Topic 2

- Climate change
- Economic Effects
  - ▷ Krusell lecture, topic02a.pdf, covered in class
  - ▷ Judd lecture, topic02b.pdf, Judd lecture, not covered in class, too technical, takeaways only
  - ▷ Troy Benson slides, topic02c.pdf, covered in class
- Climate Change and Economic Effects Takeaways
  (aka What do I need to know for midterm and final)
- Regulatory responses

Climate Change

- Climate change is almost certainly going to be the most important environmental issue that you will face in your career.
- We shall briefly review the science underlying this issue.

Climate vs. Weather

"Climate is what you expect, weather is what you get."

– Mark Twain

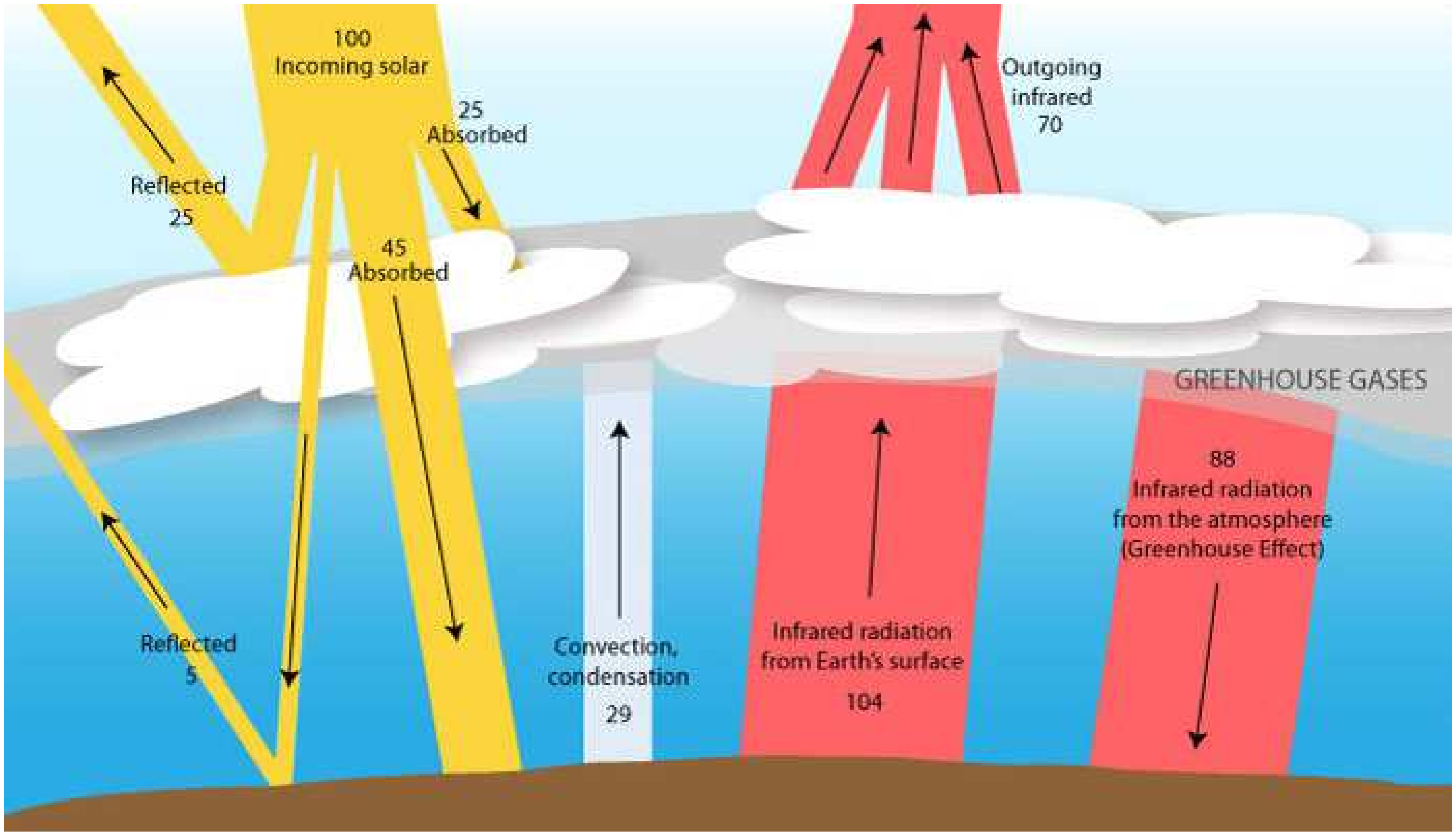
Climate Models vs. Weather Models

- The physics (thermodynamics) is the same for both.
- Weather models are run for a week to ten days
  - ▷ Run at fine time and geographical scales
  - ▷ Accept as given whatever does not change much in a week such as ocean temperature, orientation of earth's axis toward the sun, CO_2, etc.
- Climate models are run for a few decades to several centuries.
  - ▷ Run at coarse time and geographical scales
  - ▷ Explicitly model ocean temperature, orientation of earth's axis toward the sun, sea ice, land ice, CO_2, etc.
- Thousands of variables can be modeled simultaneously.
  - ▷ Focus here is on surface temperature
  - ▷ Which is the temperature six feet above the ground.

The Earth's Temperature

- Warm bodies, e.g., the sun, emit radiation.
- The sun's radiation warms the earth.
- The earth's temperature increases until the outbound radiation equals the inbound radiation.
- The frequencies of inbound and outbound radiation differ.
- This difference is what causes some gasses, e.g., CO_2, to be greenhouse gasses.
- We begin with an energy balance model.

Fig 1. Energy Balance



Energy received from the Sun balances the energy that Earth loses back into space, maintaining a stable average temperature. Source: http://www.learner.org

Power

- The measure of power used in climate models is the Watt.
  - ▷ If you raise a small apple straight up in the air for one meter once every second you are generating one Watt of power.
- Units:

$$W = \frac{J}{s} = \frac{N \cdot m}{s} = \frac{kg \cdot m^2}{s^3}$$

  - ▷ W is a Watt
  - ▷ J is a Joule (moving the apple once does one Joule of work)
  - ▷ N is a Newton (measure of force = mass $\times$ acceleration)
  - ▷ s is a second
  - ▷ kg is a kilogram
  - ▷ m is a meter

Stefan-Boltzmann Law

- The StefanBoltzmann law states that the power emitted per unit area of the surface of a black body is directly proportional to the fourth power of its absolute temperature:

$$P = \sigma T^4$$

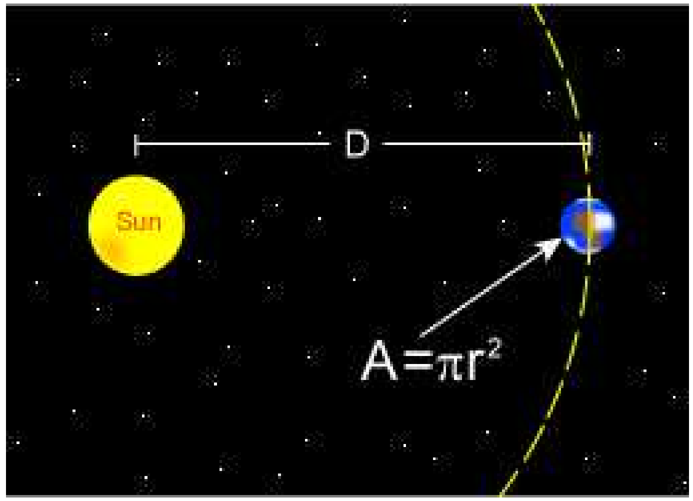
  - ▷ P is the total power radiated per unit area, units are W/m^2
  - ▷ $\sigma = 5.67 \times 10^{-8} \frac{W}{m^2 K^4}$ is the Stefan-Boltzmann constant

- Units
  - ▷ W is Watts
  - ▷ m is meters
  - ▷ T is temperature in degrees Kelvin (= 273.15 + degrees Celsius)

Sun's Total Radiation

- $P_s = 4\pi R_s^2 \, \sigma \, T_s^4$
  - ▷ $4\pi R_s^2$ is the surface area of the sun
  - ▷ $\sigma = 5.67 \times 10^{-8} \frac{W}{m^2 K^4}$ is the Stefan-Boltzmann constant
  - ▷ R_s is the radius of the sun, which is $6.96 \times 10^8 \, m$
  - ▷ T_s is the temperature of the sun, which is $5778 \, ^oK$

Fig 2. Radiation Received by the Earth



- The fraction of the sun's radiation that the earth receives is the cross sectional area of the earth divided by the surface area of a sphere about the sun of radius D.

- $P_{se} = P_s \frac{\pi R_e^2}{4\pi D^2}$

  ▷ $D = 1.496 \times 10^{11}\, m$

  ▷ $R_e = 6.371 \times 10^{6}\, m$

The Earth as a Black Body

- If the earth were a perfect black body we could now compute its temperature because the earth must radiate back into space the power receives from the sun.
- The earth's black body radiation back into space is

$$P_{bb} = 4\pi R_e^2 \, \sigma \, T_e^4$$

  ▷ We could equate $P_{se} = P_{bb}$ and solve for T_e, called the effective temperature.

- The earth is not a black body, we must make two adjustments

  1. A fraction $\alpha = 0.306$ of the incoming radiation is reflected; α is called the albedo.
  2. The greenhouse effect $\Delta T = 33\,^oC$ must be added to T_e to get the surface temperature T.

The Earth's Average Temperature is 57.57 ^oF

- Equating $P_{se} = (1 - \alpha) P_{bb}$ and solving for T_e we get

$$T_e = T_s \sqrt{R_s \frac{\sqrt{1-\alpha}}{2D}}$$

  - ▷ $T_s = 5778\,^oK$
  - ▷ $R_s = 6.96 \times 10^8\, m$
  - ▷ $D = 1.496 \times 10^{11}\, m$
  - ▷ $\alpha = 0.306$

- Without the greenhouse effect the temperature would be $T_e = 254.356\,^oK = -18.794\,^oC = -1.829\,^oF$

- With it, the earth's average surface temperature is $T = T_e + \Delta T = (254.356 + 33)\,^oK = 14.2\,^oC = 57.57\,^oF$

The Earth's Temperature

- Warm bodies emit radiation.
- The sun's radiation warms the earth.
- The earth's temperature increases until the outbound radiation equals the inbound radiation.
- The frequencies of the inbound and outbound radiation differ.
- This difference is what causes some gasses, e.g., CO_2, to be greenhouse gasses.
- We now consider the greenhouse effect.

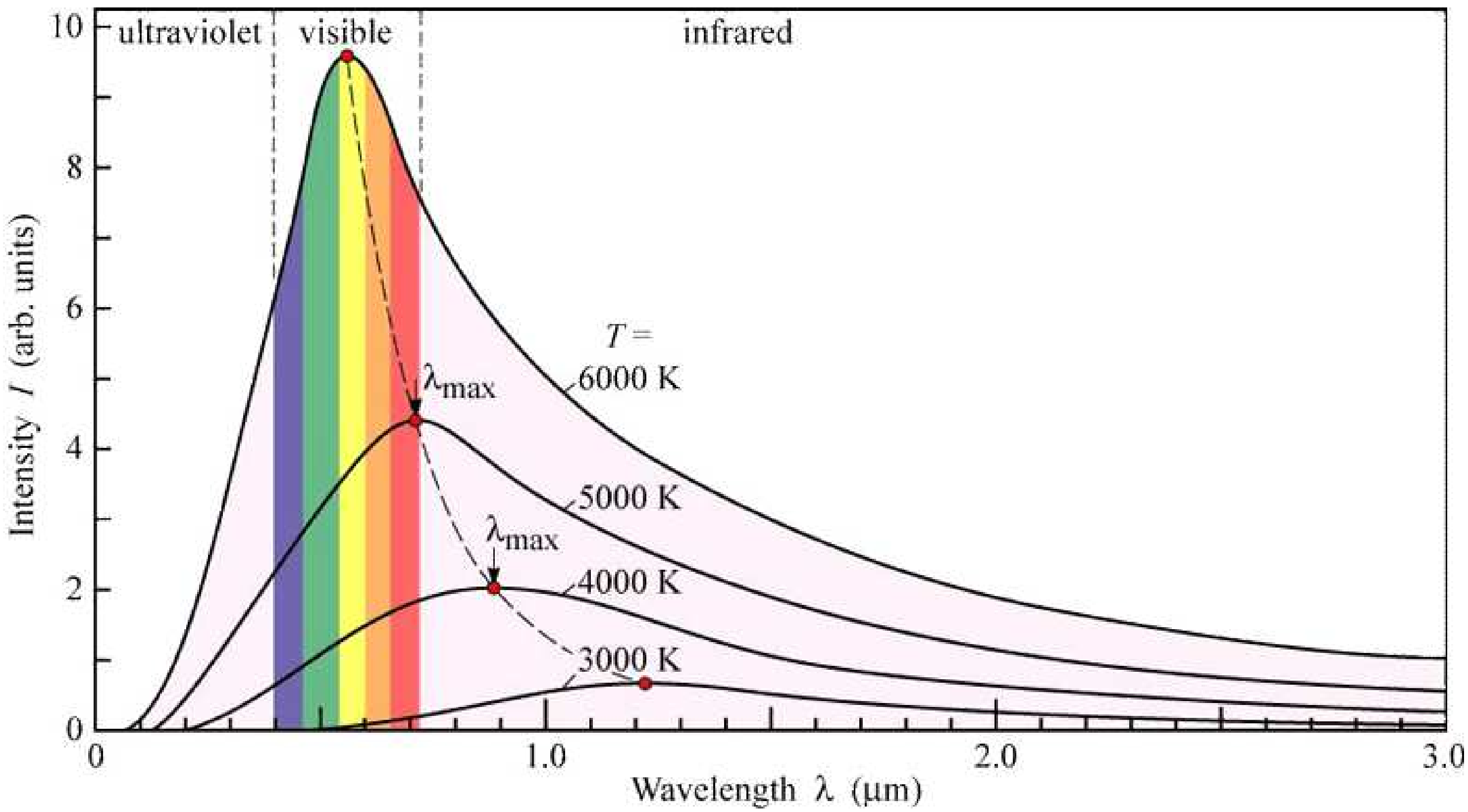
Greehouse Gasses

- The atmosphere and clouds act like a window by letting the sun's radiation pass through to the earth.

- The atmosphere and clouds act like a nearby black body by absorbing radiation from both the sun and the earth and re-radiating the absorbed radiation to the earth.

- Why does an increase in green house gases cause the atmosphere to both behave more like a window AND more like a black body?

Fig 3. The Frequency of Black Body Radiation



Spectral intensity distribution of Plancks black-body radiation as a function of wavelength for different temperatures. Source: http://physics.schooltool.nl/irspectroscopy.

The Greenhouse Effect

- The frequency of black body radiation depends on the temperature
  - ▷ $\lambda_{max} = \frac{b}{T}$
  - ▷ $b = 2.897 \times 10^{-3}\, m\, K$
- The sun's temperature is $Ts = 5778\,^oK$ and radiates in the visible light region of the spectrum.
- The earth's surface temperature is $T = 288\,^oK$ and radiates in the infrared region of the spectrum.
- Greenhouse gasses allow visible light to pass through them but absorb and re-radiate infrared light.

Fig 4. Carbon Dioxide Is a Particular Problem

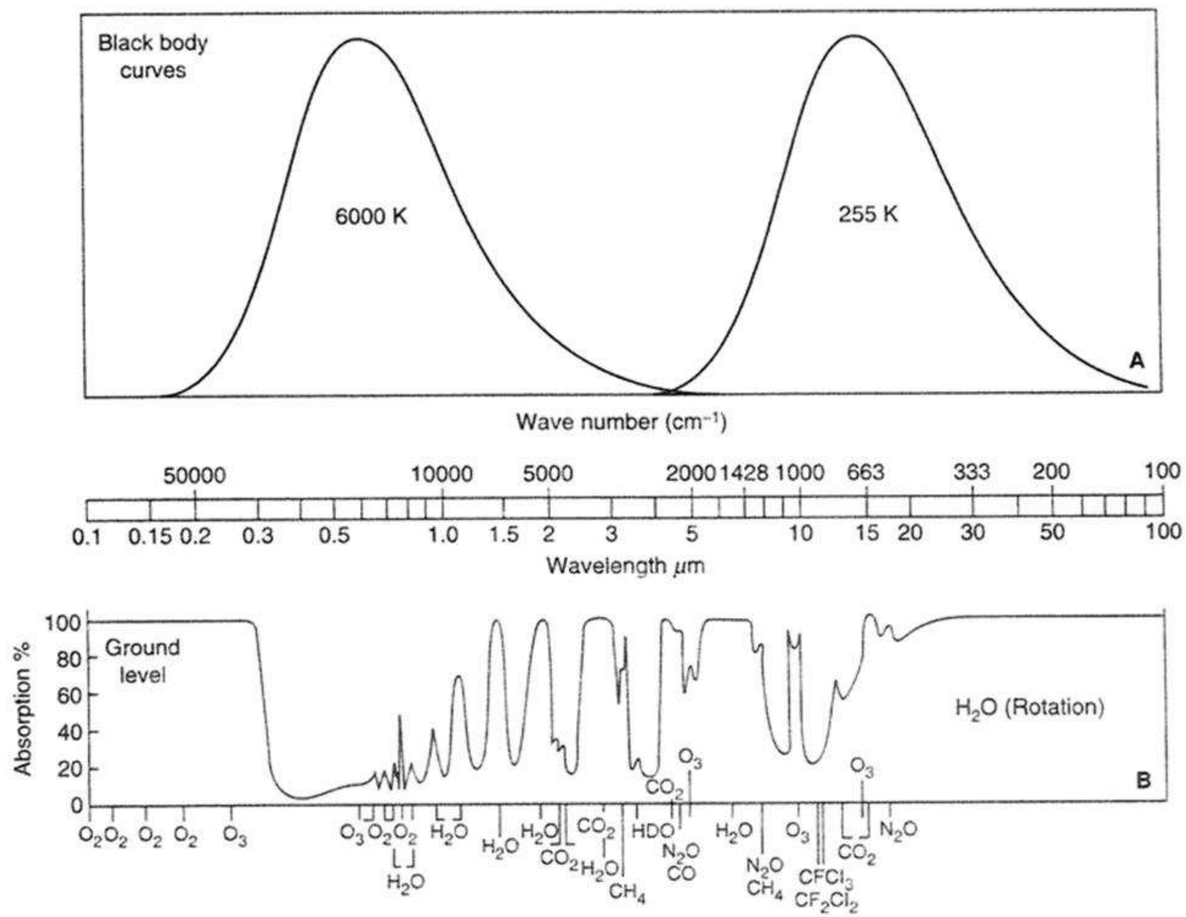
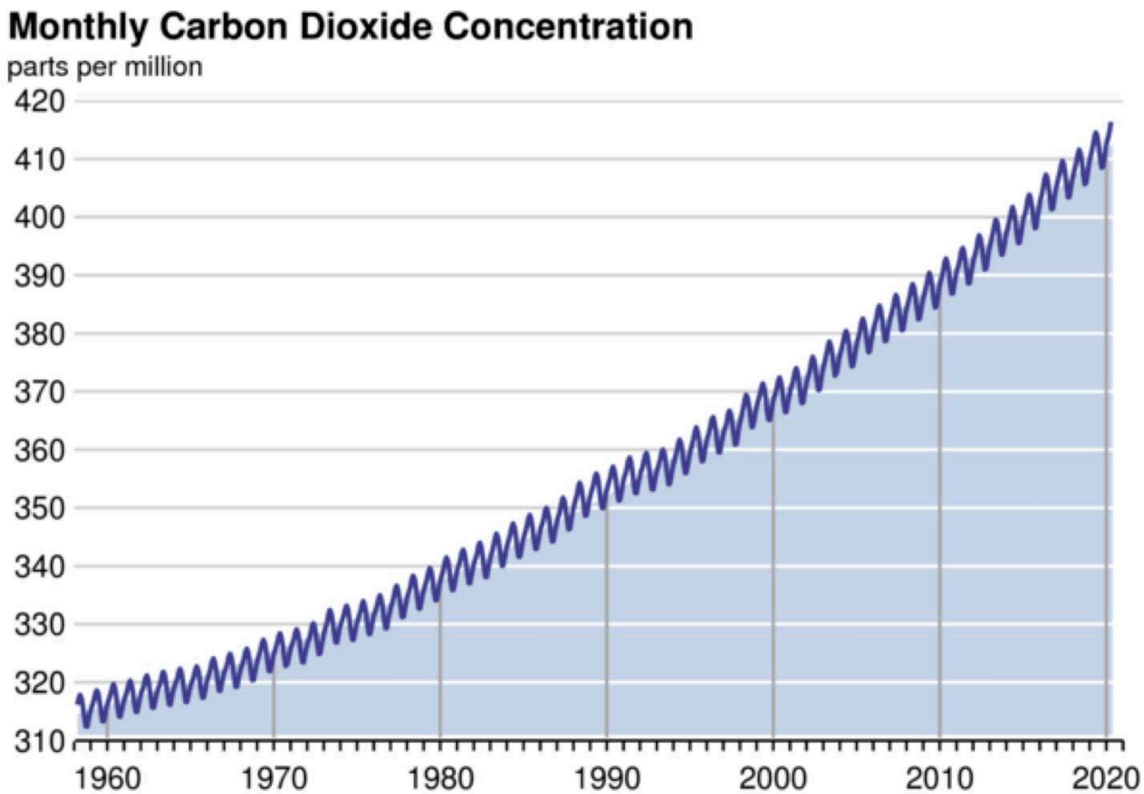


FIGURE 4-10 Distribution of relative energy of emission from sun and earth black bodies by wavelength (a), and percent of absorption by greenhouse gases (b). (*Source*: Mitchell (1989). Published by American Geophysical Union. Image is in public domain.)

- Wavelength at which Earth radiates the Sun's heat back is right at the peak absorptive capacity for CO_2

Fig 5. Carbon Dioxide in the Atmosphere



- Concentration levels of CO_2 in the atmosphere have increased (https://scrippsco2.ucsd.edu)
- Primary anthropogenic source is the combustion of fossil fuels

Fig 6. Carbon from Fossil Fuels

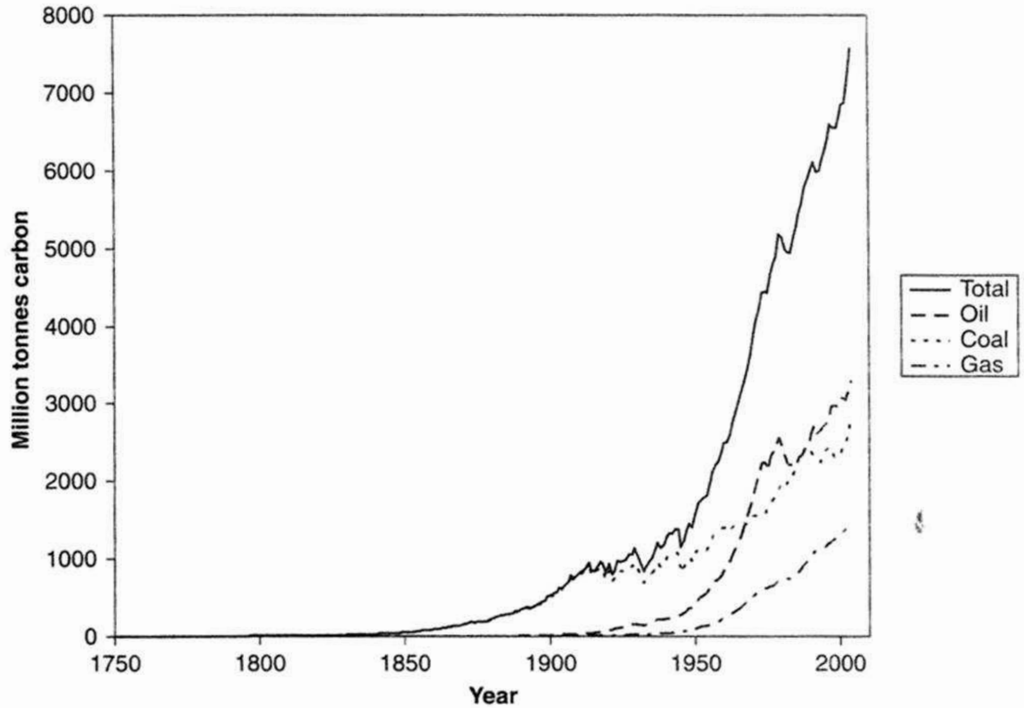


FIGURE 4-3 Carbon emissions related to fossil fuel use in tonnes carbon, 1750–2000. *Conversion*: 1 tonne carbon = ~3.7 tonnes CO_2. (*Source*: CDIAC, Oak Ridge National Laboratories. Reprinted with permission.)

Most Abundant Greenhouse Gasses

- water vapor, which contributes 36-72%

- carbon dioxide, which contributes 9-26%

  - ▷ controllable

- methane, which contributes 4-9%

- ozone, which contributes 3-7%

Higher ends of the ranges are for each gas alone; the lower ends account for overlaps with the other gases. The major non-gas contributor to the earth's greenhouse effect is clouds,

One-Dimensional Climate Models

- The energy balance model that we have discussed is often called a zero-dimensional climate model.

- The next level of complexity is a one-dimensional model.
  - ▷ The added dimension can be latitude. The primary purpose of these model is to study glaciers.
  - ▷ The added dimension can be altitude. The primary purpose of these models is to study the greenhouse effect. They are often called radiative-convective models.

- The mathematical complexity of one-dimensional climate models is daunting.

Three-Dimensional Atmospheric Models

- The three dimensions are latitude, longitude, and altitude.
  - ▷ These models are four-dimensional if one counts time.
- The mathematical complexity of these models is overwhelming.
  - ▷ They depend on seven equations from thermodynamics plus additional equations called parametrization to deal with small scale effects such as clouds.
  - ▷ The frame of reference is that of an observer at a fixed point on a rotating sphere.
  - ▷ This frame of reference makes model equations more complicated than if the frame of reference were that of an observer on a distant star (a fixed inertial frame of reference).

Three-Dimensional Earth System Models

- These are coupled models:
  - ▷ Atmosphere, ocean, land, sea-ice, land-ice.
  - ▷ Efforts are underway to couple economic models in order to determine optimum levels of CO_2 abatement and the feedback between economic activity and climate on land-use and greenhouse gas emissions.
    - ◇ Ken Judd, Stanford, is a major player
- The best of these models is the Community Earth System Model (CESM1) from the National Center of Atmospheric Research.
  - ▷ Not that difficult to understand if treated as a black box.
  - ▷ Usually run on super-computers.

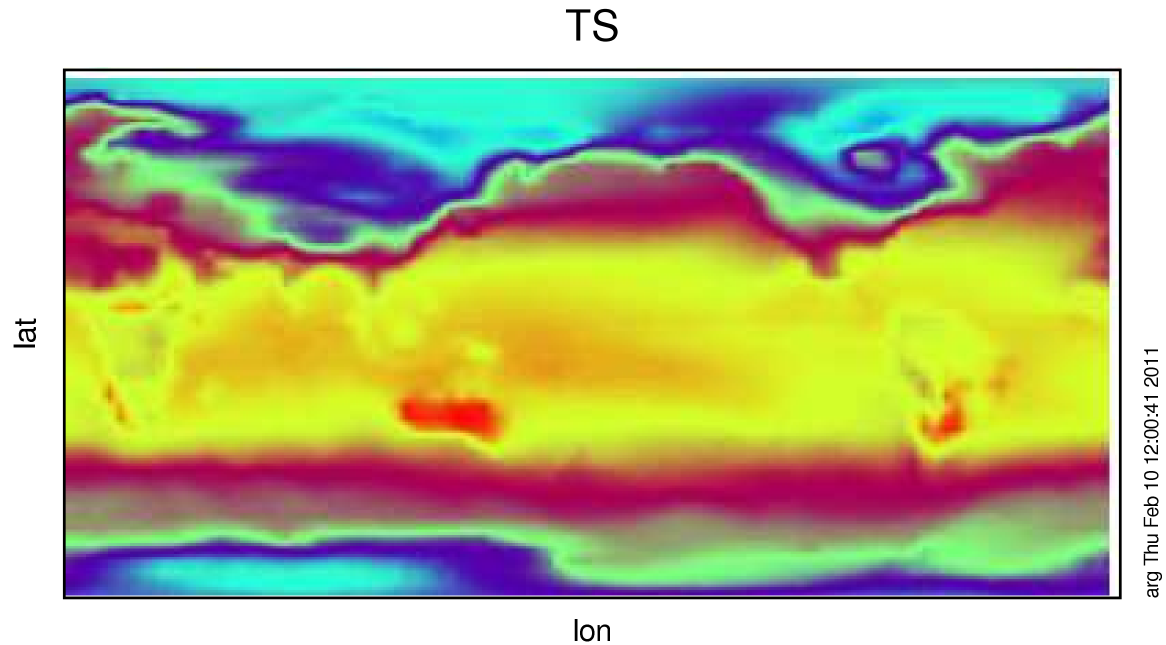
Fig 7. NCAR's Bluefire

IBM Power 575: 128 nodes, 32 CPUs per node
Each CPU is 4.7GHz, 4096 CPUs in total
Weight is 33,000 lbs. not counting the circulating water cooling equipment.

Nonetheless

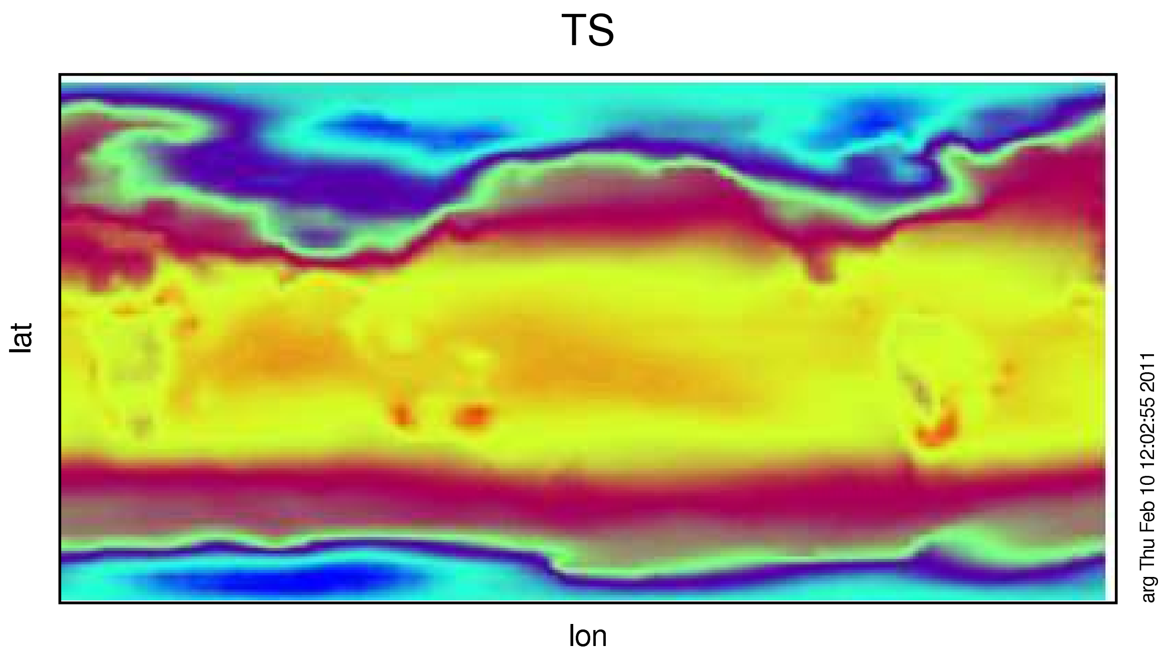
- NCAR's CESM1 code is in the public domain
- It is quite easy to download
- It is well documented.
- It can be run on a Linux box:
  - ▷ Four-chip motherboard populated with 12-core AMD chips; 48 CPUs total.
  - ▷ RedHat Enterprise Linux 5.0 (CentOS public domain variant).
  - ▷ PGI Fortran compiler
  - ▷ Cost is $14,000 including compiler.

Fig 8. CESM1 Surface Temperature, Jan 2000



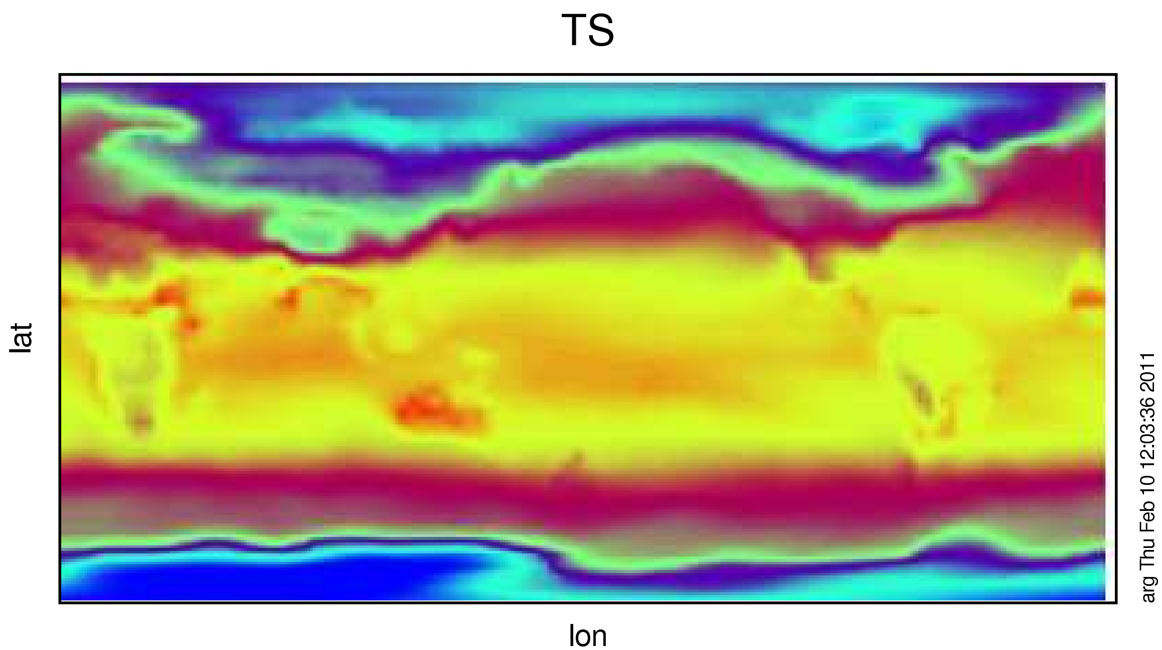
Range of TS: 223.105 to 311.27 (null)
Range of lon: 0 to 356.25
Range of lat: -87.1591 to 87.1591
Current time: 31
Frame 1 in File TS.nc

Fig 9. CESM1 Surface Temperature, Feb 2000



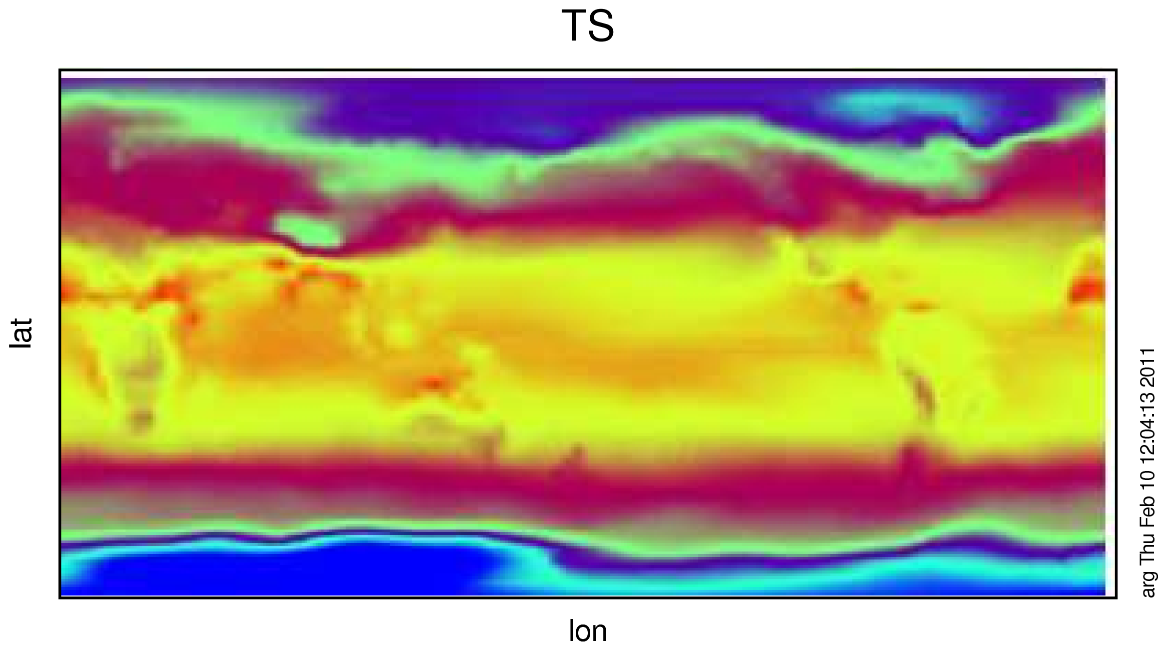
Range of TS: 223.105 to 311.27 (null)
Range of lon: 0 to 356.25
Range of lat: -87.1591 to 87.1591
Current time: 59
Frame 2 in File TS.nc

Fig 10. CESM1 Surface Temperature, Mar 2000



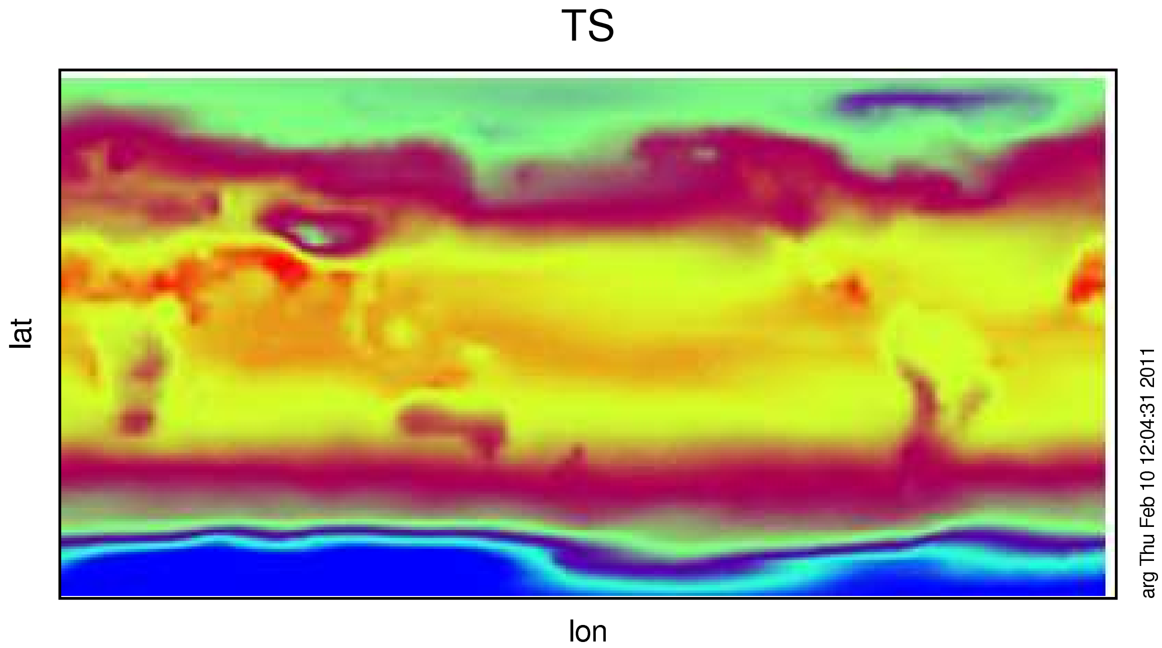
Range of TS: 223.105 to 311.27 (null)
Range of lon: 0 to 356.25
Range of lat: -87.1591 to 87.1591
Current time: 90
Frame 3 in File TS.nc

Fig 11. CESM1 Surface Temperature, Apr 2000



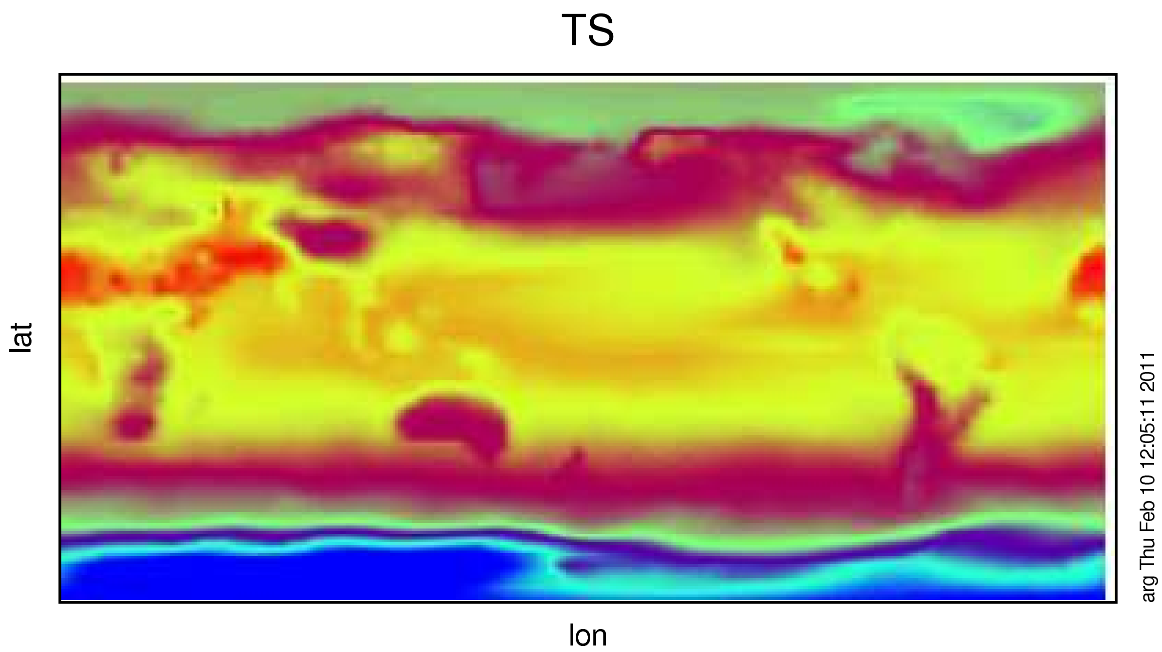
Range of TS: 223.105 to 311.27 (null)
Range of lon: 0 to 356.25
Range of lat: -87.1591 to 87.1591
Current time: 120
Frame 4 in File TS.nc

Fig 12. CESM1 Surface Temperature, May 2000



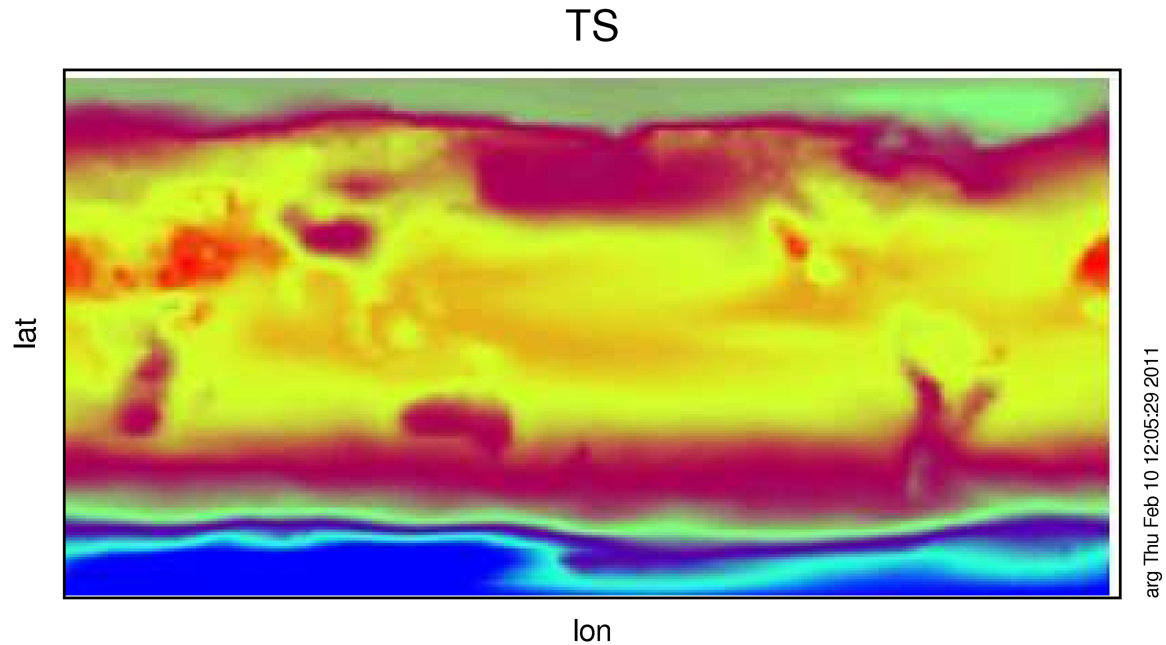
Range of TS: 223.105 to 311.27 (null)
Range of lon: 0 to 356.25
Range of lat: -87.1591 to 87.1591
Current time: 151
Frame 5 in File TS.nc

Fig 13. CESM1 Surface Temperature, Jun 2000



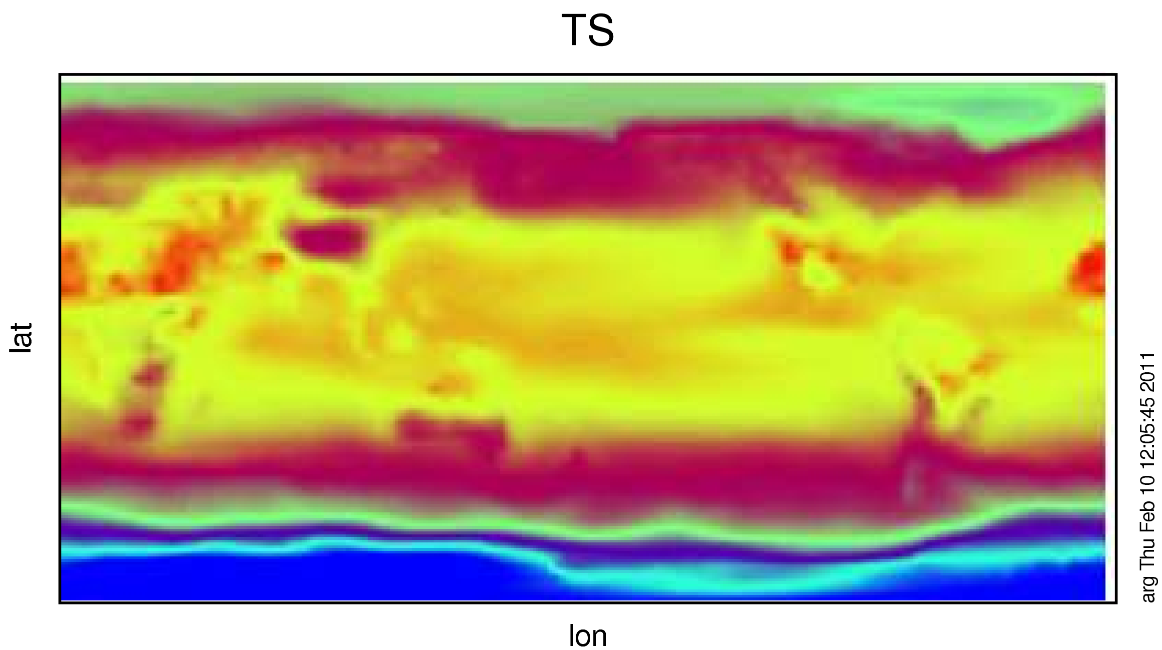
Range of TS: 223.105 to 311.27 (null)
Range of lon: 0 to 356.25
Range of lat: -87.1591 to 87.1591
Current time: 181
Frame 6 in File TS.nc

Fig 14. CESM1 Surface Temperature, Jul 2000



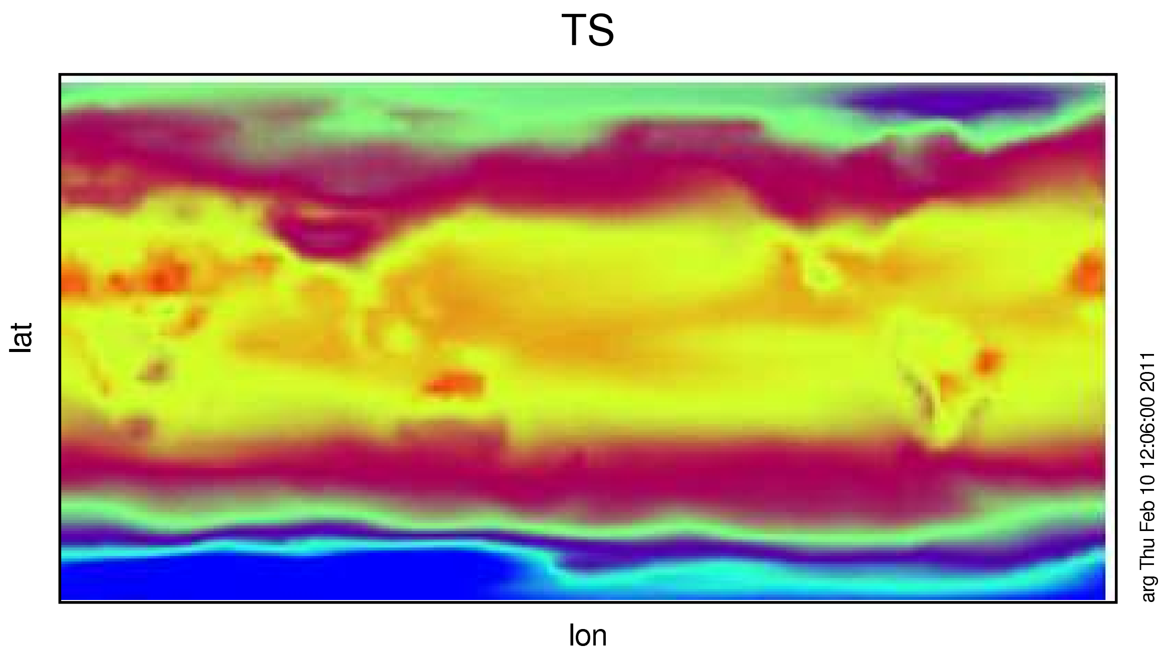
Range of TS: 223.105 to 311.27 (null)
Range of lon: 0 to 356.25
Range of lat: -87.1591 to 87.1591
Current time: 212
Frame 7 in File TS.nc

Fig 15. CESM1 Surface Temperature, Aug 2000



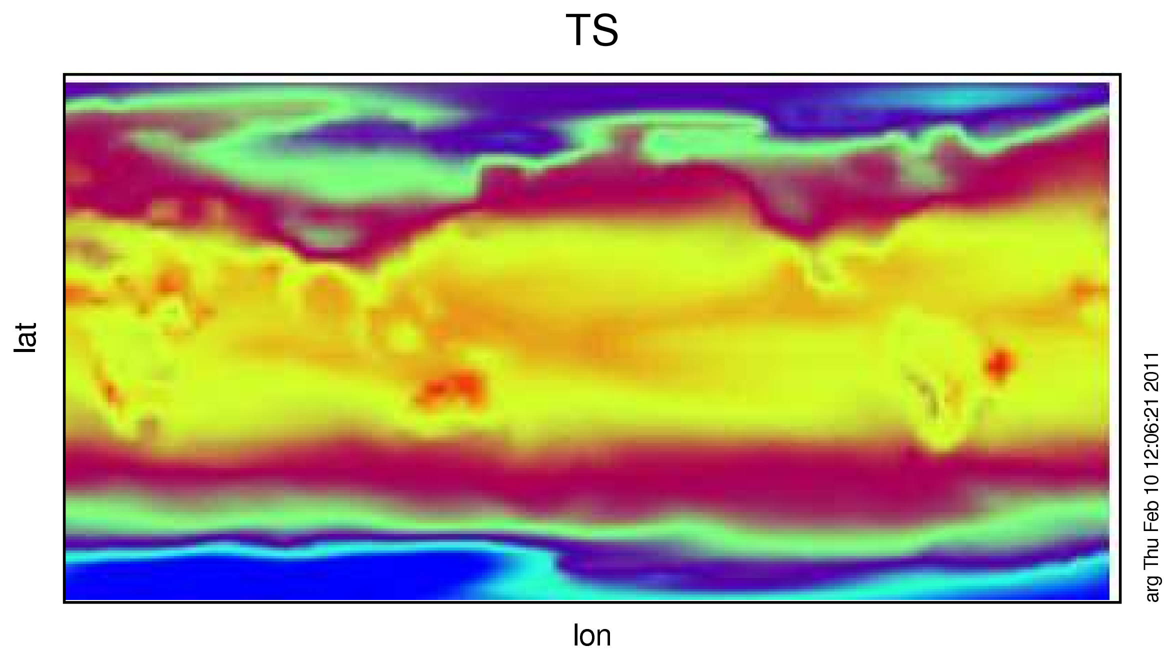
Range of TS: 223.105 to 311.27 (null)
Range of lon: 0 to 356.25
Range of lat: -87.1591 to 87.1591
Current time: 243
Frame 8 in File TS.nc

Fig 16. CESM1 Surface Temperature, Sep 2000



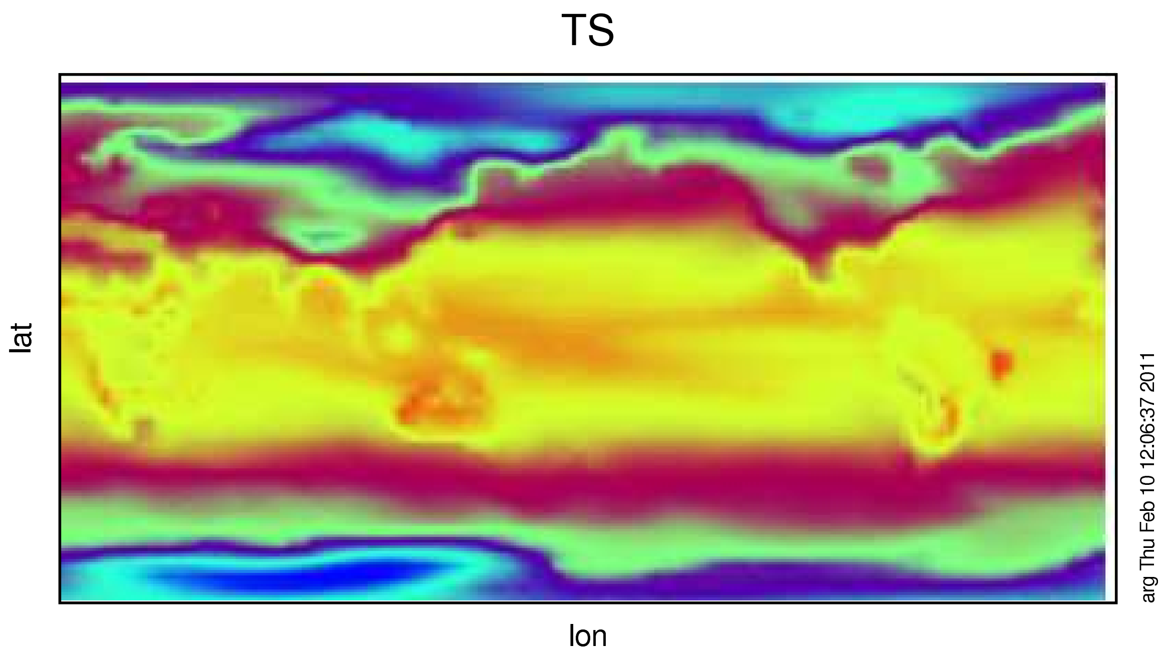
Range of TS: 223.105 to 311.27 (null)
Range of lon: 0 to 356.25
Range of lat: -87.1591 to 87.1591
Current time: 273
Frame 9 in File TS.nc

Fig 17. CESM1 Surface Temperature, Oct 2000



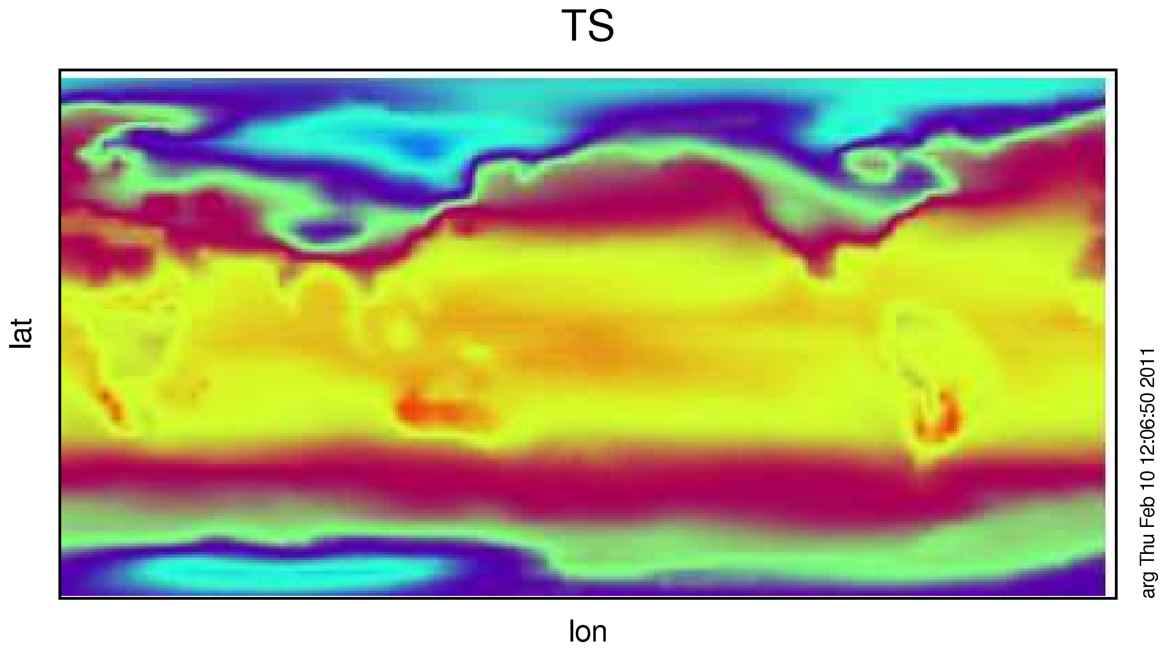
Range of TS: 223.105 to 311.27 (null)
Range of lon: 0 to 356.25
Range of lat: -87.1591 to 87.1591
Current time: 304
Frame 10 in File TS.nc

Fig 18. CESM1 Surface Temperature, Nov 2000



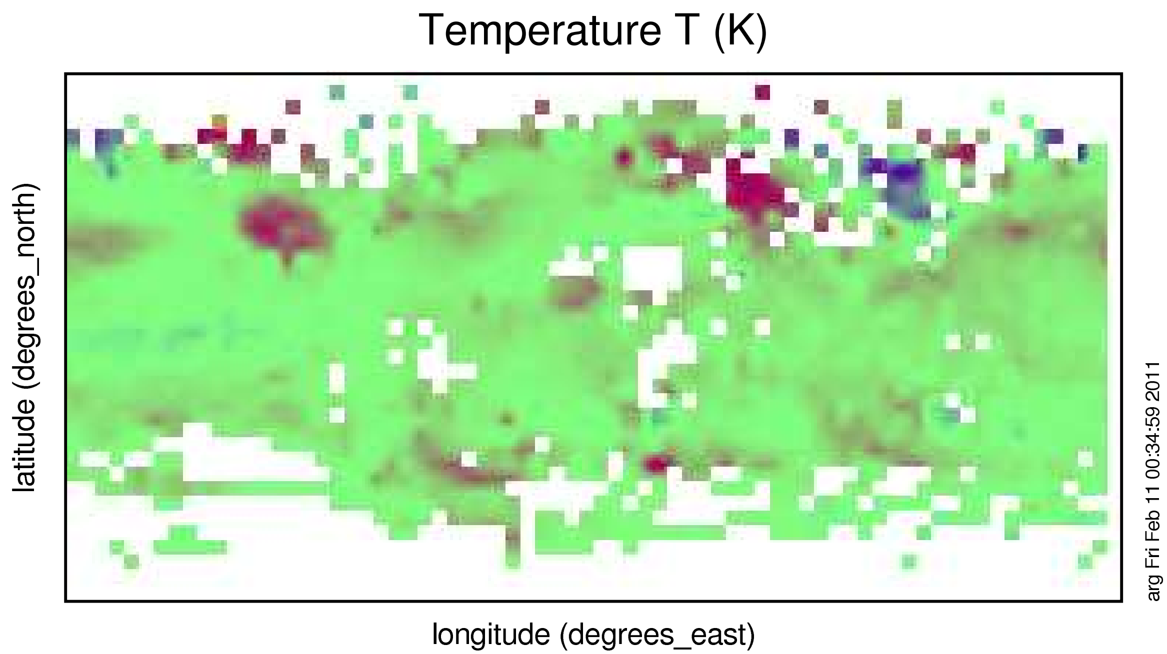
Range of TS: 223.105 to 311.27 (null)
Range of lon: 0 to 356.25
Range of lat: -87.1591 to 87.1591
Current time: 334
Frame 11 in File TS.nc

Fig 19. CESM1 Surface Temperature, Dec 2000



Range of TS: 223.105 to 311.27 (null)
Range of lon: 0 to 356.25
Range of lat: -87.1591 to 87.1591
Current time: 365
Frame 12 in File TS.nc

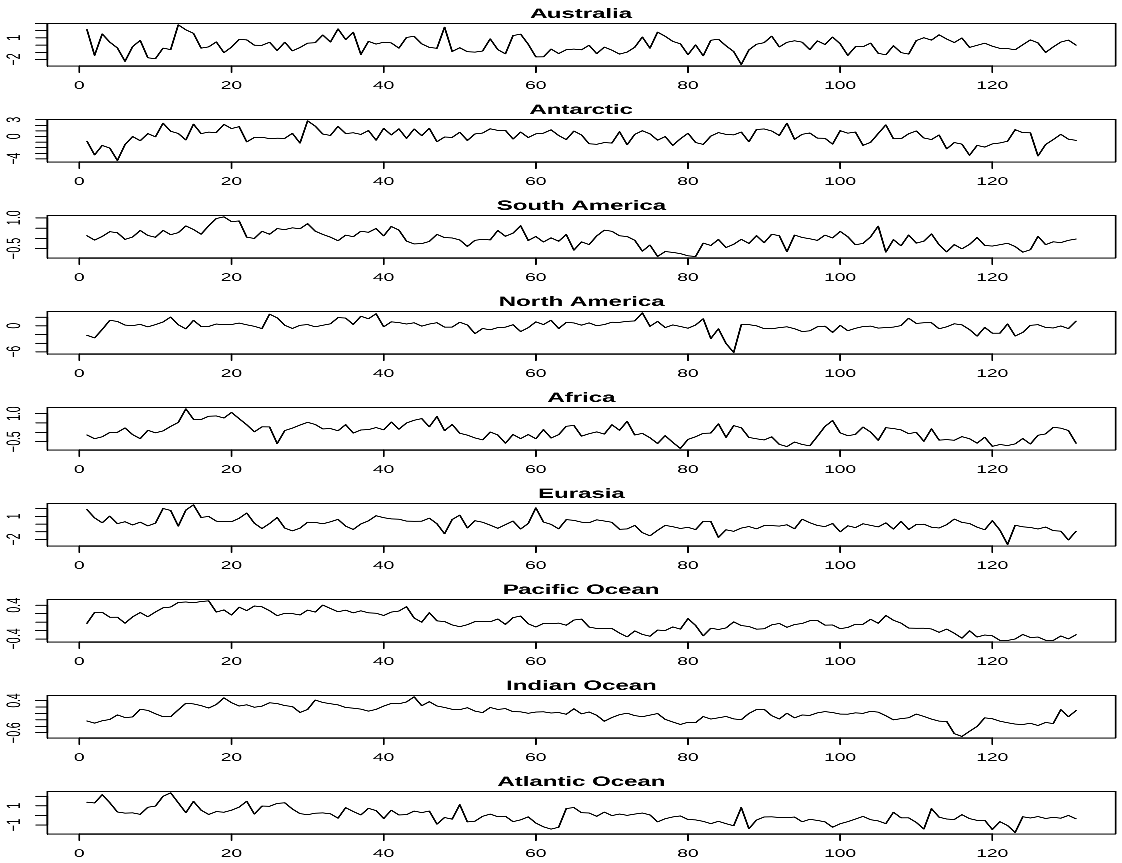
Fig 20. Surface Temperature Measurements, Jan 2000



Range of Temperature T: -18.97 to 17.3524 K
Range of longitude: -177.5 to 177.5 degrees_east
Range of latitude: -87.5 to 87.5 degrees_north
Current t: 54801.5 days since 1850-01-01 00:00:00
File HadCRUT3v.nc

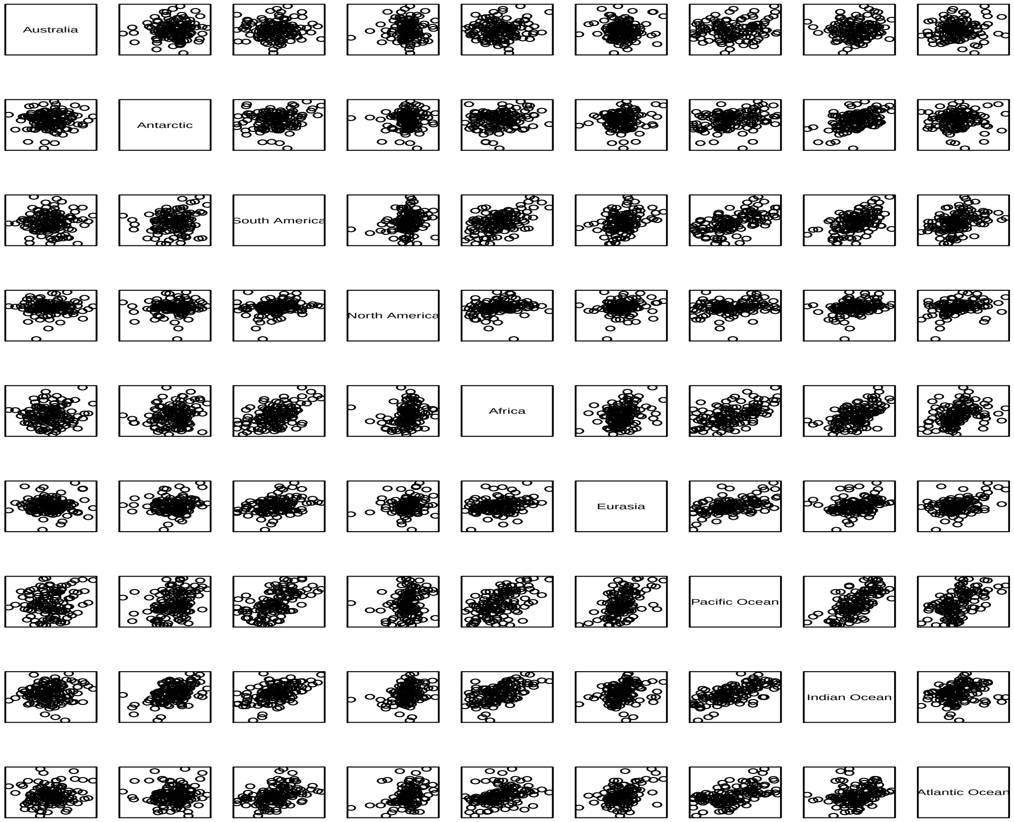
Shown are deviations from the base period 1961-90, about 3,000 observations unevenly distributed. Ocean readings are water temperatures, not surface temperatures. Source: http://www.cru.uea.ac.uk/cru/data/temperature/

Fig 21. Series by Region



Hadley data averaged over continents and oceans and adjusted to remove monthly means. Monthly values from 2000 through 2010.

Fig 22. Correlations among Regions



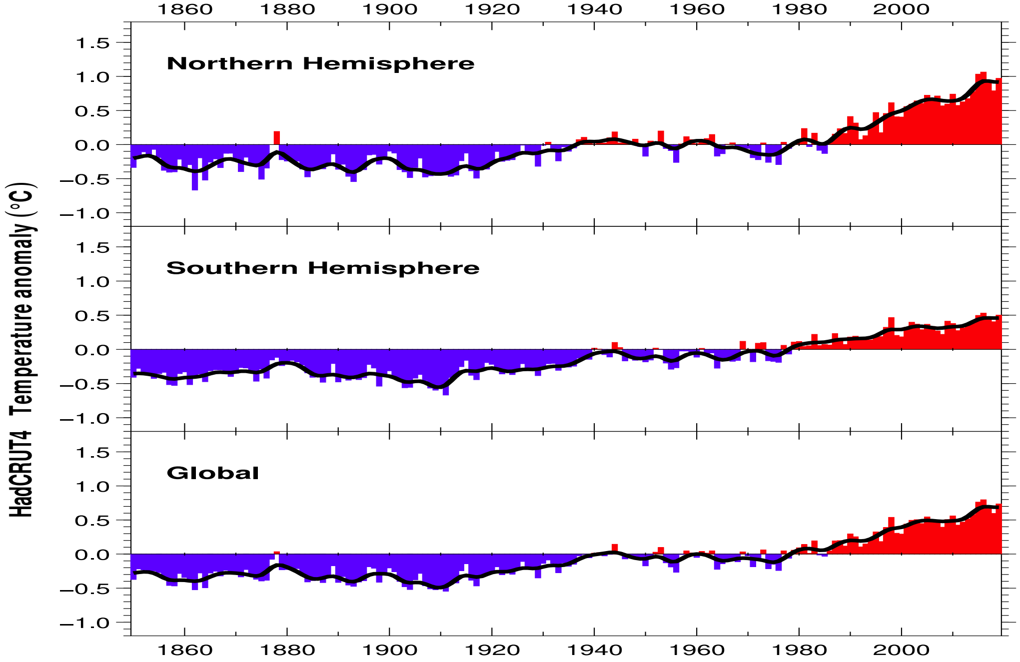
Hadley data averaged over continents and oceans and adjusted to remove monthly means. Monthly values from 2000 through 2010.

Climate Change by Region?

Region	Trend	Change
Australia	0.00090316	0.11831
Antarctic	0.00301373	0.39480
South America	0.00025332	0.03318
North America	0.00299326	0.39211
Africa	0.00069985	0.09168
Eurasia	0.00468737	0.61404
Pacific Ocean	-0.00202225	-0.26491
Indian Ocean	-0.00286582	-0.37542
Atlantic Ocean	0.00195583	0.25621

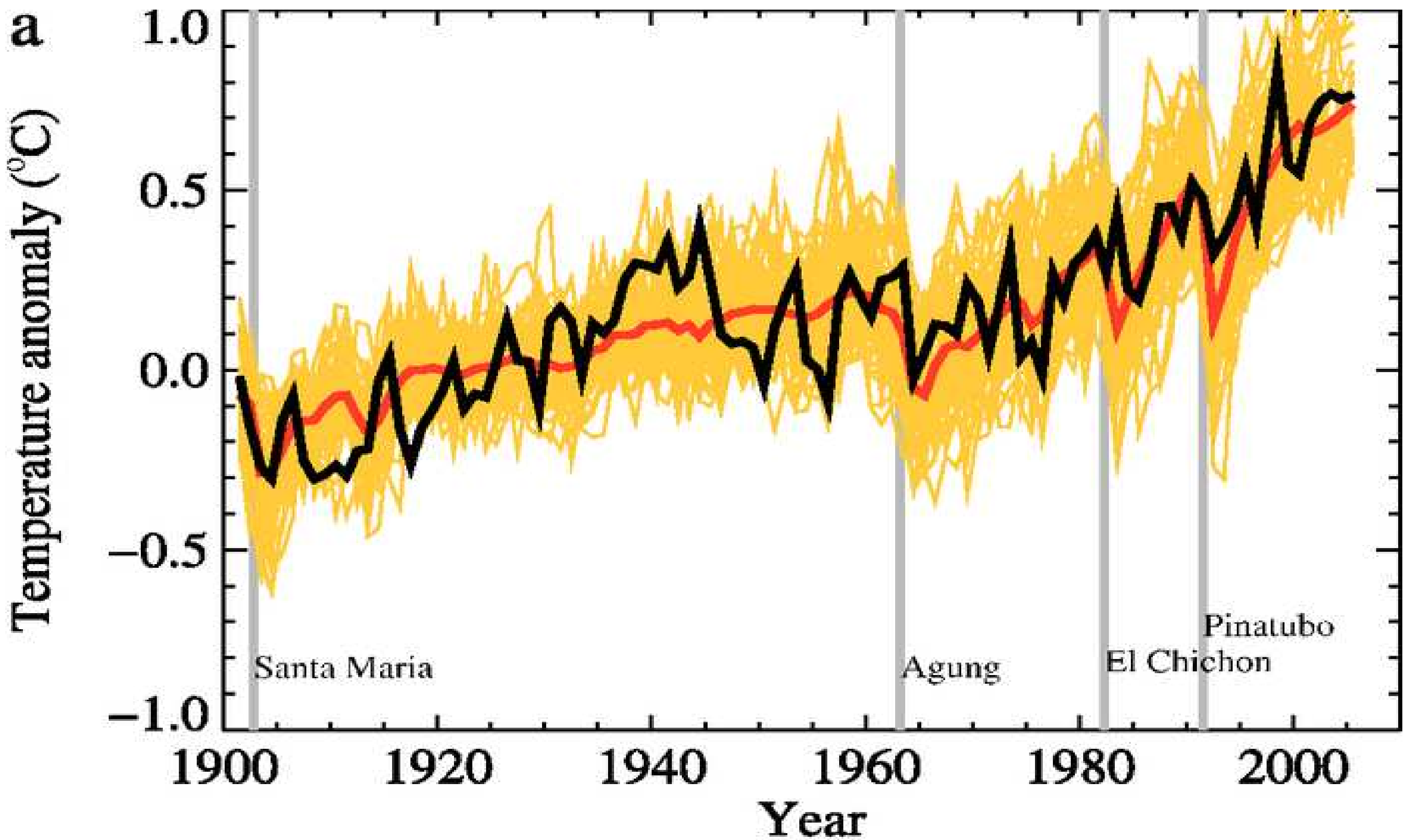
The data show climate change over the period 2000 through 2010. Hadley data. Trend is degrees C per month; change is degrees C per decade.

Fig 23. Trends by Hemisphere as of December 2019



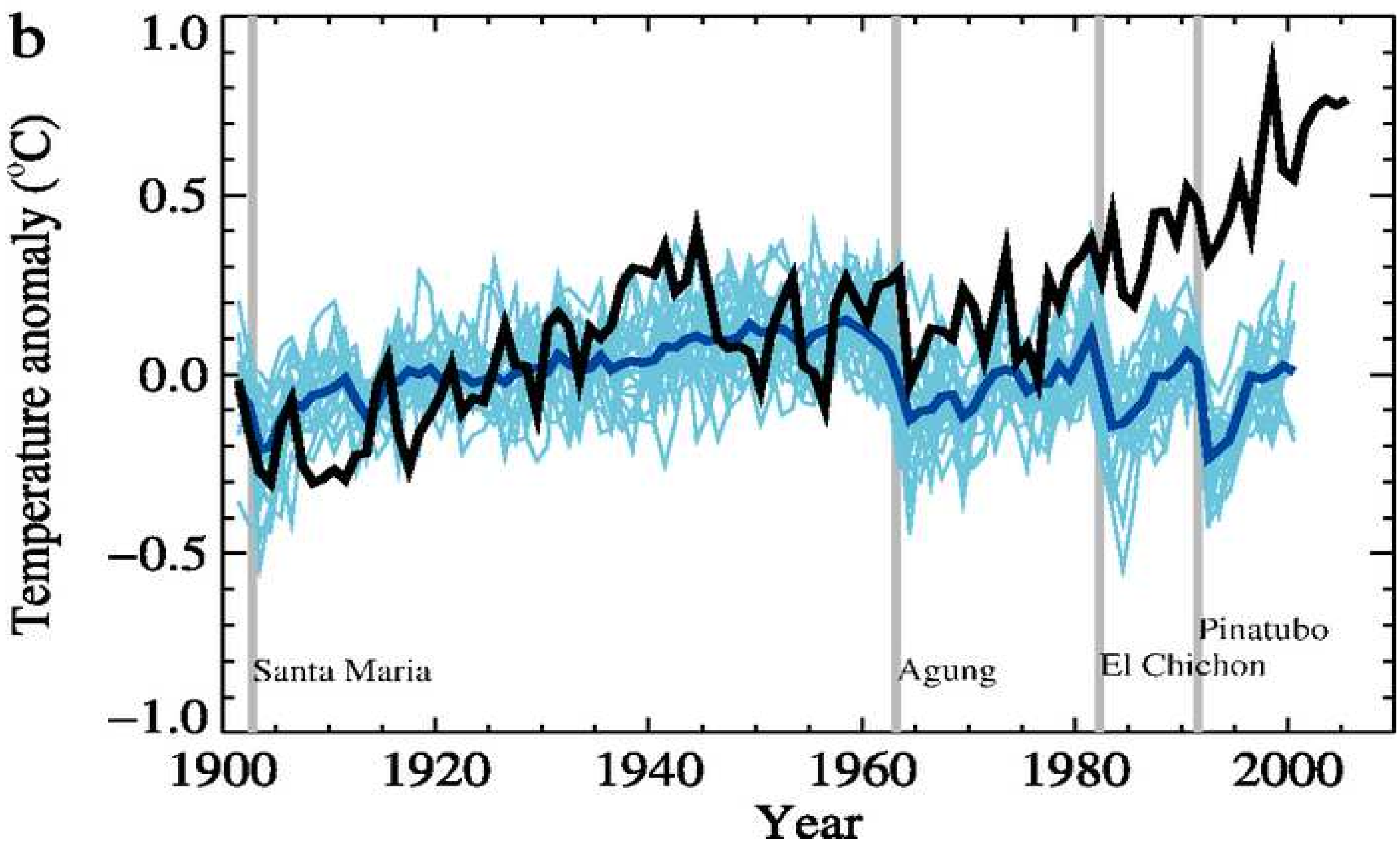
Source: https://crudata.uea.ac.uk/cru/data/temperature

Fig 24. Climate Models over Longer Periods



Yellow: 58 simulations, 14 models; Red: their mean; Black: Hadley data. Source: IPCC AR5

Fig 25. Climate Models without Anthropogenic Forcing



Light blue: 19 simulations, 5 models; Blue: their mean; Black: Hadley data. Source: IPCC AR5

Statistical Uncertainty

- InterAcademy Council, Committee to Review the IPCC Report dated August 31, 2010
  - ▷ Chapter 3: "IPCCs Evaluation of Evidence and Treatment of Uncertainty"
    - ◇ Highly critical of the IPCC's methods of assessing uncertainty.
    - ◇ 35% of the body of the report.
  - ▷ Recommendation: Quantitative probabilities should be used to describe the probability of well-defined outcomes only when there is sufficient evidence.
  - ▷ Source: http://reviewipcc.interacademycouncil.net/report.html
- Conclusion: The scientific payoff to an influential contribution on this topic would be large.

How Much Carbon Dioxide?

- Atmospheric CO_2 is about 3,000 gigatons (billion metric tons)
  - ▷ Weight of atmosphere = 4.41 million billion tons
  - ▷ CO_2 is 0.06% by weight (0.04% by volume)
- World CO_2 emissions from the consumption and flaring of fossil fuels in 2006: 28 gigatons
- US CO_2 emissions in 2006: 6 gigatons

Carbon vs. Carbon Dioxide

- CO_2 weighs 44 / 12 times the weight of carbon
  - ▷ Atomic weight of carbon is 12 and of oxygen is 16
  - ▷ Molecular weight (MW) of CO_2 is $12 + (2 \times 16) = 44$
  - ▷ So CO_2 is $44/12 = 3.67$ times heavier than carbon
- Burning one ton of carbon produces 3.67 tons of CO_2

Annual 2006 CO_2 Emissions by Country

Country	Metric Tons in 1000's	Percent
China	6,103,493	21.5
United States	5,752,289	20.2
European Union	3,914,359	13.8
Russia	1,564,669	5.5
India	1,510,351	5.3
Japan	1,293,409	4.6
Canada	544,680	1.9
South Korea	475,248	1.7
Iran	466,976	1.6
Mexico	436,150	1.6
South Africa	414,649	1.5
Rest of World	5,955,468	21.9

Source:http://en.wikipedia.org/wiki/List_of_countries_by_carbon_dioxide_emissions

Economic Effects of Climate Change

- Go through Troy Benson slides, topic02c.pdf, in class
- Go through Krusell lecture, topic02a, in class.
- Skip Judd lecture, topic02b, too technical, takeaways in these slides only.

Climate Model and Economic Effects Takeaways

- You are not responsible for the mathematics in the climate model and economic effects slides
  - ▷ Expect that you will understand the in-class verbal descriptions of what each equations says.
  - ▷ If you are contemplating graduate work in economics, be aware that the mathematics you have seen is what you will be expected to know and use.

- The mathematics requirements for this class are basic high school or first year college algebra.
  - ▷ Plus the extra information of how to compute the slope of a curve and the area under a curve presented from time to time in the slides.
  - ▷ Homework 1 is an illustration of what is required.

Climate Model Takeaways – 1 of 4

- Warm bodies emit radiation.
- The sun's radiation warms the earth.
- The earth's temperature increases until the outbound radiation equals the inbound radiation.
- The frequencies of the inbound and outbound radiation differ.
- This difference is what causes some gasses, e.g., CO_2, to be greenhouse gasses.
- Greenhouse gasses allow visible light to pass through them but absorb and re-radiate infrared light.

Climate Model Takeaways – 2 of 4

- Know the reason for each of the arrows in Fig 1.

- E.g. incoming solar is from the sun's black body radiation in the visible portion of the electromagnetic spectrum and outgoing infrared is the earth's black body radiation in the infrared portion.

Climate Model Takeaways – 3 of 4

Most Abundant Greenhouse Gasses

- water vapor, which contributes 36-72%
- carbon dioxide, which contributes 9-26%
  - ▷ controllable
- methane, which contributes 4-9%
- ozone, which contributes 3-7%

Higher ends of the ranges are for each gas alone; the lower ends account for overlaps with the other gases. The major non-gas contributor to the earth's greenhouse effect is clouds,

Climate Model Takeaways – 4 of 4

- Be able to explain why the difference between Figures 24 and 25 is the most persuasive evidence in favor of climate change due to greenhouse gas emissions.

- Be able to discuss the notion of geoengineering by stratospheric SO_2 injection.

Economic Effects Takeaways, Krusell

- Climate change affects regions very differently. Stakes big at regional level.
- Though a tax on carbon would affect welfare positively in some average sense, huge disparity of views: 55% of regions for tax, 45% against.
- Disparity so huge that transfer payments would be needed to compensate those losing from carbon tax.
- Findings almost identical for two extreme market structures (autarky and international capital markets).
- Climate equilibrium response to CO_2 is $T = 1.44\lambda \ln(\frac{S}{\bar{S}})$ where $1.44\lambda = 4.3^o \pm 2^o C$, current $S = 840$ Gt, preindstrial $\bar{S} = 600$ Gt, current annual $\Delta S = 4.5$ Gt.

Economic Effects Takeaways, Judd, 1 – 3

- Due to the uncertainty of payoffs one is willing to pay more for a riskless payoff stream than a risky one
  - ▷ The annual return, adjusted for inflation, 1929-2011, on US stocks is 7.86% with a standard deviation of 19.87%; for one year treasury bills it is 1.01% with a standard deviation of 0.04%
  - ▷ The price of stock expected to return \$100 is, therefore, \$93 = \$100/(1.0786) whereas the price of a bond is \$99 = \$100/(1.0101).
- One is willing to pay \$6 to get rid of the risk of stocks

Economic Effects Takeaways, Judd, 2 – 3

- Judd's model is standard
  - ▷ Capital and labor combine to produce output that has business cycle fluctuations due to random factors built into the model.
  - ▷ The only unusual aspect of Judd's model is the use of Epstein-Zin utility, which is supported by the asset pricing literature.
- The economy produces CO2 emissions proportional to output.
- CO2 feeds into a very simplistic climate model – details not important – and causes random damage to the economy that is proportional to output – damage function details not important.
- One can reduce damage by taxing CO2 emissions.

Economic Effects Takeaways, Judd, 3 – 3

- Without uncertainty, Judd computes the damage due to carbon as \$37 per ton, which agrees with most other estimates.

- With uncertainty, Judd computes \$126 per ton.

- As we shall see later, the correct tax on environmental damage is exactly equal to the damage done.

- The main takeaway is that damage estimates that do not take uncertainty into account are likely to be too low.

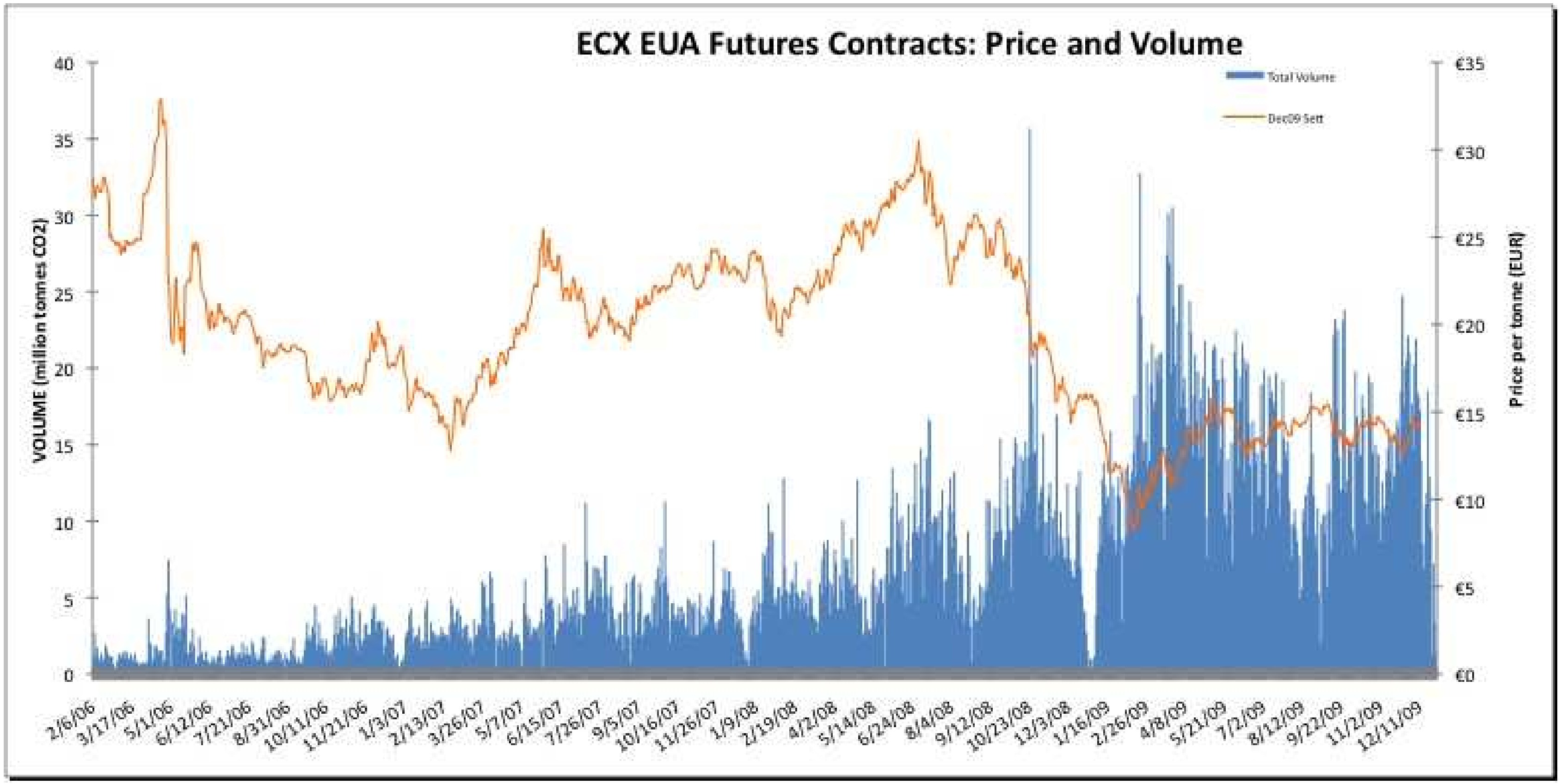
Significant CO_2 Control Measures – 1

- European Union Greenhouse Gas Emission Trading Scheme
  - ▷ Cap and trade, two periods, 2005–2007, 2008–2012, goal 20% reduction by 2020
  - ▷ Per year allowances given away first year, emitters can trade across years within period,
- Regional Greenhouse Gas Initiative
  - ▷ Participants: Maine, New Hampshire, Vermont, Connecticut, New York, New Jersey, Delaware, Massachusetts, Maryland, Rhode Island
  - ▷ Cap and trade, 2009–2012, permits auctioned, fossil fuel power plants, goal 10% reduction by 2020
- Western Regional Climate Action Initiative
  - ▷ Participants: Arizona, California, Montana, New Mexico, Oregon, Utah, Washington, British Columbia, Manitoba, Ontario, Quebec.
  - ▷ Cap and trade, 2012–2015, goal 15% reduction by 2020.

Significant CO_2 Control Measures – 2

- Midwestern Greenhouse Gas Reduction Accord
  - ▷ Participants: Minnesota, Wisconsin, Illinois, Iowa, Michigan, Kansas, Manitoba
  - ▷ Cap and trade, plan not yet formulated
- Waxman-Markey Energy Bill (aka American Clean Energy and Security Act of 2009)
  - ▷ Cap and trade, 2012–2015, goal 17% reduction by 2020, additional clean energy requirements, etc.
  - ▷ 85% of allowances to industry for free, auction the remainder.

European Climate Exchange, 1 of 2



Source: http://www.ecx.edu

European Climate Exchange, 2 of 2

Source: http://cen.acs.org/articles/91/i7/EU-Carbon-Emissions-Trading-Scheme.html

Comparison of Policy Options

Comparative Performance of Policy Instruments		
Factor	**Cap and Trade**	**CO_2 or Carbon Tax**
Certainty about quantity of emissions	Yes	No
Certainty about price or costs	No	Yes
Encourages innovation	Yes	Yes
Raises public revenues	No if permits given freely; yes if sold	Yes
Harms competitiveness	Yes	Yes, unless tax applied comprehensively
Political feasibility	Medium (especially if given freely)	Low
New policy institutions required	Yes	Minimal

Source : Field and Field (2009, Exhibit 20.2)

HBR: What Executives Need to Know

- Promote market-based approaches
  - ▷ "Companies should speak up. They should support programs that give them flexibility in deciding how to reduce emissions."
- Think long run
  - ▷ Rather than promoting regulations with short-run advantages, promote a regulatory environment that is stable and predictable and therefore friendly to investment over the long run.
  - ▷ "Business leaders would do best to sell their elected representatives on a long-term approach to managing the effects of climate change."
- Recognize the benefits of leadership
  - ▷ "Companies known to have made early efforts to tackle climate change will have seats at the negotiating table when regulations are being debated."

Our CO_2 Contribution

- World average: 5.5
- US average: 27
- Mine
  - ▷ Without air travel: 16
  - ▷ With air travel: 86
- Calculate your own:
  http:www.nature.org/greenliving/carboncalculator/index.htm