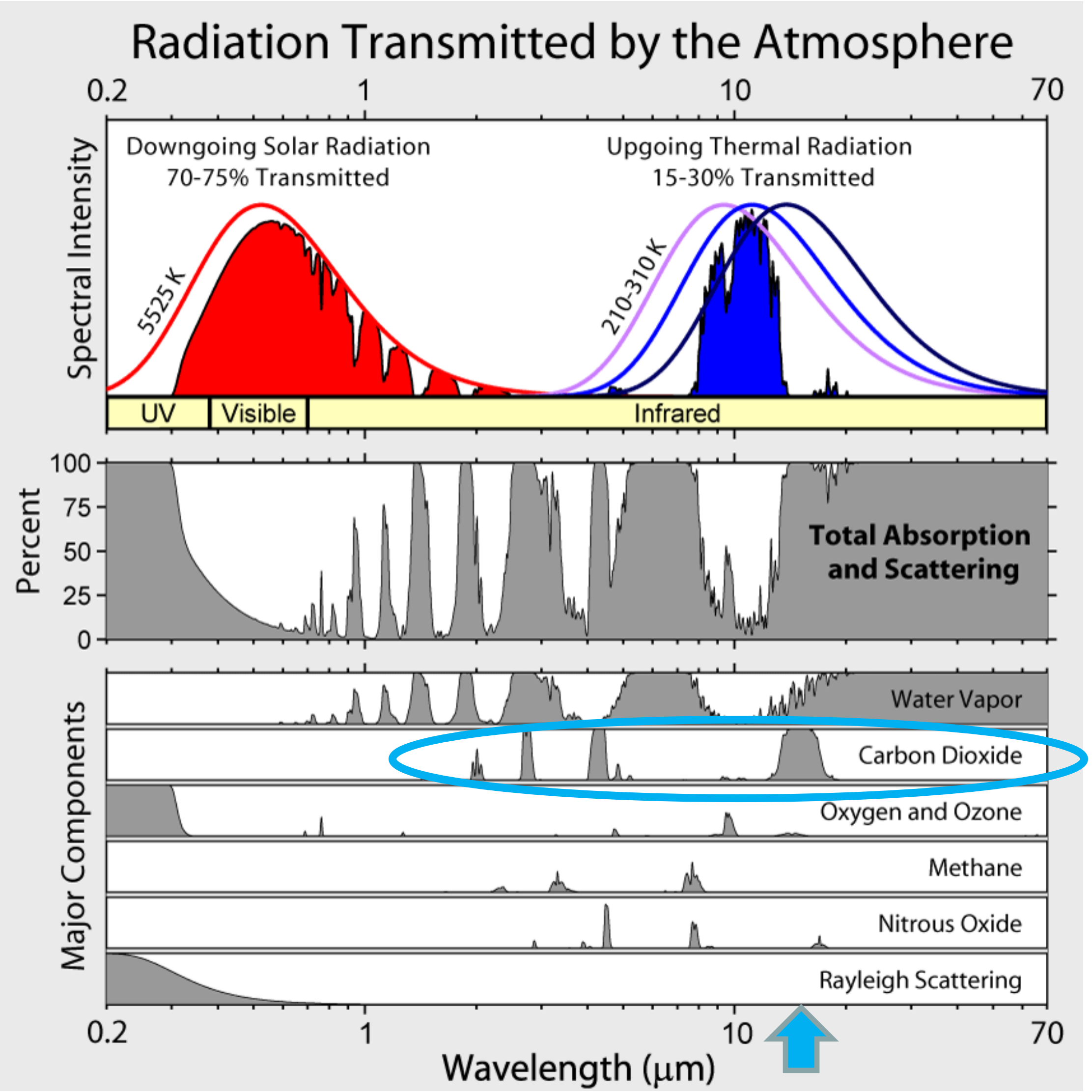
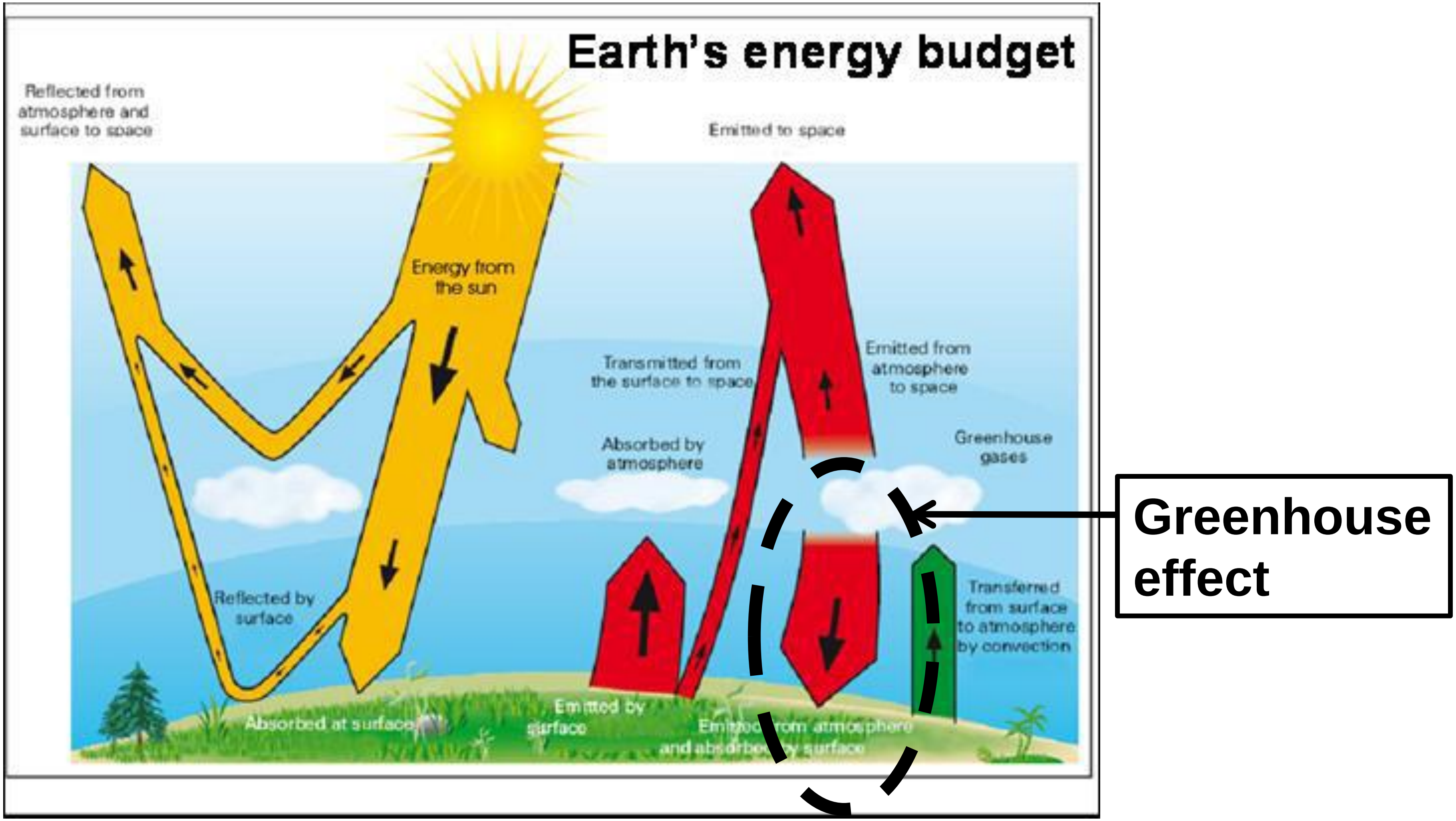


Source:
http://www.google.com/imgres?imgurl=http://milo-scientific.com/pers/essays/figs/Atmospheric_Transmission.png&imgrefurl=http://milo-scientific.com/pers/essays/gw.php&h=857&w=850&sz=75&tbnid=oJSWW8Hq-bIPlM:&tbnh=90&tbnw=89&prev=/search%3Fq%3DCarbon%2Bdioxide%2Binfrared%2Babsorption,%2Bimages%26tbm%3Disch%26tbo%3Du&zoom=1&q=Carbon+dioxide+infrared+absorption,+images&usg=__rWMYx05A2cJa_g8sinD8N-3AlbI=&docid=fC4co5zKk3RuMM&sa=X&ei=kobCT8HHNsbF6gGturWcCg&ved=0CF8Q9QEwBA&dur=3750

The Earth's energy budget



Source: Ipsos MORI, *Experiment Earth?* August 2010, p. 64

Earth’s Detailed Energy Budget

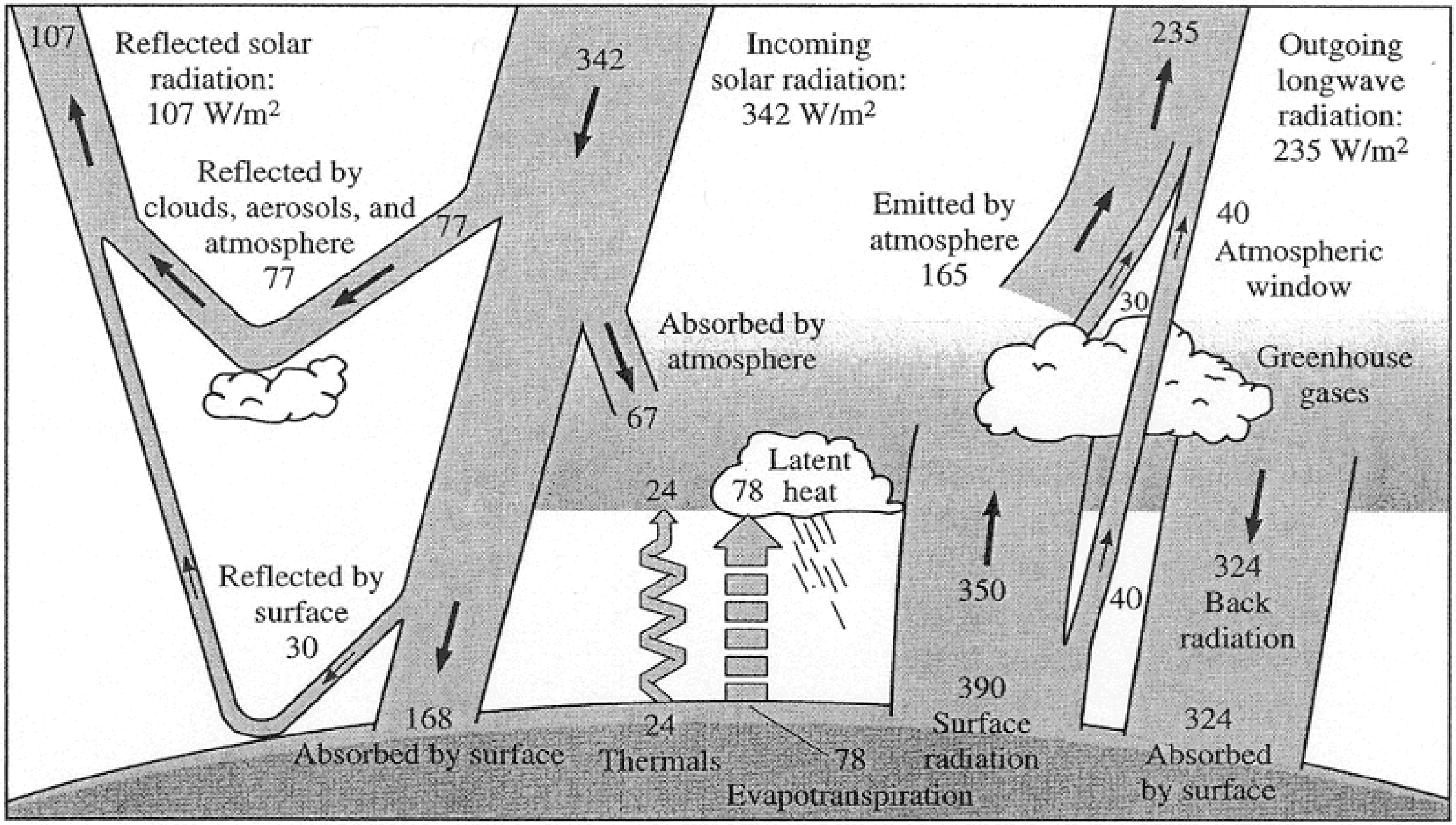
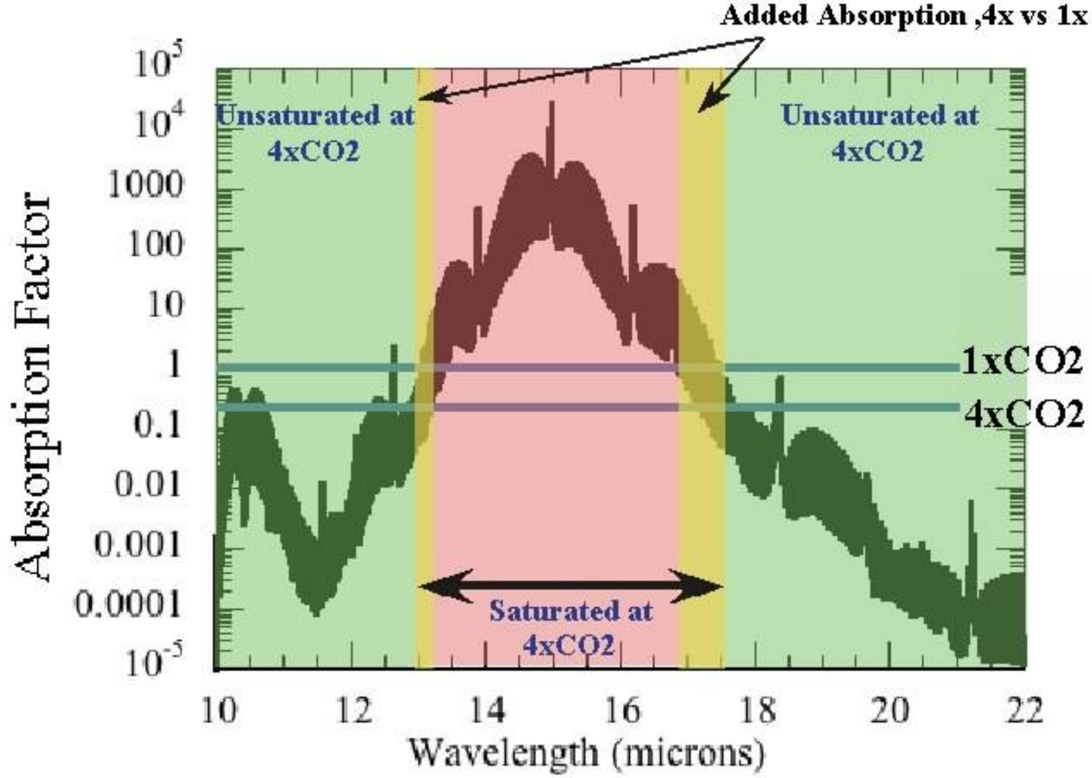
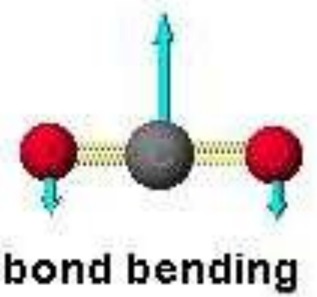


Figure 12.8 The global energy balance for earth. Figures show the average energy flows in W/m^2 based on the earth’s surface area. About 49 percent of the incoming solar radiation is directly absorbed by the surface, but the greenhouse effect adds to the overall energy flow to the surface. (*Source:* IPCC, 1996a)

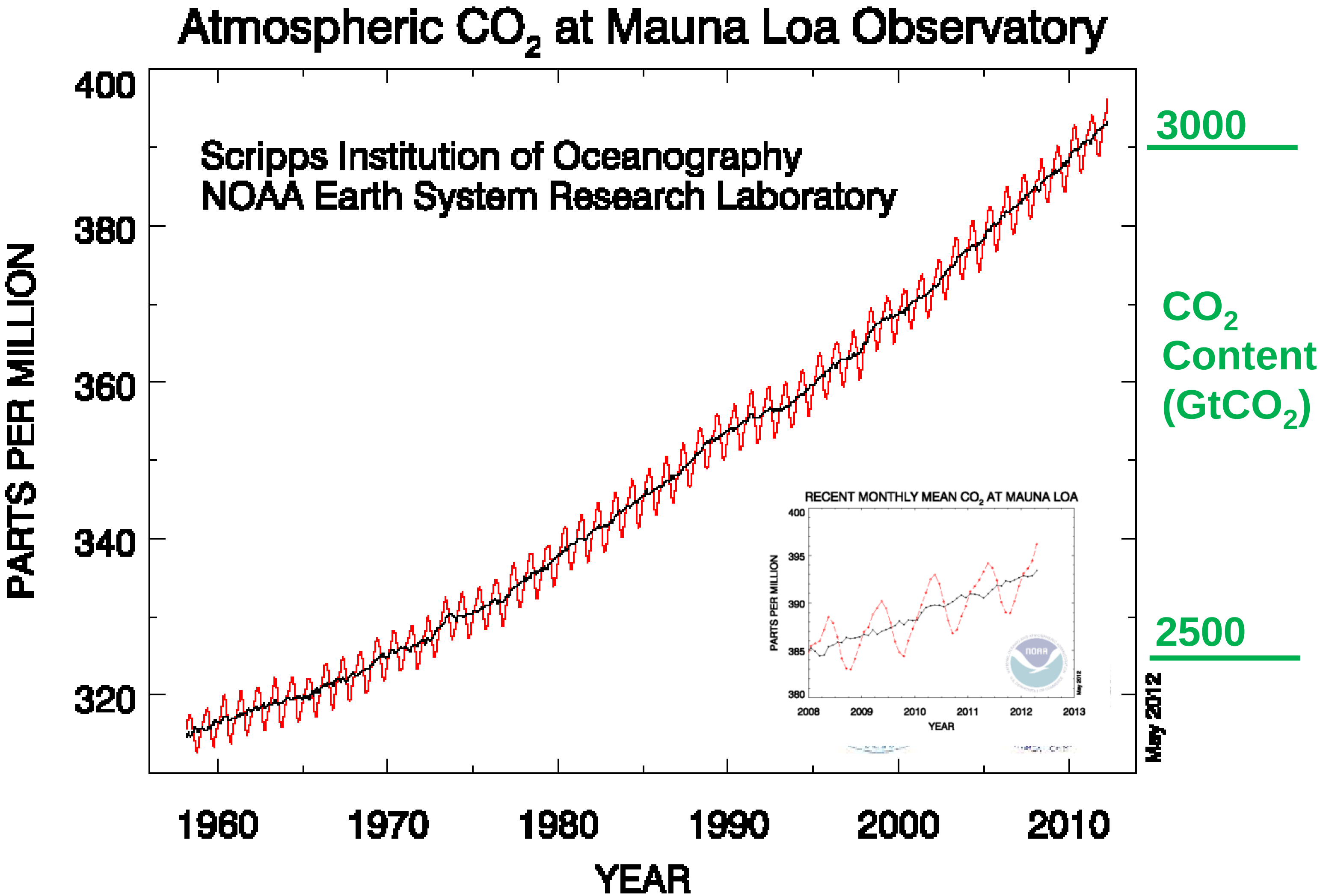
Rubin, p. 485

CO_2 absorption band





Mauna Loa CO_2 data, 1958-2010



Mauna Loa

Greenhouse gases and aerosols: how much cancelation?

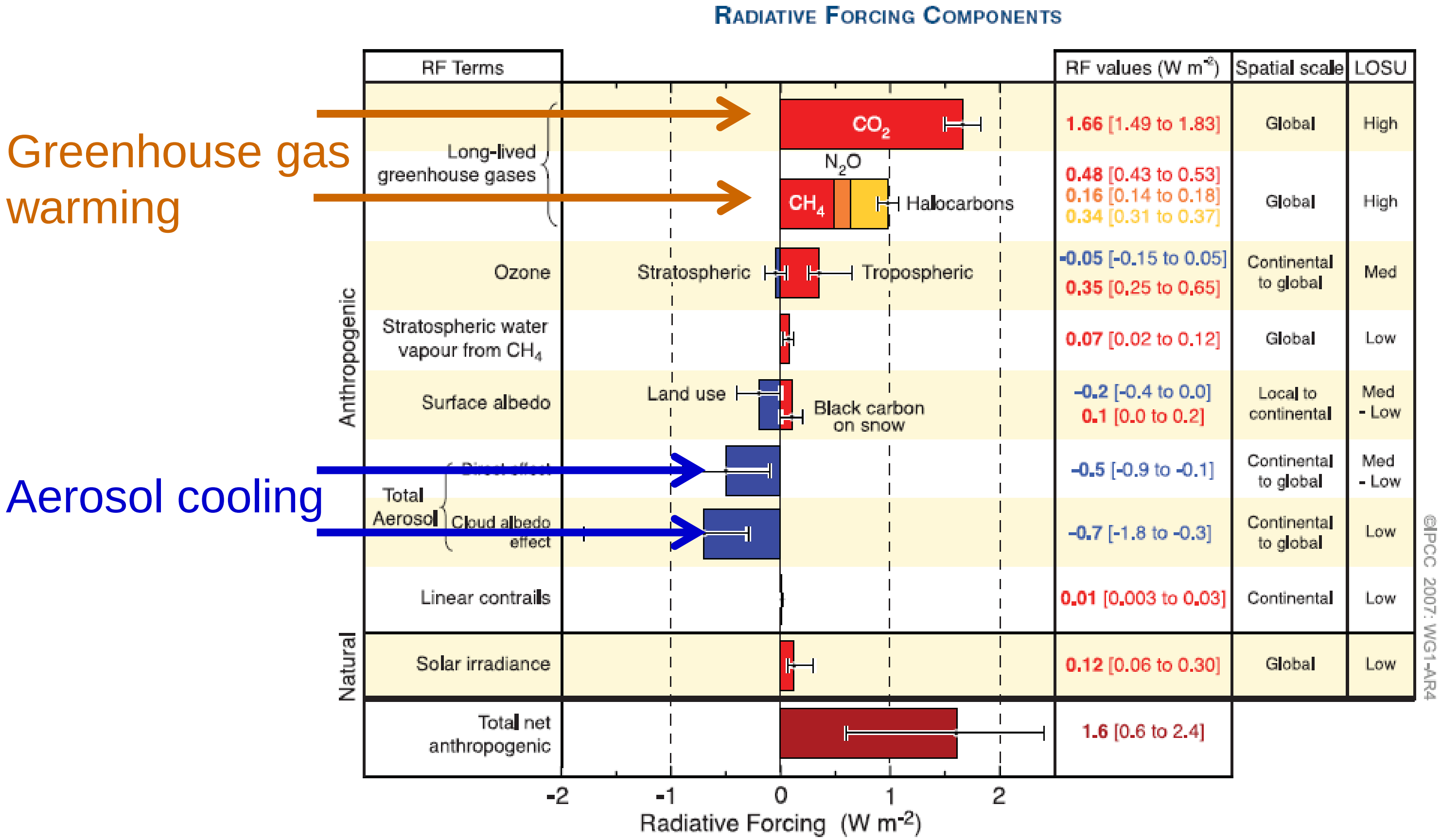


Figure SPM.2. *Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its range are also shown. These require summing asymmetric uncertainty estimates from the component terms, and cannot be obtained by simple addition. Additional forcing factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an additional natural forcing but are not included in this figure due to their episodic nature. The range for linear contrails does not include other possible effects of aviation on cloudiness. {2.9, Figure 2.20}*

Source: 2007 IPCC Summary for Policy Makers

Sources of aerosols

Diesel engines

Forest fires

Biomass cooking

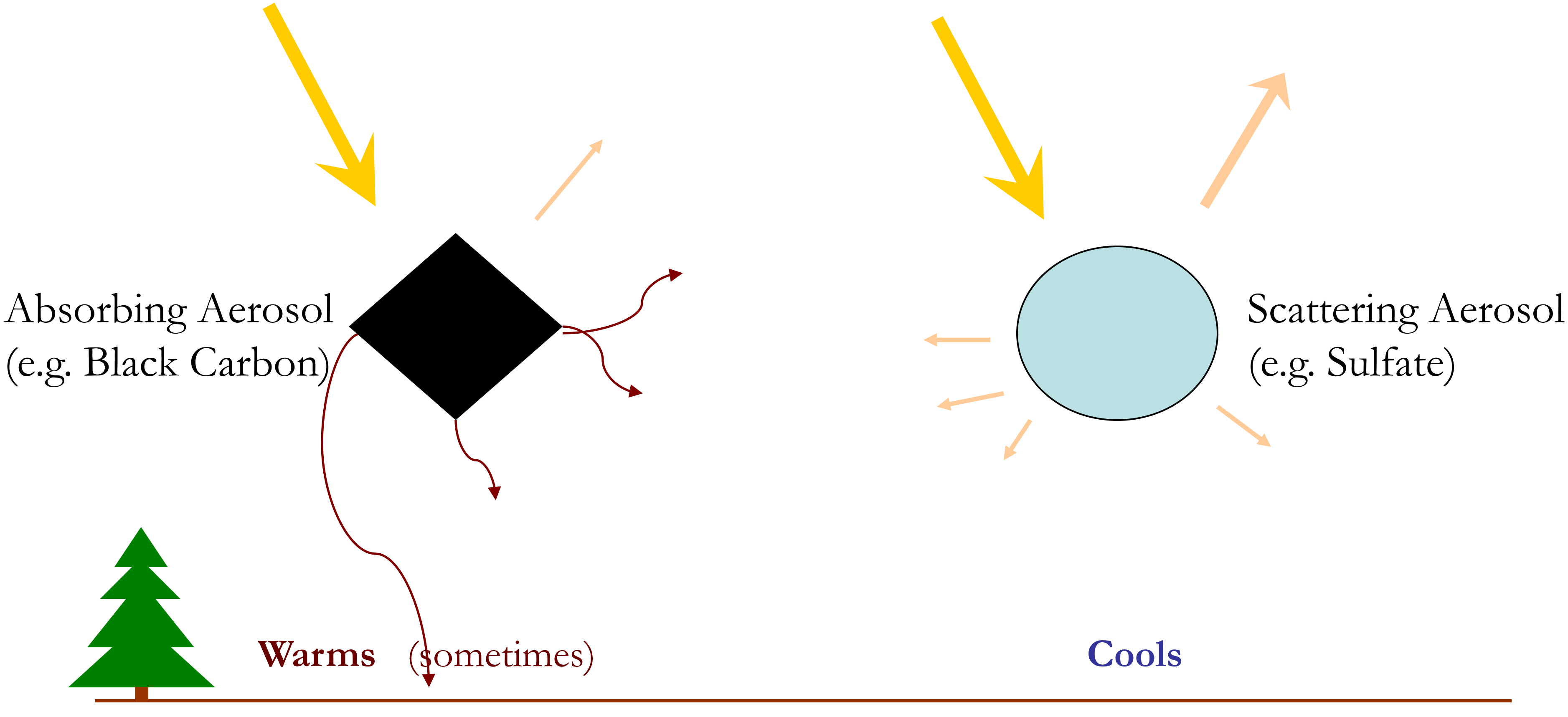
Coal power plants

Desert dust storms

Source: Geeta Persad, Program in Atmospheric and Oceanic Sciences, WWS 585b - 09/24/12

Direct effects of aerosols on climate

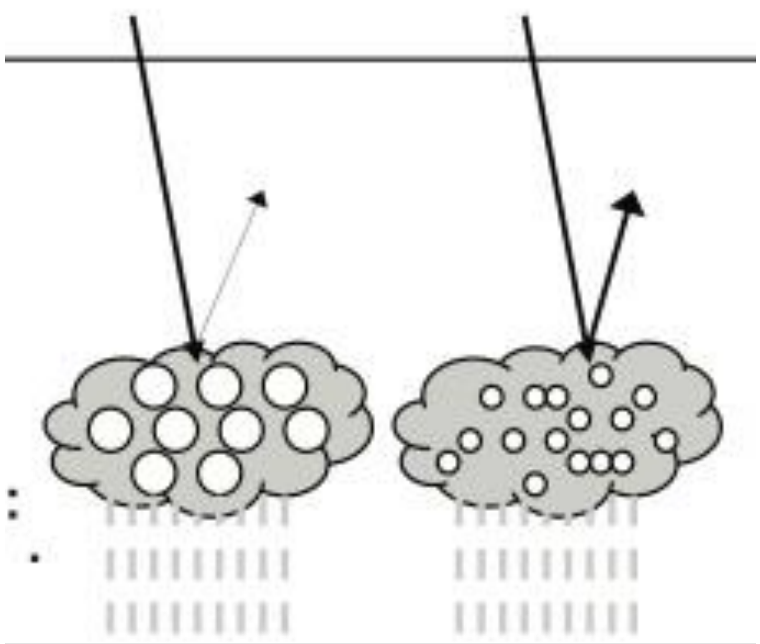
Direct effects: individual particles scatter and absorb sunlight.



Source: Geeta Persad, Program in Atmospheric and Oceanic Sciences, WWS 585b - 09/24/12

Indirect effects of aerosols on climate

Indirect effects: aerosols affect the brightness and lifetimes of clouds.



Cloud are brighter (reflect more sunlight) when their liquid water content is in the form of more, smaller droplets – which aerosols encourage.

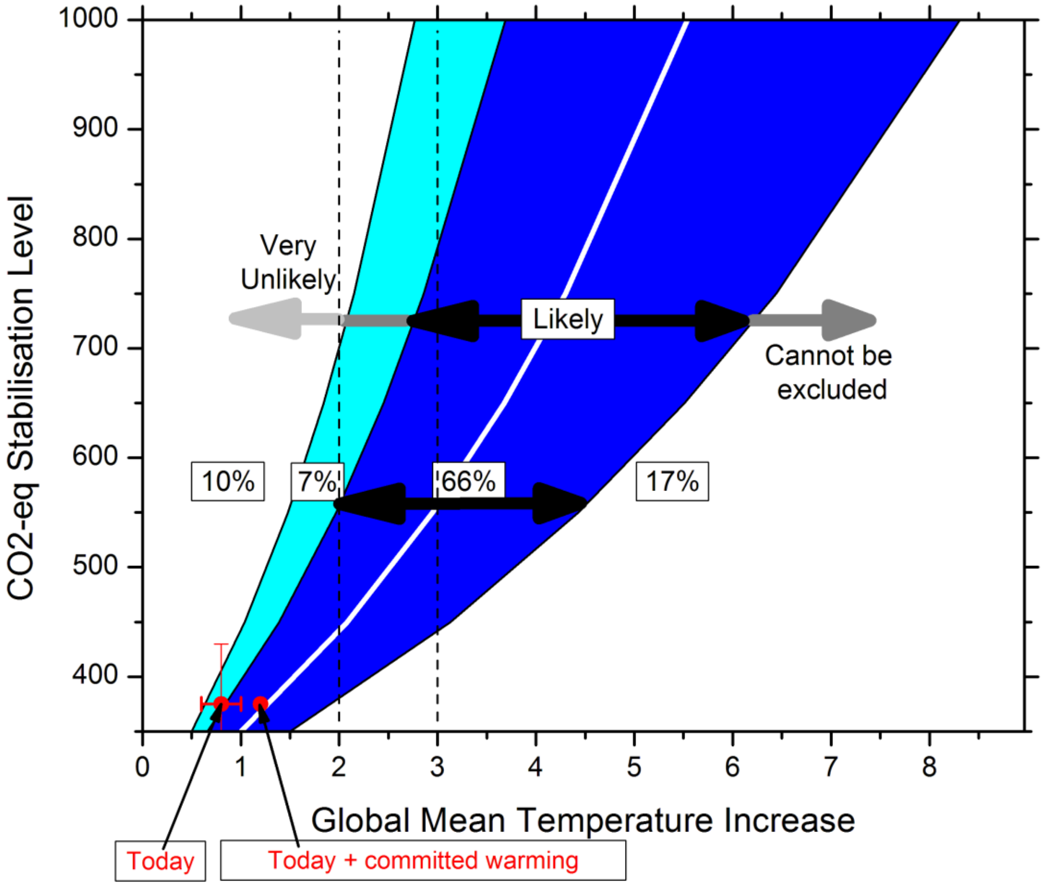
Source: Geeta Persad, Program in Atmospheric and Oceanic Sciences, WWS 585b - 09/24/12

Equilibrium Climate Sensitivity

The “equilibrium climate sensitivity (ECS)” is the rise in the average surface temperature of the earth, relative to its pre-industrial value, that would result if the atmospheric concentration of CO_2 were held constant for a long time at double its pre-industrial concentration, i.e., at approximately 560 ppm. It specifically takes into account feedbacks like additional water vapor in the atmosphere, melting of ice, and effects on vegetation.

(All other greenhouse gases and aerosols are assumed to be at their preindustrial concentrations).

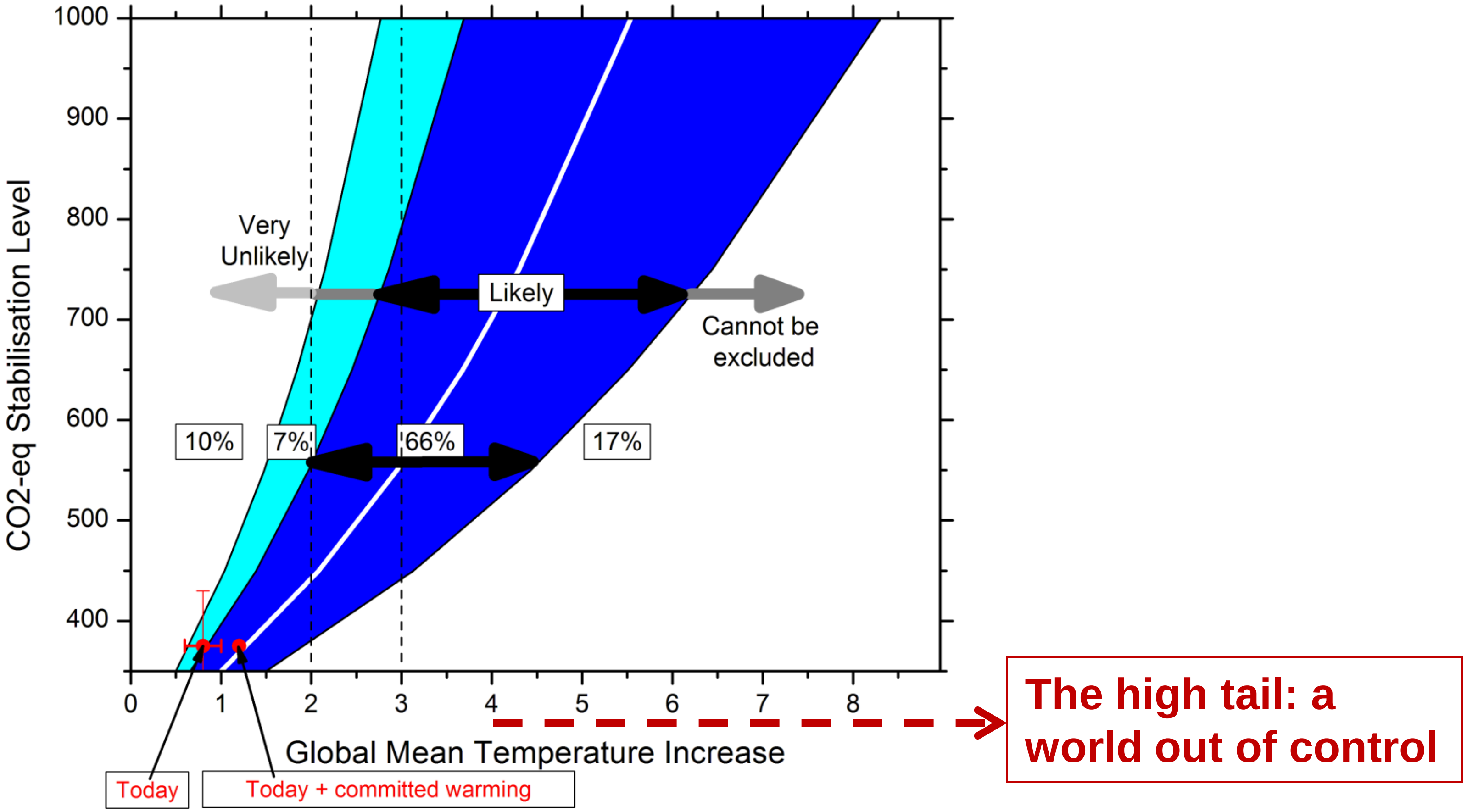
Long-term: temperature rise vs. CO_2 level



This graph is not found in IPCC AR4 WG1. There was no consensus about the probability shown here as 17%.

Source: From Martin Manning.

Long-term: temperature rise vs. CO_2 level



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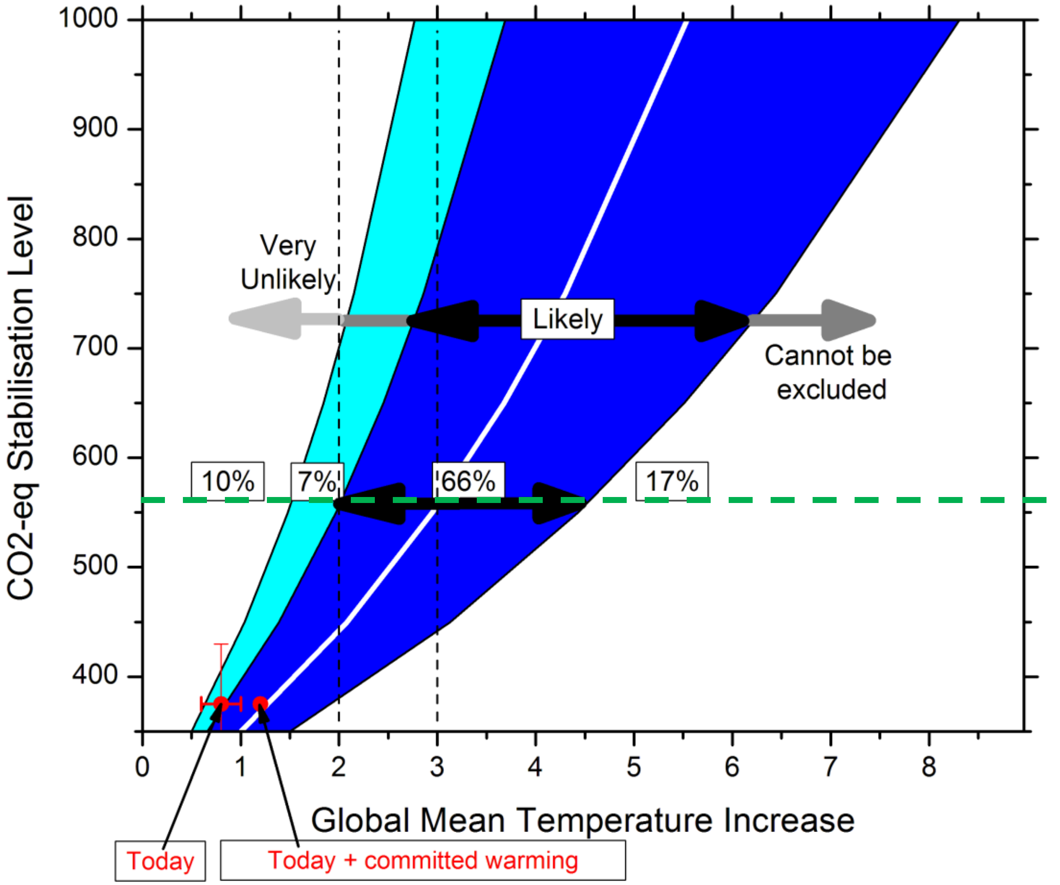
Source: From Martin Manning.

Long-term: temperature rise vs. CO_2 level

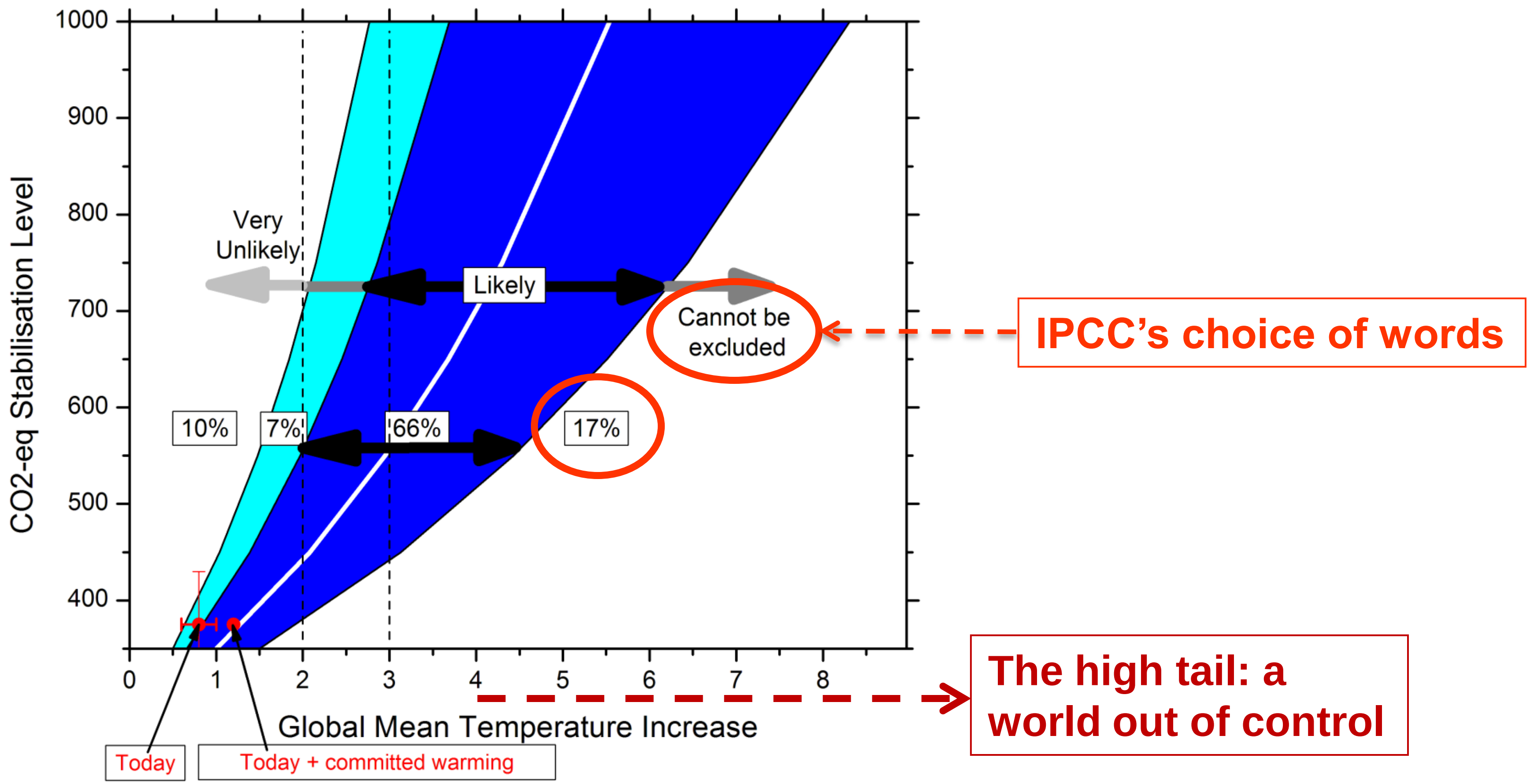


The long-term temperature increase for this concentration (x coordinate for this value of y) is the equilibrium climate sensitivity.

This graph is not found in IPCC AR4 WG1. There was no consensus about the probability shown here as 17%.

Source: From Martin Manning.

Long-term: temperature rise vs. CO_2 level



This graph is not found in IPCC AR4 WG1. There was no consensus about the probability shown here as 17%.

Source: From Martin Manning.

ECS Summary

The equilibrium climate sensitivity is a convenient and widely used measure of the amount of feedback in the climate system. The higher its value, the greater will be the consequences of our emissions at every stage

The poor level of understanding of aerosols limits the ability of models to estimate ECS. The first step of models is to replicate the past, and if aerosols are actually more important than assumed in some model, that model will underestimate the ECS. (The aerosols will actually be doing more cooling, and therefore the gases will be doing more heating, than in the models.)

Readers will compare what is said in AR5 about ECS later this month with what was said in AR4 in 2007.

EXTRA SLIDES
Syllabus Snapshots
longer version

Syllabus, Part One

Part One, Weeks 1-4: Climate Change, Carbon, and Business-As-Usual

Week 1: Overview. *Sept. 11*

Week 2: The earth's response to human activity. Future targets. *Sept. 18*

Week 3: Abundant fossil fuels. Shale gas, Keystone. Land use and biocarbon. – *Sept 25*

Week 4: The energy system and its policies: grids (oil, natural gas, electricity), sectors (transport, buildings, factories), scales (centralized, decentralized), end uses (transport, heating and cooling, lighting, electronics…), energy and carbon embedded in trade. – *Oct. 2*

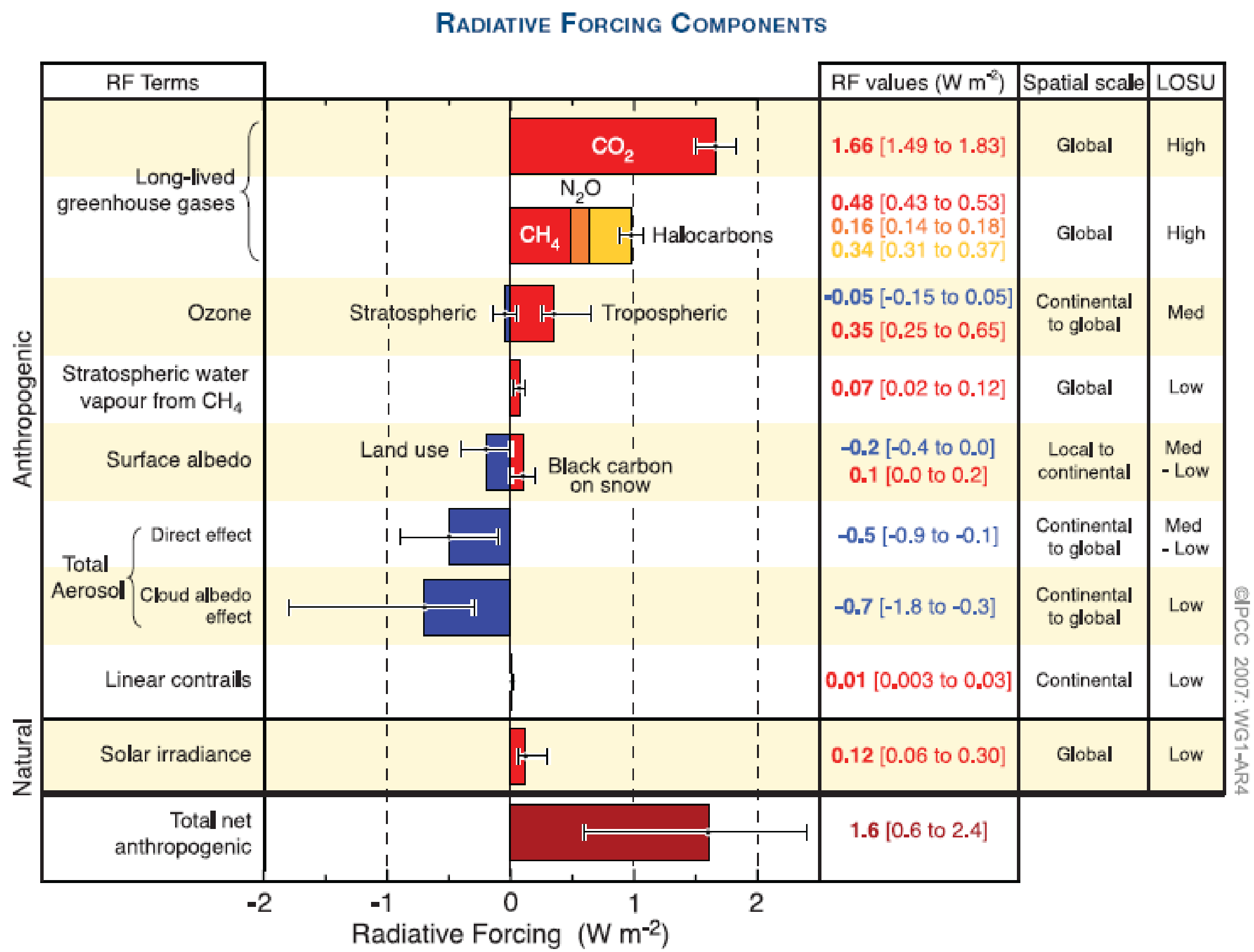


Figure SPM.2. *Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its range are also shown. These require summing asymmetric uncertainty estimates from the component terms, and cannot be obtained by simple addition. Additional forcing factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an additional natural forcing but are not included in this figure due to their episodic nature. The range for linear contrails does not include other possible effects of aviation on cloudiness. {2.9, Figure 2.20}*

Source: 2007 IPCC Summary for Policy Makers

Uncertain emissions

Thirty year changes for Massachusetts:

2010-2039:
Done!

2040-2069:
Princeton vs. Washington

2070-2099:
Baltimore vs. South Carolina

This graph probably shows how winters could feel too (to be verified).

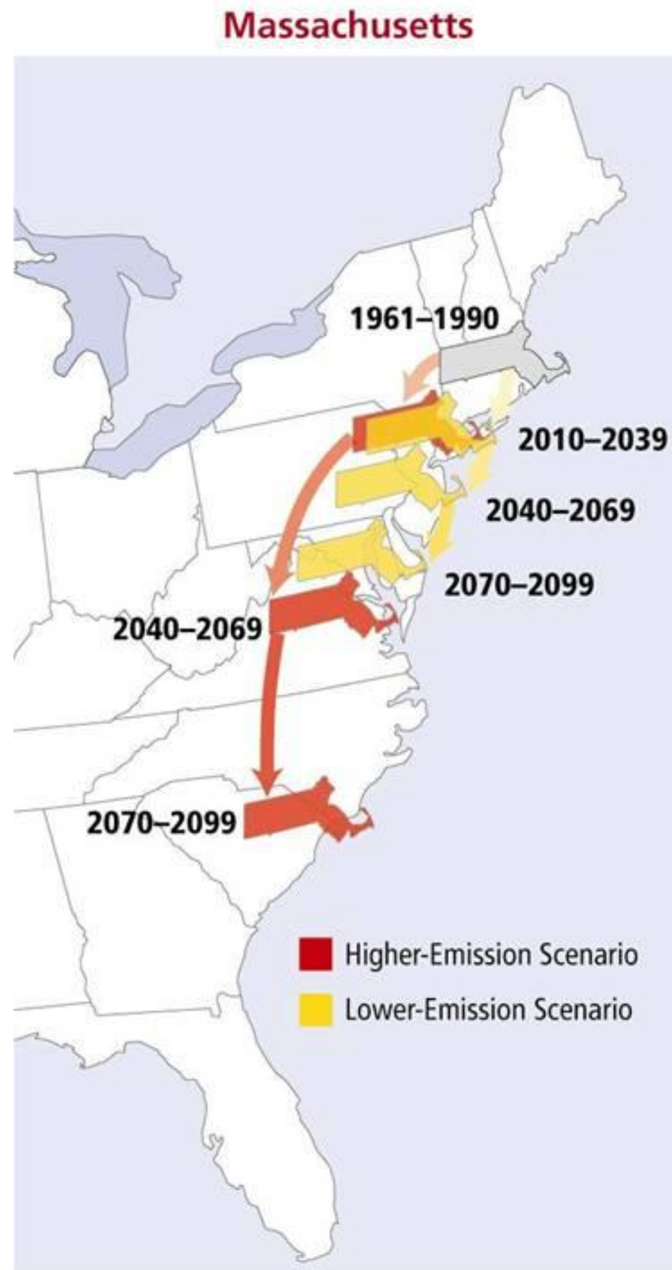


Figure from James McCarthy, Harvard

NECIA, 2007 (see: www.climatechoices.org/ne/)

Four World Views

		Are fossil fuels hard to displace?	
		NO	YES
Is climate change an urgent matter?	NO	A nuclear or renewables world unmotivated by climate.	Most people in the fuel industries and most of the public are here. **5ºC.**
	YES	Environmentalists, nuclear advocates are often here. **2ºC.**	OUR WORKING ASSUMPTIONS. **3ºC, tough job.**

Syllabus, Part Two

<u>Part Two, Weeks 5-7: Personal, Sub-National, National, and International Initiative</u>

Week 5: The student's carbon footprint, behavior, affluence and poverty, demography. – *Oct. 9*

Week 6: National and sub-national policy. Parallel mitigation campaigns across multiple stabilization wedges. Carbon markets (California). Regulation (EPA and coal). – *Oct 16*

Week 7: International governance and cooperation. [Guest Lecture, Phil Hannam] – *Oct 23*

Four ways to emit 4 ton CO_2/yr (today's global per capita average)

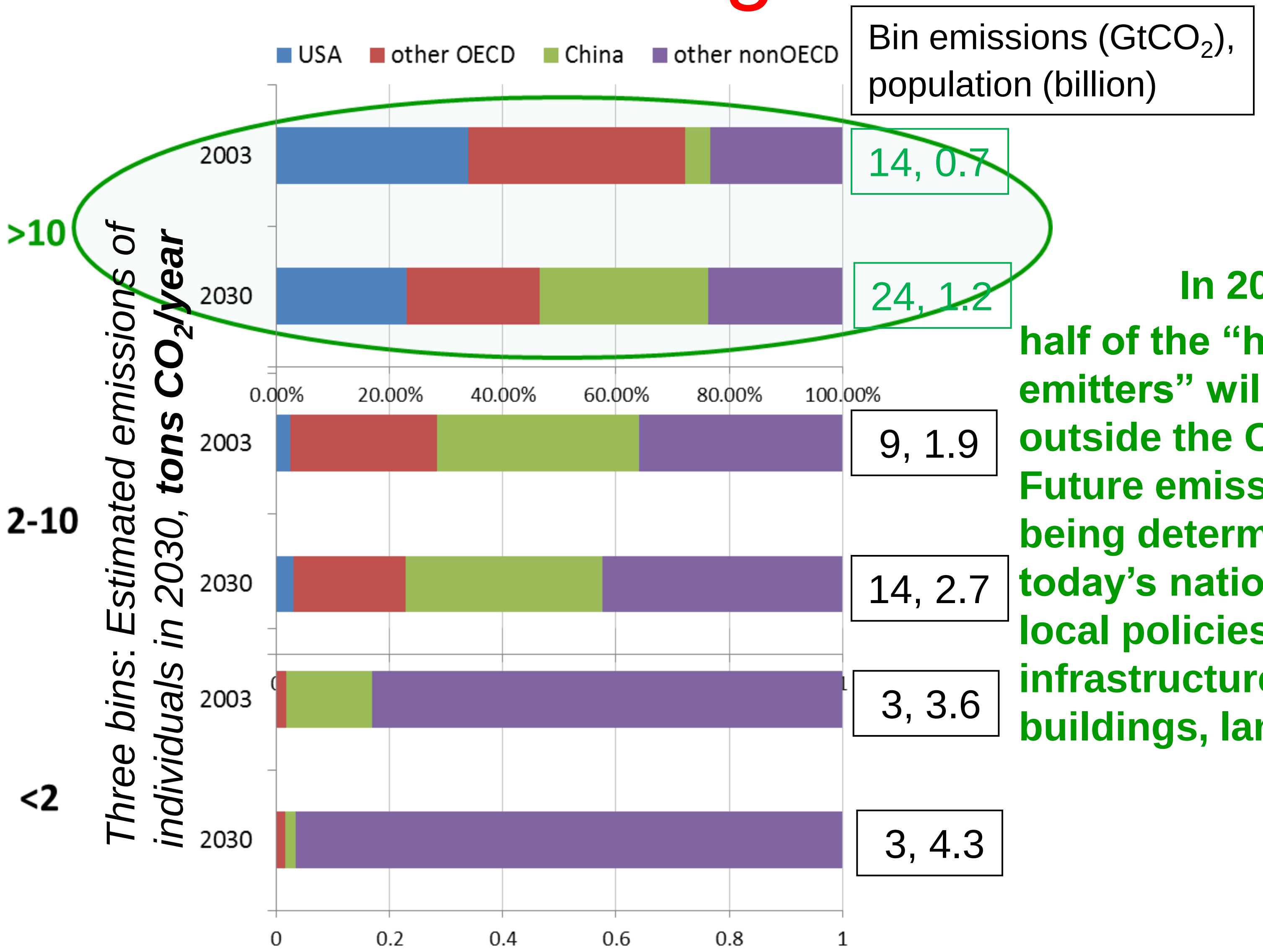
Activity	**Amount producing 4 ton CO_2/yr emissions**
a) Drive	24,000 km/yr, 5 liters/100km (45 mpg)
b) Fly	24,000 km/yr
c) Heat home	Natural gas, average house, average climate
d) Lights	300 kWh/month if all coal-power (1000 gCO_2/kWh) 600 kWh/month, natural-gas-power (500 gCO_2/kWh)

System efficiency

Most cars have only one person in them most of the time.

Many trips can be replaced by information technology.

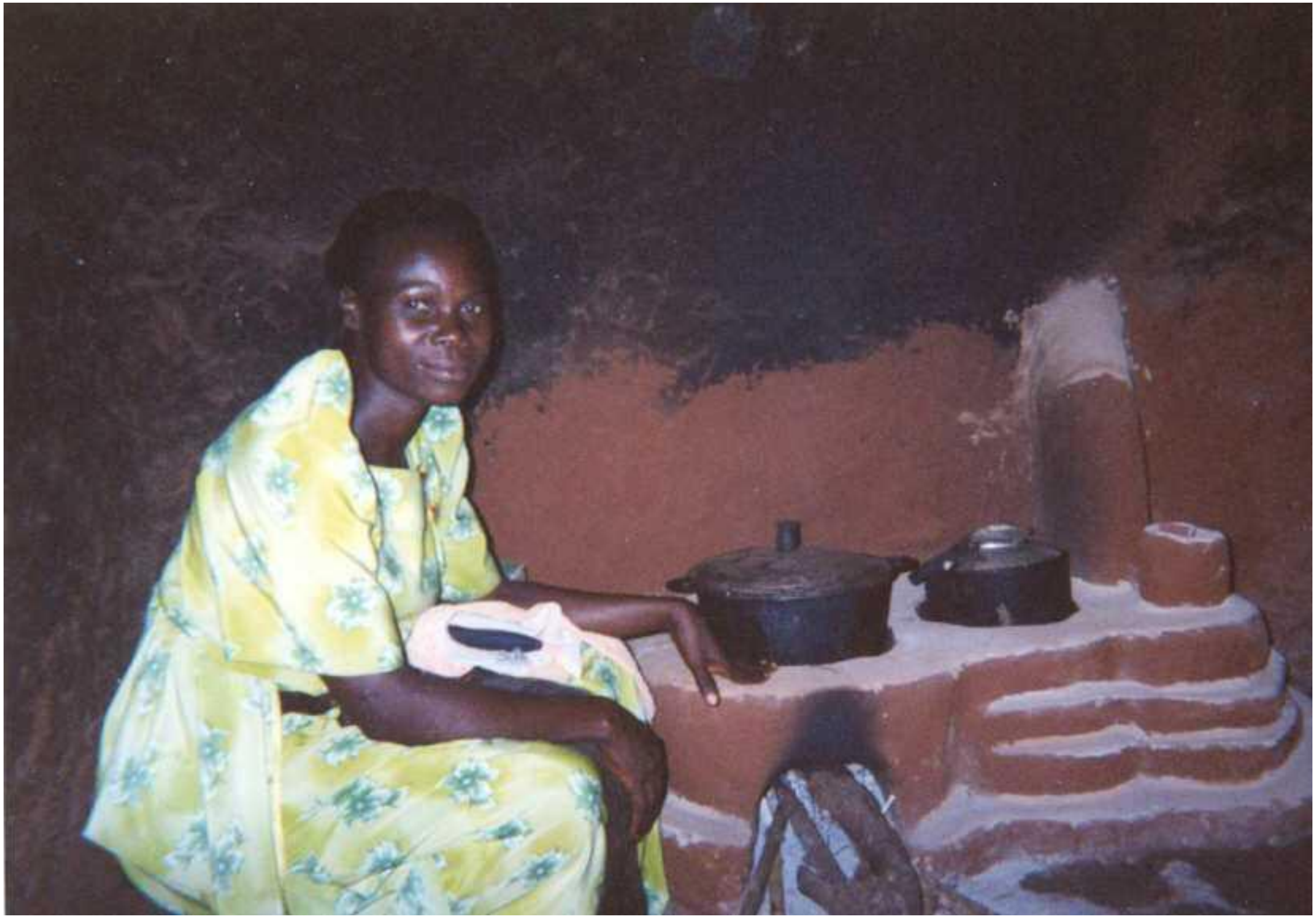
One billion "high-emitters"



In 2030, over half of the "high-emitters" will live outside the OECD. Future emissions are being determined by today's national and local policies on infrastructure, buildings, land use.

Source: http://www.climatescienceandpolicy.eu/2009/11/afocus-on-individuals-can-guide-nations-towards-a-low-carbon-world

Efficient vented stoves



Syllabus, Part Three

Part Three, Weeks 8-12: Technological options and related policy

Week 8: Energy efficiency. Electrification and biofuels for transport. – *Nov 8*

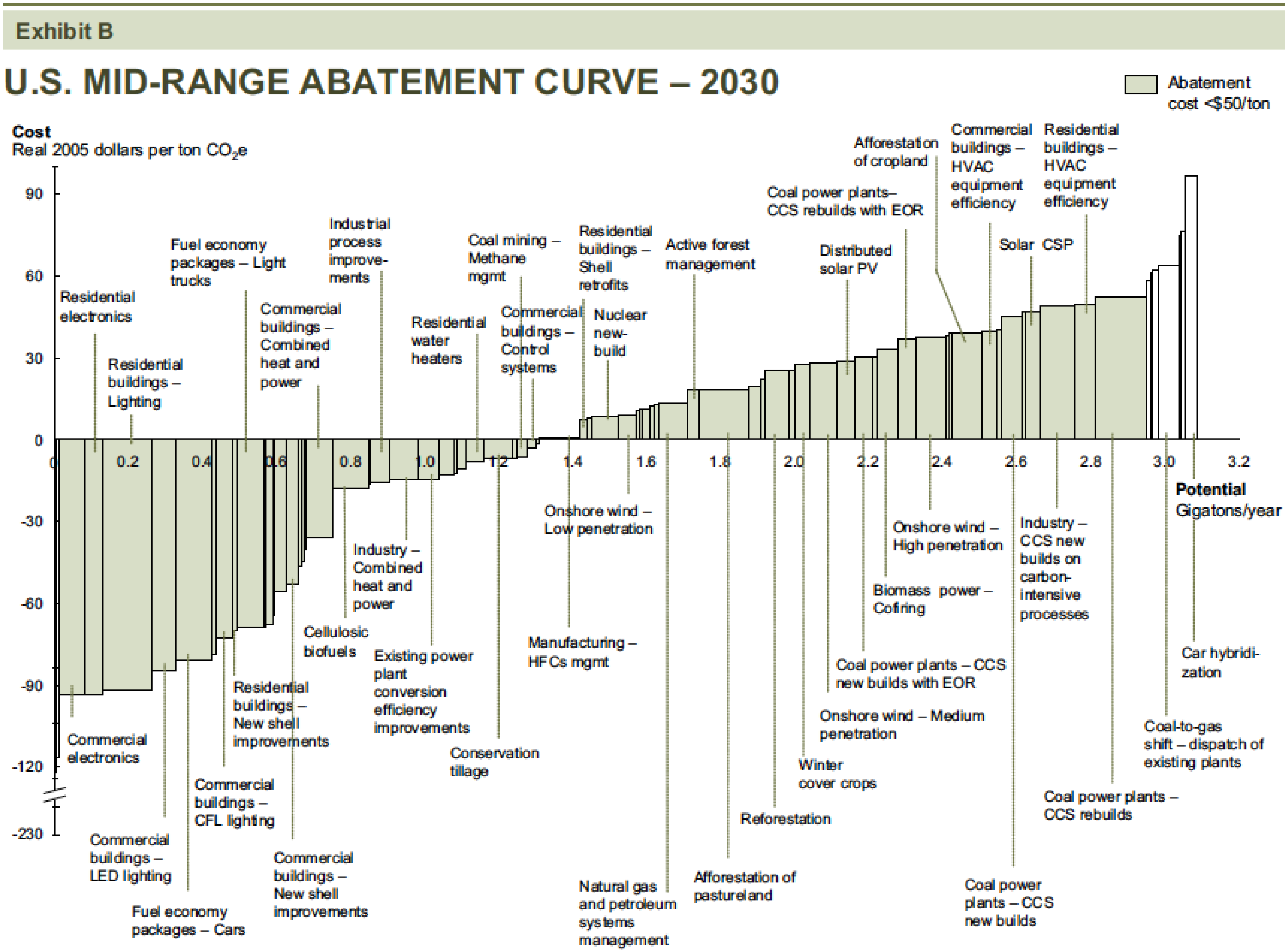
Week 9: Low-carbon fossil-fuel-based energy via CO_2 capture and storage. – *Nov 15*

Week 10: Intermittent and constantly available renewable energy; energy storage. – *Nov. 29*

Week 11: Nuclear power. – *Dec 4*

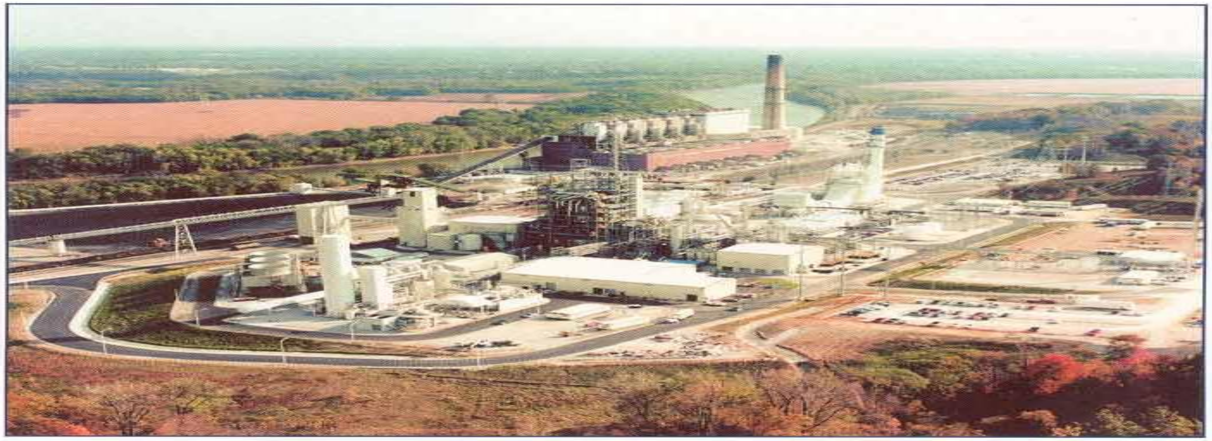
Week 12: Geoengineering. The enduring human project of planetary stewardship. – *Dec 11*

"McKinsey Curve"

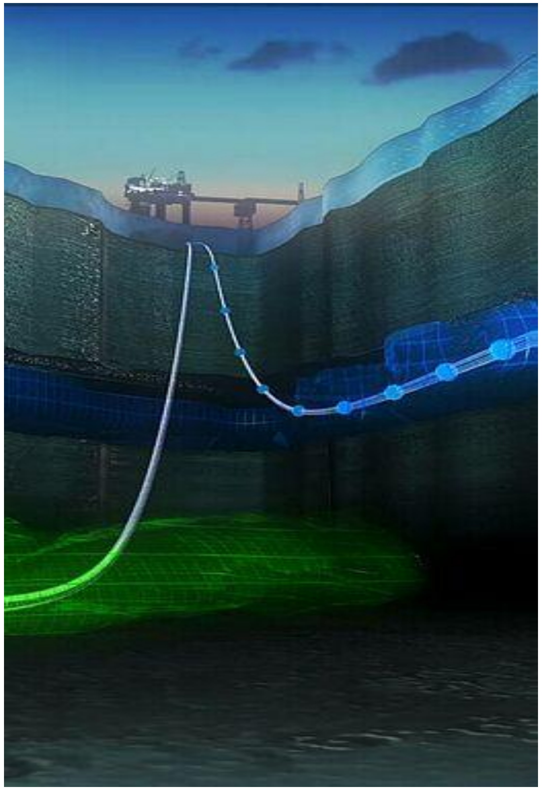


Source: McKinsey analysis

Coal with Carbon Capture and Storage



The Wabash coal gasification reprocessing project



Sleipner field, Norway

1 wedge: By 2062, 800 GW, if 90% capture.

Graphics courtesy of DOE Office of Fossil Energy and *Statoil ASA*

Wind Farms – Out of Sight

Offshore New Jersey: 96 turbines, 346 MW, 16 to 20 miles from coast. $1 billion project. Power "starting in 2013."

Source: http://www.nytimes.com/2008/10/04/nyregion/04wind.html?ref=nyregion, *New York Times*, October 3, 2008.

Princeton solar field

Princeton's 5.4 MW Solar PV website is now up and running. You can get access to some basic live data about the system and some introductory data about solar PV technology via the facilities energy project web page: http://www.princeton.edu/facilities/info/major_projects/solar_field/. The same website has a photo gallery that tracks the construction.

Fission Power – with Dry Cask Storage

Site: Surry station, James River, VA; 1625 MW since 1972-73,. *Credit*: Domir

Geoengineering by imitating volcanoes

On June 15, 1991 (three days after this photo) , Mt. Pinatubo. injected 10 million tons of sulfur into the stratosphere.

The Earth's average surface temperature was 0.5^{o}C cooler six months later, then rebounded.

"Perpetual volcanos" is being discussed: Efficacy, risks, governance.
Motivation: To be able to respond to an emergency.

Planetary identity

In the process of taking climate change seriously, we develop a planetary identity.

We augment our previous loyalties to family, village, tribe, and nation.

Do *you* have a planetary identity?

EXTRA SLIDES
Science

Global albedo change if arctic icecap disappears

A. Arctic ice albedo is 0.46; ocean albedo is close to zero

Divide by two because half of arctic icecap is shielded by clouds.

Divide by three to take into account seasonal issues (this is a summer effect).

So, annually averaged change in arctic albedo if arctic icecap disappears is 0.08.

B. The average solar flux in summer on arctic ice is 400 W/m^2. So solar heating of the arctic increases by 32 W/m^2.

C. The average area of Arctic icecap is about $8x10^{12}$ m^2, about 1.6% of the planet's surface area. So arctic icecap disappearance increases the global forcing by 0.5 W/m^2.

D. The climate sensitivity relates an increase in forcing to a rise in the average surface temperature. The rise is about 0.5^oC for a "climate sensitivity" of 3^oC. (We'll get back to this.)

Forcing and climate sensitivity (1 of 2)

If we assume the earth is a black body with an albedo and no greenhouse effect, there is a direct relationship between albedo change and temperature change:

$$-da/(1-a) = 4dT/T.$$

The change in forcing resulting from an albedo change, dF, is

$$dF = -S_o da = -(\Omega/4)da, \text{ so}$$

$$dT = \{T/[(1-a)\Omega]\}dF$$

relates a change in forcing to a change in surface temperature in this model.

Using this equation with a real surface temperature provides the relationship between forcing and surface temperature change for an earth with a greenhouse effect but no feedback: For a = 0.31, T = 288K, and Ω = 1368 W/m^2,

$$dT = [0.305\ K/(W/m^2)]*dF$$

So, for the problem above, an increase in the forcing of 0.5W/m^2 would produce an 0.15K rise in average surface temperature. An amplification factor of 3.3 corresponds to the rule of thumb that 1 W/m^2 of extra forcing produces a 1K rise in average surface temperature.

Forcing and climate sensitivity (2 of 2)

This discussion can be related to the climate sensitivity (CS) via the similar dependencies of T and F on CO2 concentration:

$$T = CS*\ln(C/C_o)/\ln 2, \text{ and } F = F_d*\ln(C/C_o)/\ln 2,$$

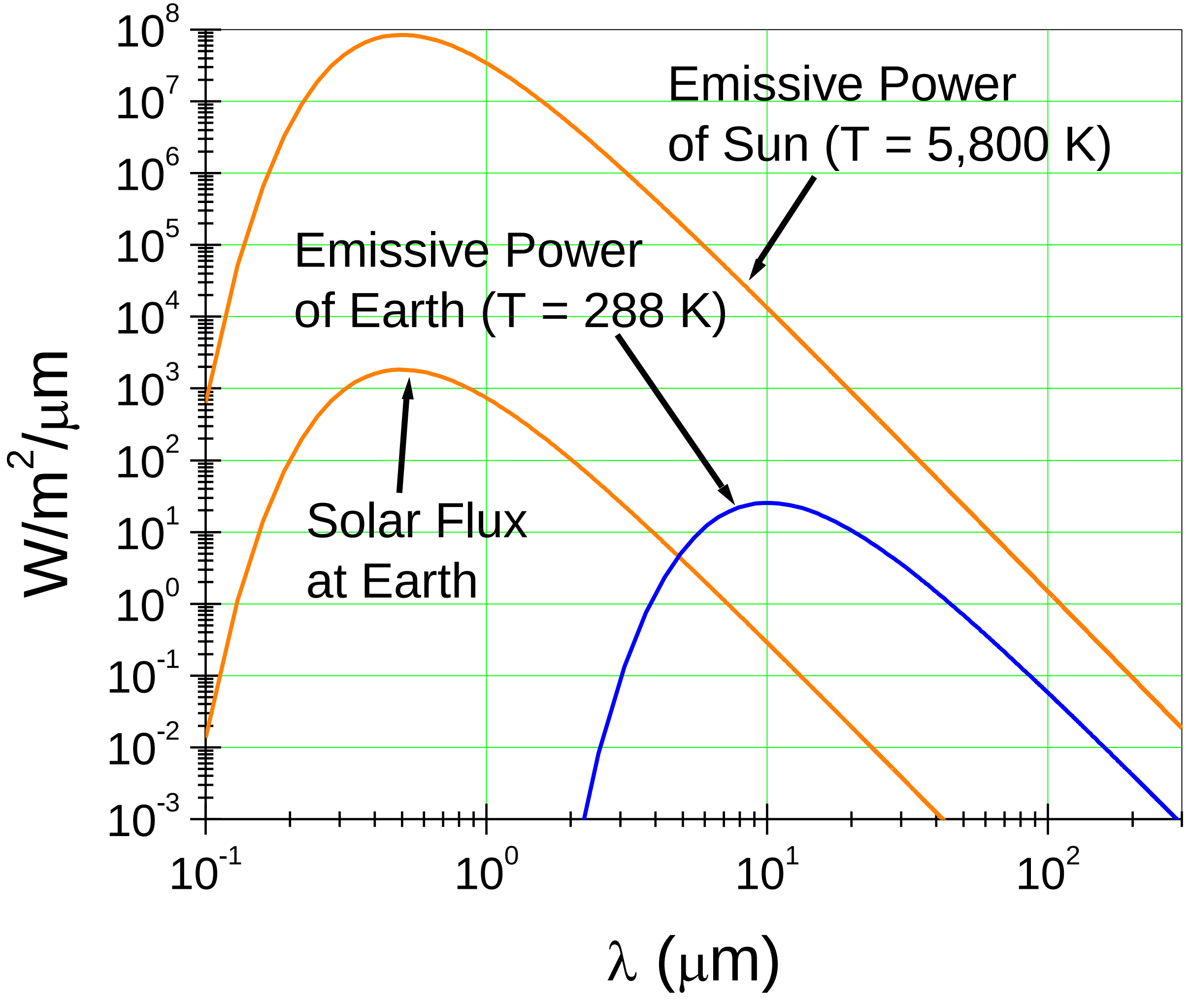
where C_o is the preindustrial concentration and F_d is the forcing due to a doubling of the CO_2 concentration. T and F are then linearly related:

$$T = (CS/F_d)*F.$$

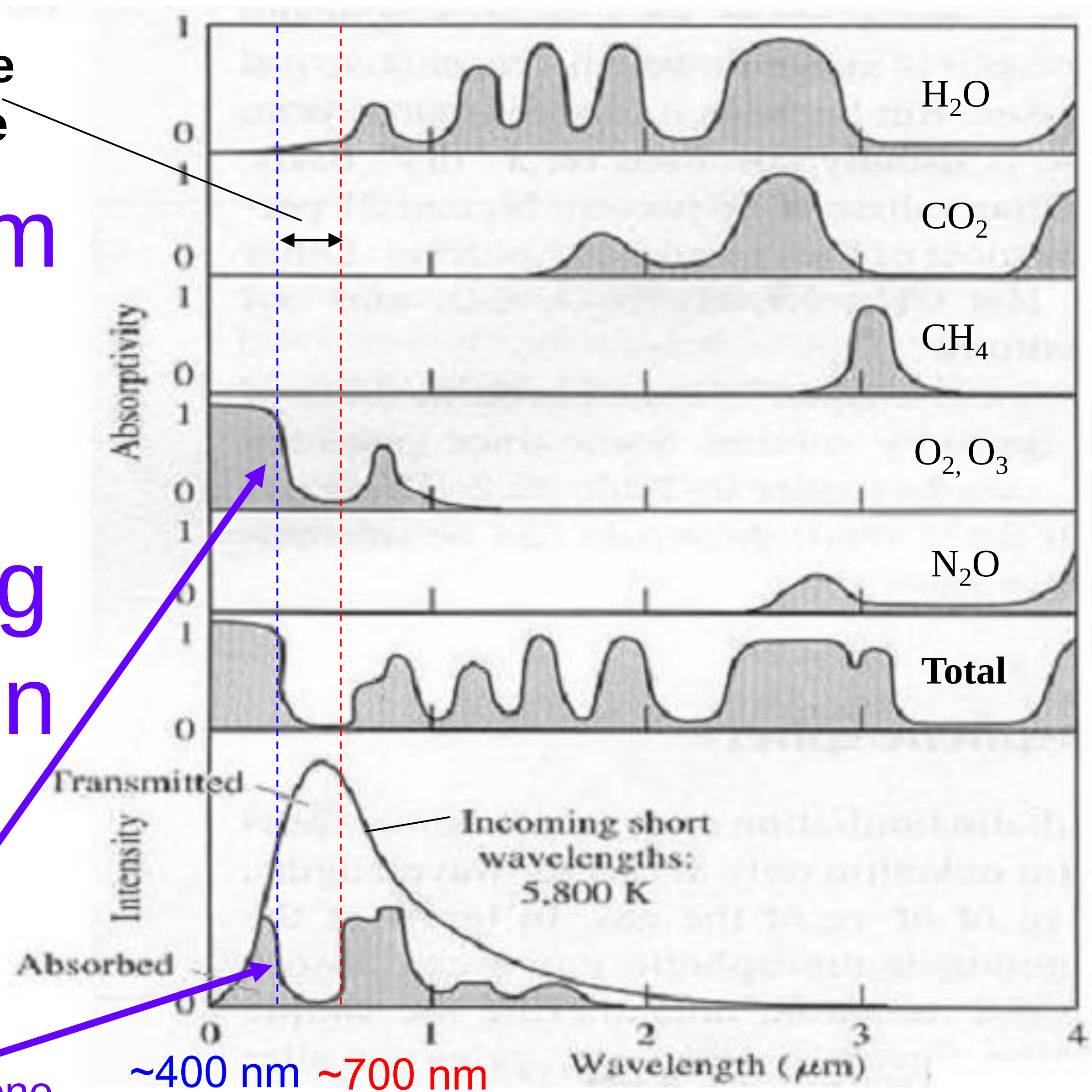
For C_o = 275K, Fd = 3.71 W/m2 (Ref?). Thus, Model 2 above corresponds to CS = 1.13K, and the “rule of thumb” above corresponds to CS = 3.71K.

IPCC AR4 reports today’s best judgment: 2.0 < CS < 4.5K is the “likely” (i.e., 66%) interval for CS, with a central value of 3.0K.

Emissive Power of Sun and Earth (from blackbody equation)



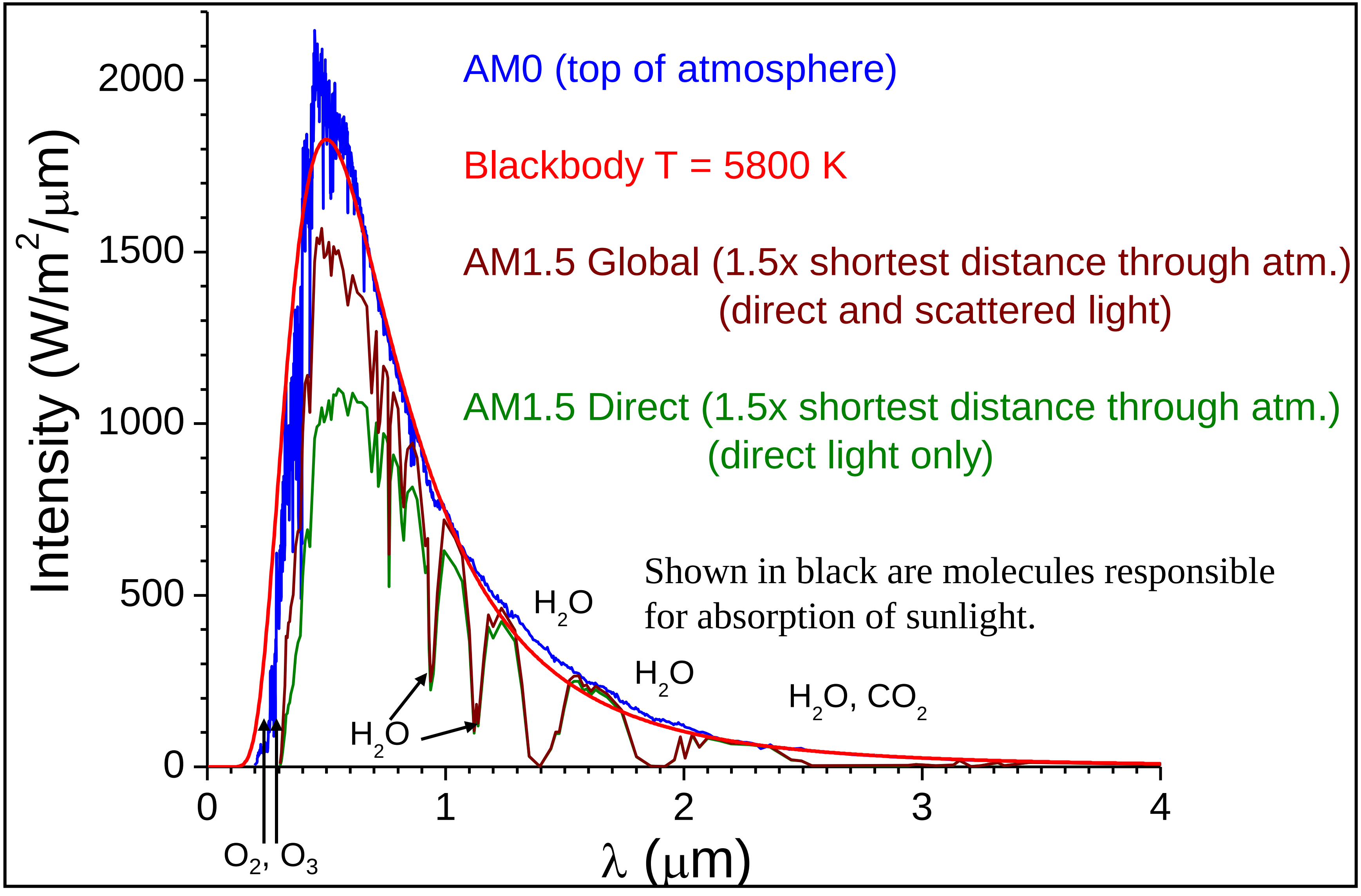
Spectrum of the Sun's Incoming Radiation



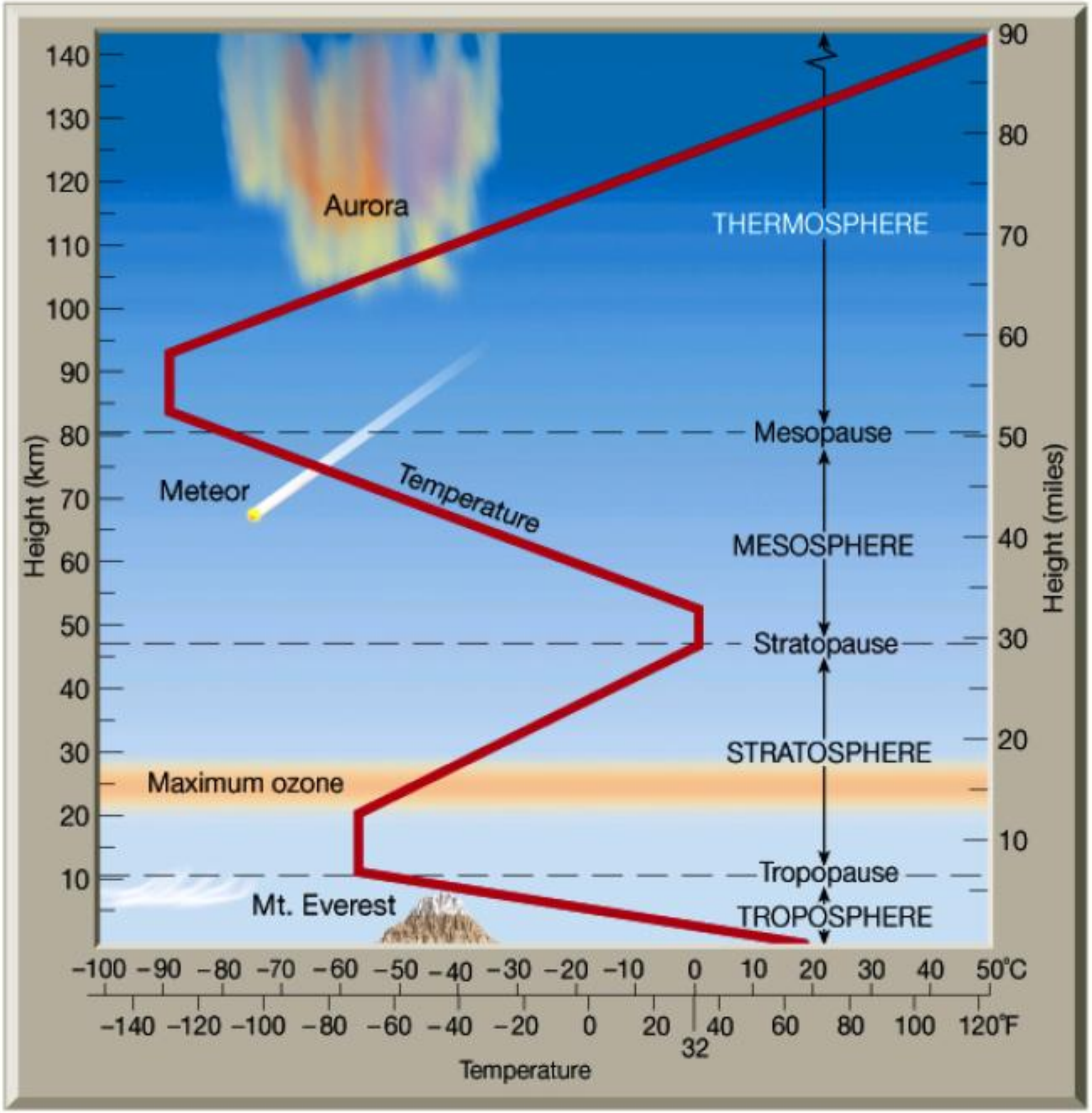
Stratospheric ozone shields us against ultraviolet rays

Rubin, p. 482

Solar Spectrum at Earth

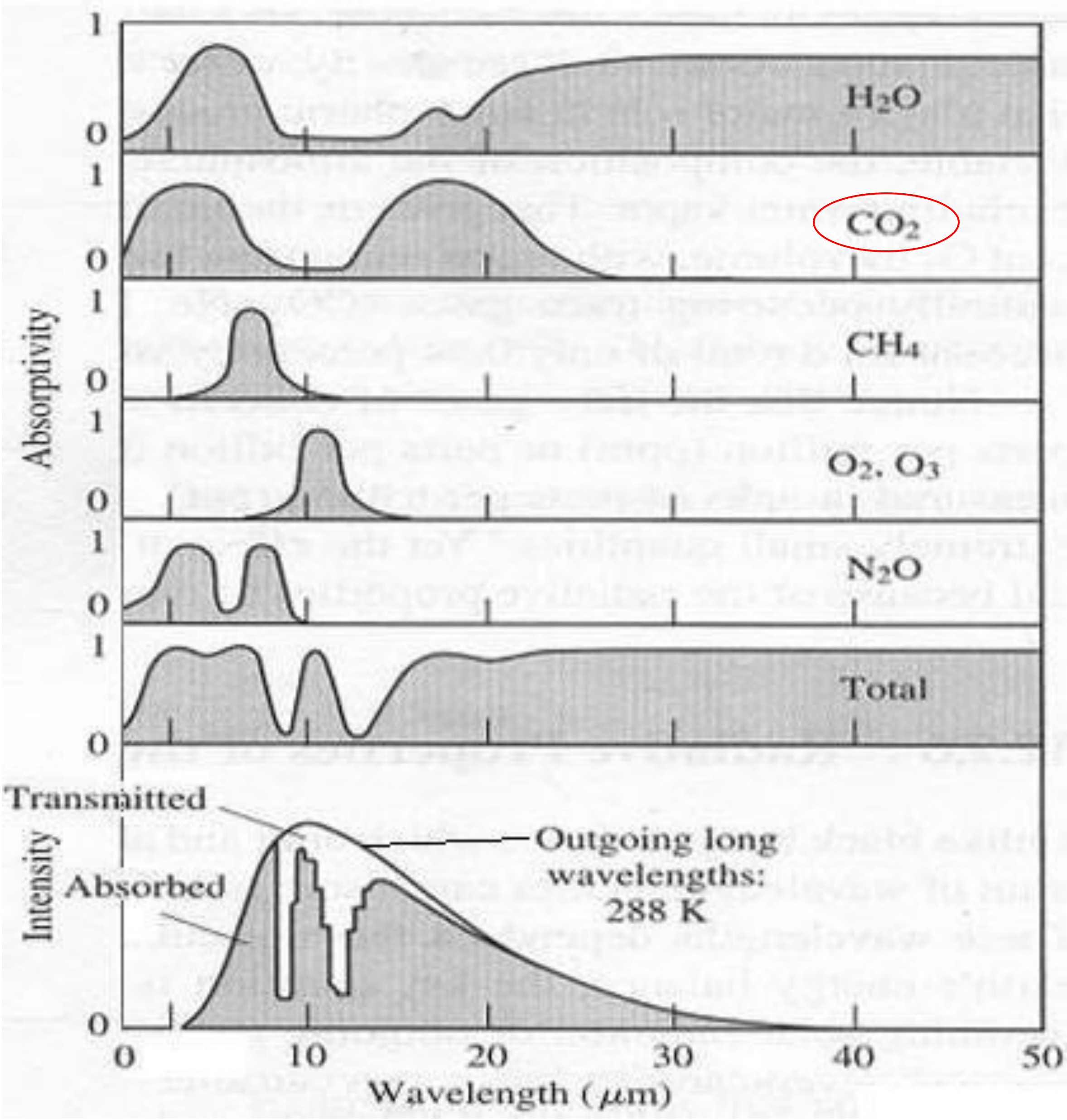


The Temperature of the Earth's Atmosphere



Source: Figure 1-19, p. 20 in Lutgens and Tarbuck's *The Atmosphere*, 2001). Reproduced at http://www.ux1.eiu.edu/~cfjps/1400/atmos_struct.html

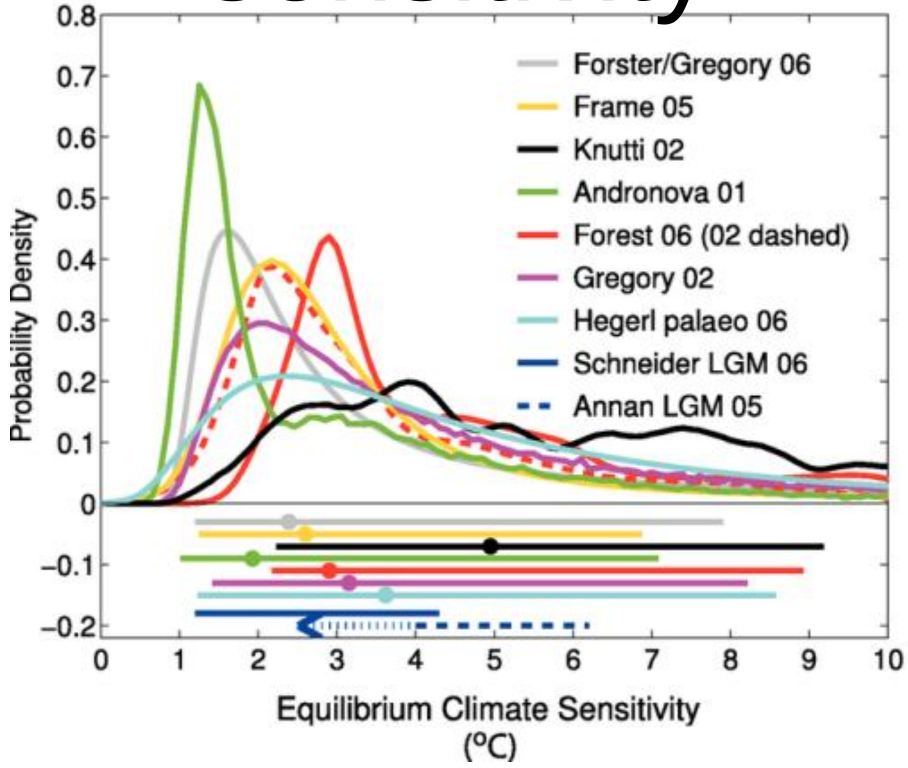
Spectrum of the Earth's Outgoing Radiation



Rubin, p. 482

EXTRA SLIDES
More on climate sensitivity

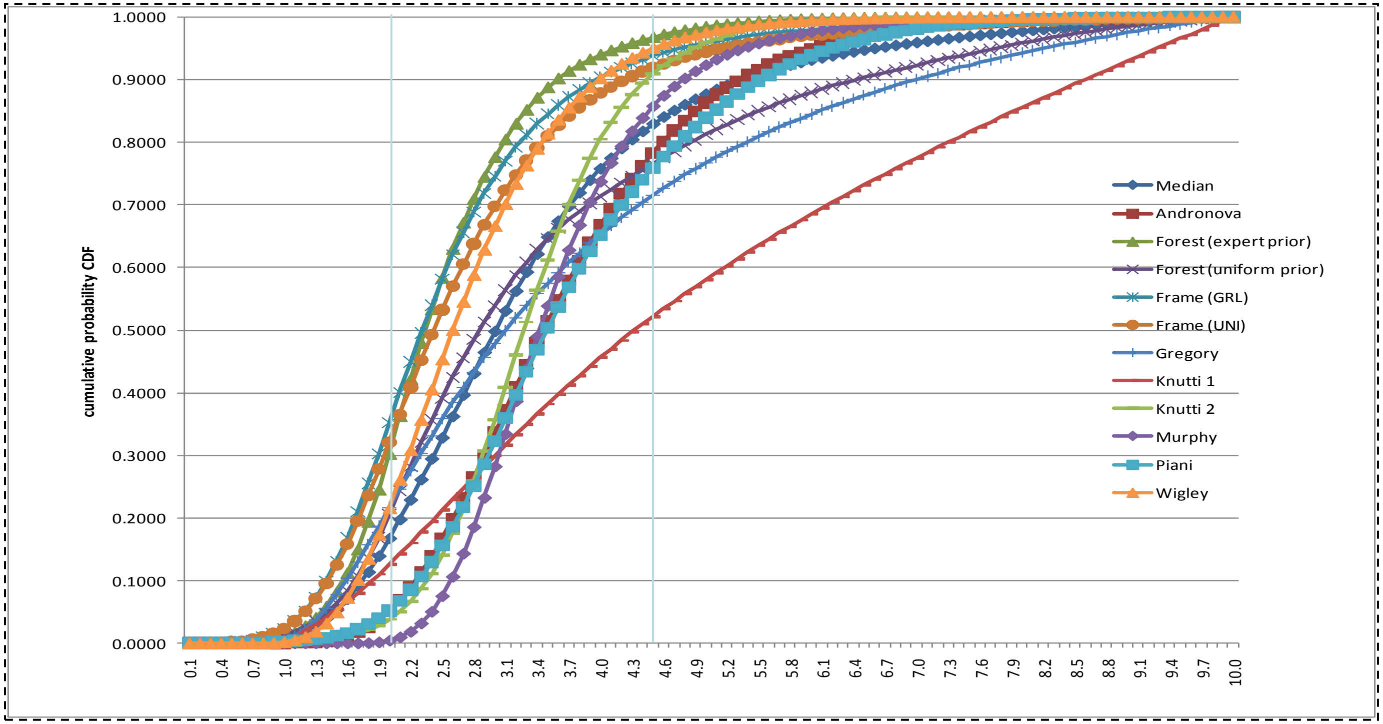
Seven views of the climate sensitivity



Identical to Figure 9.20 in [IPCC 2007b, p. 720], except for the addition of vertical lines at 2ºC and 4.5ºC to assist the reader. *Partial caption*: "Comparison between different estimates of the PDF (or relative likelihood) for ECS (°C). All PDFs/likelihoods have been scaled to integrate to unity between 0°C and 10°C ECS. The bars show the respective 5 to 95% ranges, dots the median estimate…."

Note: Probability densities can only be positive or zero: the two negative y-axis values (-0.1 and -0.2) are meaningless and should have been removed.

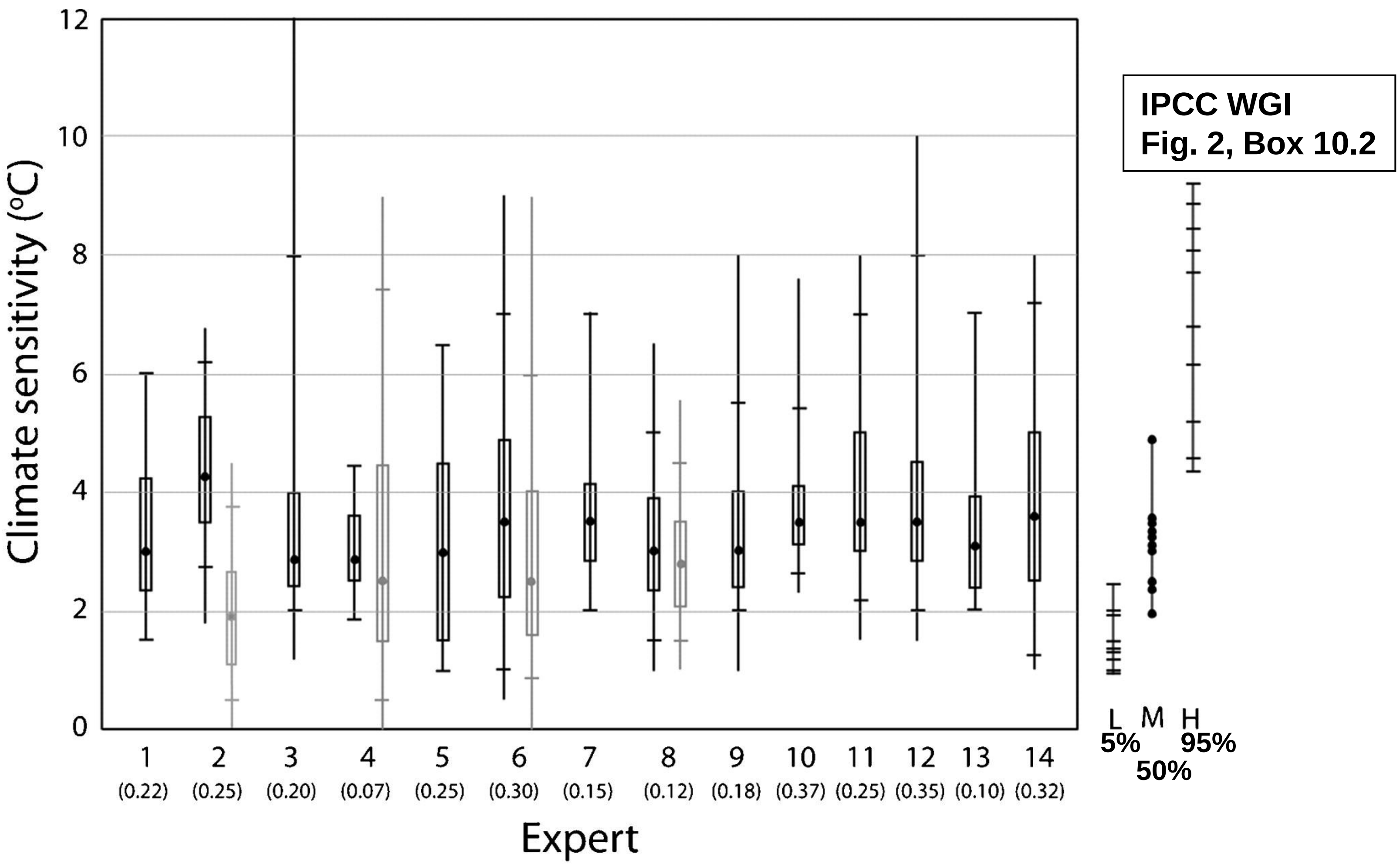
Eleven views of the climate sensitivity



Eleven pdf's for the Equilibrium Climate Sensitivity [Meinshausen 2006] are displayed as cumulative distribution functions. Meinshausen cuts off all distributions at 10ºC. Vertical lines at 2ºC and 4.5ºC have been added to assist the reader.

IIASA authors used this data base [O'Neill et al. 2010] and made it available as an Excel file at http://www.iiasa.ac.at/~riahi/Interim_Targets/; see the spreadsheet labeled "climate sensitivity PDFs."

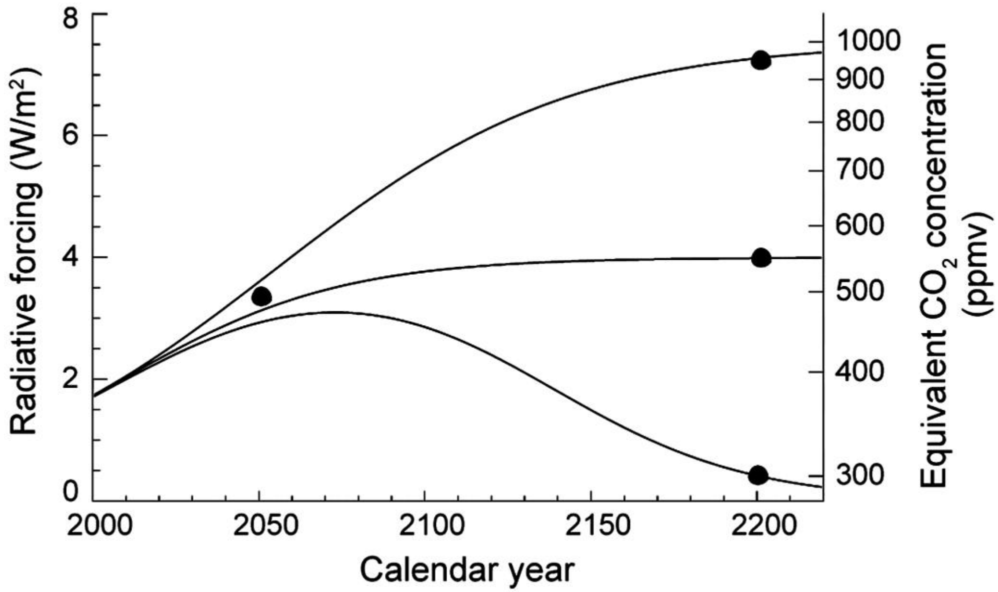
Experts views of climate sensitivity

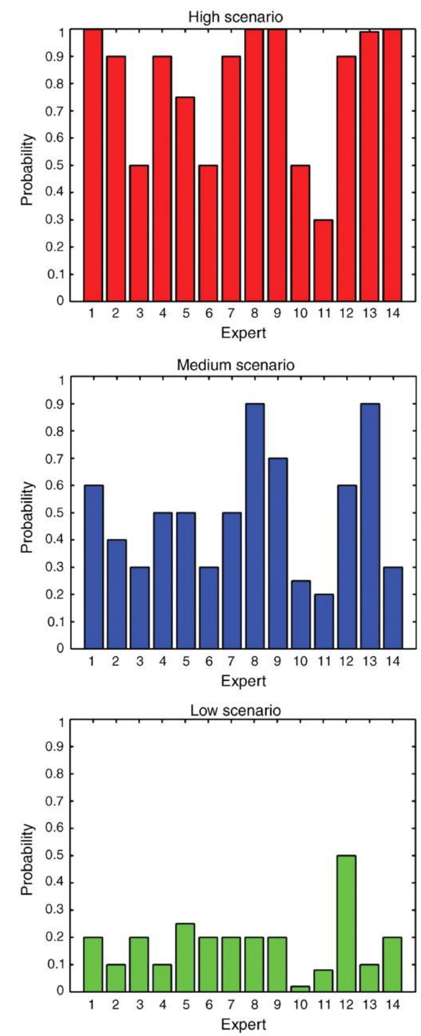


Box plots of probability distributions for equilibrium climate sensitivity, elicited from 14 "experts." In brackets, expert's p > 4.5°C. In gray, earlier elicitation, same expert.

***Source*: Zickfeld K et al. *PNAS* 2010;107:12451-12456**

Uncertain chance of havoc

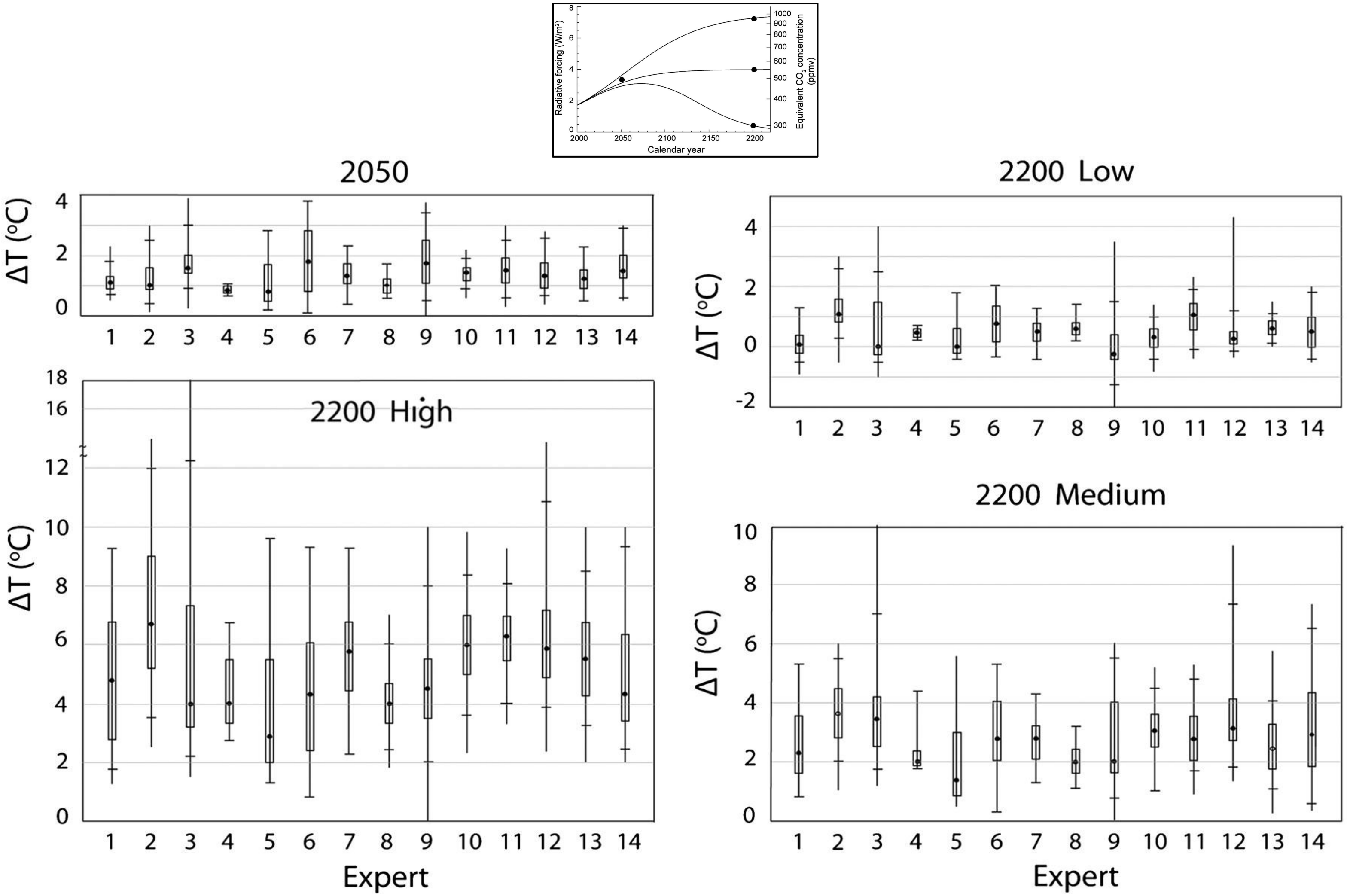




At right, **elicited probabilities from 14 "experts" that the climate system will undergo, or would be irrevocably committed to a fundamental state change (i.e., a state change with global consequences persisting for several decades) by 2200 in response to the three forcing trajectories shown above.**

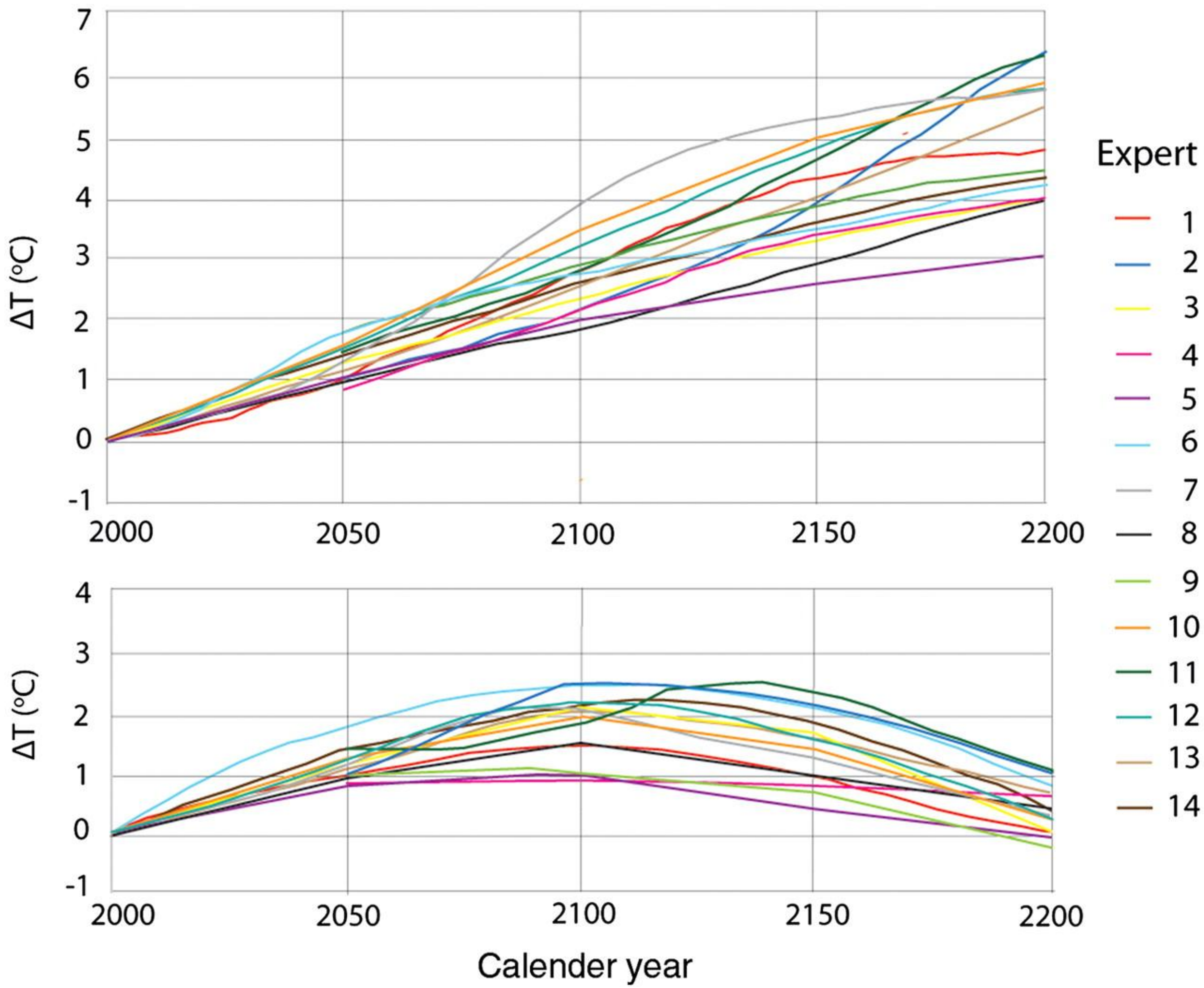
***Source*: Zickfeld K et al. *PNAS* 2010;107:12451-12456**

Uncertain future surface temperatures



Box plots of probability distributions elicited from 14 "experts": global mean surface air temperature change (ΔT) relative to 2000, for four points shown in the inset.

Experts' median estimates of the transient response of globally averaged temperature change (relative to 2000) for the high (Upper) and low (Lower) forcing trajectories.



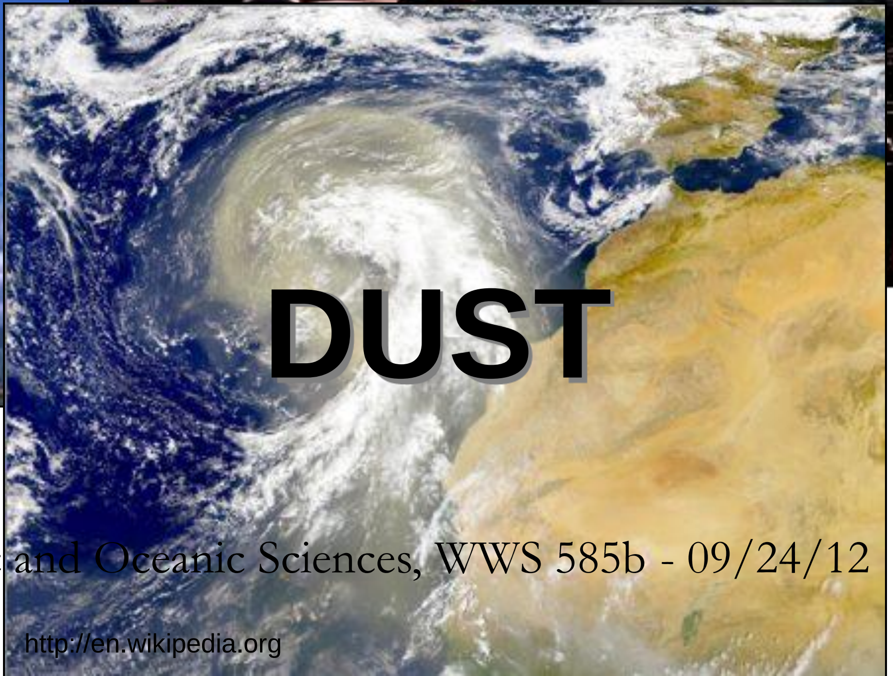
Zickfeld K et al. PNAS 2010;107:12451-12456

PNAS

EXTRA SLIDES
Cameo on aerosols
Geeta Persad, L2, 2012

What are aerosols?

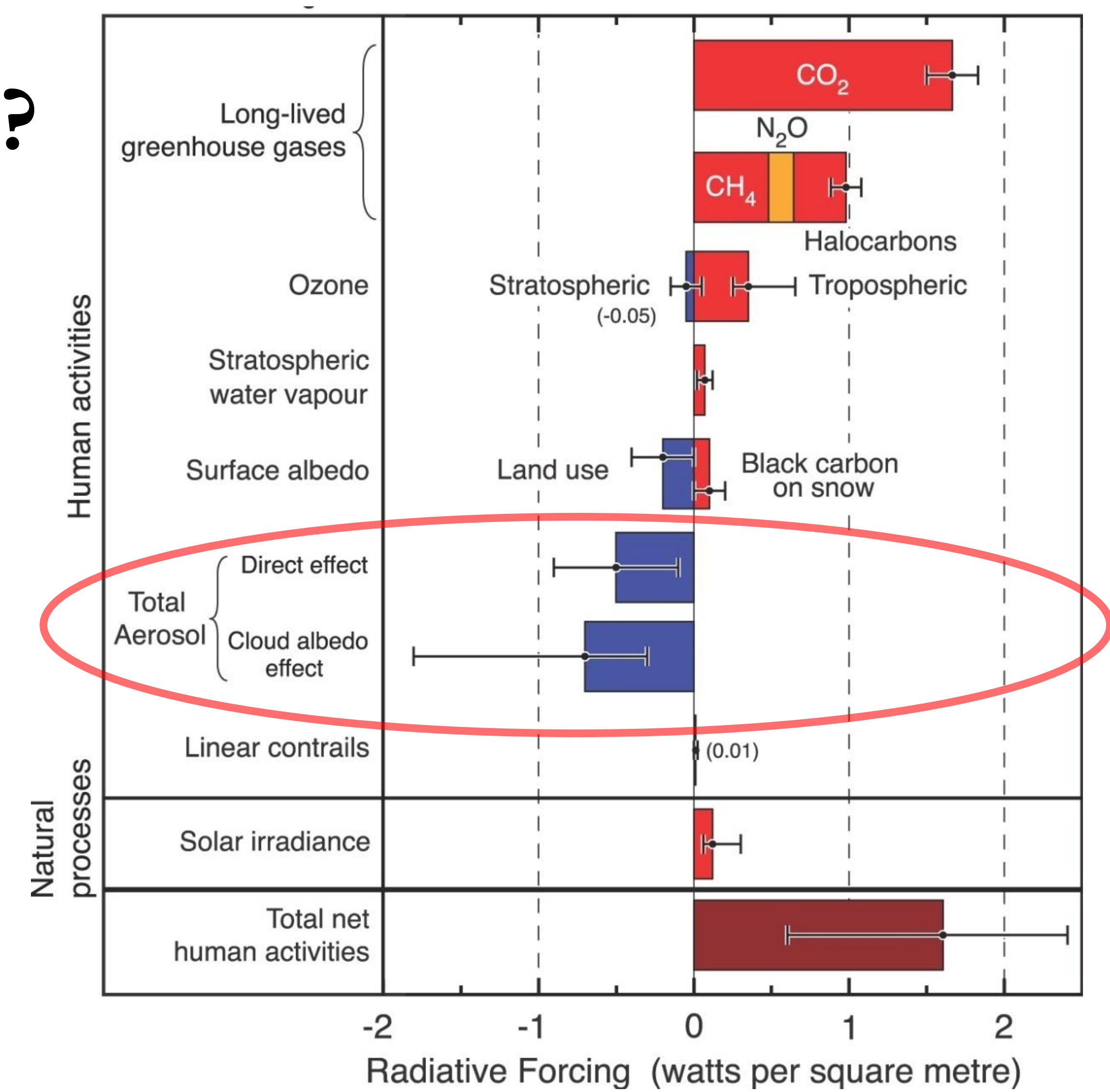
- Particles in the atmosphere that scatter and absorb sunlight



Source: Geeta Persad, Program in Atmospheric and Oceanic Sciences, WWS 585b - 09/24/12

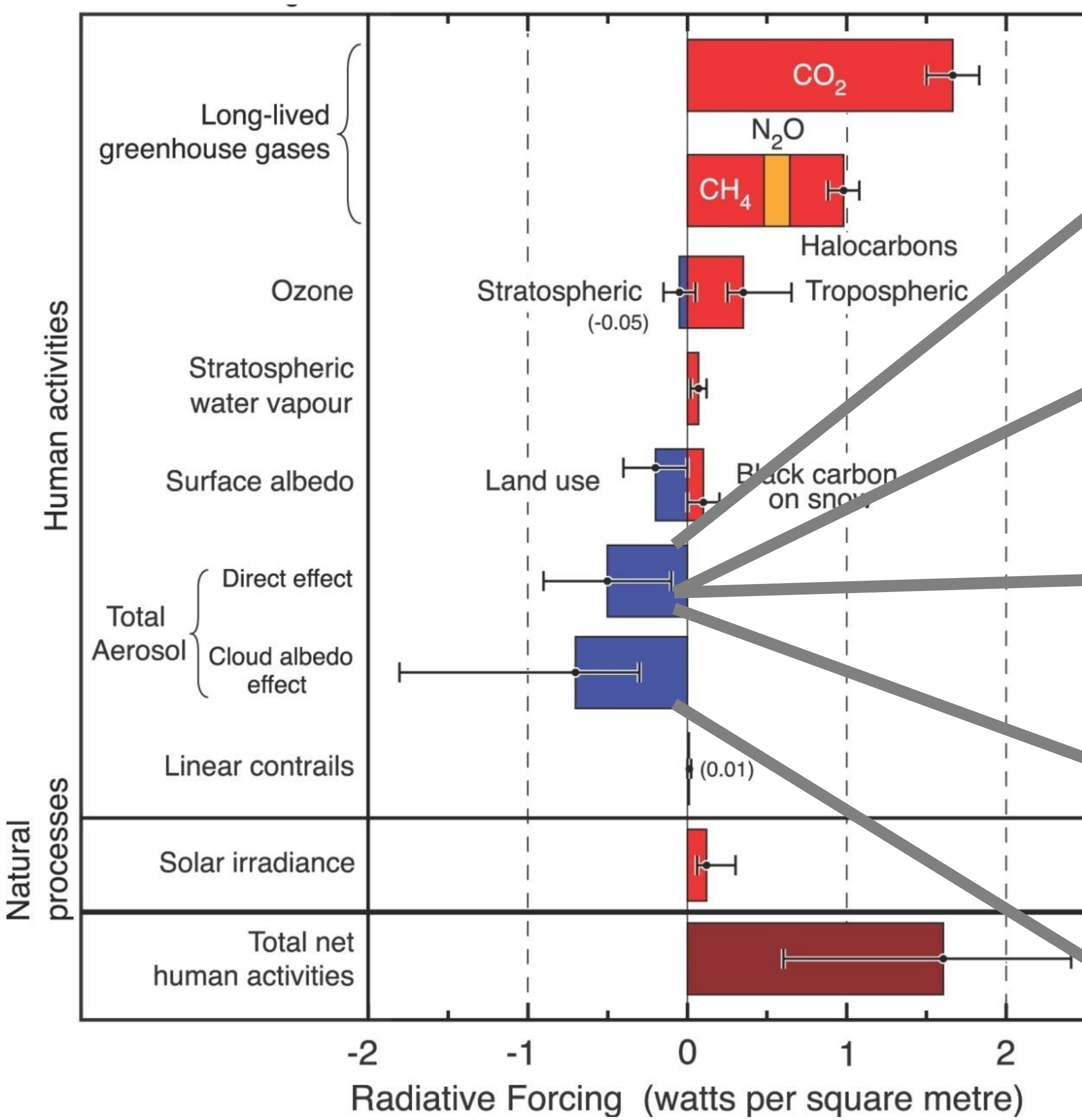
What are aerosols?

And why are they one of the biggest question marks for climate change?



Source: Geeta Persad, Program in Atmospheric and Oceanic Sciences, WWS 585b - 09/24/12

Why are aerosols the big question mark?



Emissions

Transport and Location

Particle Mixing

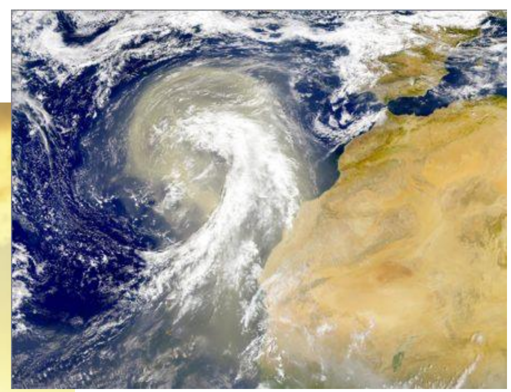
Evolution and Removal

Interaction with clouds

Why are aerosols the big question mark?

Transient and variable sources

Poor constraints on stationary sources



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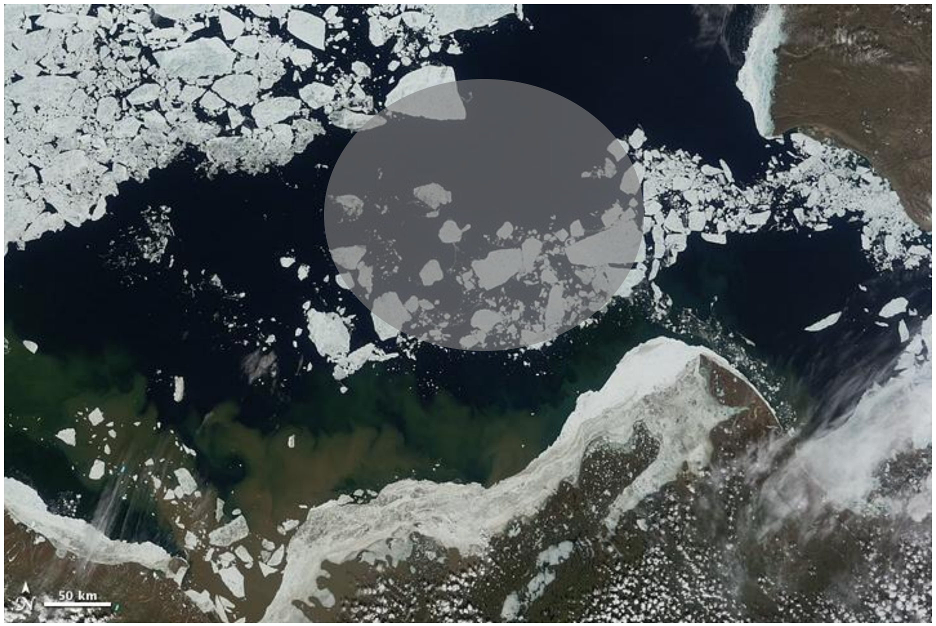

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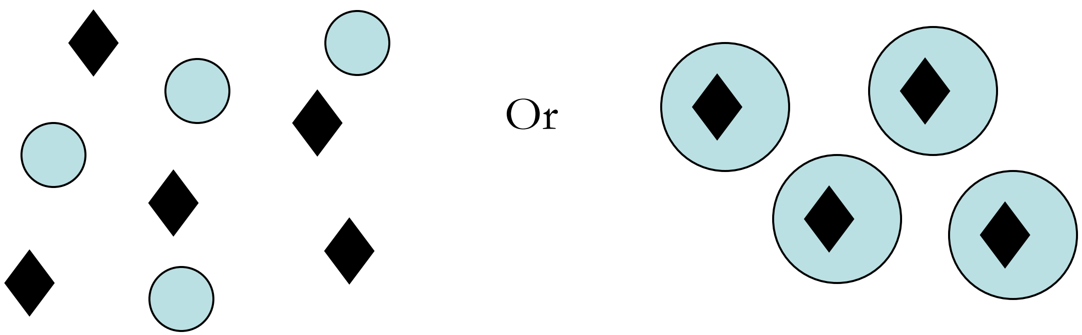

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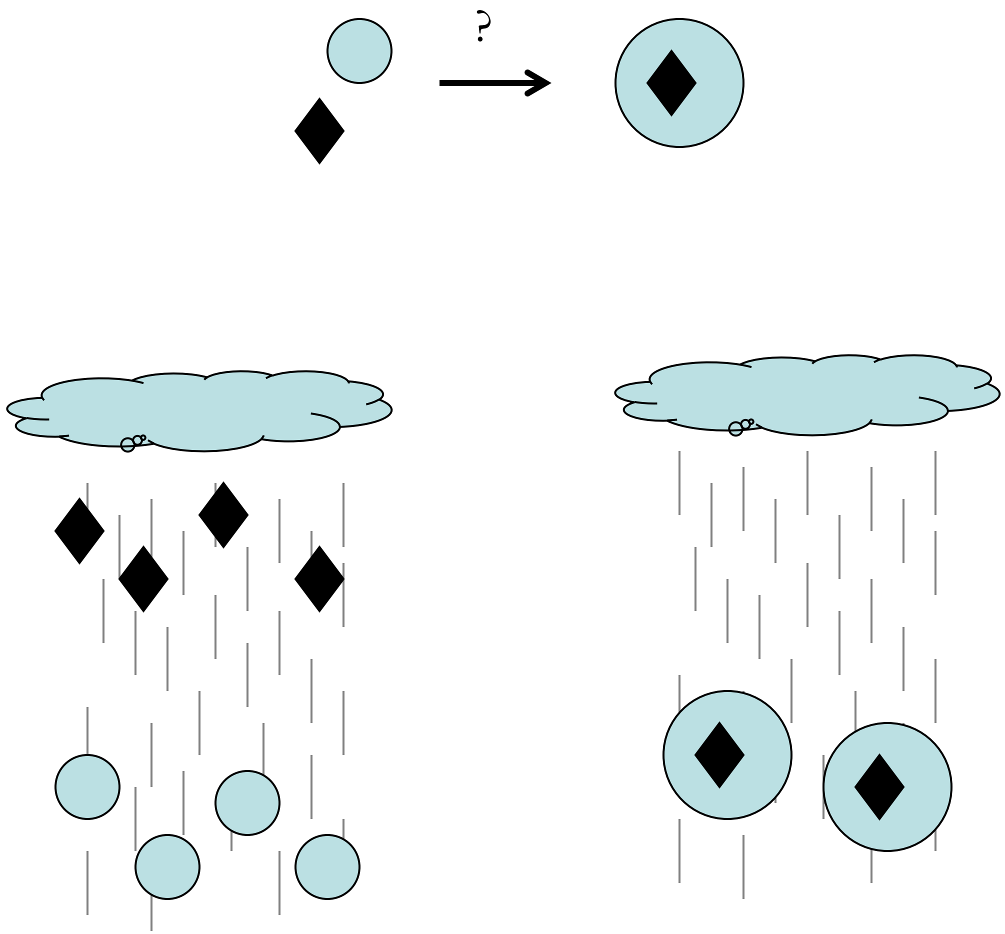

Emissions

Transport and Location

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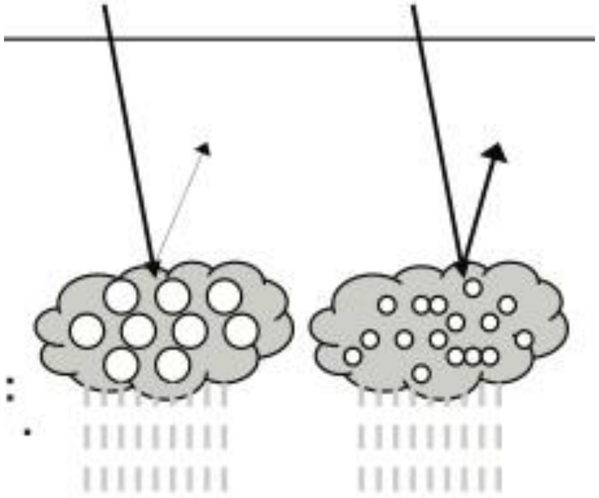
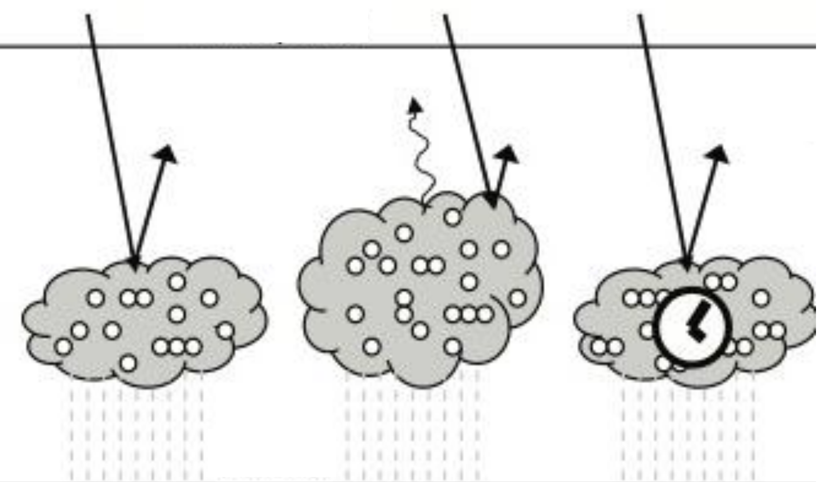
Interaction with clouds

Source: Geeta Persad, Program in Atmospheric and Oceanic Sciences, WWS 585b - 09/24/12

Why are aerosols the big question mark?



Cloud brightening



Cloud lifetime

Emissions

Transport and Location

Particle Mixing

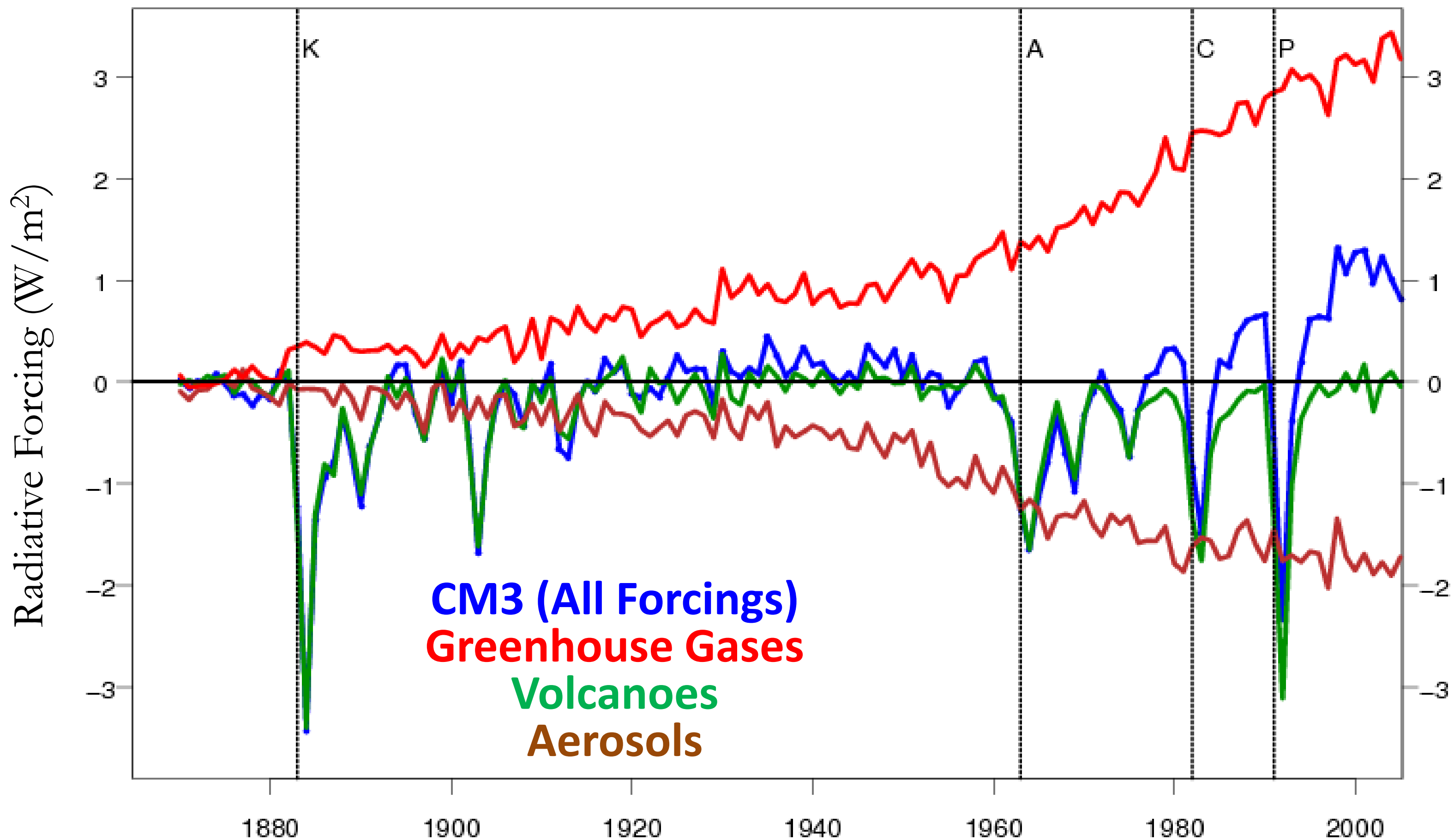
Evolution and Removal

Interaction with clouds

Source: Geeta Persad, Program in Atmospheric and Oceanic Sciences, WWS 585b - 09/24/12

How do aerosols affect climate?

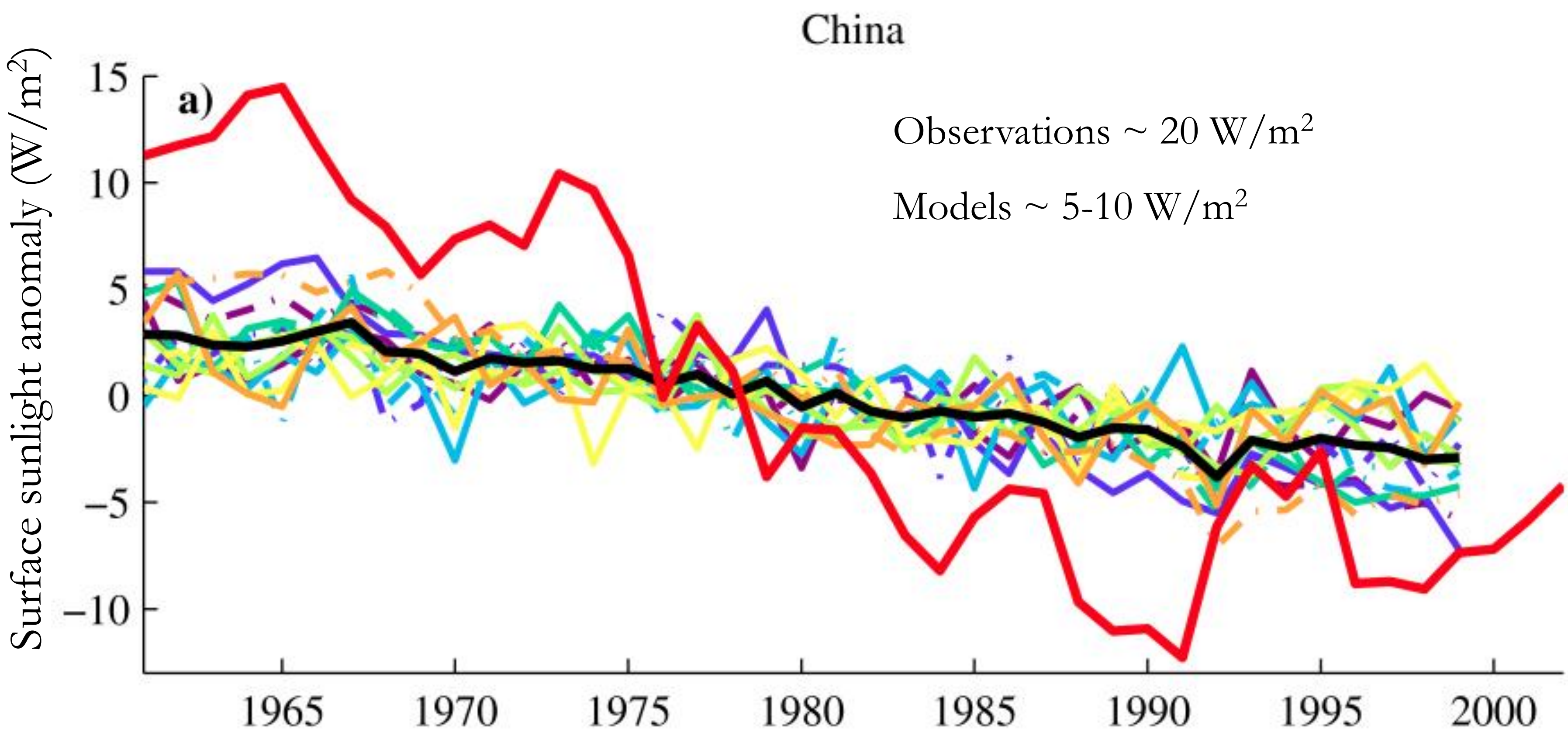
Cooling from **aerosols** partially counteracts heating from **greenhouse gases**



Source: Geeta Persad, Program in Atmospheric and Oceanic Sciences, WWS 585b - 09/24/12

How do we reduce the error bar?

- Recreate an aerosol-driven trend with a model and determine what aerosol characteristics cause it.



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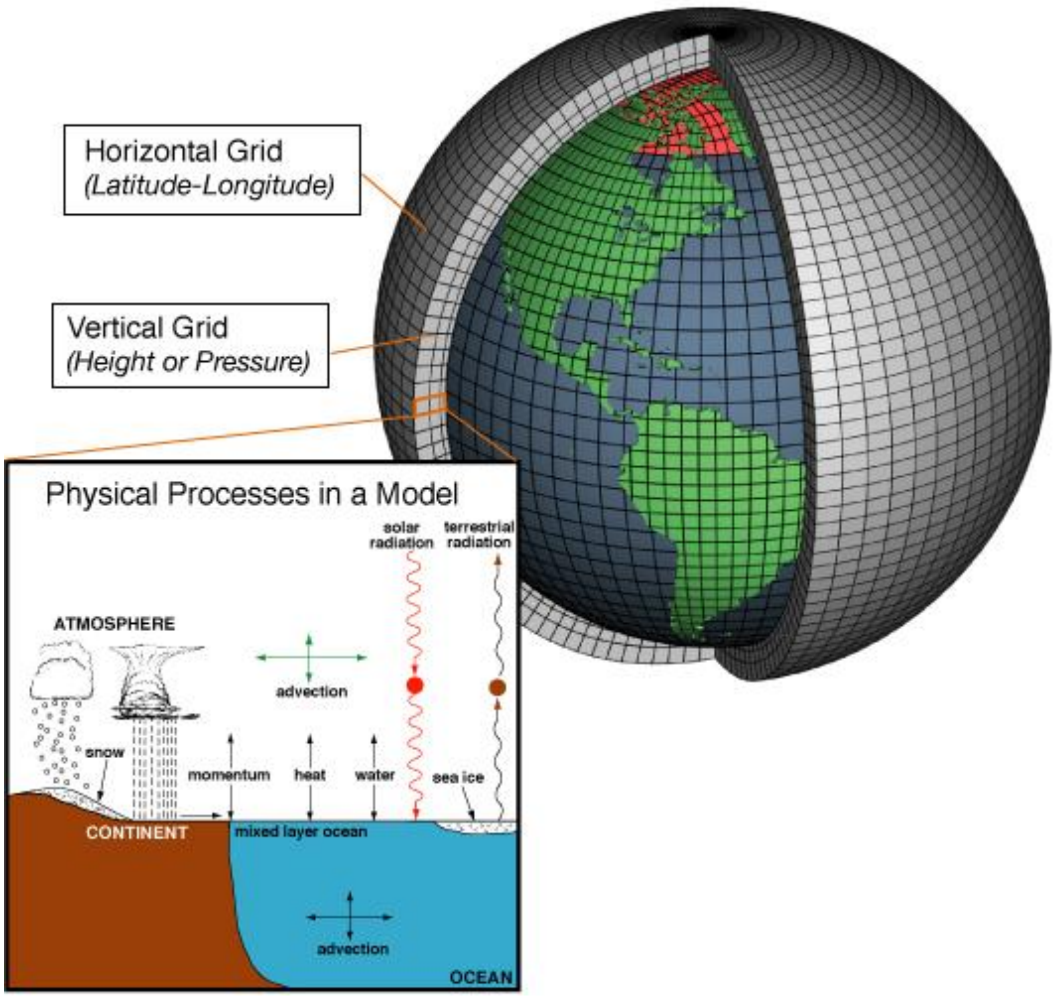

Emissions

Transport and Location

Particle Mixing

Evolution and Removal

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How do we reduce the error bar?

- Recreate an aerosol-driven trend with a model and determine what aerosol characteristics cause it.

Less Aerosol	**More Aerosol**
-11 W/m^2	**-15 W/m^2**
Reduced sunlight over China	Reduced sunlight over China

Observations ~ 20 W/m^2

Emissions

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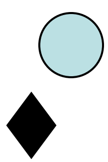
How do we reduce the error bar?

- Recreate an aerosol-driven trend with a model and determine what aerosol characteristics cause it.

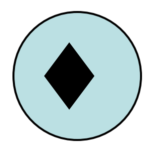
More Aerosol
Ext. Mixed



-15 W/m²

Reduced sunlight over China

More Aerosol
Int. Mixed



-19 W/m²

Reduced sunlight over China

Observations ~ 20 W/m²

Emissions

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Summary

- What aerosols are, why they are a ?, and how we can make them a ? …

<u>Interesting Questions</u>

How do we deal with the trade-off between health concerns and climate concerns with aerosols?

How do we deal with the uncertainty in how much CO_2-driven climate change will be revealed by the removal of aerosols?