Weather

- Depends on time
  - weather nearby (especially upwind!)
  - weather yesterday
  - which way the wind blows
- Changes a lot!
  - from day to day
  - from season to season
  - from place to place on a given day
- Unpredictable more than a few days ahead

Climate

- Depends on where you live:
  - Latitude!
  - Altitude (mountains vs plains)
  - What's upwind (ocean vs land)
- Changes very slowly
- Very predictable
- We can predict that Miami is warmer than Minneapolis for precisely the same reasons that we can predict a warmer future!

Climate vs. Weather

"Climate is what you expect … weather is what you get!"

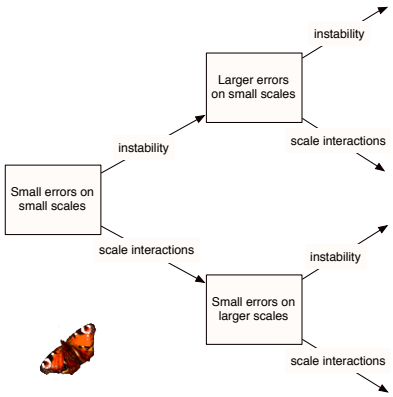
- Climate is an "envelope of possibilities" within which the weather bounces around
- Climate is determined by the properties of the Earth system itself (the boundary conditions), whereas weather depends very sensitively on the evolution of the system from one moment to the next

Predictability

"If they can't predict the weather, how can they possibly hope to predict the climate?"

- Weather forecasts are only useful for a few days, maybe a week at best
- Forecasting is limited by modeling skill and inadequate observations, but even if these were perfect, the limit of predictability would be about 2 weeks
- This limit is a property of the atmosphere itself, not a failure of our science!

Limits to Predictability



- Instability and scale interactions make long-range weather forecasting impossible (not just hard!)
- This is not true for climate!

Airplane analogy

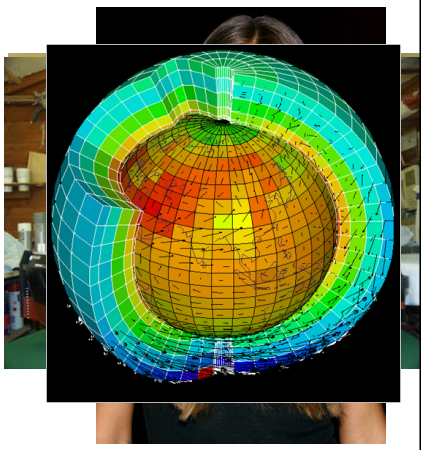
- The flow around an airplane wing is governed by the same strongly nonlinear Navier-Stokes equations that govern the atmosphere
- For the same reasons we will never forecast the weather a month in advance, we can never predict the details of the flow around the wing
- But given boundary values and parameters, we can predict with confidence the statistics of this flow, or flight would be impossible!

Long-term Forecasting

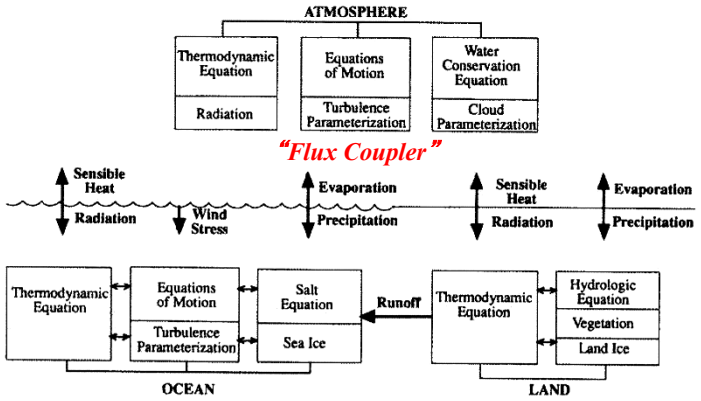
- Can't forecast the weather in Fort Collins on the day of the ATS 150 final exam in May (Snow? Sunshine? 50° F? 90° F?)
- Can "forecast" with complete confidence that $-100\ C < T_{max} < +100\ C$, or even that May will be warmer than March
- Why?
- Boundary conditions!
  - Solar constant, position of Earth in orbit
  - Atmospheric composition
  - Tilt of Earth's axis, Fort Collins latitude, etc

Climate Models

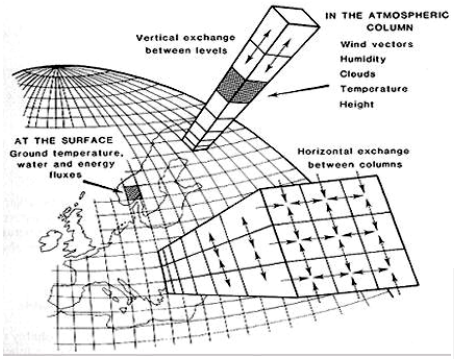
- What is a "model"
- What does it mean to model the climate?
- How do modern climate models work?
- How good are they?
- What can they tell us?
- What can't they tell us?



Climate Model Structure

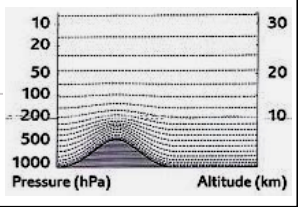


Climate Model Grids

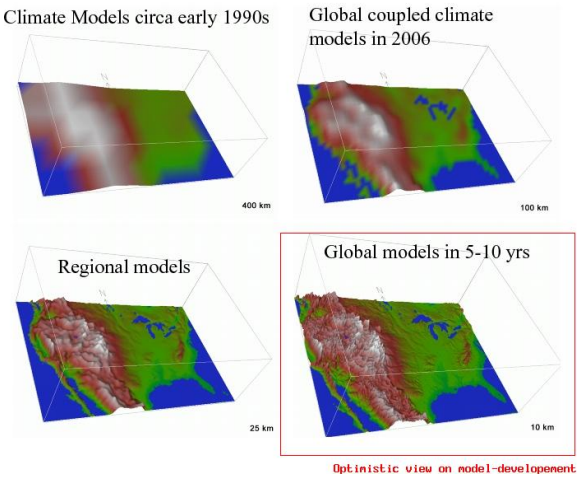


Typical climate model
$\Delta x \sim 200$ km

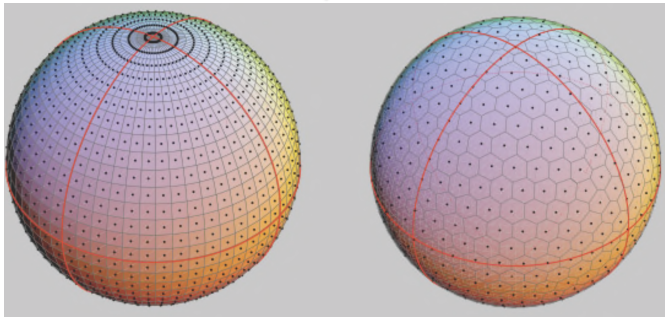
Typical weather forecast model
$\Delta x \sim 40$ km



Topography at Different Resolutions



Boxes on a Spherical Earth!



- Must fit gridded variables on a rotating sphere
- Traditional latitude-longitude approach has severe problems with tiny cells near poles
- Geodesic approach (like a soccer ball) fixes this, but introduces very complicated math!

Thing #1:
Atmosphere

- Mass
- Momentum
- Energy
- Moisture
- Carbon, ozone and other chemical species

- Advection
- Pressure-gradient
- Rotation
- Solar radiation
- Terrestrial radiation
- Turbulence
- Moist convection
- Phase changes and other "microphysical" processes
- Momentum transfer by small-scale buoyancy waves

Thing #4:
Ocean

- Mass
- Momentum
- Energy
- Salt
- Sea ice
- Various chemical species
- Ocean biology

- Advection
- Pressure-gradient
- Rotation
- Solar radiation
- Terrestrial radiation XXX
- Turbulence
- Moist convection XXX
- Phase changes and other "microphysical" processes XXX
- Momentum transfer by small-scale buoyancy waves

Thing #5:
Land Surface

- Soil
- Veggies
- Energy
- Water
- Snow, etc.
- Carbon

An Appetite for FLOPS

NCAR

NERSC

Oak Ridge

NASA Ames

Others...

About a *million million* floating-point operations to simulate one day.

36,500 days in a century.

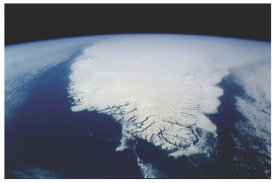
Computer power has increased by a factor of a million since I was in graduate school.

The machines are getting harder to program.

Thing #9:

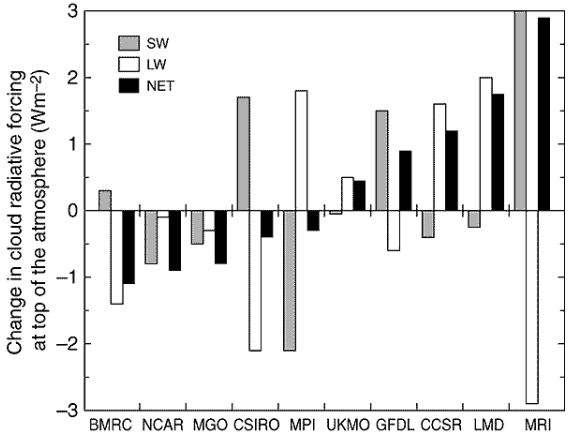
What's Missing

- Ice sheets
- Many chemical processes
- Interactive biology on the land surface
  - Seasonal greening
  - Biome change
- Interactive biology in the ocean
  - Carbon
  - Turbidity
  - Mixing



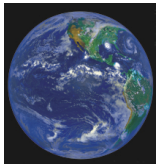
Cloud Parameterization

Change in TOA Cloud Radiative Forcing for 2xCO2

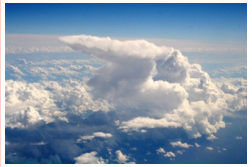


Change in the Top of the Atmosphere (TOA) Cloud Radiative Forcing (CRF) associated with a CO_2 doubling (from a review by Le Treut and McAvaney, 2000). The models are coupled to a slab ocean mixed layer and are brought to equilibrium for present climatic conditions and for a double CO_2 climate. The sign is positive when an increase of the CRF (from present to double CO_2 conditions) increases the warming, negative when it reduces it.

Modeling Across Scales



Global circulation

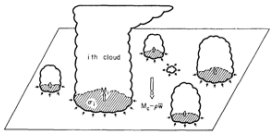


Cloud dynamics

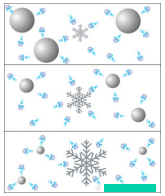
Radiation, Microphysics, Turbulence

Parameterized

Parameterizations



Toy cloud dynamics

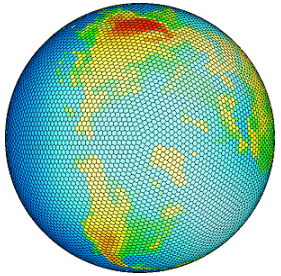


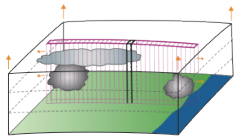
Toy microphysics

Super-Parameterization

Insert a simplified cloud-resolving model into every grid column of the global model.

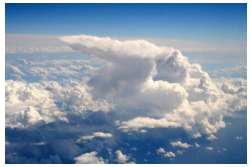
The cloud-resolving model takes the place of the toy cloud dynamics.



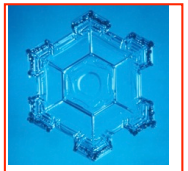


Parameterize less.

Global circulation



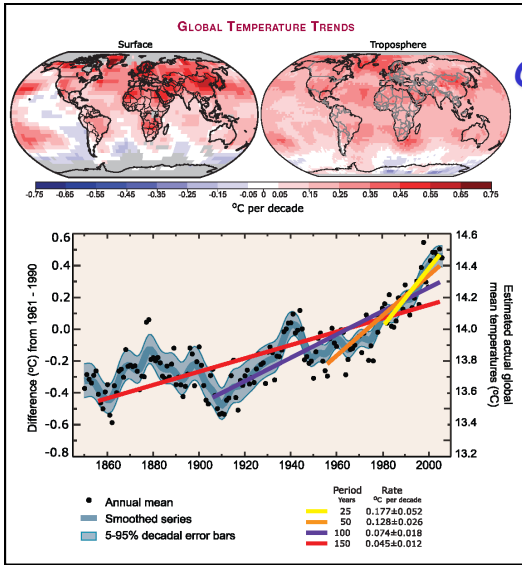
Cloud dynamics



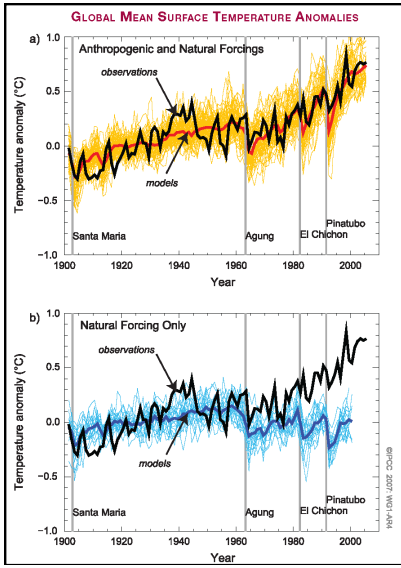
Radiation, Microphysics, Turbulence

Parameterized

Observations

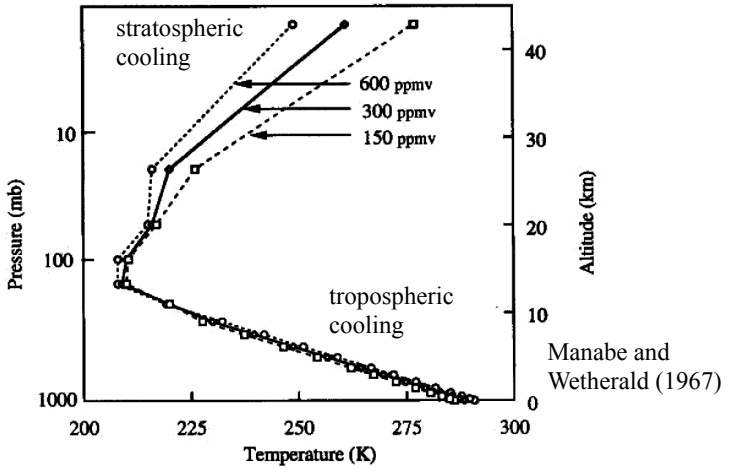


- Much stronger trend on land than ocean
- North > South
- Surface > Troposphere
- Acceleration of trend



20th-Century Temperatures

- Black lines show observations, yellow lines show each model, red line shows model average temperature
- With all forcings, models capture much of historical record of real temperatures
- Bottom panels: models without CO2 increase don't agree with real observations



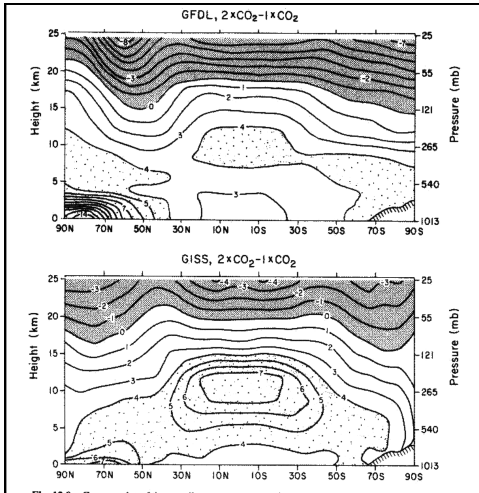
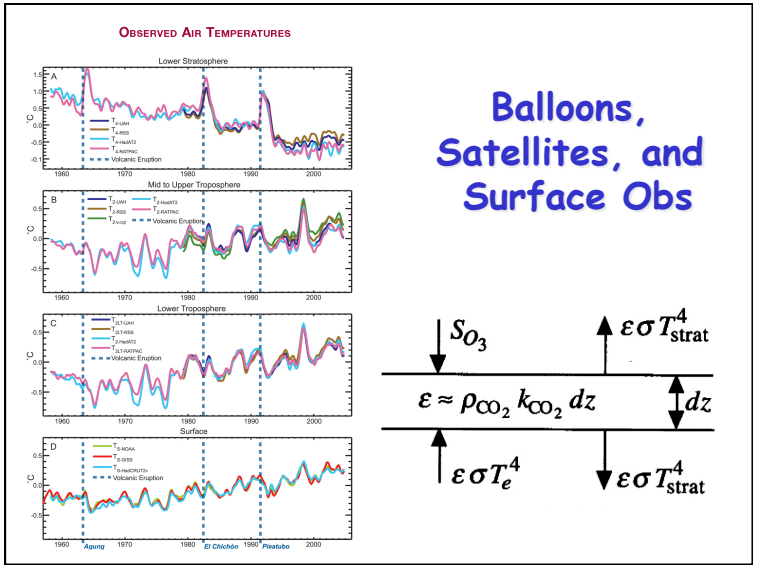


Fig. 12.9 Contour plot of the zonally averaged change in air temperature during DJF resulting from a CO_2 doubling in two models that each give a global-average surface temperature increase of 4°C. Cooling and warming greater than 4°C are shaded. [Top panel, Wetherald and Manabe (1986), reprinted with permission from Kluwer Academic Publishers; bottom panel, Hansen *et al.* (1984), © American Geophysical Union, as printed in Schlesinger and Mitchell (1987), © American Geophysical Union.]

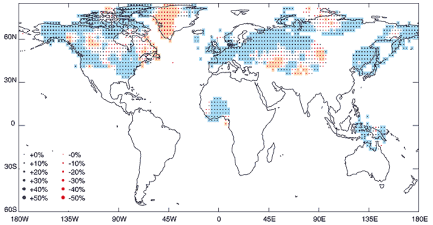
Predicted Vertical Structure

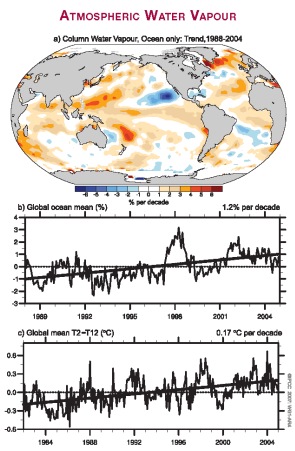
- Greenhouse "signature" is tropospheric warming and stratospheric cooling
- Predicted in mid-1980's by climate models



Balloons, Satellites, and Surface Obs

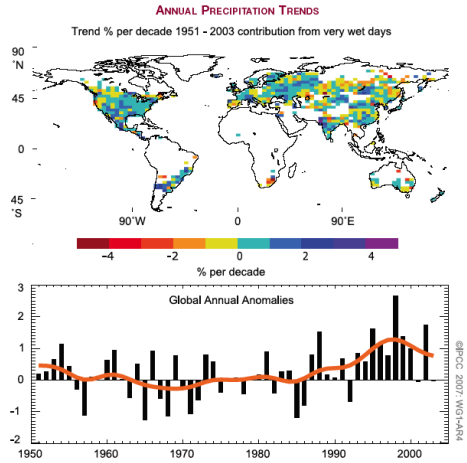
Water Vapor Trends





Trends in annual mean surface water vapour pressure, 1975 to 1995, expressed as a percentage of the 1975 to 1995 mean. Areas without dots have no data. Blue shaded areas have nominally significant increasing trends and brown shaded areas have significant decreasing trends, both at the 5% significance level. Biases in these data have been little studied so the level of significance may be overstated. From New et al. (2000).

Accelerating Hydrologic Cycle



Radiative Forcing Scenarios

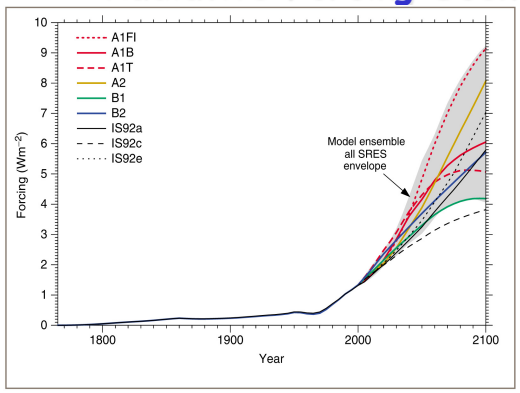
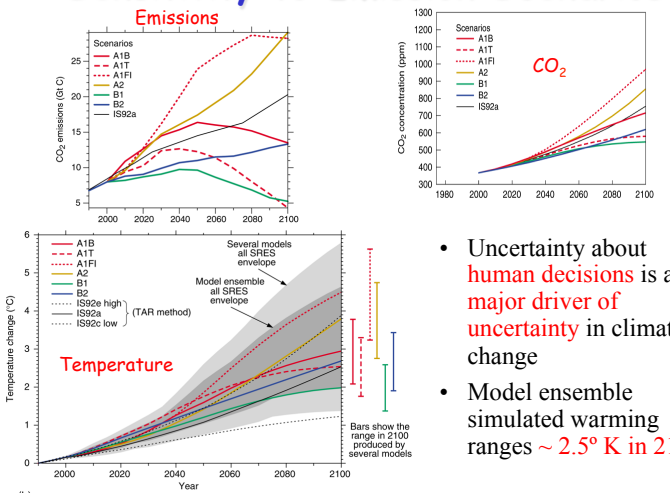


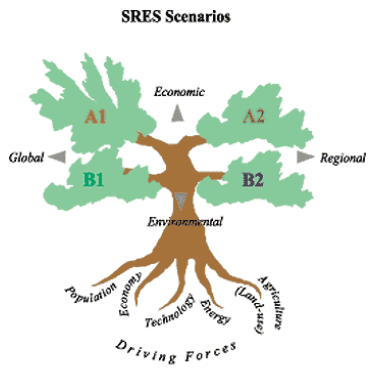
Figure 19: Simple model results: estimated historical anthropogenic radiative forcing up to the year 2000 followed by radiative forcing for the six illustrative SRES scenarios. The shading shows the envelope of forcing that encompasses the full set of thirty five SRES scenarios. The method of calculation closely follows that explained in the chapters. The values are based on the radiative forcing for a doubling of CO_2 from seven AOGCMs. The IS92a, IS92c, and IS92e forcing is also shown following the same method of calculation. [Based on Figure 9.13a]

Sensitivity to Emission Scenarios



- Uncertainty about human decisions is a major driver of uncertainty in climate change
- Model ensemble simulated warming ranges ~ 2.5º K in 2100

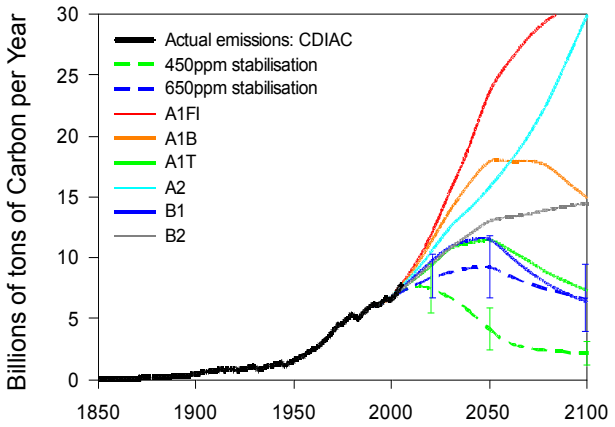
Emission Scenarios



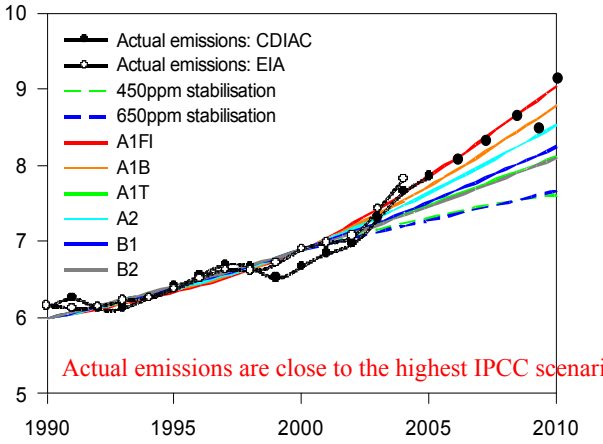
- **A1**: Globalized, with very rapid economic growth, low population growth, rapid introduction of more efficient technologies.
- **A2**: very heterogeneous world, with self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, resulting in high population growth. Economic development is regionally oriented and per capita economic growth & technology more fragmented, slower than other storylines.
- **B1**: convergent world with the same low population growth as in A1, but with rapid changes in economic structures toward a service and information economy, reductions in material intensity, introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, without additional climate initiatives.
- **B2**: local solutions to economic, social, and environmental sustainability. Moderate population growth, intermediate levels of economic development, and less rapid and more diverse technological change than in B1 and A1.

Each "storyline" used to generate 10 different scenarios of population, technological & economic development

Emission Scenarios



Emission Scenarios vs Reality



Raupach et al. 2007 PNAS, updated 4/8/2012

Probabilities of Change

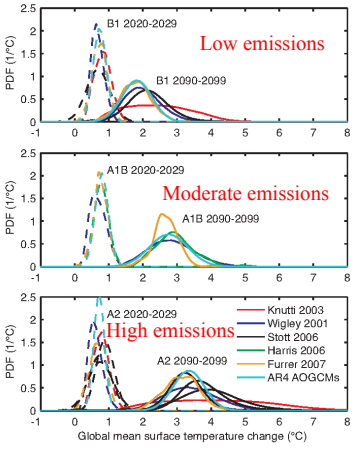
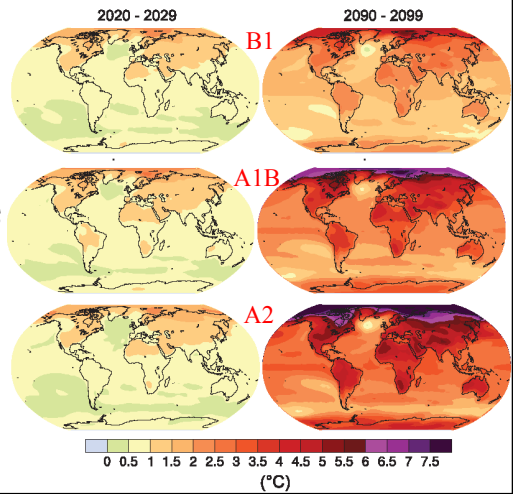


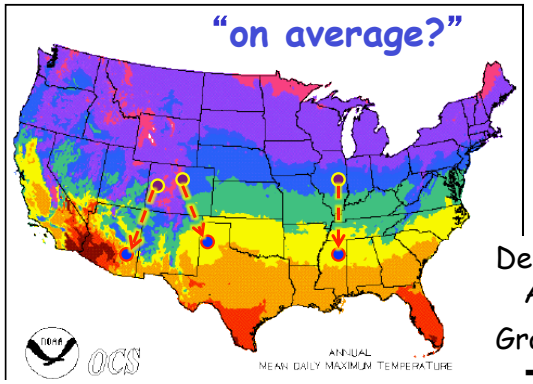
Figure 10.28. *Probability density functions from different studies for global mean temperature change for the SRES scenarios B1, A1B and A2 and for the decades 2020 to 2029 and 2090 to 2099 relative to the 1980 to 1999 average (Wigley and Raper, 2001; Knutti et al., 2002; Furrer et al., 2007; Harris et al., 2006; Stott et al., 2006b). A normal distribution fitted to the multi-model ensemble is shown for comparison.*

Global Projections of Sfc Temp

- Land vs ocean!
- North vs South
- Snow/ice albedo effects
- 2° – 6° C in USA
- 4° to 11° F in USA
- Up to 8° C = 15° F in Arctic



Where is it 10°F Warmer



Denver ➔ Amarillo

Grand Junction ➔ Tucson

Illinois ➔ Mississippi

Water? Crops?
Real Estate? Health?