Climate Models

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Climate vs. Weather

“Climate is what you expect, weather is what you get.”

– Mark Twain

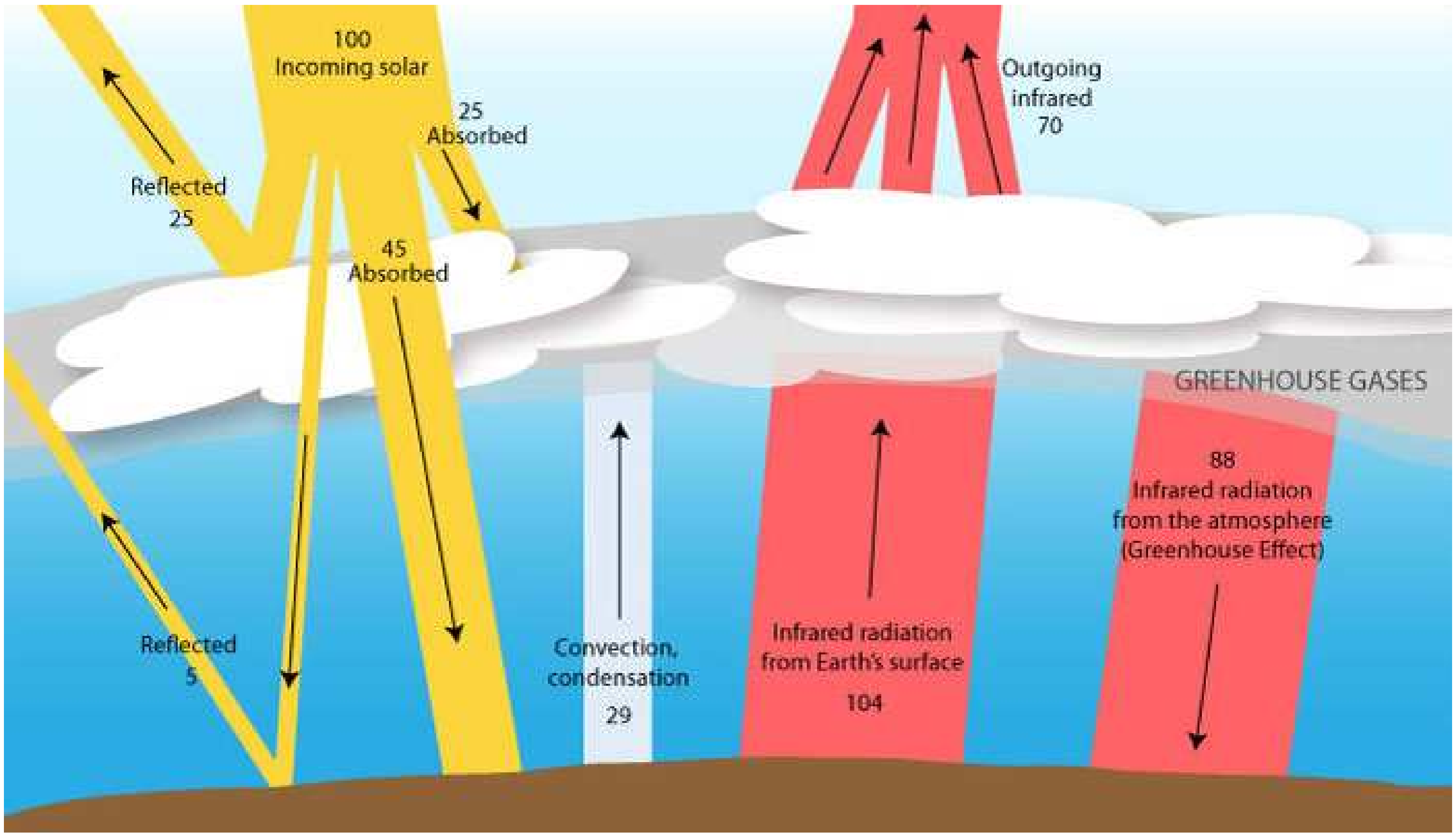
Climate Models vs. Weather Models

- 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:

$$P = \sigma T^4$$

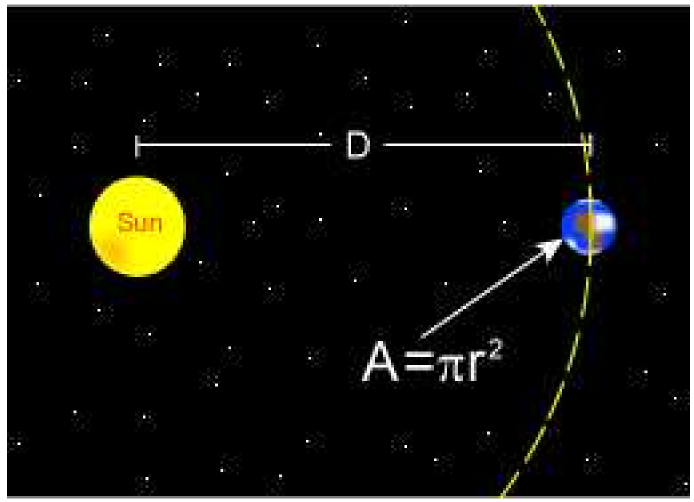
  - ▷ P is the total power radiated per unit area, units are W/m^2
  - ▷ $\sigma = 5.67 \times 10^{-8} \frac{W}{m^2 K^4}$ is the Stefan-Boltzmann constant

- 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

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

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

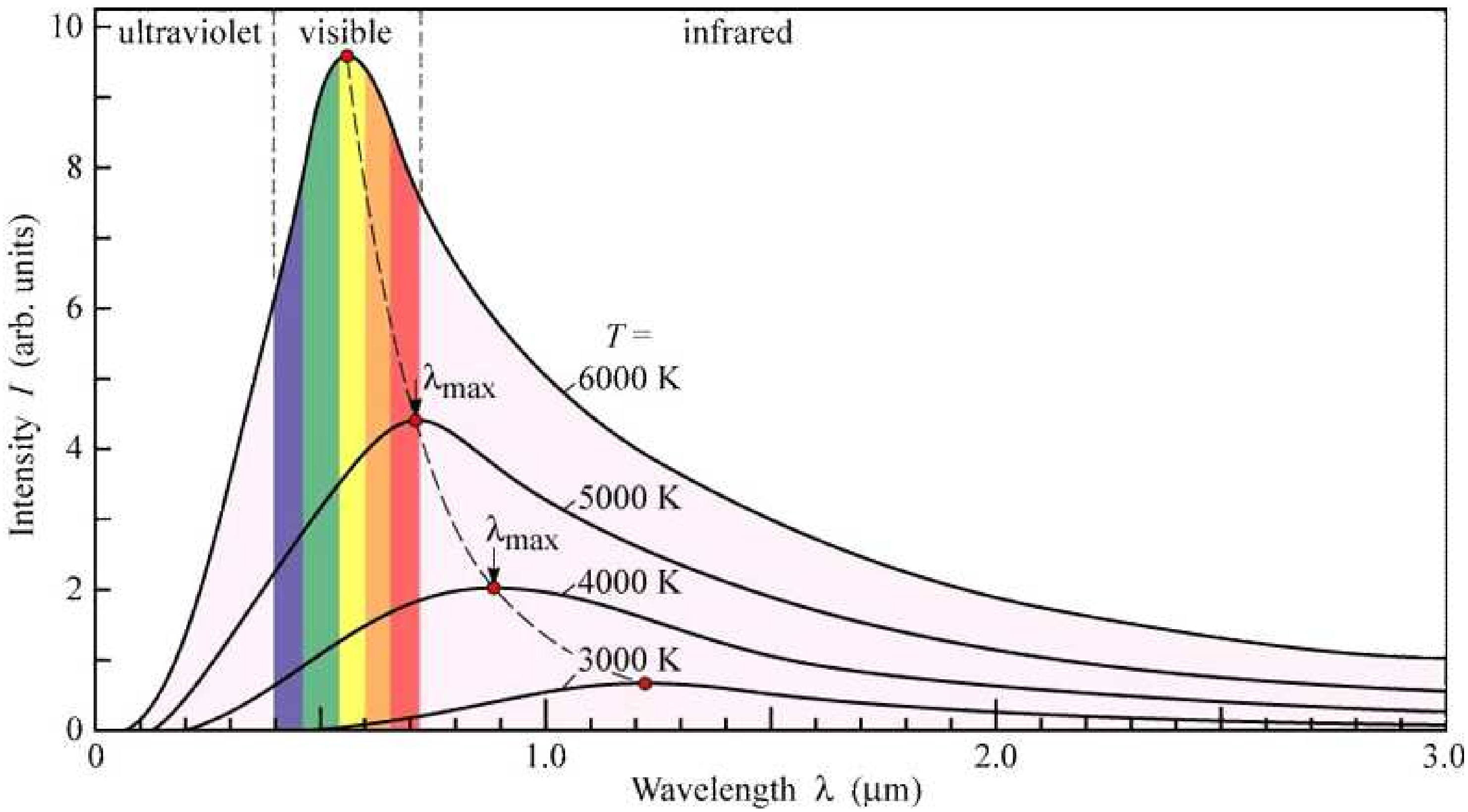
- Without the greenhouse effect the temperature would be $T_e = 254.356\,^oK = -18.794\,^oC = -1.829\,^oF$

- 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.

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.

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.
  - ▷ These models would not be so complex if they used Newtonian physics from the point of view of an observer on a distant star (a fixed inertial frame of reference).
  - ▷ What makes them so difficult is that the description is from the point of view of an observer at a fixed point on a rotating sphere.

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.

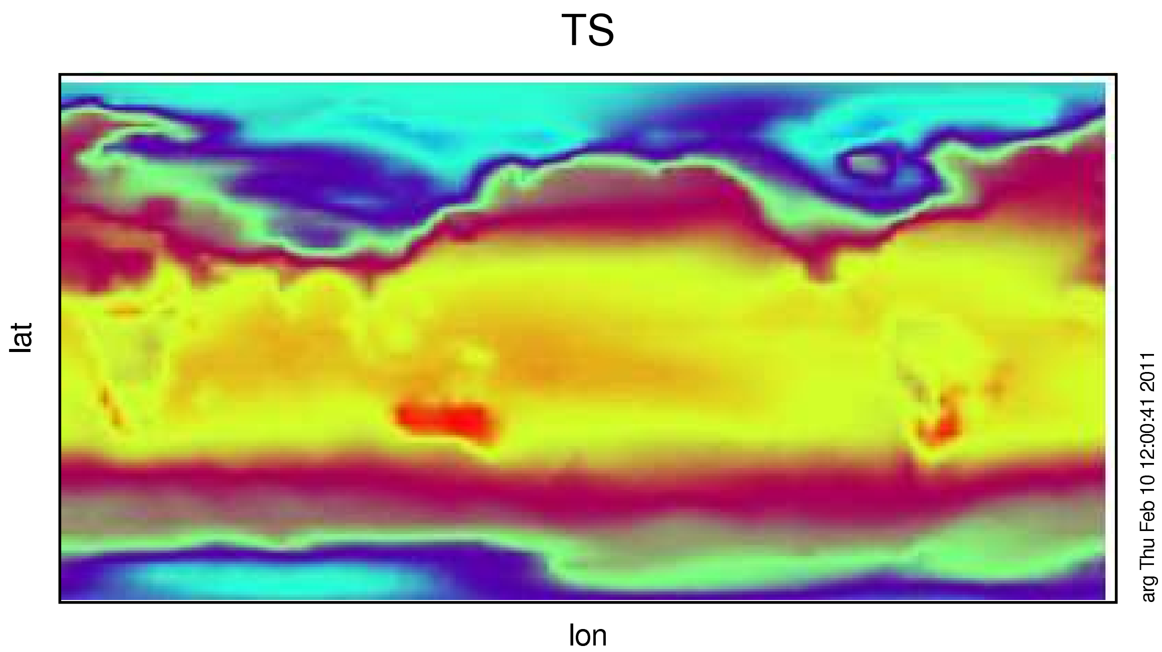
Fig 4. NCAR's Bluefire

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

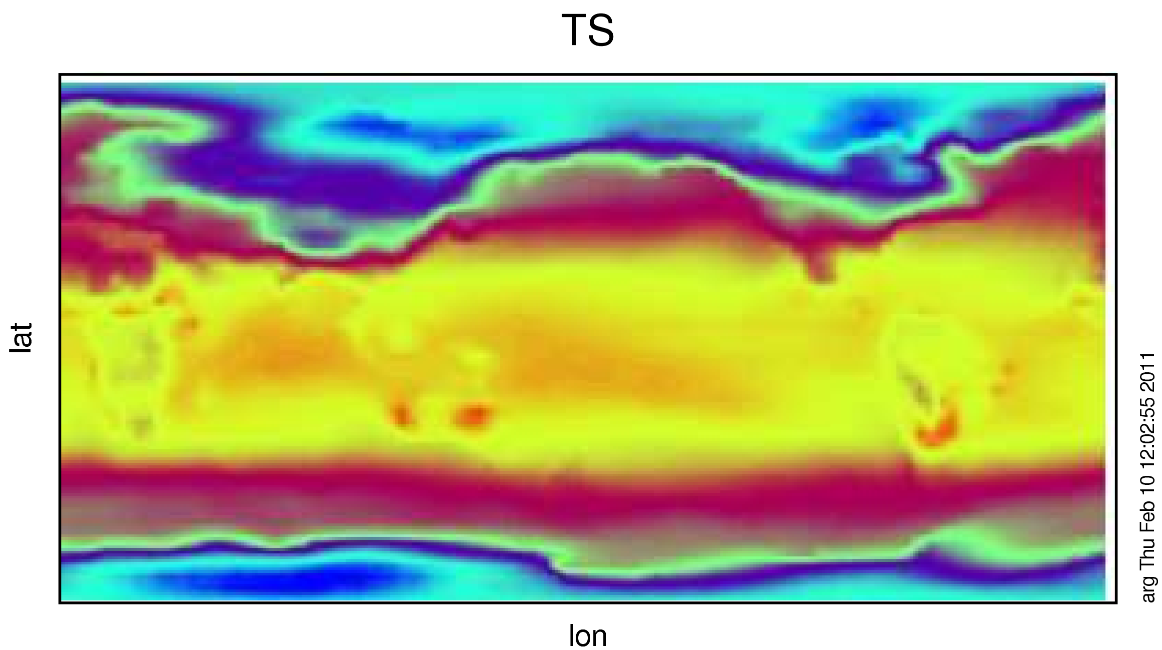
- NCAR's CESM1 code is in the public domain
- It is quite easy to download
- It is well documented.
- It can be run on a Linux box:
  - ▷ Four-chip motherboard populated with 12-core AMD chips; 48 CPUs total.
  - ▷ RedHat Enterprise Linux 5.0 (CentOS public domain variant).
  - ▷ PGI Fortran compiler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

Fig 5. CESM1 Surface Temperature, Jan 2000



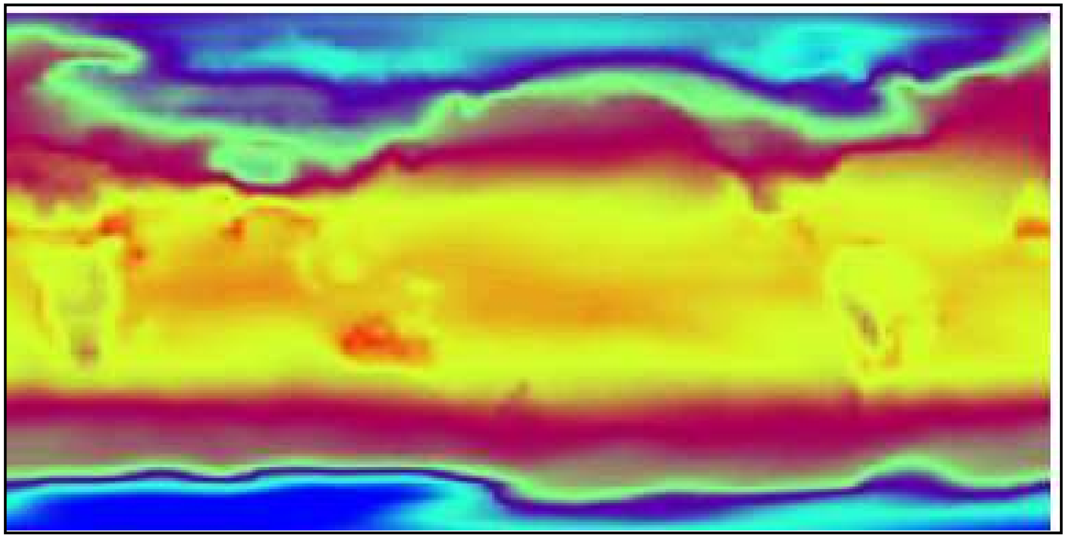
Range of TS: 223.105 to 311.27 (null)
Range of lon: 0 to 356.25
Range of lat: -87.1591 to 87.1591
Current time: 31
Frame 1 in File TS.nc

Fig 6. CESM1 Surface Temperature, Feb 2000



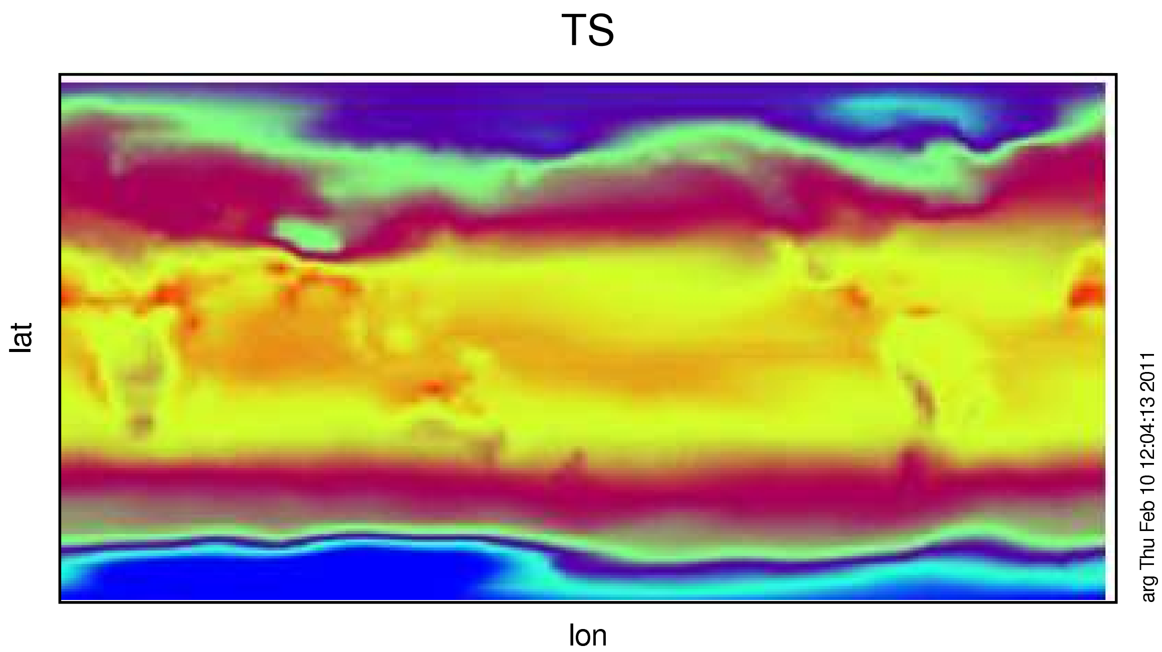
Range of TS: 223.105 to 311.27 (null)
Range of lon: 0 to 356.25
Range of lat: -87.1591 to 87.1591
Current time: 59
Frame 2 in File TS.nc

Fig 7. CESM1 Surface Temperature, Mar 2000



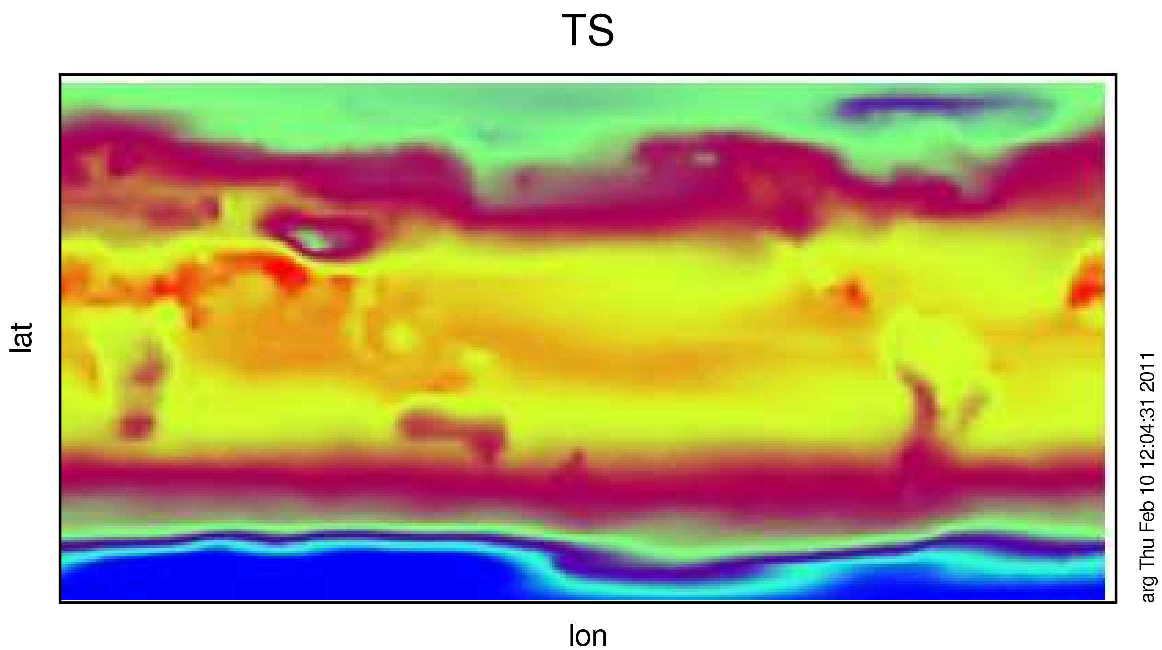
Range of TS: 223.105 to 311.27 (null)
Range of lon: 0 to 356.25
Range of lat: -87.1591 to 87.1591
Current time: 90
Frame 3 in File TS.nc

Fig 8. CESM1 Surface Temperature, Apr 2000



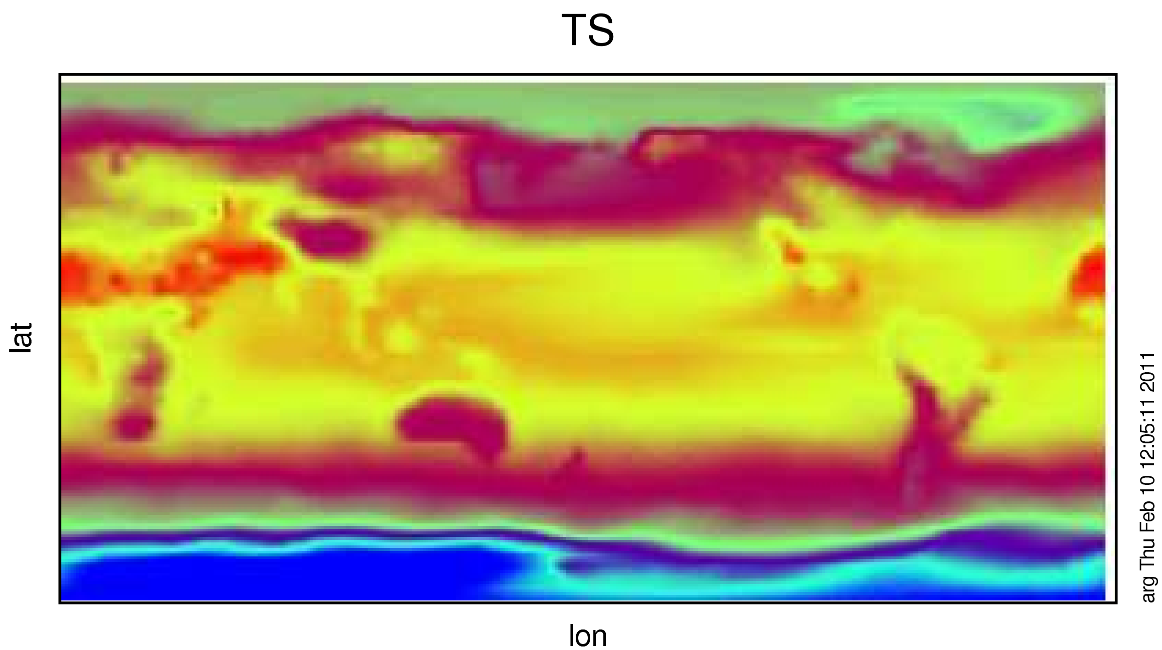
Range of TS: 223.105 to 311.27 (null)
Range of lon: 0 to 356.25
Range of lat: -87.1591 to 87.1591
Current time: 120
Frame 4 in File TS.nc

Fig 9. CESM1 Surface Temperature, May 2000



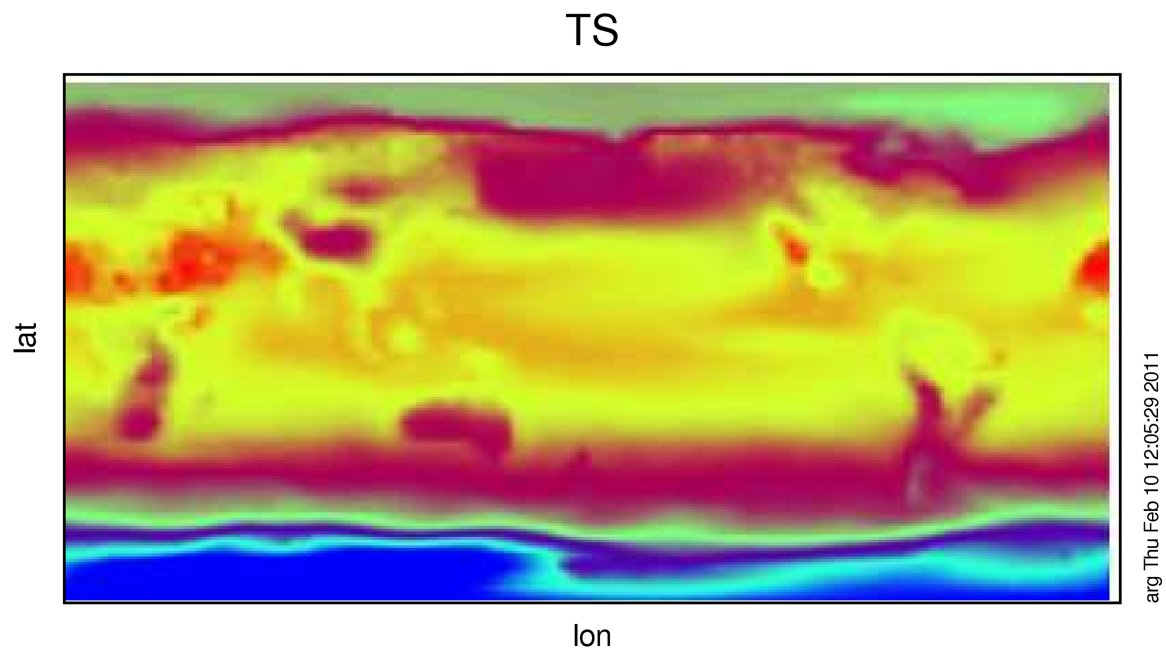
Range of TS: 223.105 to 311.27 (null)
Range of lon: 0 to 356.25
Range of lat: -87.1591 to 87.1591
Current time: 151
Frame 5 in File TS.nc

Fig 10. CESM1 Surface Temperature, Jun 2000



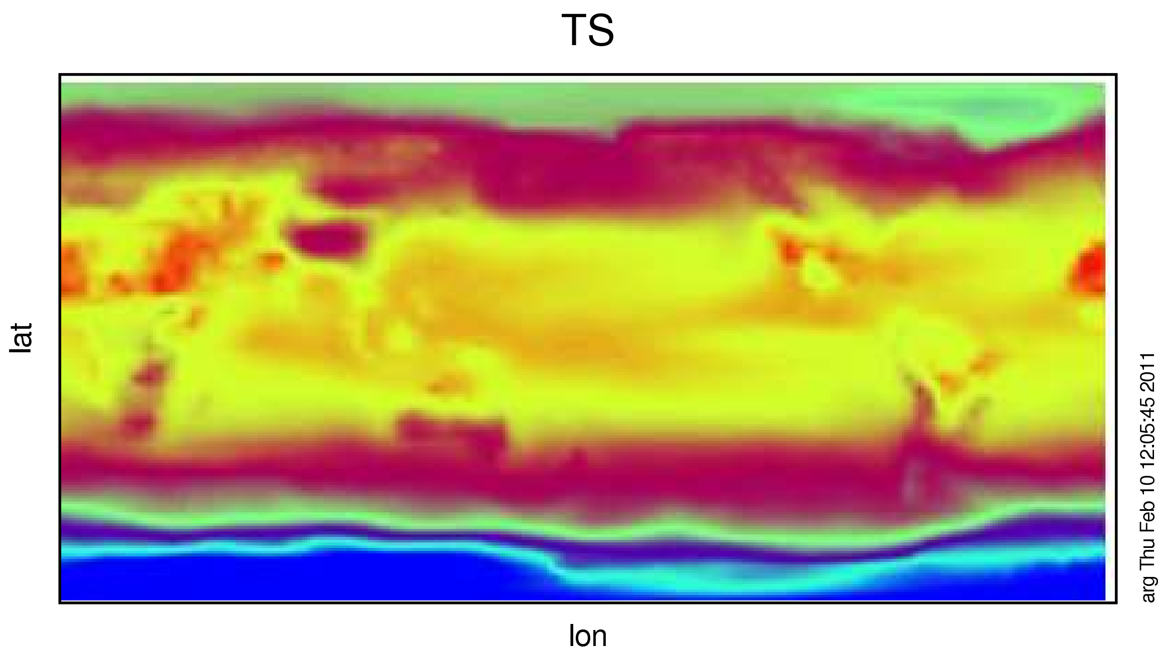
Range of TS: 223.105 to 311.27 (null)
Range of lon: 0 to 356.25
Range of lat: -87.1591 to 87.1591
Current time: 181
Frame 6 in File TS.nc

Fig 11. CESM1 Surface Temperature, Jul 2000



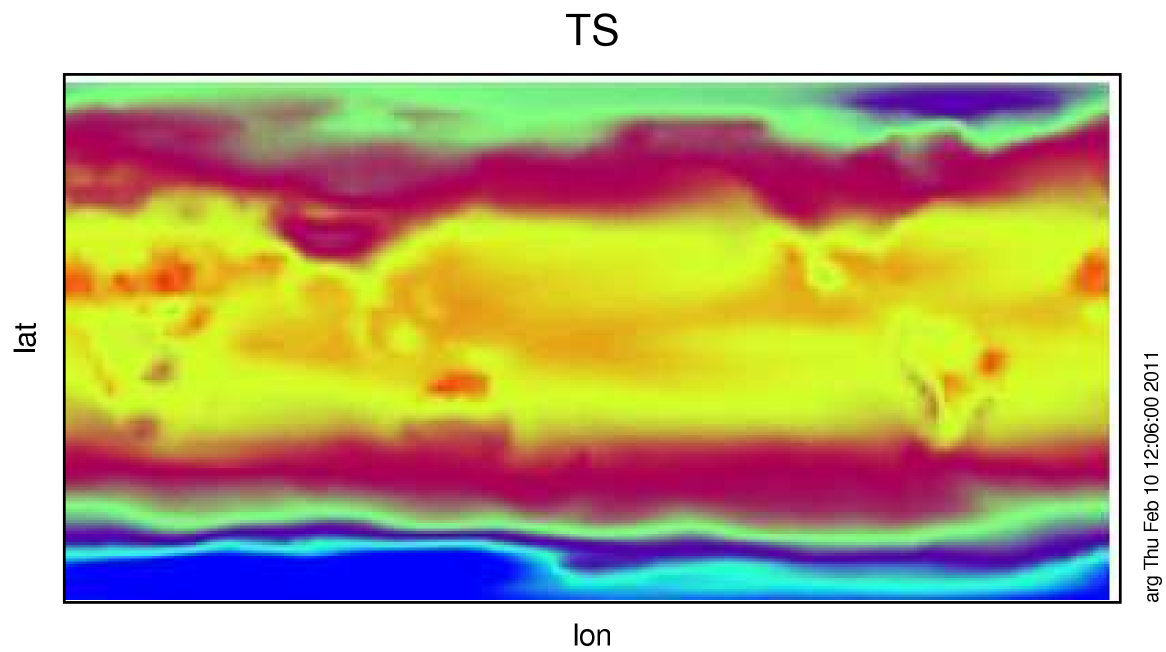
Range of TS: 223.105 to 311.27 (null)
Range of lon: 0 to 356.25
Range of lat: -87.1591 to 87.1591
Current time: 212
Frame 7 in File TS.nc

Fig 12. CESM1 Surface Temperature, Aug 2000



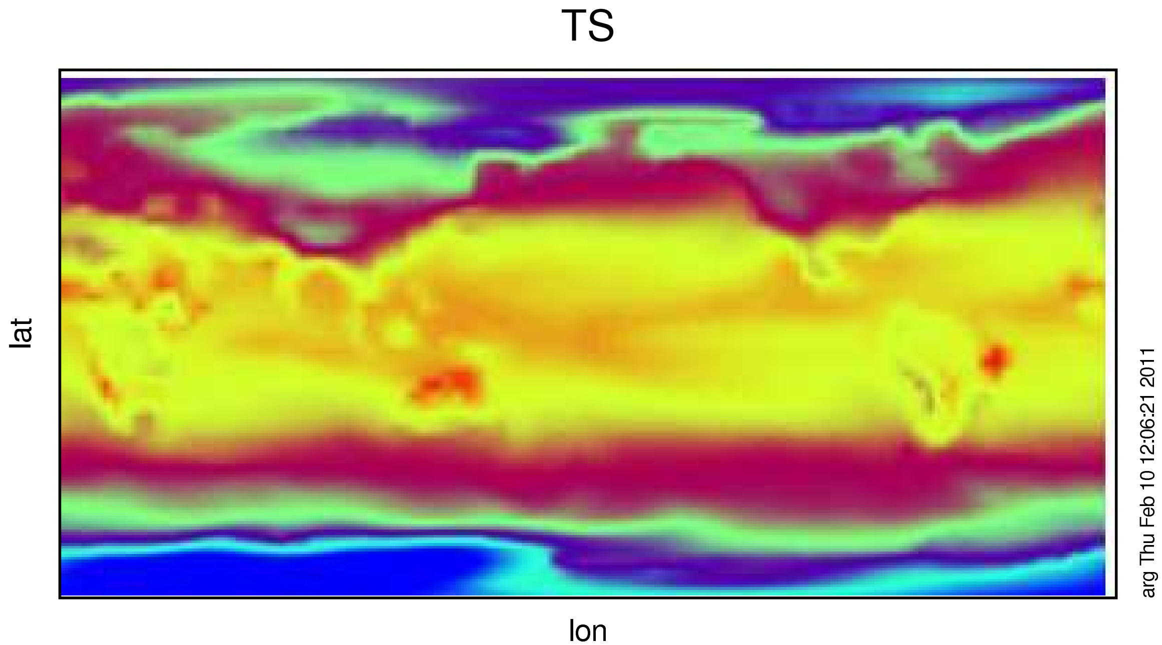
Range of TS: 223.105 to 311.27 (null)
Range of lon: 0 to 356.25
Range of lat: -87.1591 to 87.1591
Current time: 243
Frame 8 in File TS.nc

Fig 13. CESM1 Surface Temperature, Sep 2000



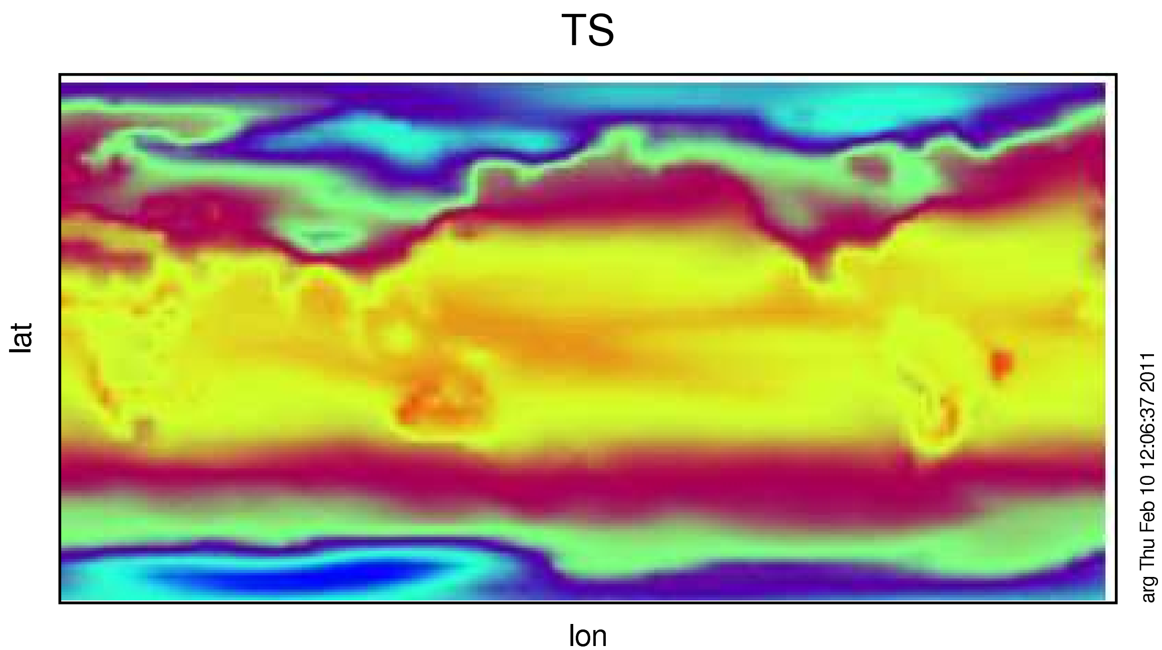
Range of TS: 223.105 to 311.27 (null)
Range of lon: 0 to 356.25
Range of lat: -87.1591 to 87.1591
Current time: 273
Frame 9 in File TS.nc

Fig 14. CESM1 Surface Temperature, Oct 2000



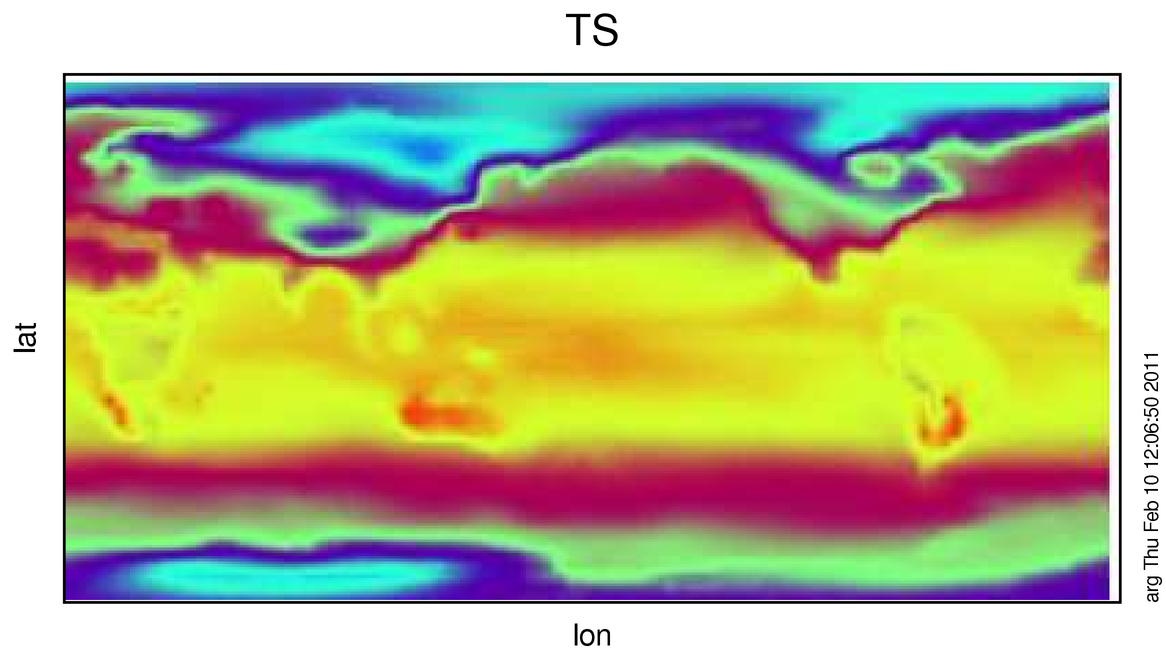
Range of TS: 223.105 to 311.27 (null)
Range of lon: 0 to 356.25
Range of lat: -87.1591 to 87.1591
Current time: 304
Frame 10 in File TS.nc

Fig 15. CESM1 Surface Temperature, Nov 2000



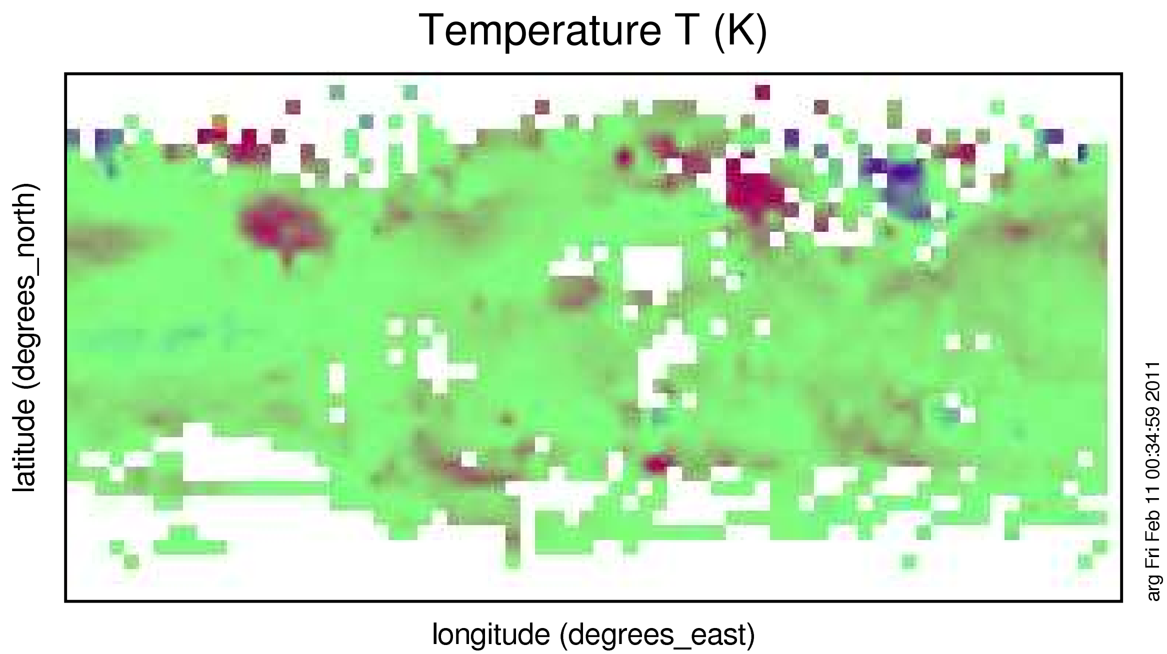
Range of TS: 223.105 to 311.27 (null)
Range of lon: 0 to 356.25
Range of lat: -87.1591 to 87.1591
Current time: 334
Frame 11 in File TS.nc

Fig 16. 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

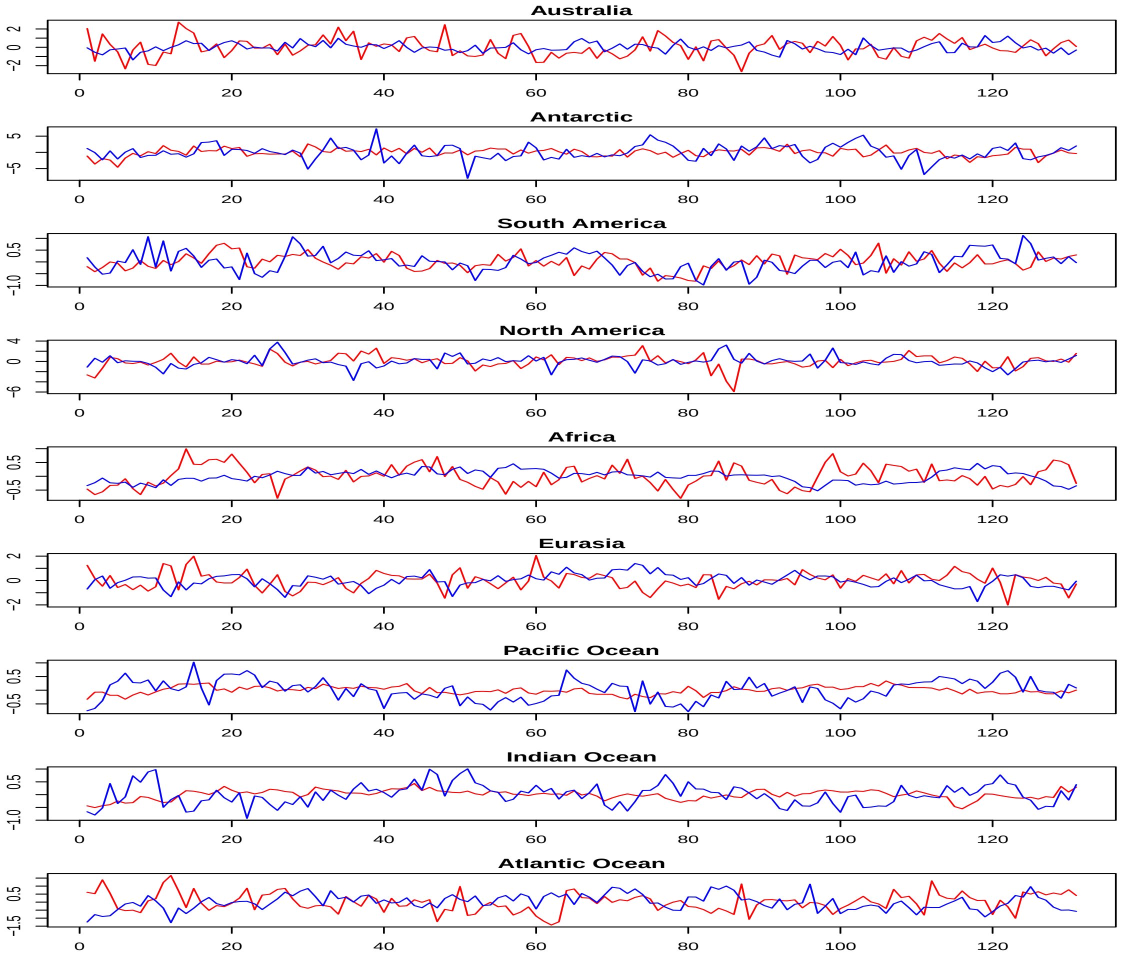
Fig 17. Surface Temperature Measurements, Jan 2000



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

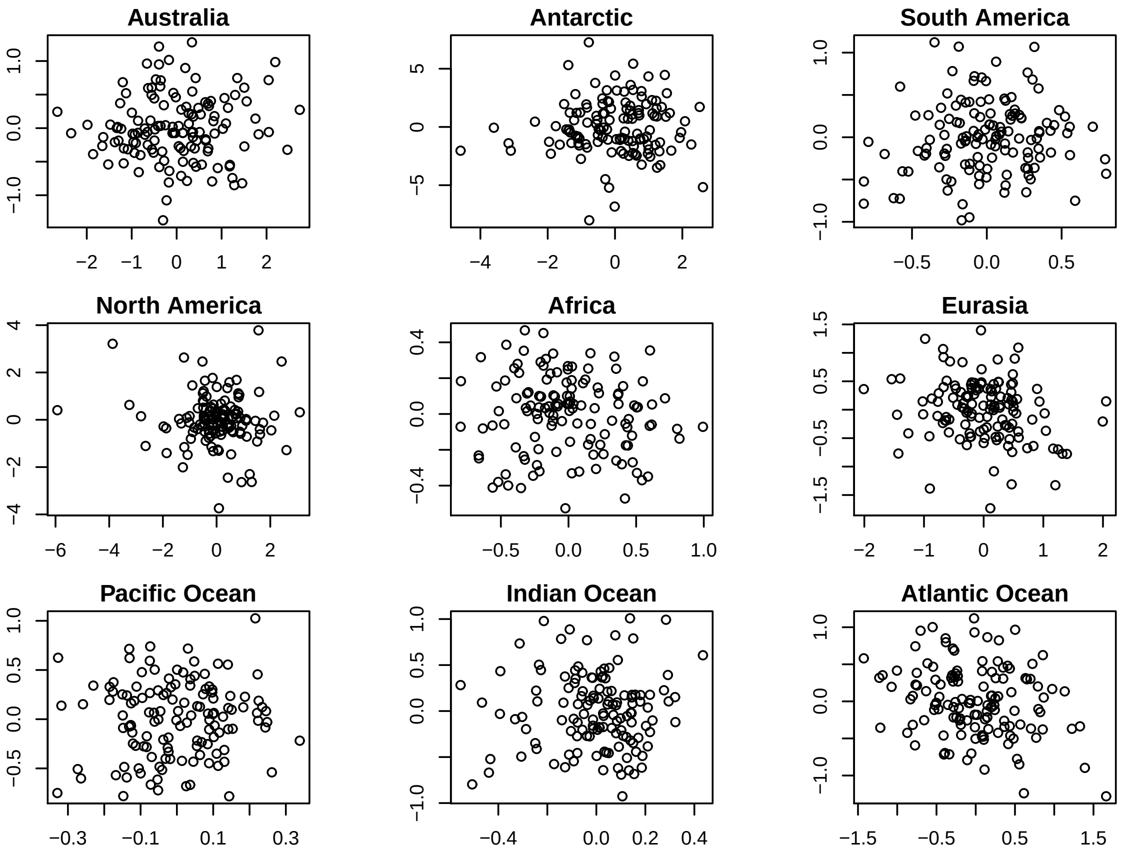
Shown are deviations from the base period 1961-90, about 3,000 observations unevenly distributed. Ocean readings are water temperatures, not surface temperatures. Source: http://www.cru.uea.ac.uk/cru/data/temperature/

Fig 18. How Well Does CESM Track the Data?



Hadley data (blue) and CESM output (red) are averaged over continents and oceans and adjusted to remove linear trend and monthly means. Monthly values from 2000 through 2010.

Fig 19. How Well Does CESM Track the Data?



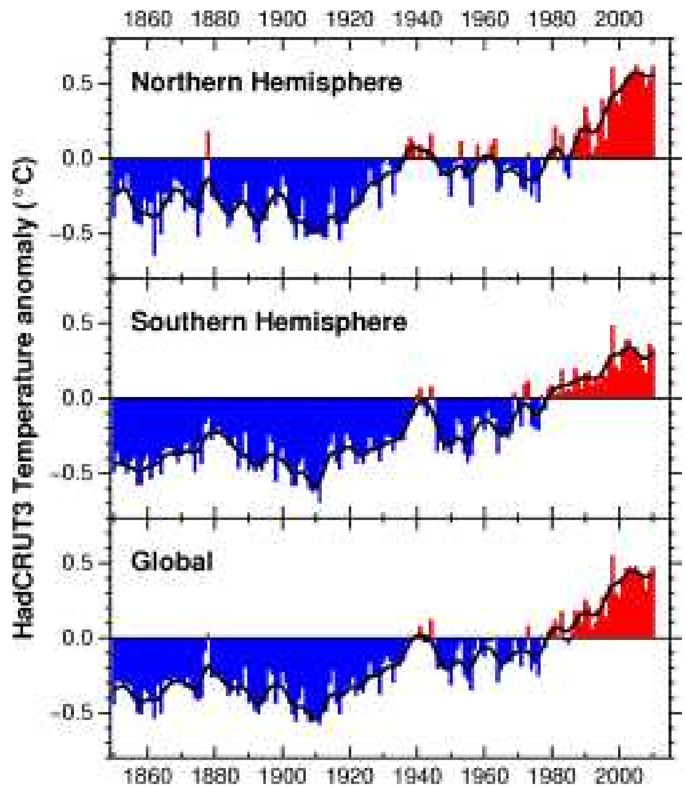
Hadley data and CESM output are averaged over continents and oceans and adjusted to remove linear trend and monthly means. Monthly values from 2000 through 2010.

How Well Does CESM Track Trend?

Region	Hadley data trend	CESM output trend
Australia	0.00090316	0.00093928
Antarctic	0.00301373	-0.00293036
South America	0.00025332	-0.00301899
North America	0.00299326	-0.00579180
Africa	0.00069985	-0.00315344
Eurasia	0.00468737	-0.00678664
Pacific Ocean	-0.00202225	-0.00275240
Indian Ocean	-0.00286582	-0.00200936
Atlantic Ocean	0.00195583	-0.00867359

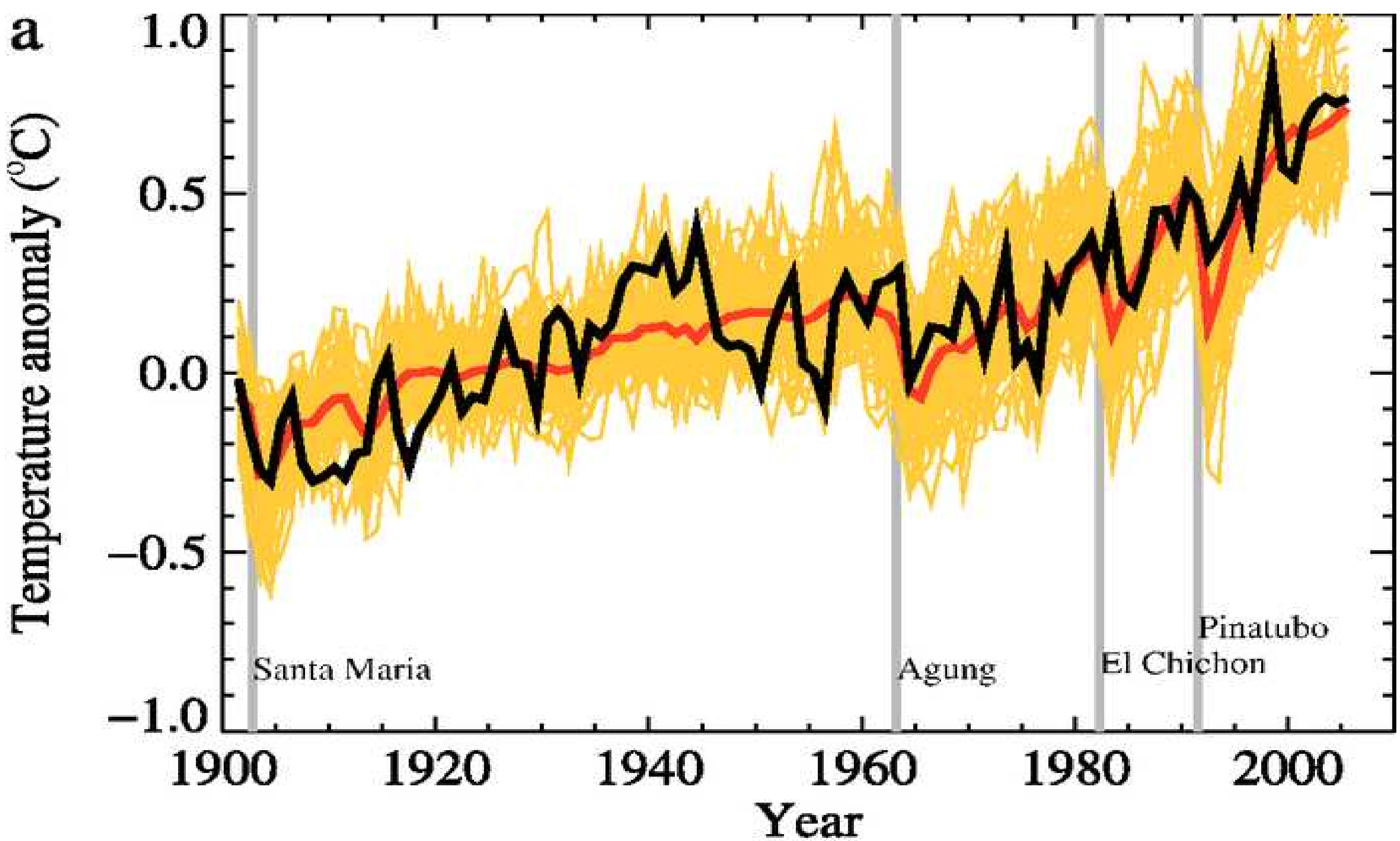
The data show no growth because $t = 1, \ldots, 131$. Are these trends reasonable? See next slide.

Fig 20. Are the Trends Reasonable?



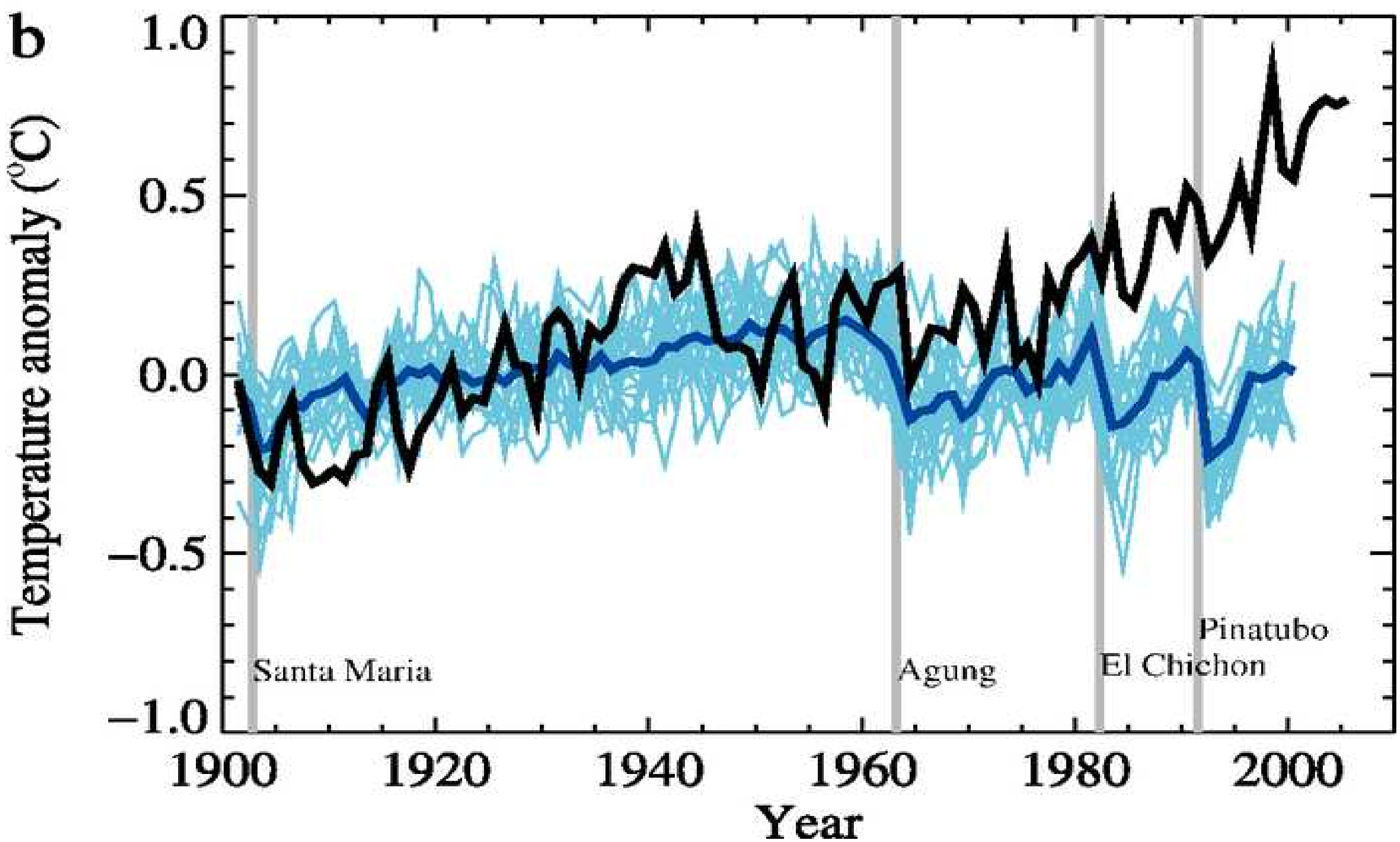
Apparently the trends are reasonable for the period 2000 to 2010. Source: http://www.cru.uea.ac.uk/cru/data

Fig 21. Climate Models over Longer Periods



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

Fig 22. Climate Models without Anthropogenic Forcing



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