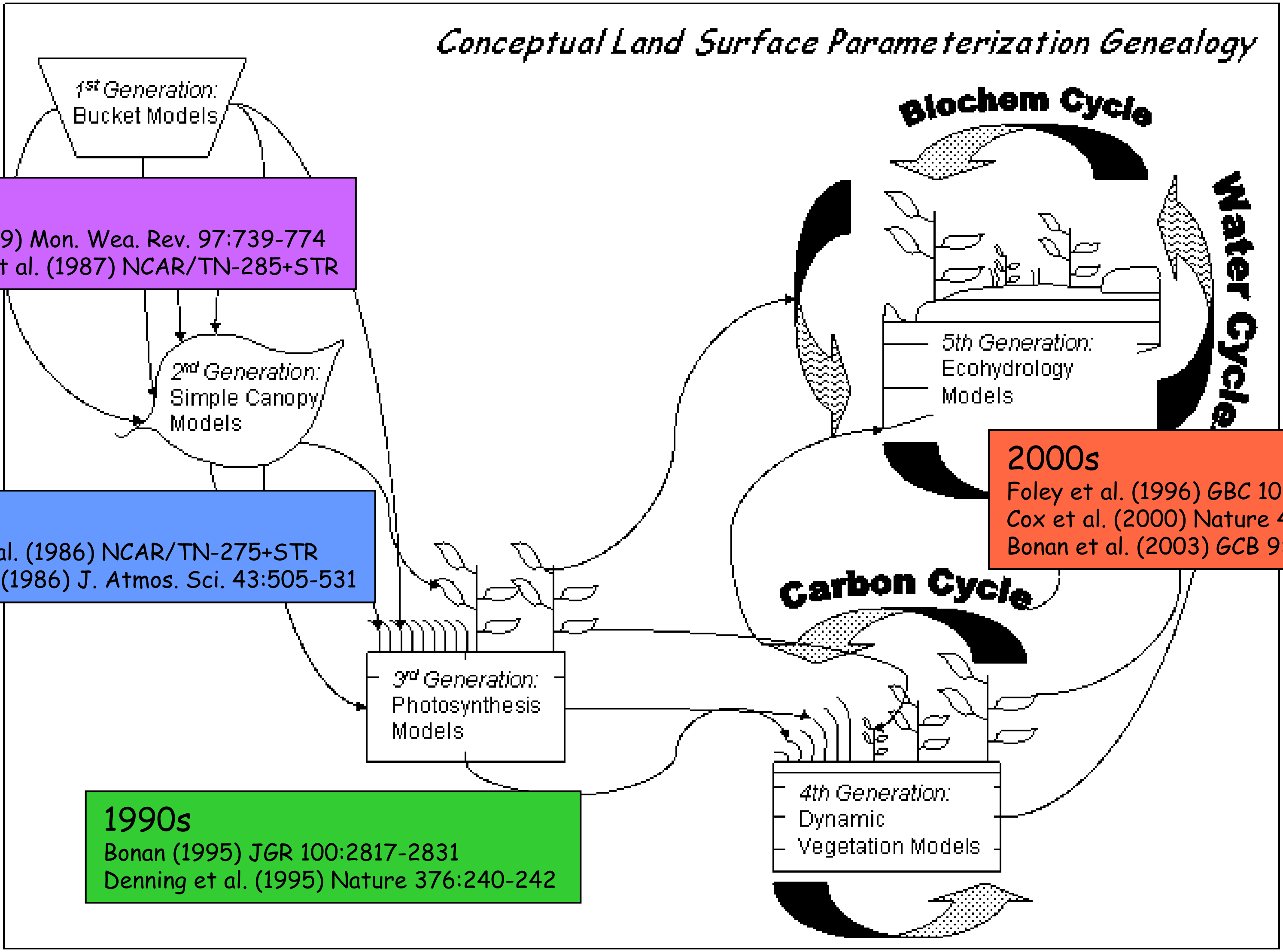
# "Advances in land-climate interactions for earth system models: The Community Land Model (CLM) experience"

Gordon Bonan
National Center for Atmospheric Research
Boulder, Colorado

With contributions from
Dave Lawrence (NCAR)
Dave Gochis (NCAR)

European Geosciences Union
General Assembly 2008
Vienna, Austria
14 April 2008

# Evolution of land surface models



**1960s**
Manabe (1969) Mon. Wea. Rev. 97:739-774
Williamson et al. (1987) NCAR/TN-285+STR

**1980s**
Dickinson et al. (1986) NCAR/TN-275+STR
Sellers et al. (1986) J. Atmos. Sci. 43:505-531

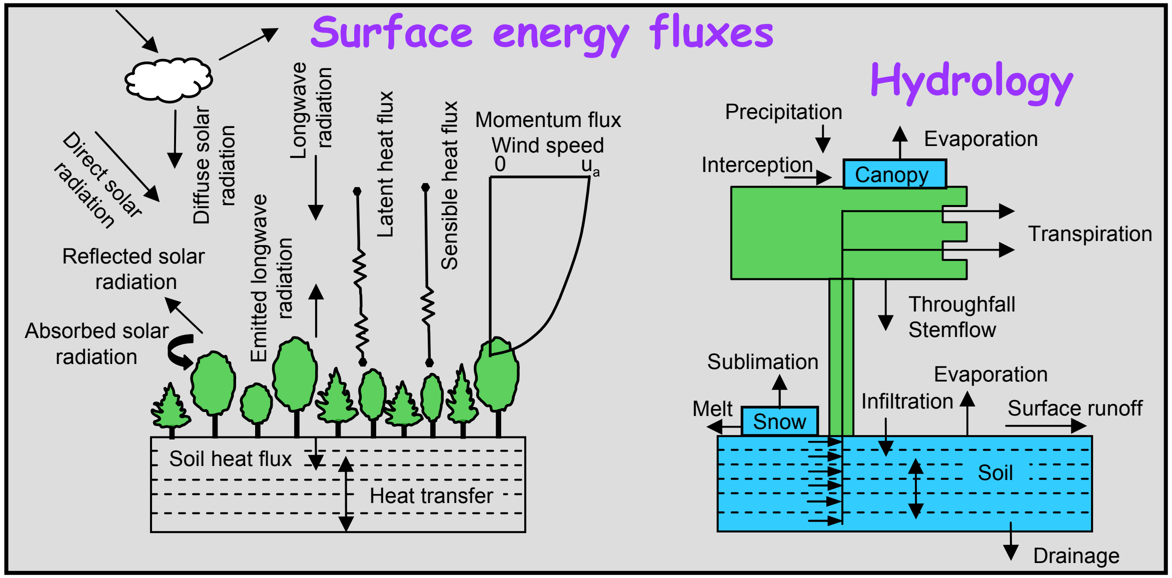
**1990s**
Bonan (1995) JGR 100:2817-2831
Denning et al. (1995) Nature 376:240-242

**2000s**
Foley et al. (1996) GBC 10:603-628
Cox et al. (2000) Nature 408:184-187
Bonan et al. (2003) GCB 9:1543-1566

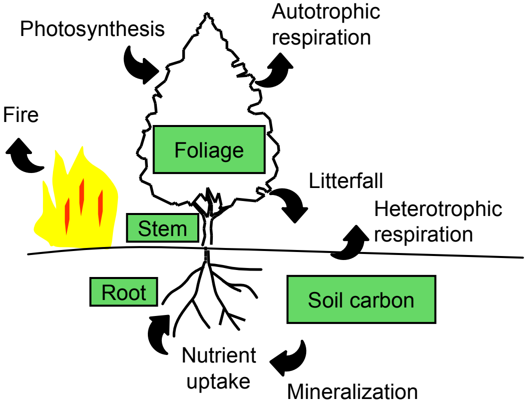
Gochis et al., 2004

## Surface energy fluxes

## Hydrology



## Carbon cycle



## Ice sheets

## Climate change

Establishment

Disturbance

# Current-generation models

Deforestation

## Land use

Reforestation

## Urbanization

## Vegetation dynamics

Competition

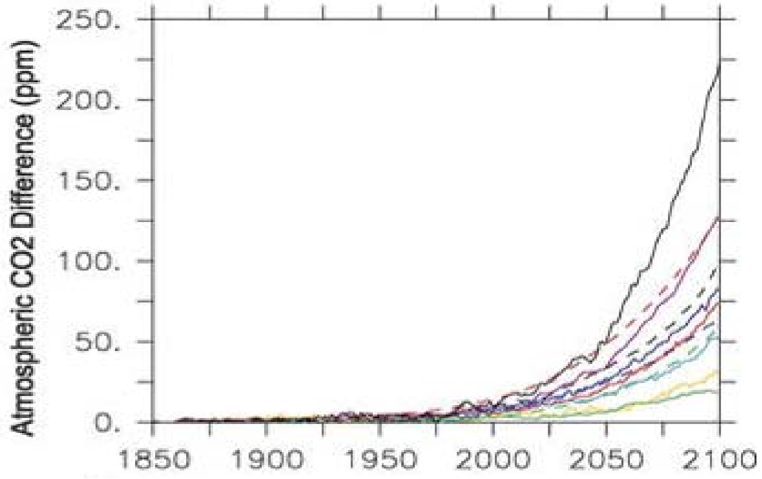
Growth

# Land as set of interacting systems

- Biogeochemical systems
  - nutrient cycling, trace gas emissions, reactive chemistry, constituent tracing, isotopes
- Water systems
  - water resources management, freshwater availability and water quality
- Human systems
  - land use, urbanization, energy use
- Ecosystems
  - resilience, good and services
- Ice sheet and glacier systems
  - slow and fast ice sheet dynamics

# The future of (land) climate change science

## Climate-carbon cycle feedback

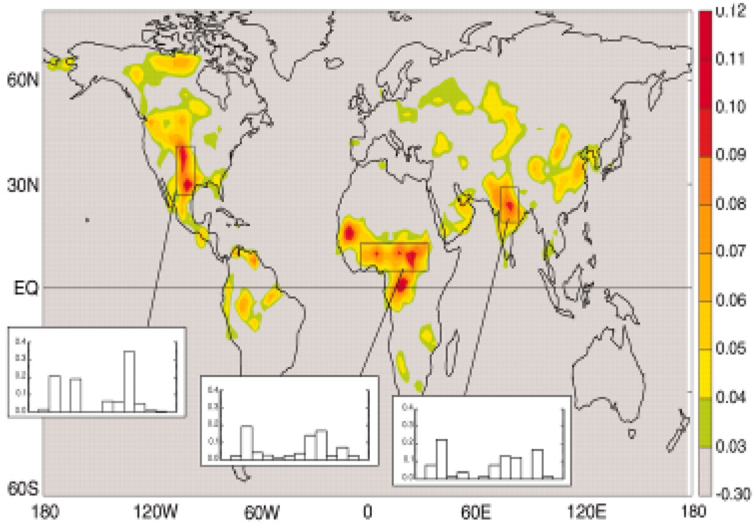


Friedlingstein et al. (2006) J. Climate 19:3337–3353

These models are being used to explore forcings and feedbacks in the earth system

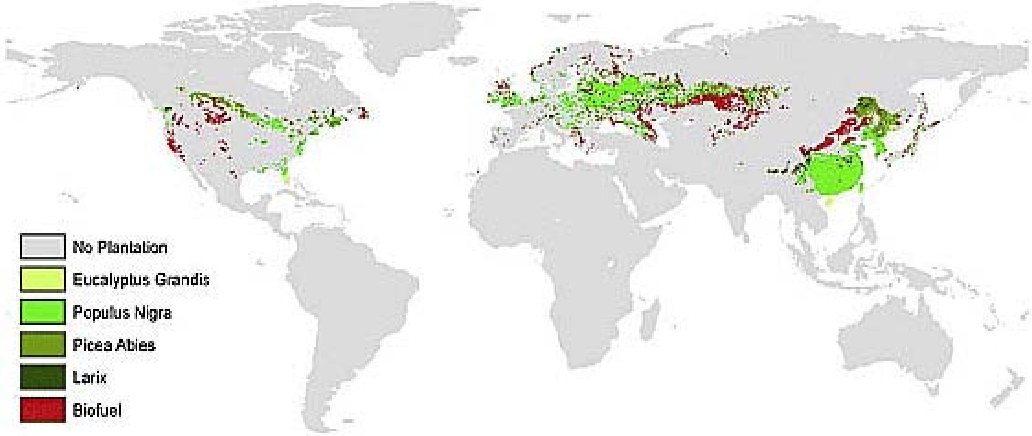
Increasing demand for information on impacts (especially regional), adaptation strategies, and mitigation solutions

## Land-atmosphere coupling strength



Koster et al. (2004) Science 305:1138-1140

## Land management mitigation strategies



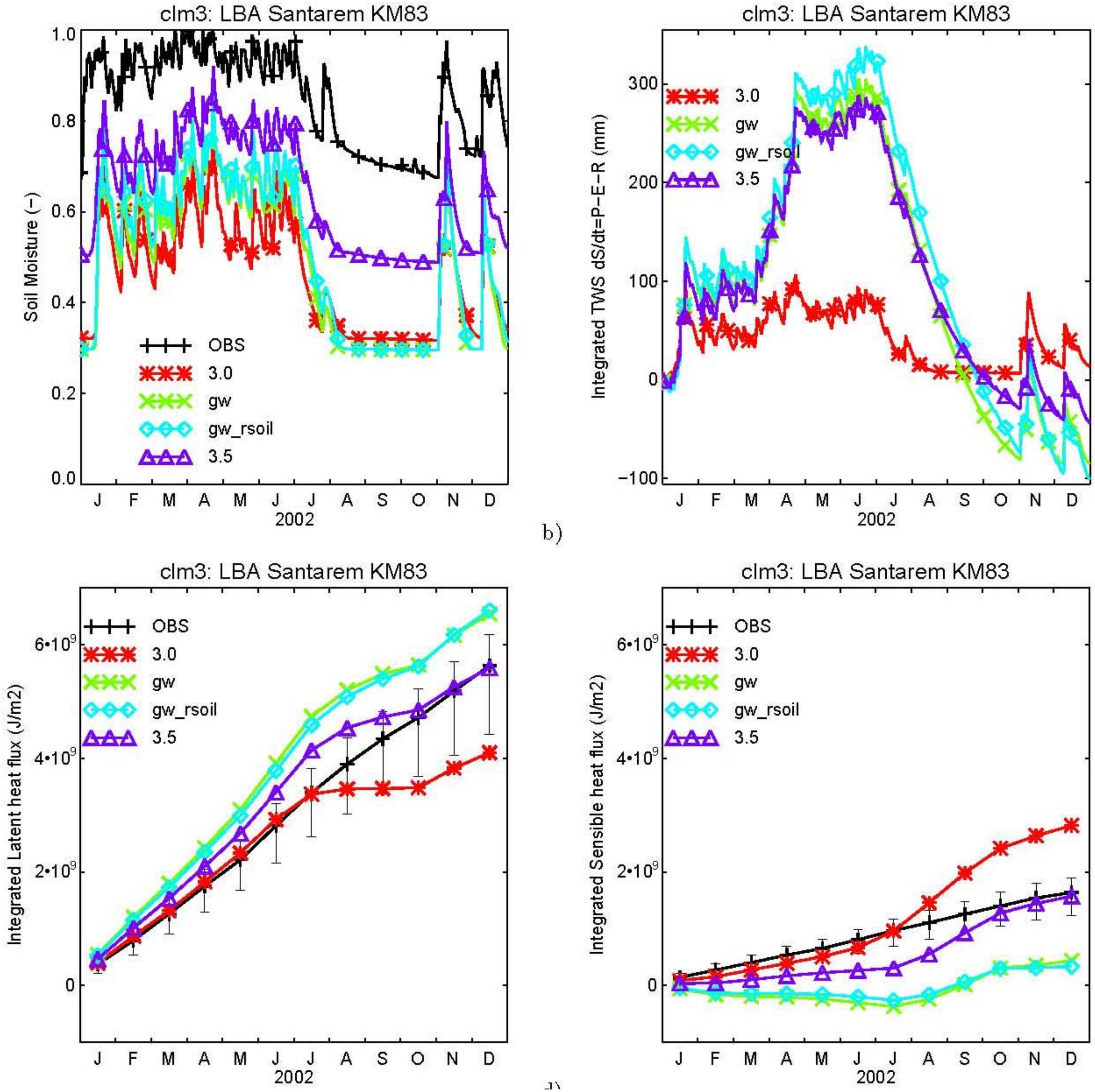
Schaeffer et al. (2006) GBC, doi:10.1029/2005GB002581

# Hydrometeorology

Flux tower observations, tropical evergreen forest, Brazil

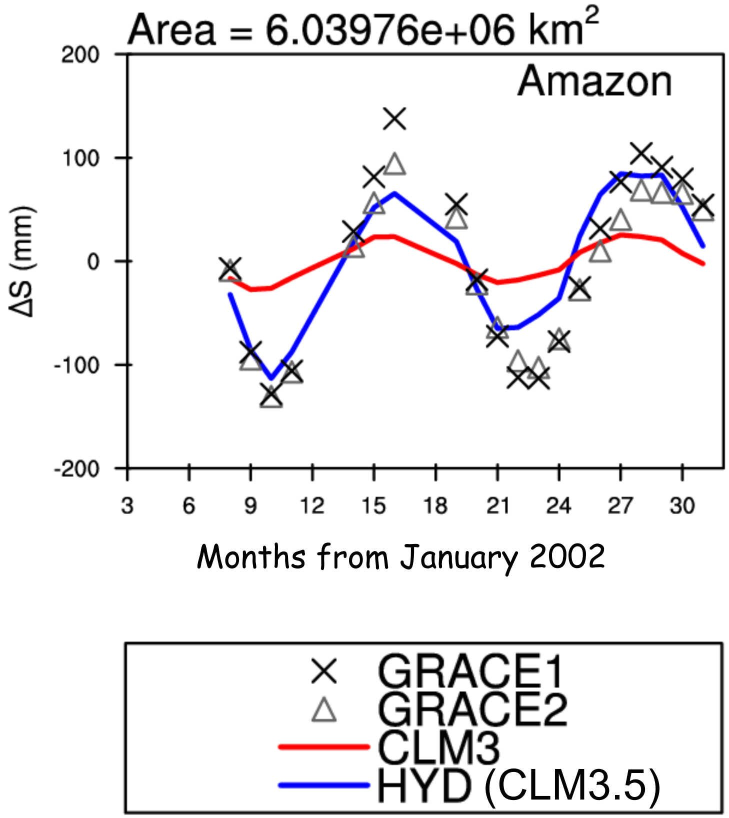
CLM3 – dry soil, low dry season latent heat flux, high dry season sensible heat flux

CLM3.5 – wetter soil and higher latent heat flux during dry season

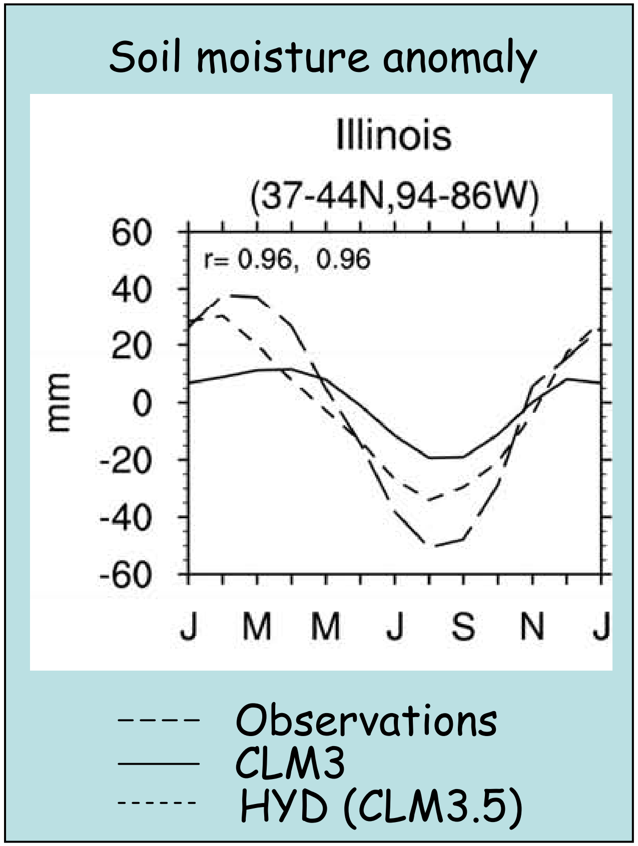


Stöckli et al. (2008) JGR, doi:10.1029/2007JG000562

# Hydrologic cycle



Soil moisture anomaly



Observations – Large annual cycle in soil moisture storage

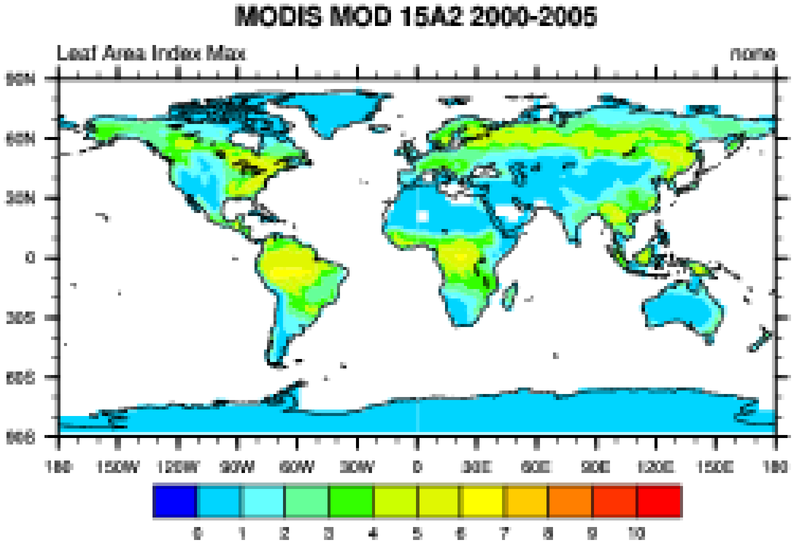
CLM3 – Small change in soil moisture storage

CLM3.5 – Better reproduces observations

Oleson et al. (2008) JGR, doi:10.1029/2007JG000563

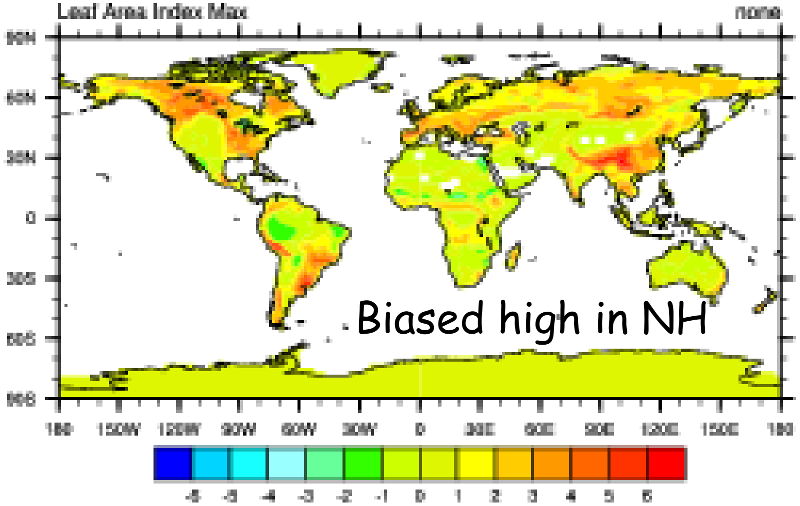
# Improved leaf area index bias

Better hydrologic cycle improves carbon cycle



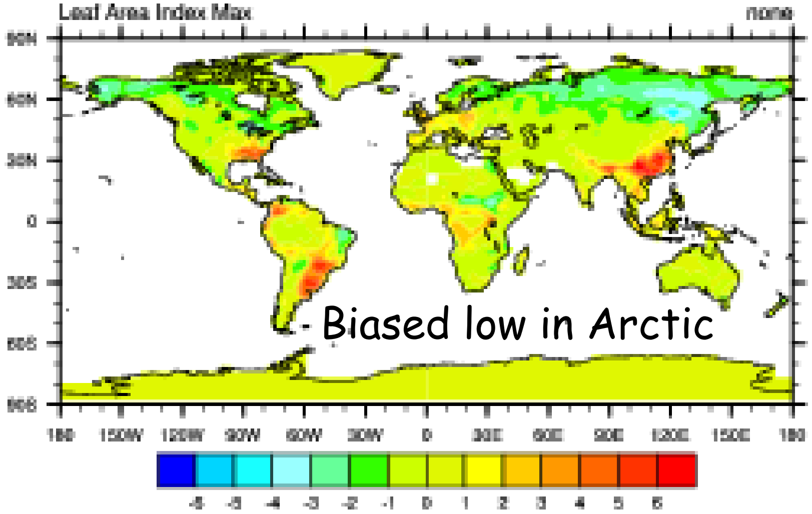
MODIS MOD 15A2 2000-2005

CLM3.5 - MODIS



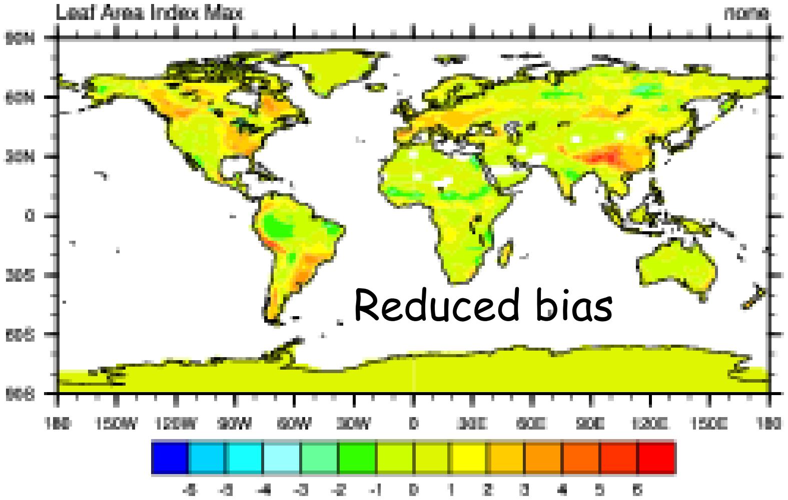
Biased high in NH

CLM3.1 - MODIS



Biased low in Arctic

CLM3.6 - MODIS

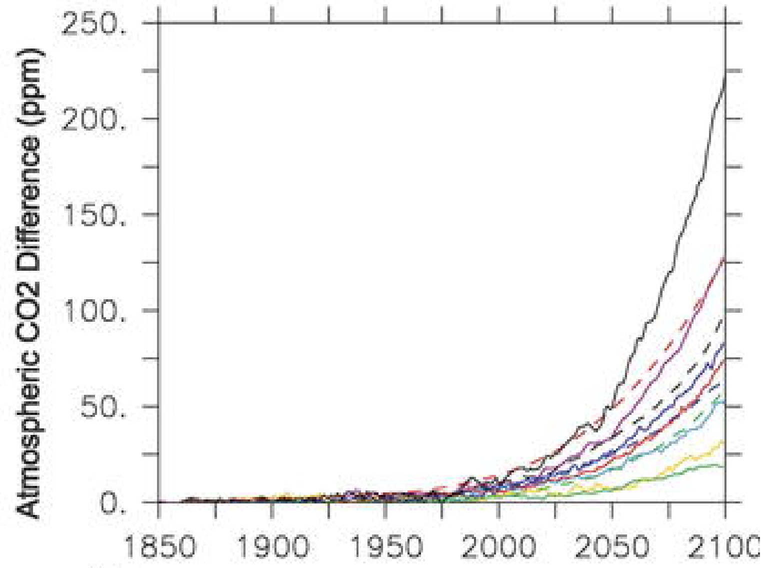


Reduced bias

Thornton et al., unpublished

# C4MIP – Climate and carbon cycle

Effect of climate change on carbon cycle

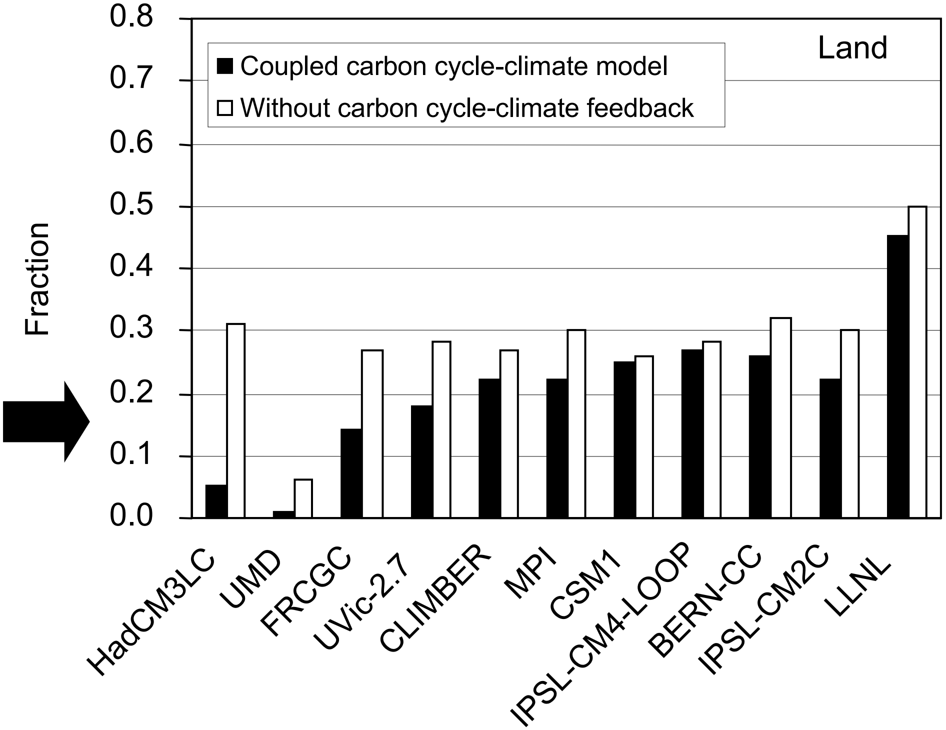


**Climate-carbon cycle feedback**

All models have a positive climate-carbon cycle feedback. The difference between fully coupled carbon cycle climate simulations and uncoupled simulations ($CO_2$ has no radiative effect) ranges from 20 ppm to >200 ppm

**Distribution at 2100 of cumulative anthropogenic carbon emissions**

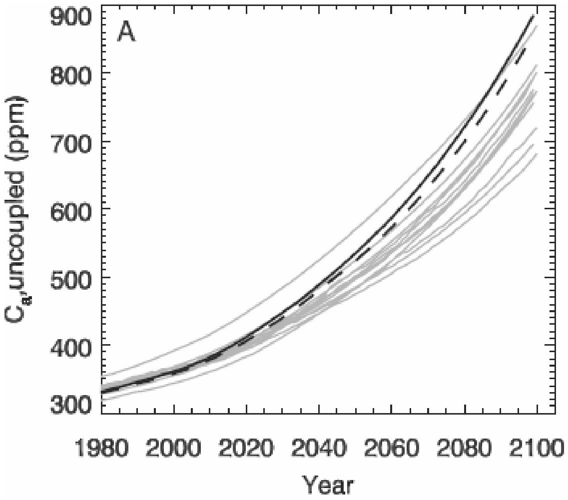
The amount of carbon stored in the atmosphere increases in each model compared with the comparable simulation without climate-carbon cycle feedback, while the land carbon storage decreases.



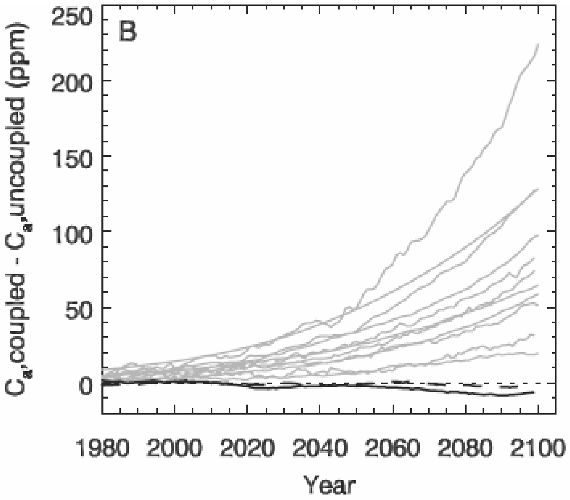
Friedlingstein et al. (2006) J. Climate 19:3337–3353

# Climate, carbon, and nitrogen cycle

Ca from uncoupled experiments

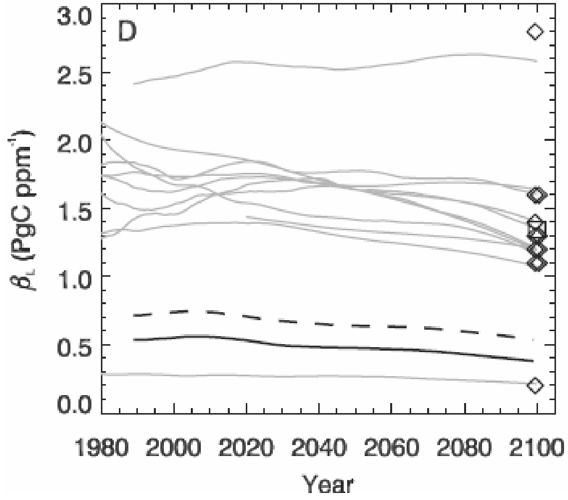


∆Ca due to radiative coupling

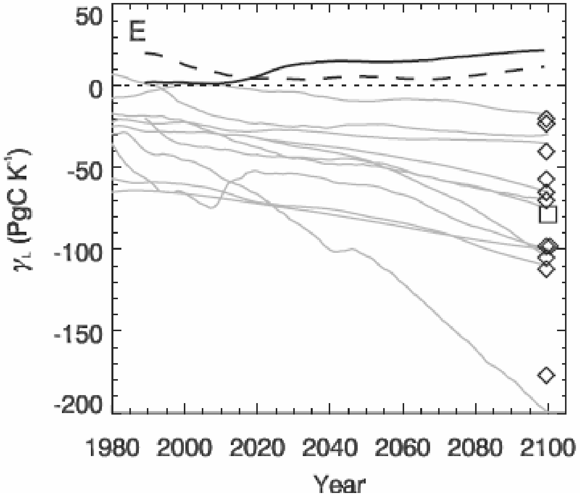


Panel A: Atmospheric $CO_2$ (Ca) of 884 ppm by 2100, radiatively-uncoupled

Panel B: Radiative coupling reduces Ca by 6 ppm, with a further reduction of 27 ppm due to anthropogenic N deposition



Land biosphere response to increasing atmospheric $CO_2$



Land biosphere response to increasing temperature

Gray lines show archived results from eleven previous studies

Thick solid line is for CLM with preindustrial N deposition

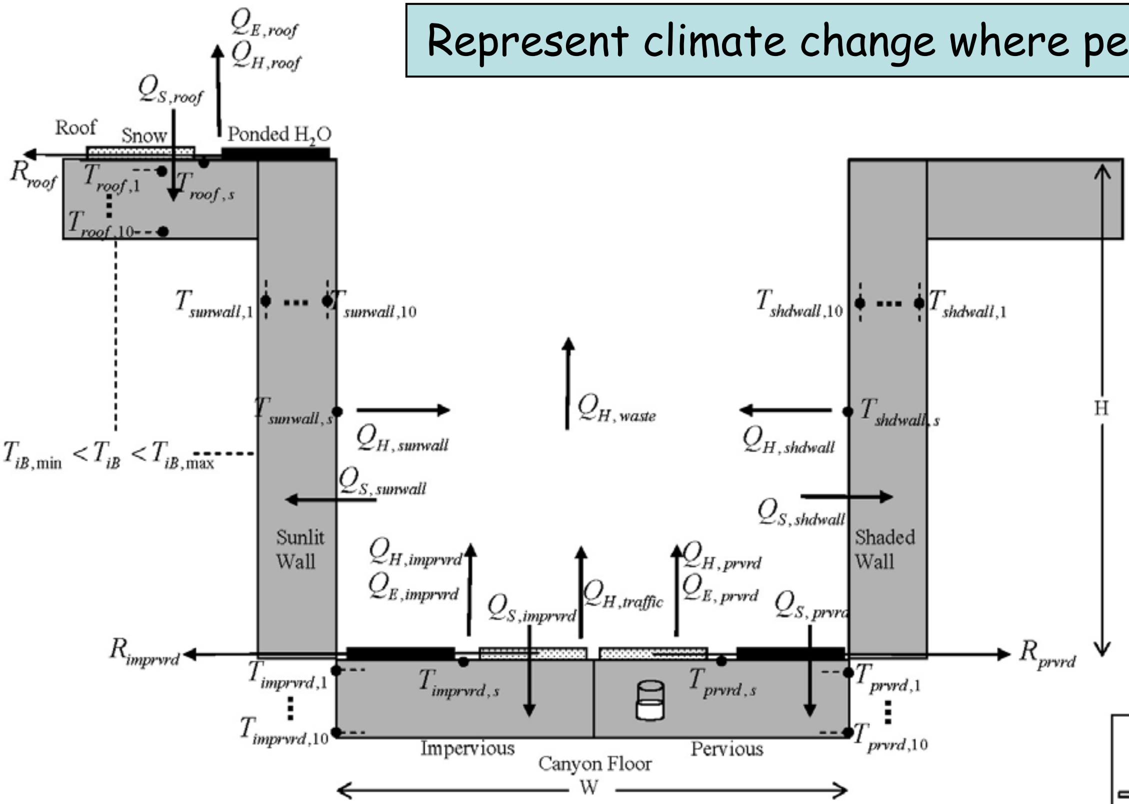
Thick dashed line is for CLM with anthropogenic N deposition

——— low Ndep
– – – – – high Ndep

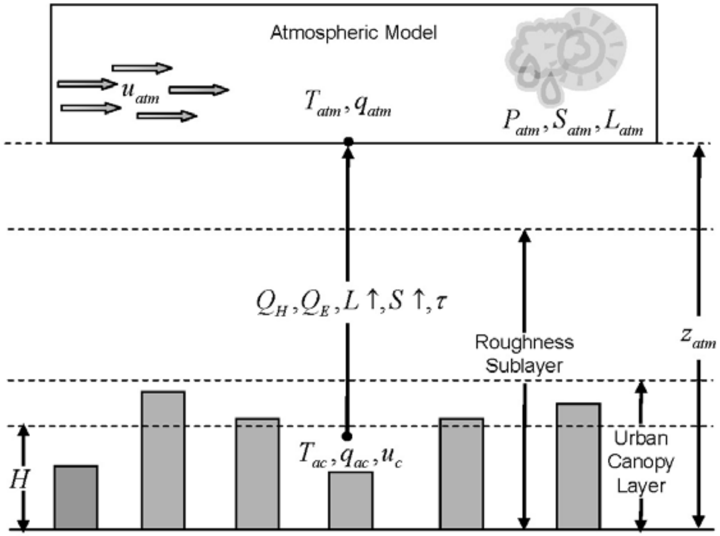
Thornton et al., unpublished

# Urban systems

Represent climate change where people live



Urban canyon

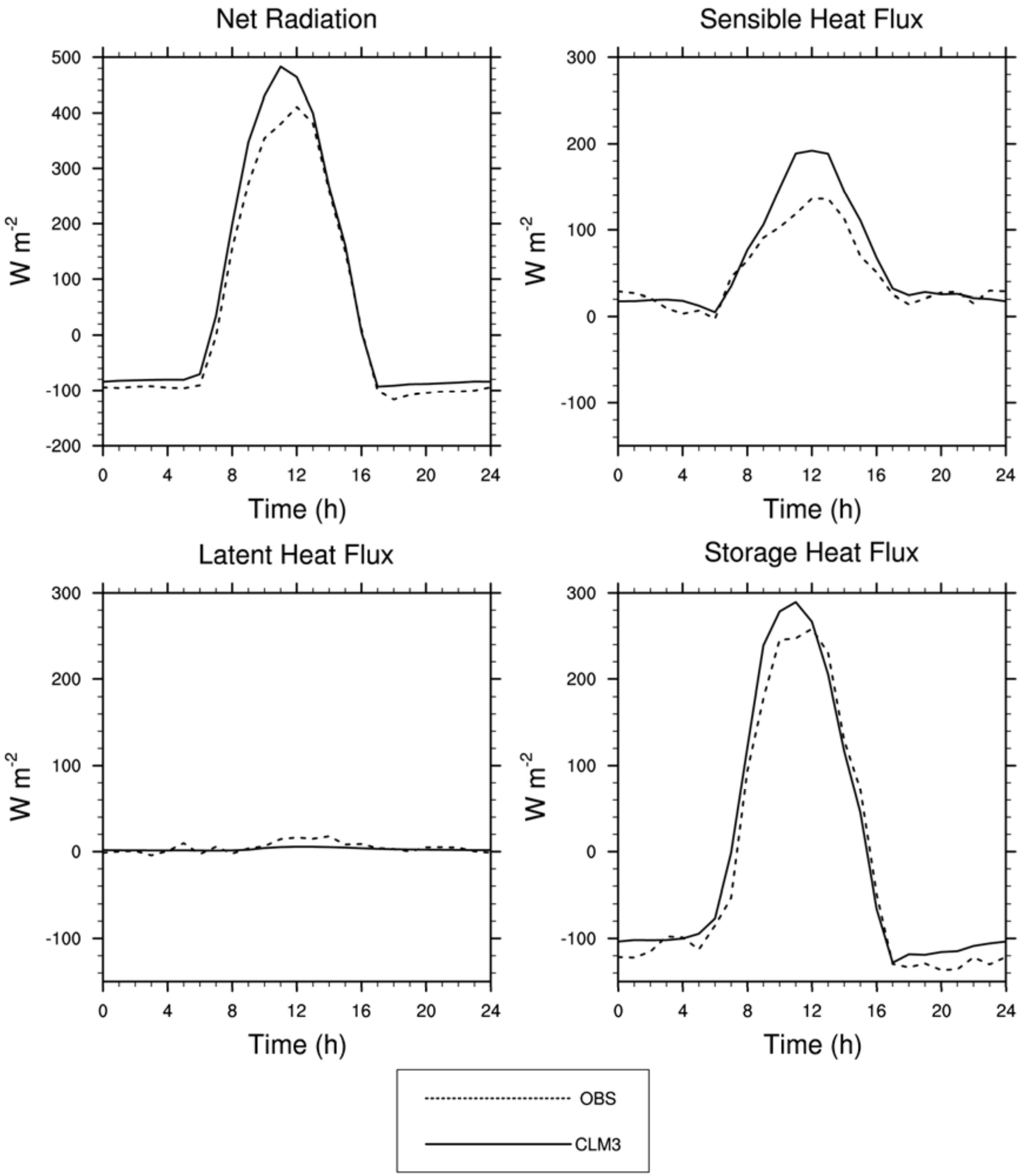


Energy fluxes are modeled for an idealized urban canyon. Key model parameters are:

H/W – ratio of building height and street width
$W_{roof}$ – fractional roof area
$f_{pervious}$ – fractional greenspace
Building materials – thermal and radiative properties

Oleson et al. (2008) J. Appl. Meteor. Climatol., in press

# Simulated urban energy balance



Average diurnal cycle of simulated and observed heat fluxes for the Mexico City site (Me93) for 2-7 Dec 1993

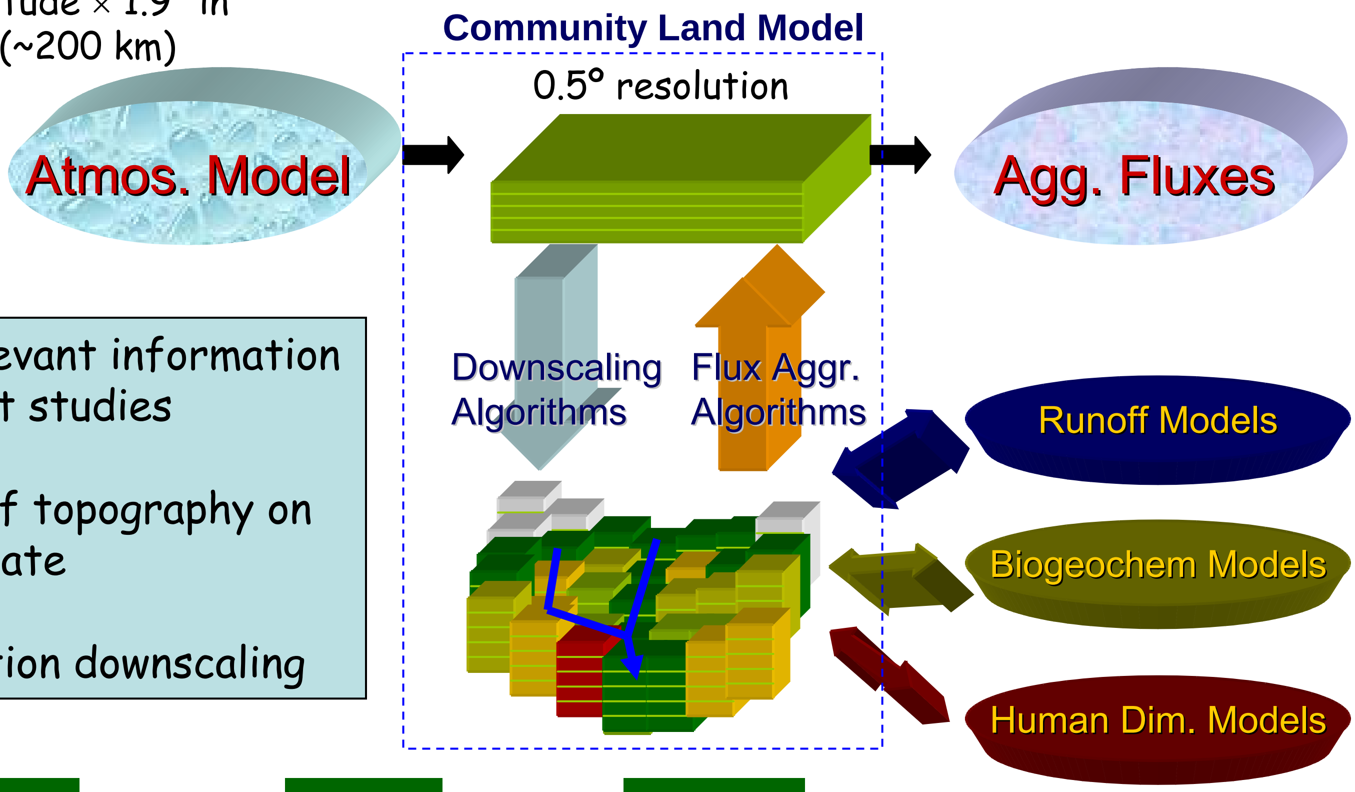
**Key features**

- Diurnal cycle is well represented
- Simulated net radiation is too high (model ignores pollution), which drives high sensible heat
- Negligible latent heat flux
- Large storage heat flux

Oleson et al. (2008) J. Appl. Meteor. Climatol., in press

# Fine-mesh Community Land Model

2.5° in longitude × 1.9° in latitude (~200 km)



**Community Land Model**

0.5° resolution

Atmos. Model

Agg. Fluxes

Downscaling Algorithms

Flux Aggr. Algorithms

Runoff Models

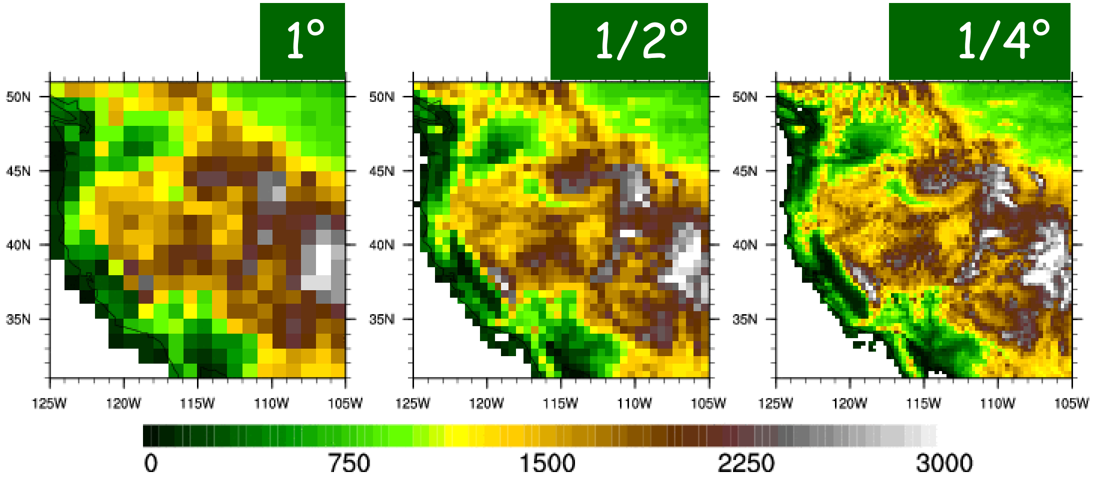
Biogeochem Models

Human Dim. Models

Scale-relevant information for impact studies

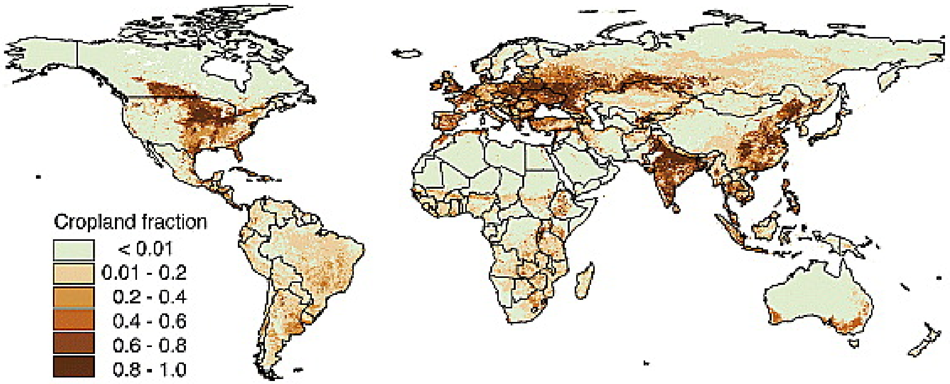
Effects of topography on hydroclimate

Precipitation downscaling



Hahmann & Dickinson (2001) J. Climate 14:1634-1646
Gochis, Hahmann et al., unpublished

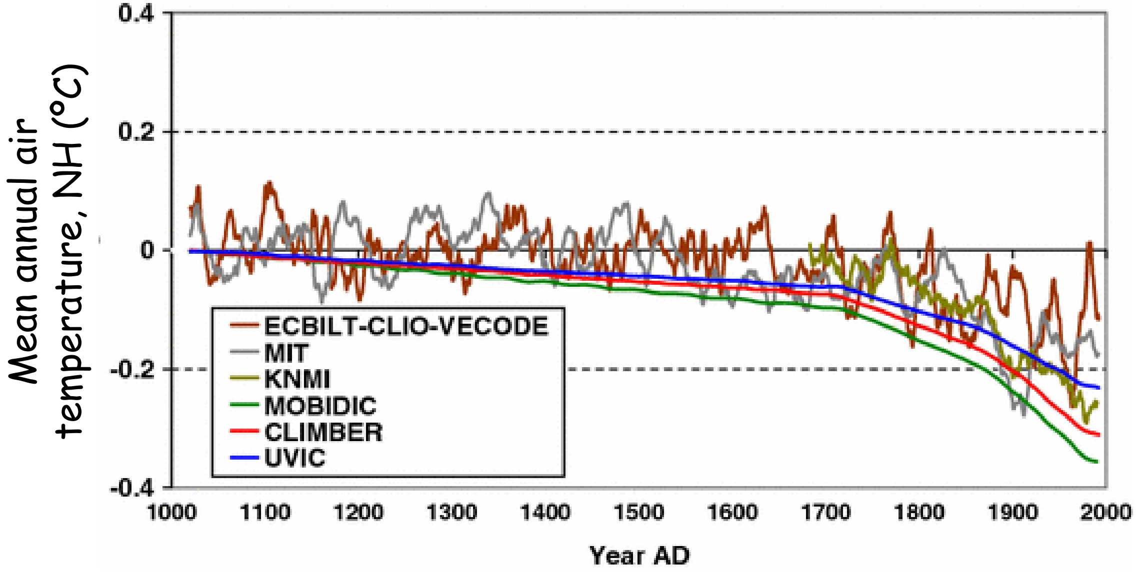
# Historical land use forcing of climate



The emerging consensus is that land cover change in middle latitudes has cooled the Northern Hemisphere (primarily because of higher surface albedo in spring)

Northern Hemisphere annual mean temperature decreases by 0.19 to 0.36 °C relative to the pre-industrial era

Comparison of 6 EMICs forced with historical land cover change, 1000-1992



Brovkin et al. (2006) Climate Dynamics 26:587-600

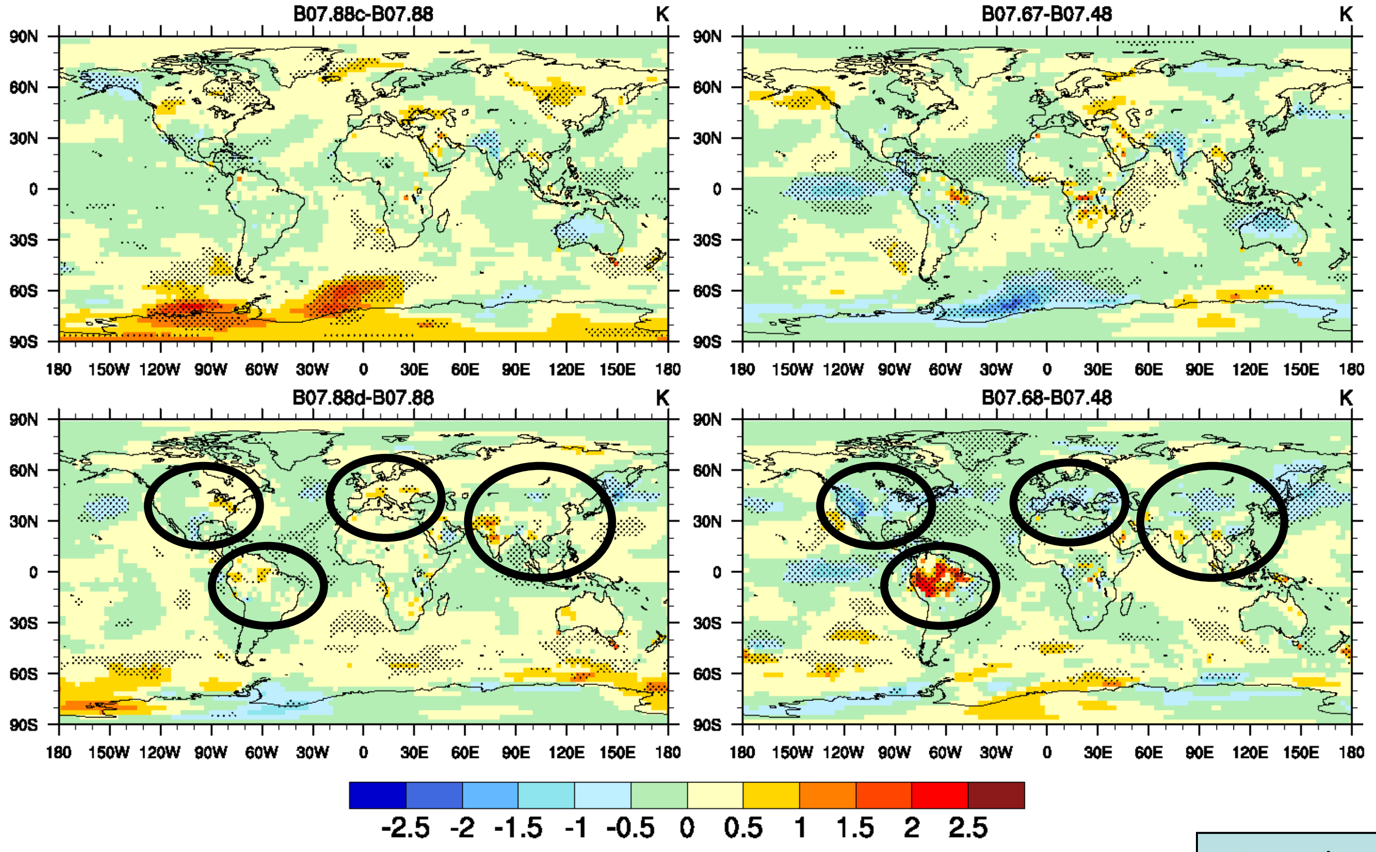
# Future land cover change as a climate forcing

(SRES land cover + SRES atmospheric forcing) - SRES atmospheric forcing

SRES B1 JJA reference height temperature SRES A2

2050

2100



A2 – Widespread agricultural expansion with most land suitable for agriculture used for farming by 2100 to support a large global population

B1 - Loss of farmland and net reforestation due to declining global population and farm abandonment in the latter part of the century

Land use choices affect climate

Feddema et al. (2005) Science 310:1674-1678

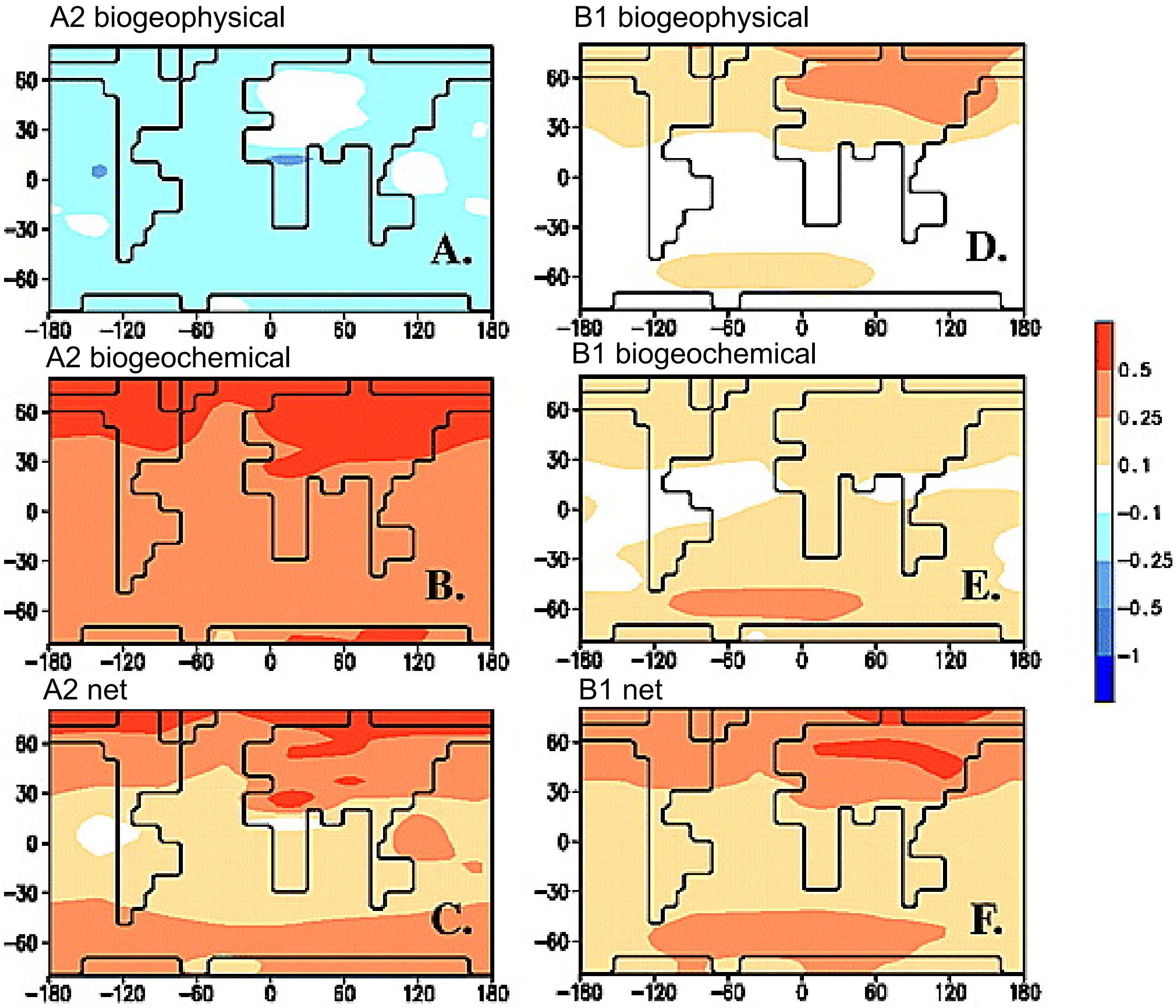
# Integrated biogeophysical and carbon effects

**Biogeophysical**
*A2 – cooling with widespread cropland*
*B1 – warming with temperate reforestation*

**Biogeochemical**
*A2 – large warming; widespread deforestation*
*B1 – weak warming; less tropical deforestation, temperate reforestation*

**Net effect similar**
*A2 – BGC warming offsets BGP cooling*
*B1 – moderate BGP warming augments weak BGC warming*

Land cover change impact on 2100 climate



Sitch et al. (2005) *GBC*, doi:10.1029/2004GB002311

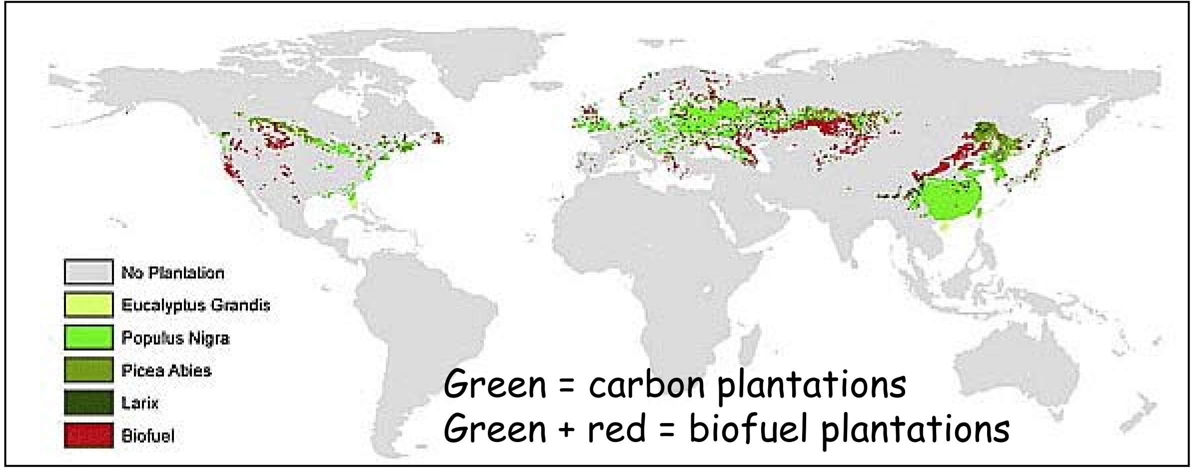
# Land management policies to mitigate climate change

Reforestation might be chosen as an option for the enhancement of terrestrial carbon sequestration or biofuel plantations may be used as a substitute for fossil fuels

Ethanol from maize

Hybrid poplar plantation

2100 land management, IPCC A1B scenario



Green = carbon plantations
Green + red = biofuel plantations

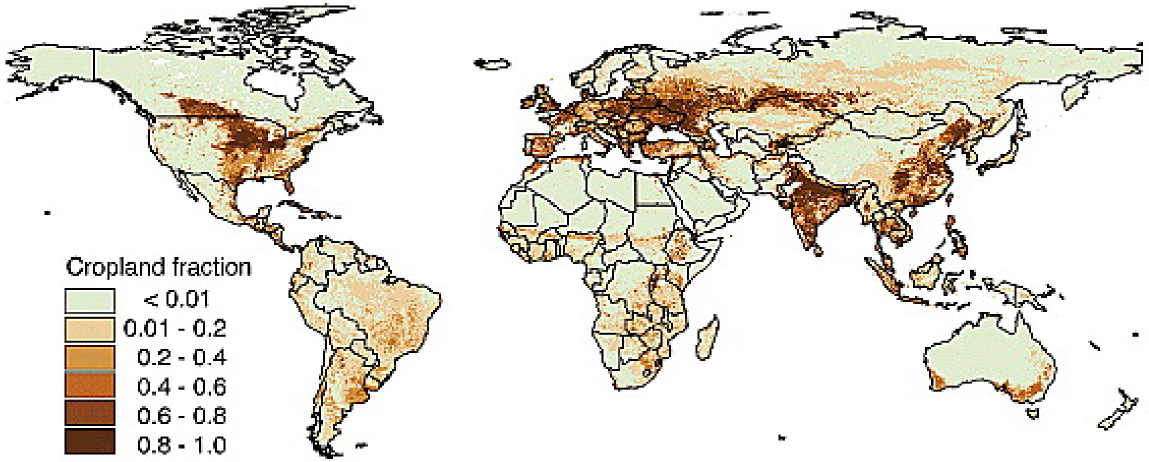
Excess agricultural land converted to carbon storage or biofuels

Carbon plantations and biofuel plantations reduce atmospheric $CO_2$, leading to cooling

Reduced surface albedo leads to warming, but carbon plantations have lower albedo than biofuels

Schaeffer et al. (2006) GBC, doi:10.1029/2005GB002581

# Multi-model ensemble of global land use climate forcing



**Models**
Atmosphere - CAM3 and CAM3.5 (differ in convection, PBL, and clouds)
Land - CLM3.5
Ocean - Prescribed SSTs and sea ice

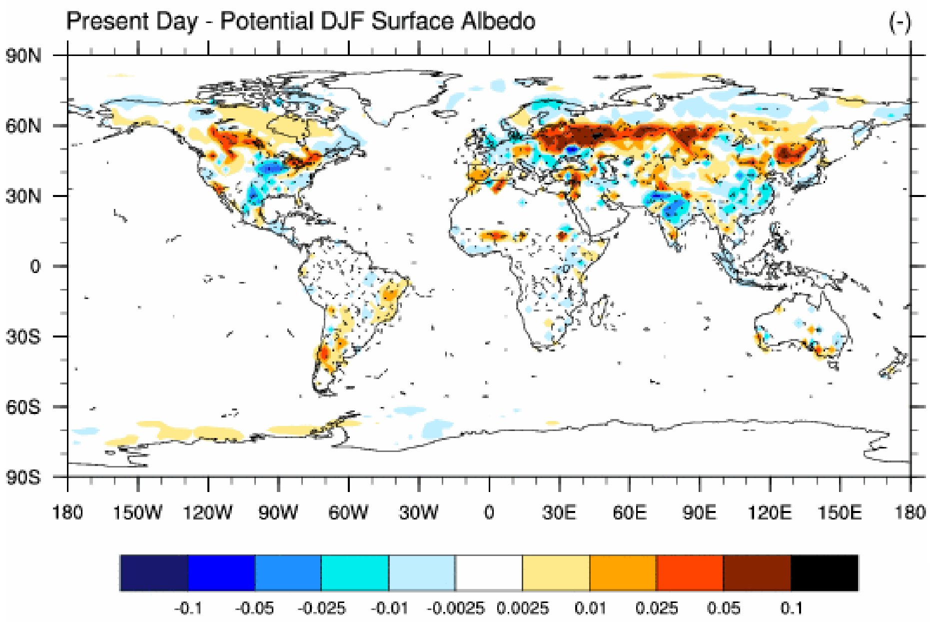
**Experiments**
30-year simulations (using SSTs for the period 1972-2001)
Two land covers: present-day vegetation and potential vegetation
5-member ensembles

Total of 20 simulations and 600 model years

Its not just albedo. The hydrologic cycle affects the land use forcing.

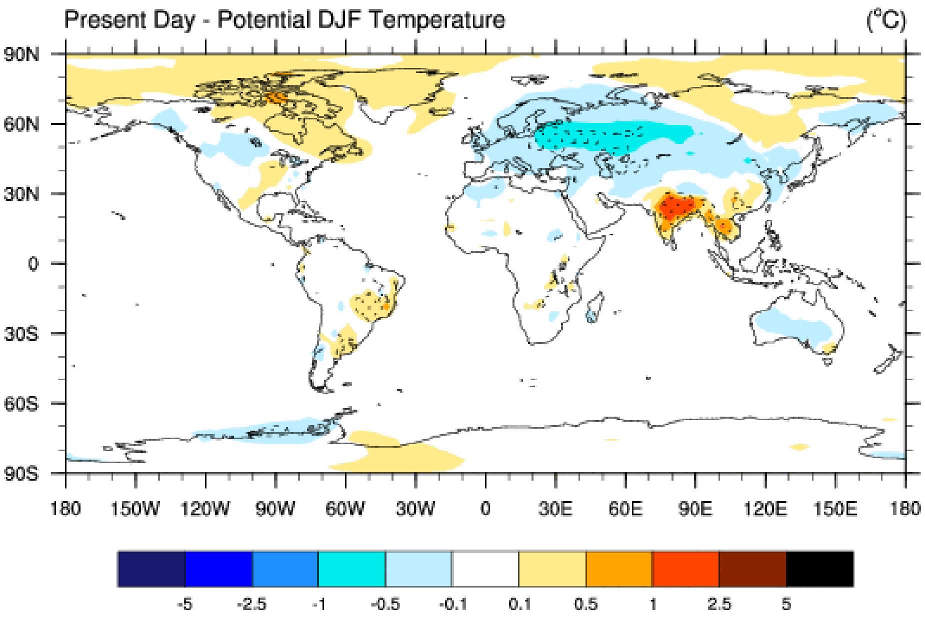
Bonan et al., unpublished

# Vegetation-snow albedo feedback



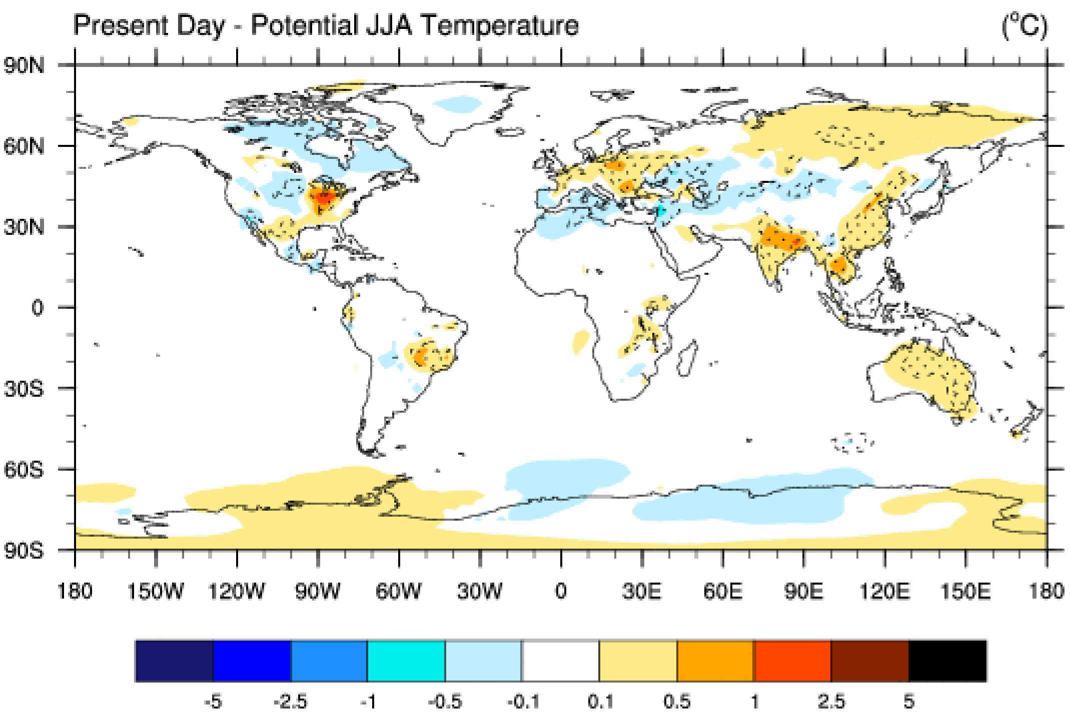
CAM3/CLM3.5 ensemble average

Increased surface albedo leads to surface cooling



Bonan et al., unpublished

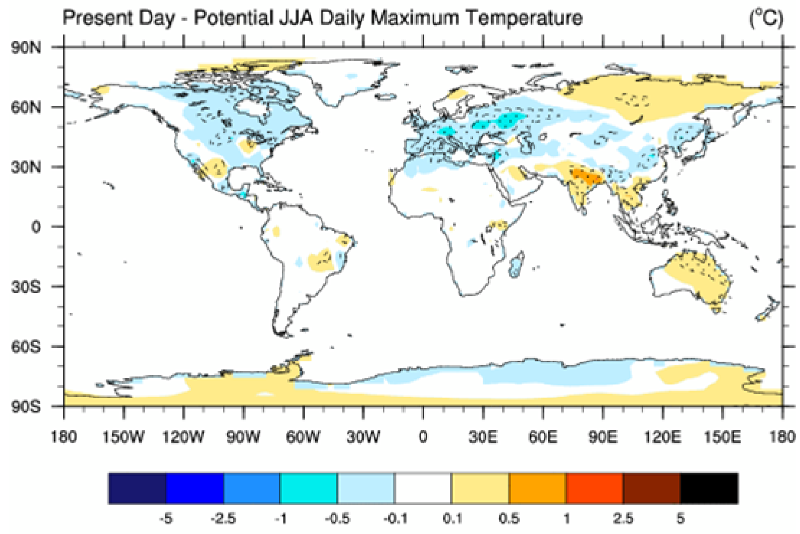
# Mid-latitude summer

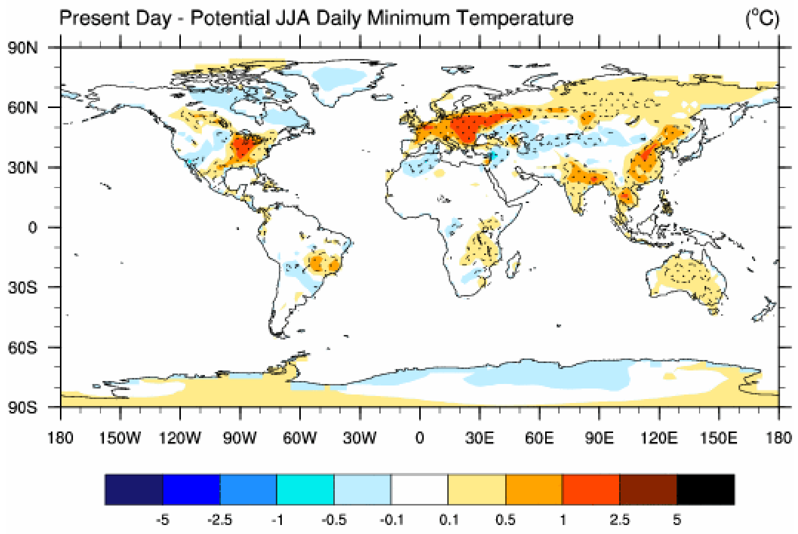

Present Day - Potential JJA Temperature

CAM3/CLM3.5 ensemble average

Decrease in daily maximum temperature is offset by increase in daily minimum temperature

Importance of feedbacks with clouds and precipitation


Present Day - Potential JJA Daily Maximum Temperature


Present Day - Potential JJA Daily Minimum Temperature

Bonan et al., unpublished

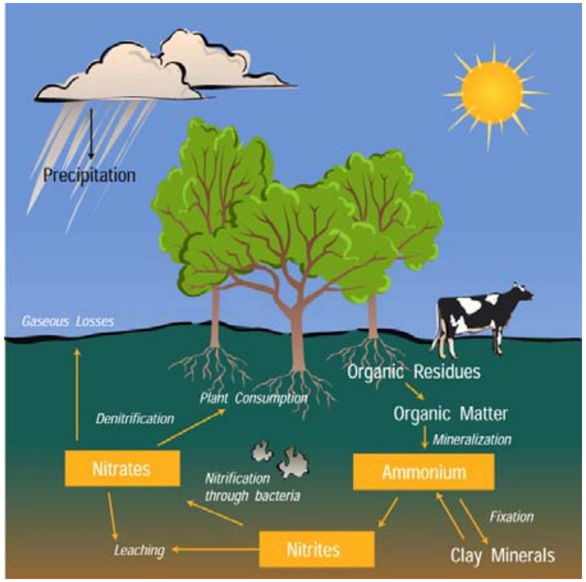
# Biofuels – research needs

Maize/Poplar/Switchgrass

Carbon cycle
Crop management
Land cover change

## Nitrogen cycle

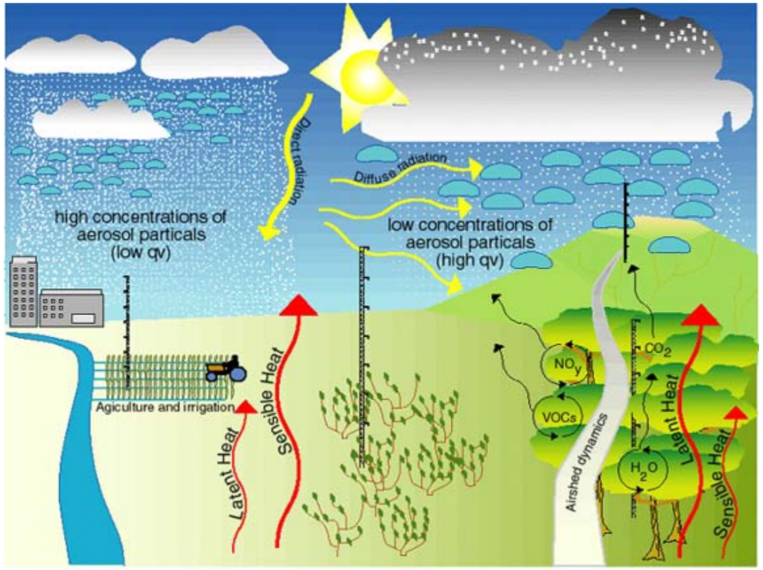
Beth Holland, NCAR



## Water systems

Center pivot irrigation, northern California

## Aerosols and biogenic emissions



BEACCHON project, NCAR

# How to integrate ecological studies with earth system models?

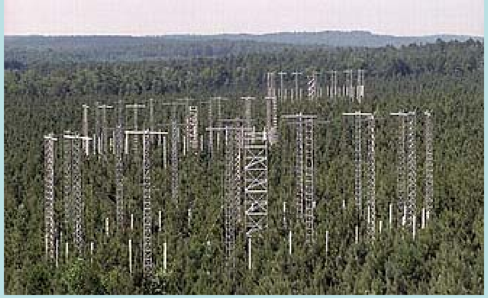
## Environmental Monitoring

Eddy covariance flux tower
(courtesy Dennis Baldocchi)

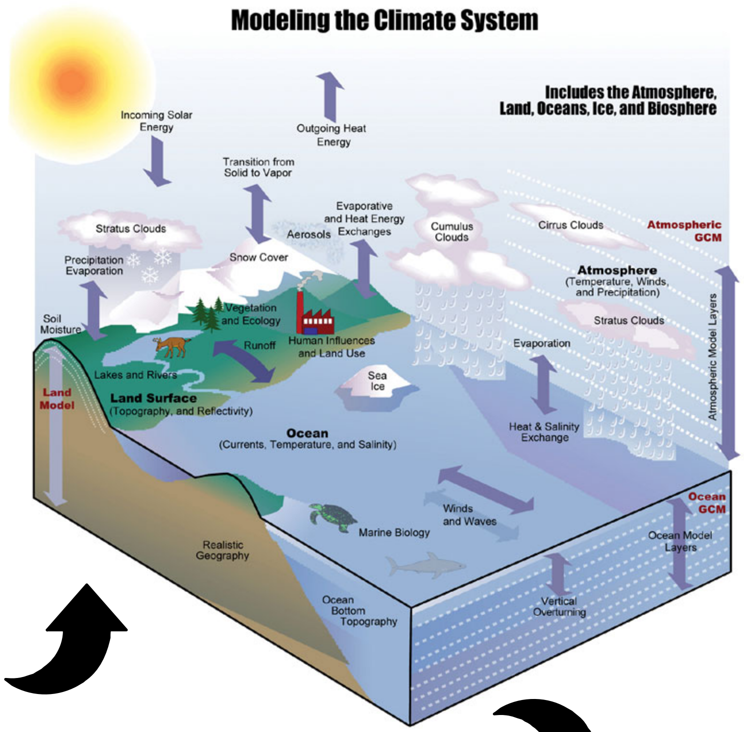
Hubbard Brook
Ecosystem Study

## Experimental Manipulation

Soil warming, Harvard Forest



$CO_2$ enrichment, Duke Forest



Planetary energetics
Planetary ecology
Planetary metabolism

# C-LAMP: Annual net primary production

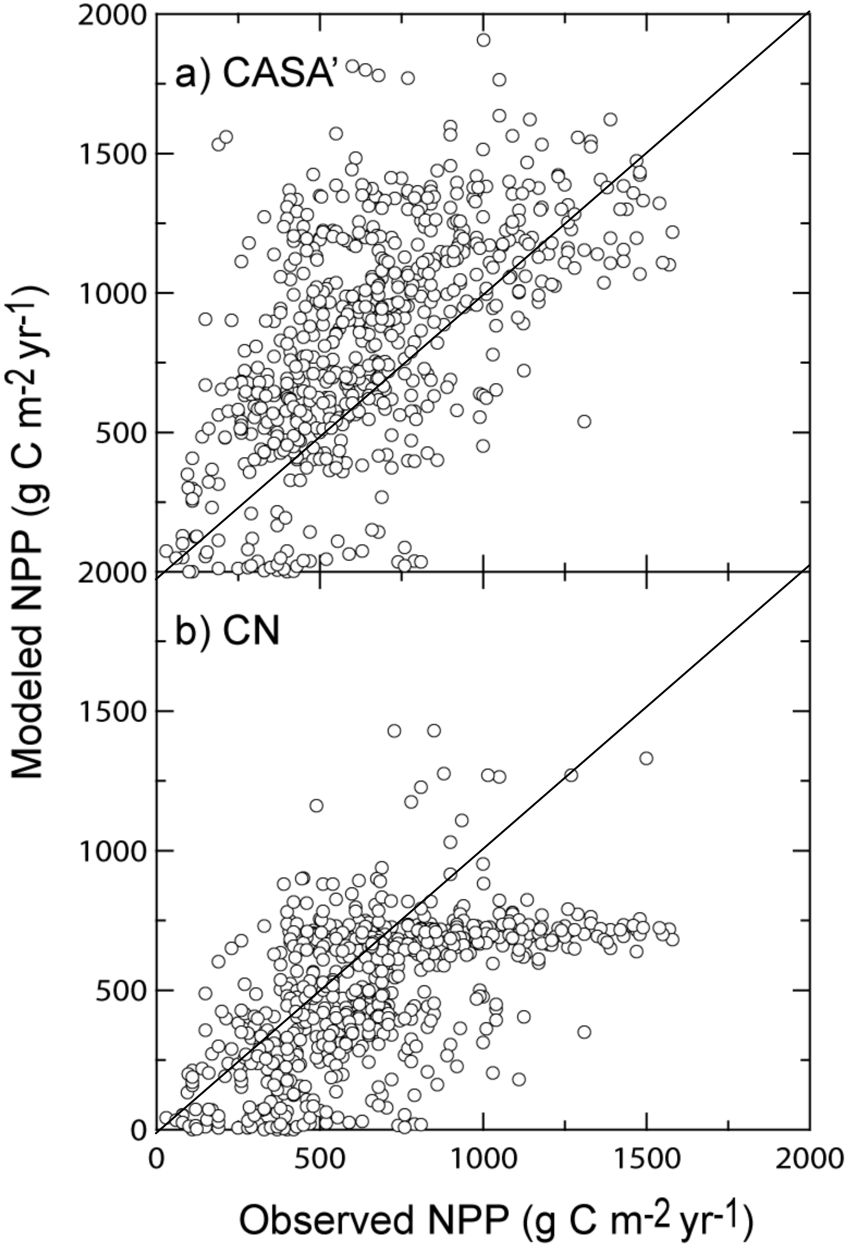
CLAMP is a project of the Community Climate System Model (CCSM) biogeochemistry working group

Ecosystem Model-Data Intercomparison (EMDI) compilation of observations

Class A and Class B observations used

NPP extracted for each model grid cell corresponding to a measurement location

Comparisons are for CLM3 coupled to two biogeochemical carbon models



Randerson et al., BGCWG, unpublished

# Comparison with FACE experiments

| | | | | | CN | | | CASA' | |
|---|---|---|---|---|---|---|---|---|---|
| Experiment | Latitude (°N) | $CO_2$ initial | $CO_2$ final | Initial NPP | final NPP | Beta | Initial NPP | final NPP | Beta |
| DukeFACE | 35.6 | 283.2 | 364.1 | 661 | 733 | 0.43 | 1091 | 1241 | 0.55 |
| AspenFACE | 45.4 | 283.2 | 364.1 | 358 | 397 | 0.43 | 524 | 595 | 0.54 |
| ORNL-FACE | 35.5 | 283.2 | 364.1 | 828 | 901 | 0.35 | 1090 | 1248 | 0.58 |
| POP-EUROFACE | 42.2 | 283.2 | 364.1 | 235 | 253 | 0.30 | 397 | 453 | 0.56 |
| Mean: | | | | | | **0.38** | | | **0.56** |

Observed mean β: **0.60**
CN model mean β: 0.38
CASA' model mean β: 0.56

Observed NPP increase (376 -> 550ppm): 23%
CN predicted (376 -> 550ppm): 14%
CASA' predicted (376 -> 550ppm): 21%

$$\beta = \frac{\left(\frac{NPP(f)}{NPP(i)} - 1\right)}{\ln\left(\frac{CO_2(f)}{CO_2(i)}\right)}$$

$$NPP(t) = NPP(i) \cdot \left[\beta \cdot \ln\left(\frac{CO_2(t)}{CO_2(i)}\right) + 1\right]$$

Randerson et al., BGCWG, unpublished

# Summary

**The land surface is a critical interface through which humans are impacted and can affect climate change**

**Land ESM development:**

- **Expand capability to simulate forcings and feedbacks in earth system**
- **Increased emphasis on suitability for impacts, adaptation, and mitigation research**
- Requires an integrated systems approach:
  - Biogeochemical systems
  - Water systems
  - Ecosystems
  - Human systems
  - Glacier systems

(IPCC 2007)