The Greening Of Land Surface Models

(or, what we have learned about climate-vegetation interactions during ten years of CCSM)

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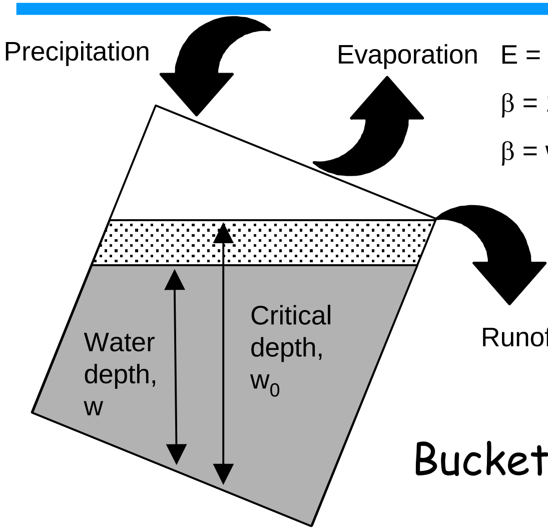
History of land surface models



$E = \beta E_p$

$\beta = 1 \quad$ for $w \geq w_0$

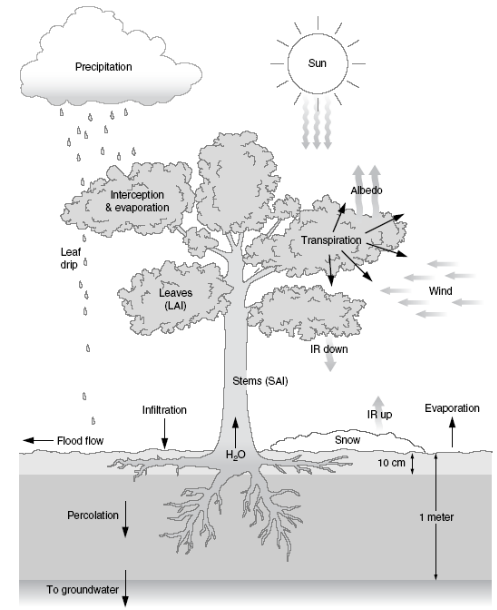
$\beta = w/w_0$ for $w < w_0$

Bucket Model

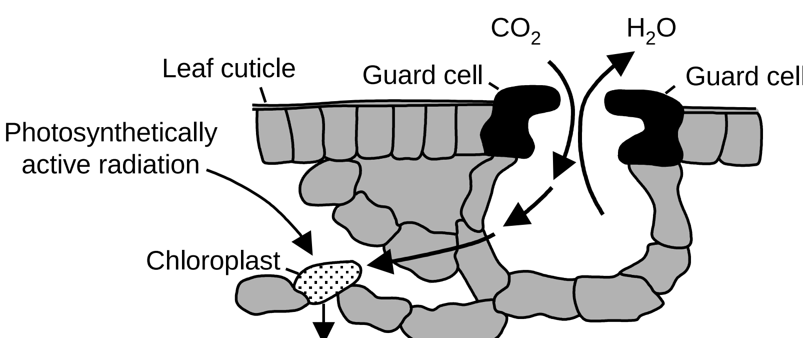
Manabe (1969) Mon Wea Rev 97:739-774
Williamson et al. (1987) NCAR/TN-285+STR

Vegetation and Hydrologic Cycle

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



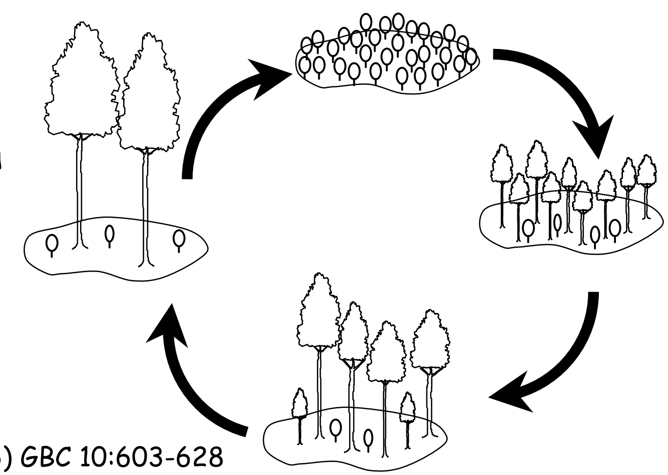
Stomatal Gas Exchange



$$CO_2 + 2\,H_2O \xrightarrow{\text{light}} CH_2O + O_2 + H_2O$$

Bonan (1995) JGR 100:2817-2831
Denning et al. (1995) Nature 376:240-242
Denning et al. (1996) Tellus 48B:521-542, 543-567

Dynamic Vegetation



Foley et al. (1996) GBC 10:603-628
Levis et al. (1999) JGR 104D:31191-31198
Levis et al. (2000) J Climate 13:1313-1325
Cox et al. (2000) Nature 408:184-187

Scales and types of vegetation interactions

Ecological processes affect climate at a variety of scales:

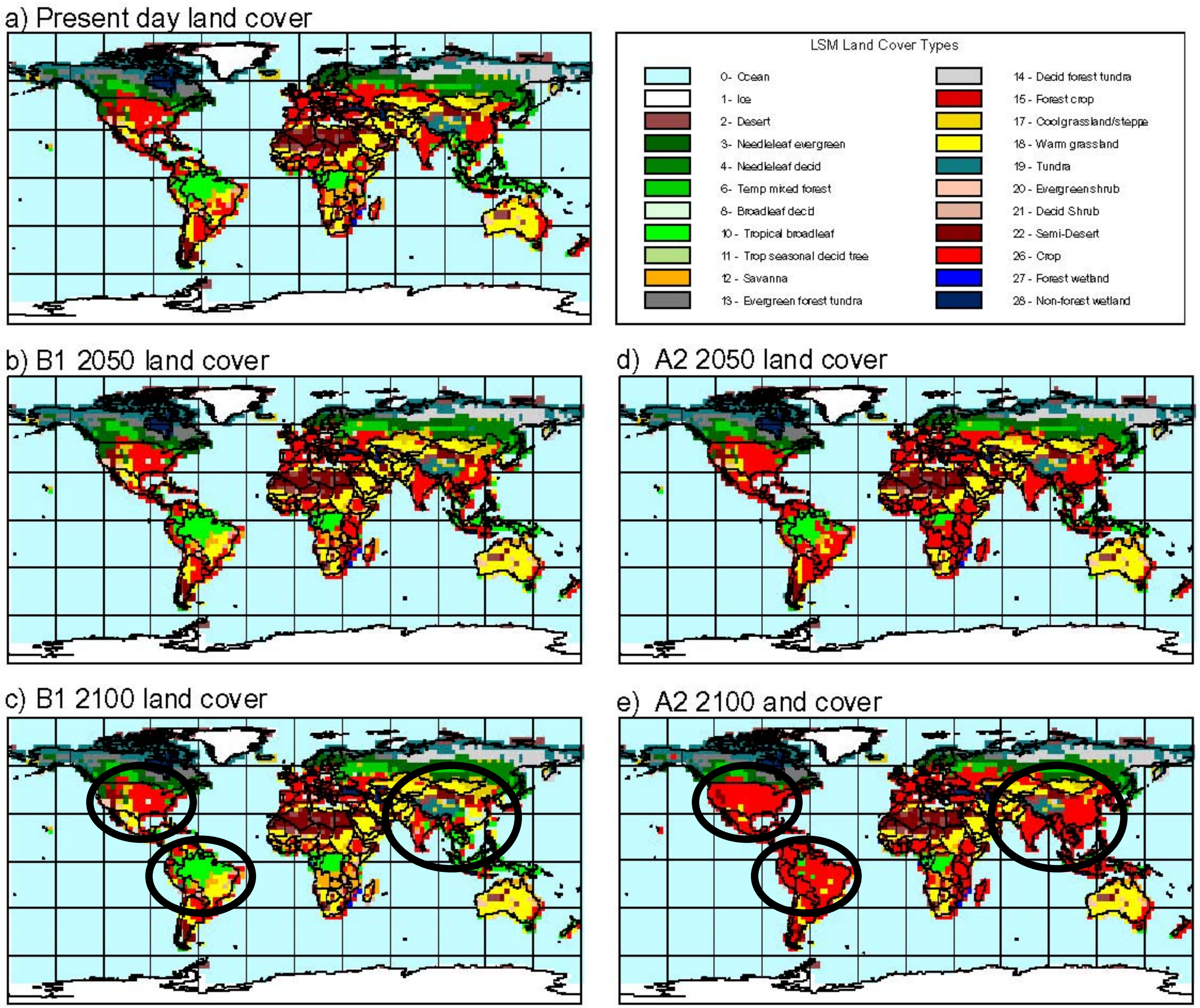
Minutes-to-hours	**Stomata** – Pores on leaf surfaces that open to allow CO_2 uptake during photosynthesis. In doing so, water is lost from the plant during transpiration
Seasonal-to-interannual	**Phenology** – The seasonal emergence and senescence of foliage
Decades-to-centuries	**Succession** – Growth and development of vegetation, typically following fire, timber harvesting, or farm abandonment
	Land use – Clearing of natural vegetation (typically forest or grassland) for agricultural uses
Centuries-to-millennia	**Biogeography** – Changes in geographic distribution of vegetation in response to climate change

These affect climate through **biogeochemical** processes (e.g., CO_2) and through **biogeophysical** processes that affect radiative forcing, turbulent fluxes, and the hydrologic cycle

The carbon cycle, for example, has direct effects on climate (atmospheric CO_2) and indirect effects (e.g., by changing leaf area)

Land cover change as a climate forcing

Future IPCC SRES Land Cover Scenarios for NCAR LSM/PCM



Forcing arises from changes in

Community composition
Leaf area
Height [surface roughness]
↓
Surface albedo
Turbulent fluxes
Hydrologic cycle

Also alters carbon pools and fluxes, but most studies of land cover change have considered only biogeophysical processes

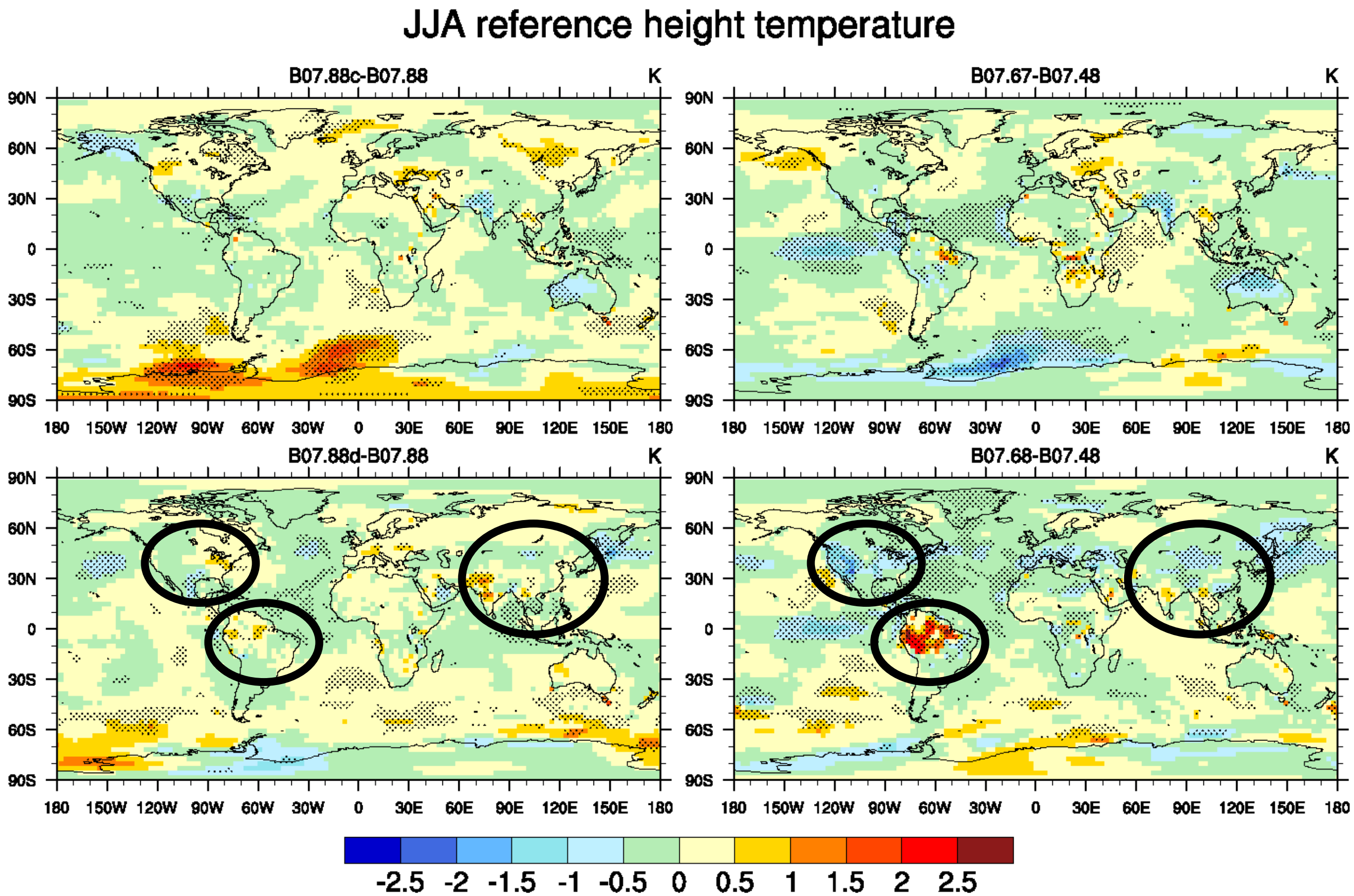
Feddema et al., unpublished

Land use climate forcing

SRES B1 SRES A2

2050

2100



<u>Dominant forcing</u>

Brazil – albedo, E

U.S. – albedo

Asia - albedo

PCM/NCAR LSM transient climate simulations with changing land cover. Figures show the effect of land cover on temperature

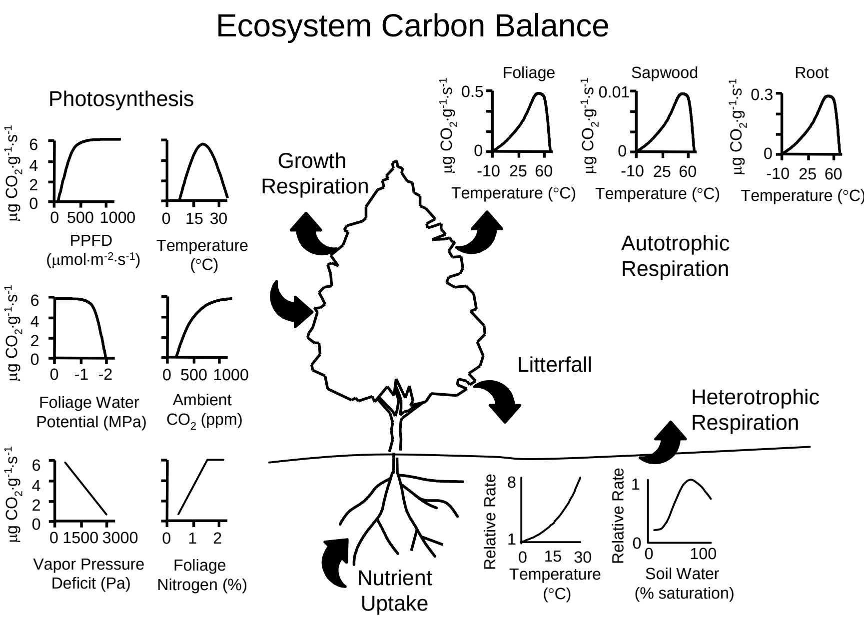
(SRES land cover + SRES atmospheric forcing) - SRES atmospheric forcing

Feddema et al., unpublished

Vegetation dynamics

Two classes of models

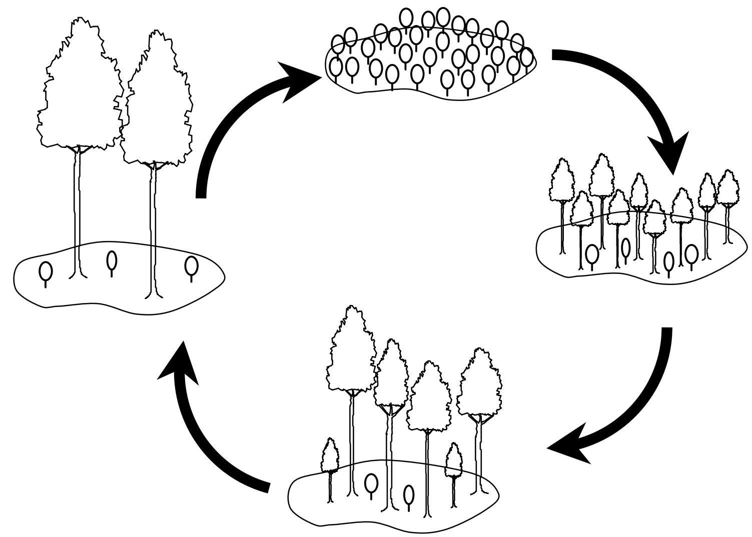
Biogeochemical model



Simulates carbon cycle. Carbon pools vary over time so that, e.g., leaf area and height [roughness] change with time. May include other BGCs (e.g., nitrogen) and fire. Uses prescribed biogeography (i.e, type of vegetation is time invariant)

CLM3-CASA' and CLM3-CN to study biogeochemical coupling with atmosphere

Dynamic global vegetation model

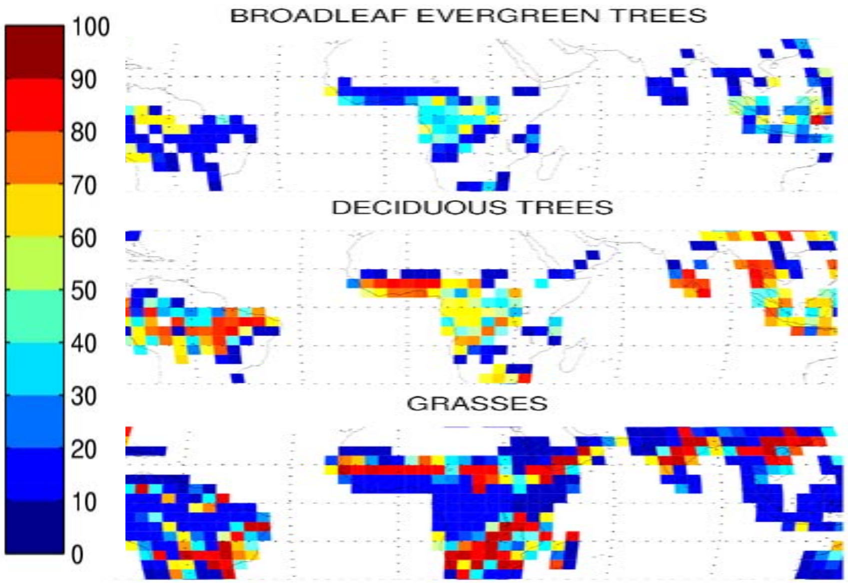


As in BGC model, but allows plant community composition to change over time (e.g., forest changes to grassland)

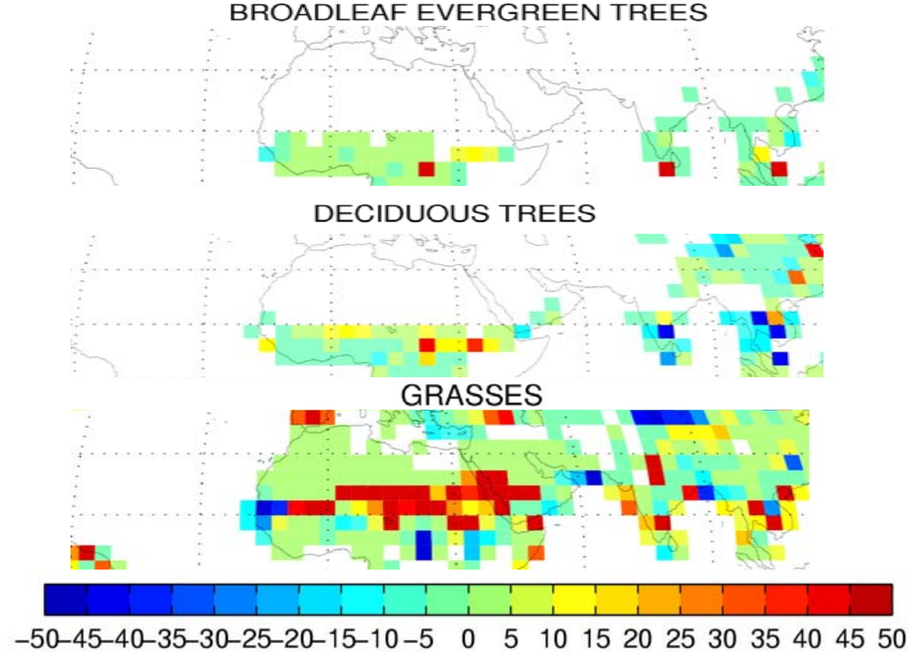
CLM3-DGVM used to study biogeophysical coupling with atmosphere.

Greening of North Africa

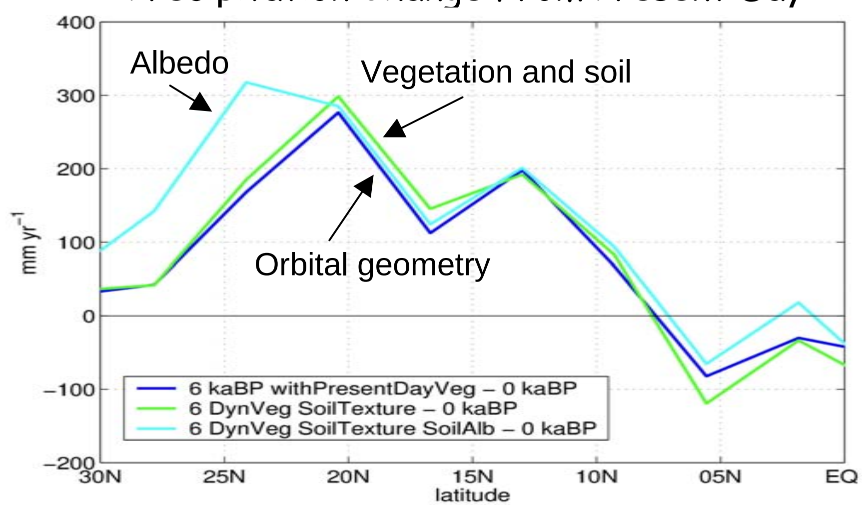
Present Day Biogeography
(percent of grid cell)



6kaBP DynVeg Soil Texture – 0 kaBP



Precipitation Change From Present Day

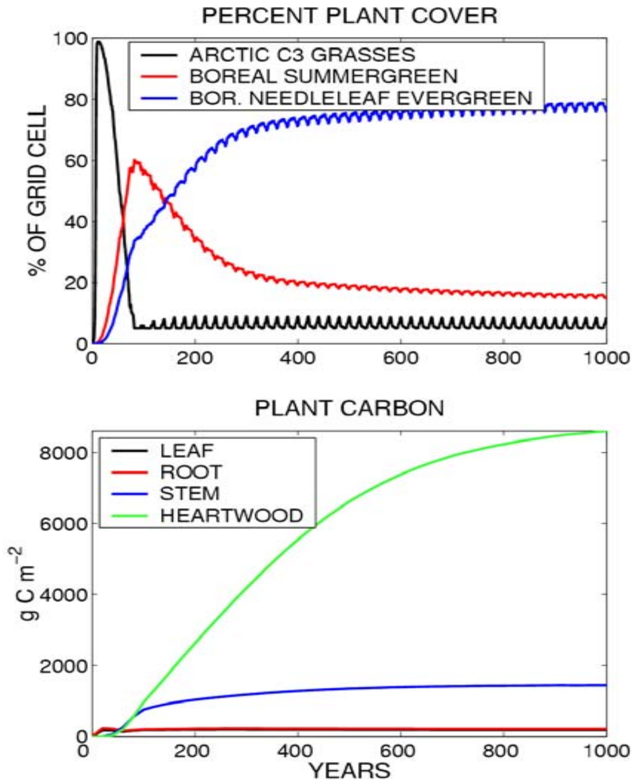


Dominant forcing
Increase in evaporation
Decrease in soil albedo

Levis et al. (2004) Clim Dyn 23:791-802

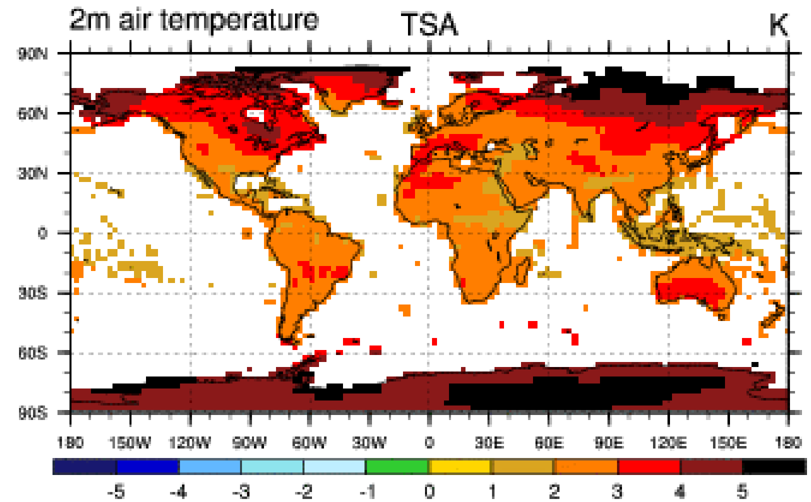
Boreal forest expansion

One Grid Cell In Canada

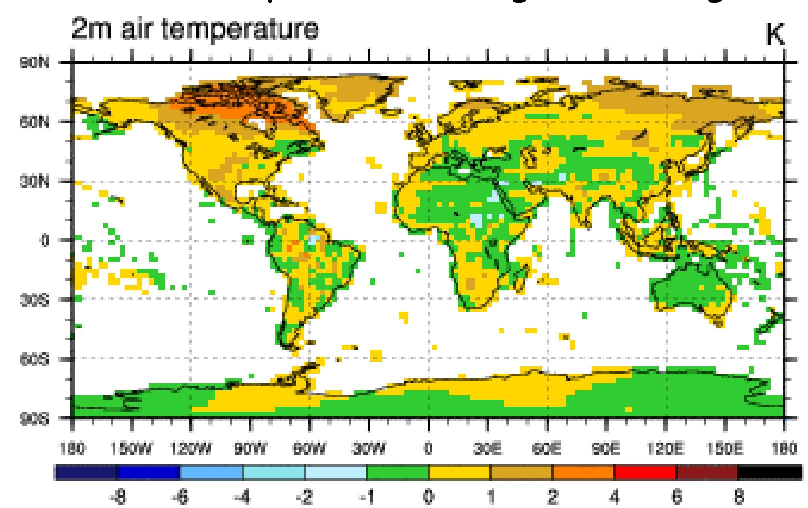


Bonan et al. (2003) Global Change Biology 9:1543-1566

Mean Annual Temperature (2×CO_2)



Additional Temperature Change With Vegetation



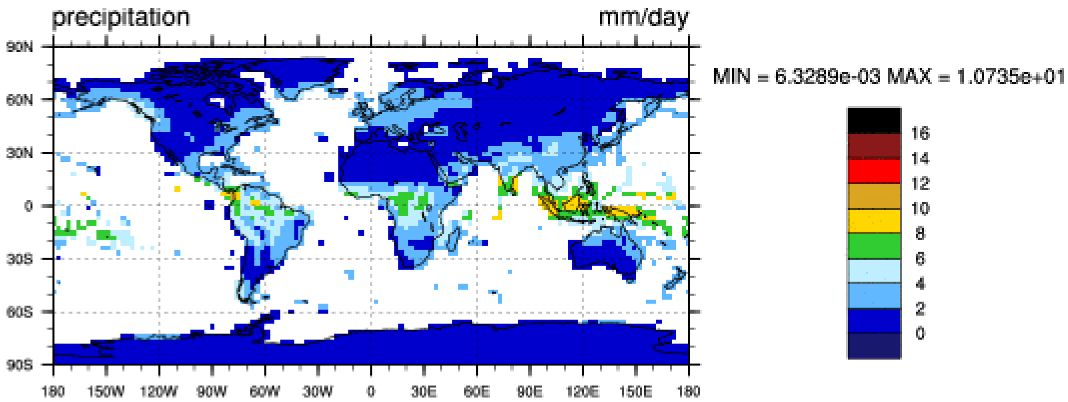
Bonan & Levis, unpublished

<u>Dominant forcing</u>

Decrease in albedo

[Carbon storage could mitigate warming]

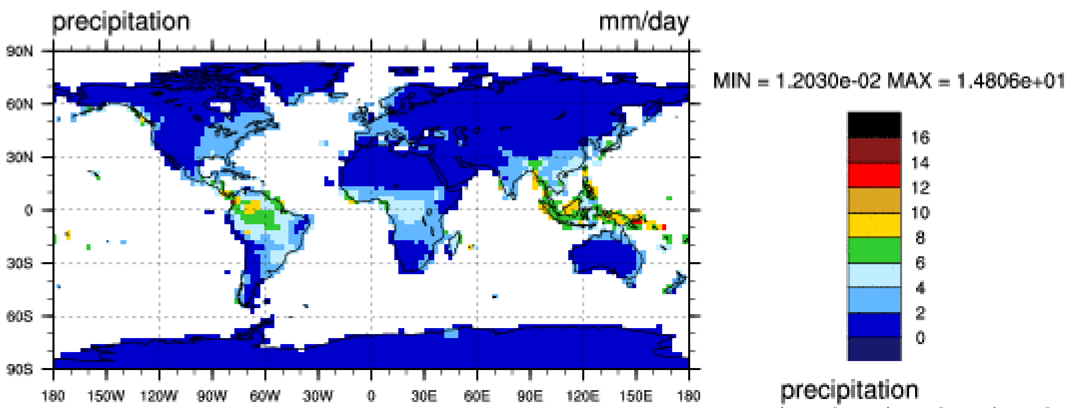
Precipitation biases



CAM3/CLM3 (1984-2000)

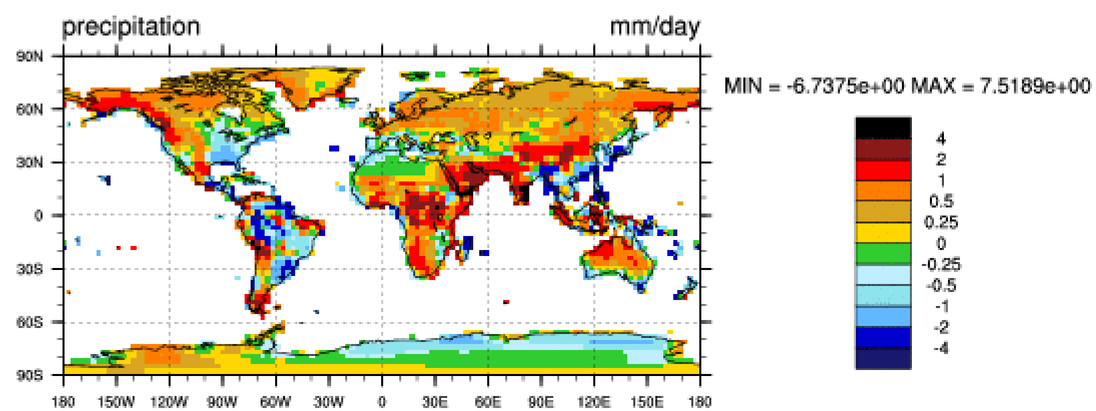
Annual Precipitation

Willmott-Matsuura



<u>Precipitation Bias</u>

Too little precipitation in eastern U.S. and Amazonia



Hydrology biases and vegetation

CAM3 and CLM3 have dry biases that adversely affect the simulation

The coupled CAM3/CLM3-DGVM cannot simulate a forest in eastern U.S.

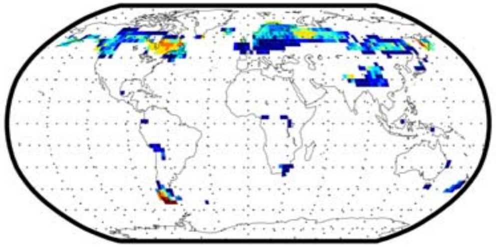
	P (mm d^{-1})	E (mm d^{-1})	R (mm d^{-1})	Vegetation (% tree, grass)
CLM3	1.99	1.66	0.33	0/65

Uncoupled CLM3-DGVM simulations demonstrate the sensitivity of vegetation to precipitation

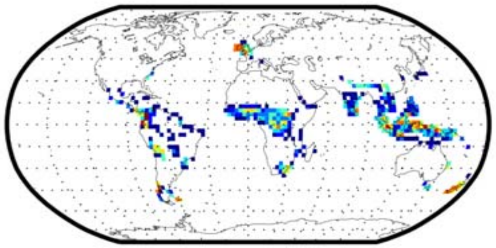
Precipitation (% observed)	Tree (%)	Grass (%)	Bare (%)
100%	59	39	2
90%	51	47	2
80%	31	67	2
70%	16	81	3
60%	4	88	8

Bonan & Levis (2005) J. Climate, CCSM special issue

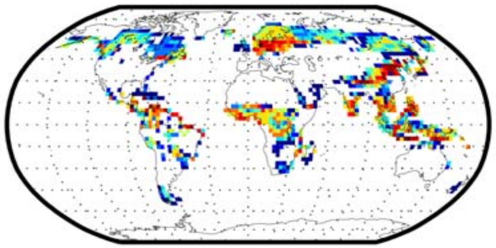
Needleleaf Evergreen Trees (%)



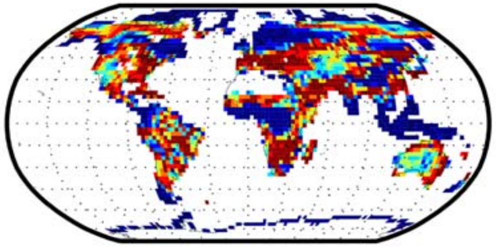
Broadleaf Deciduous Trees (%)



Other Deciduous Trees (%)



Grasses (%)



Similar problems occur in Amazonia

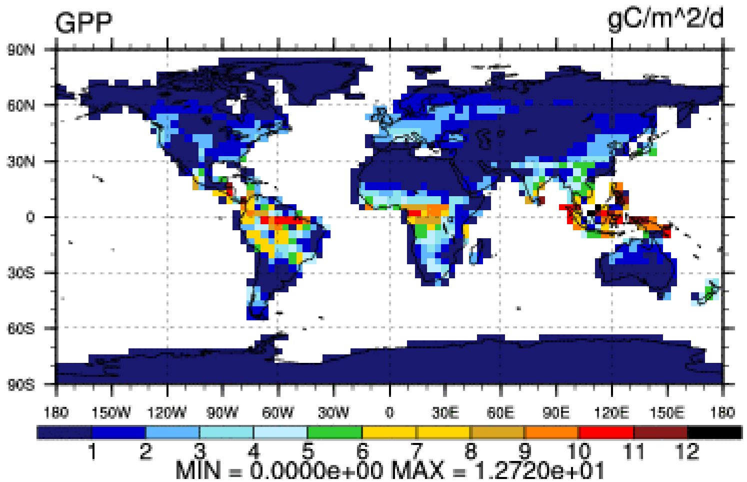
The coupled CAM3/CLM3-DGVM cannot simulate a tropical evergreen forest. Hydrology changes that improve CLM3-DGVM uncoupled to CAM3 initiate a catastrophic decrease in precipitation and forest dieback when coupled to CAM3

	P (mm d^{-1})	E (mm d^{-1})	R (mm d^{-1})	Tree		
				Evergreen (%)	Deciduous (%)	Grass (%)
CLM3	5.21	3.43	1.78	11	44	37
CLM3+	4.42	2.88	1.54	2	23	60

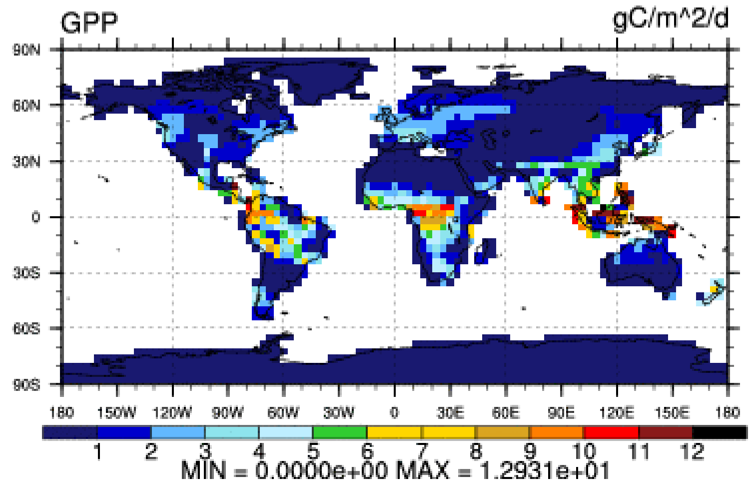
Bonan & Levis (2005) J. Climate, CCSM special issue

BGC model shows similar sensitivity

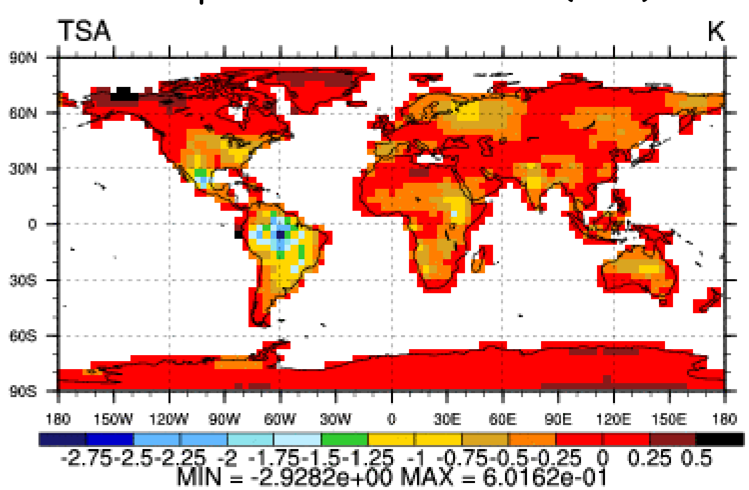
Model A:
CAM3/CLM3-CN (Thornton hydrology)
cooler Amazon



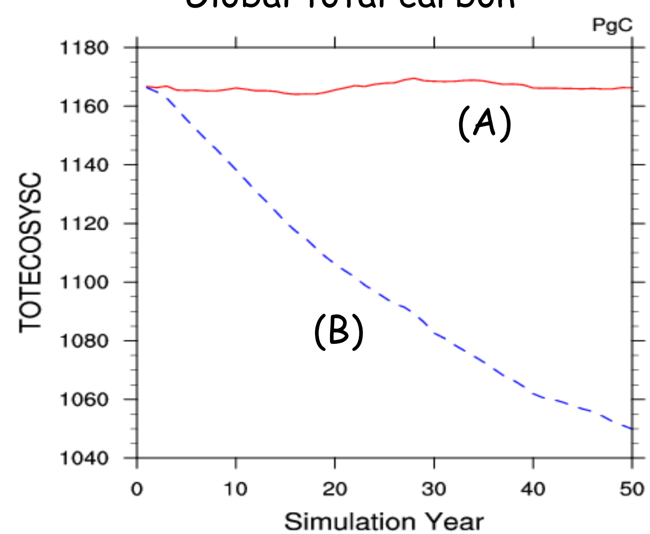
Model B:
CAM3/CLM3-CN (Lawrence hydrology)
warmer Amazon



Temperature difference (A-B)

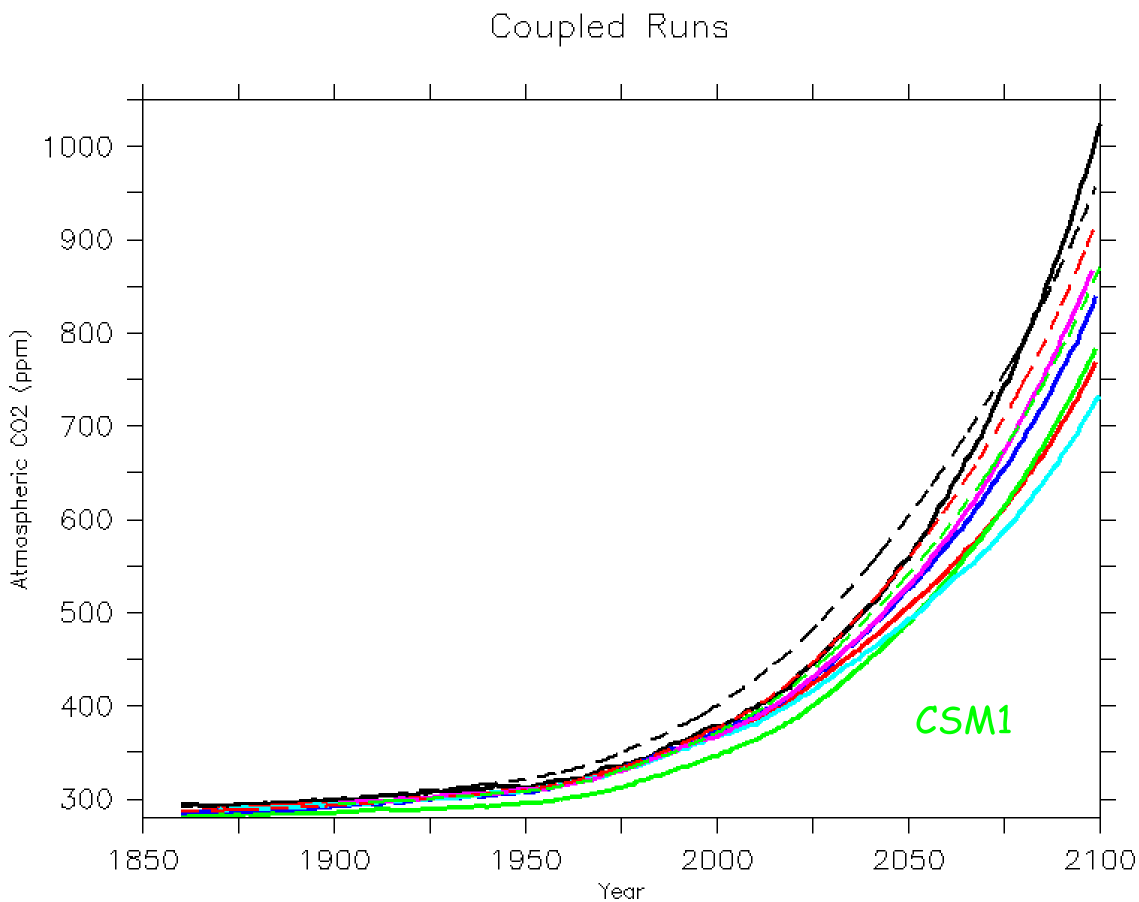


Global total carbon



Thornton, unpublished

C4MIP – Climate and carbon cycle



Nine climate models of varying complexity with active carbon cycle

Transient climate simulations through 2100

<u>Vegetation forcings of climate</u>

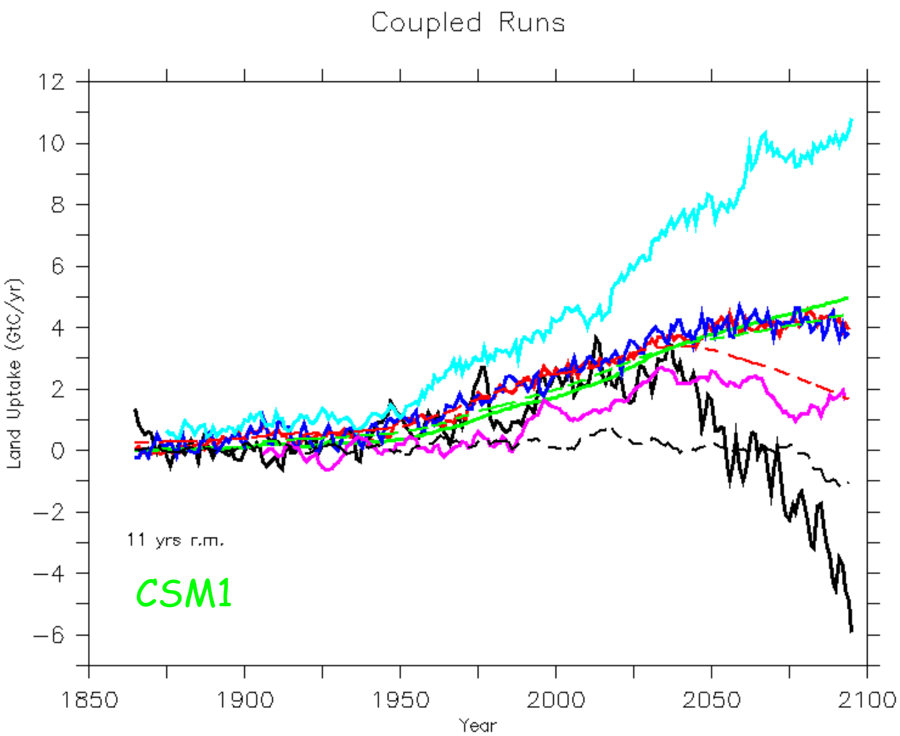
- Direct biogeochemical effect (atmos. CO_2)
- Indirect biogeophysical effect (stomata, leaf area, biogeography)
- Transient land cover change

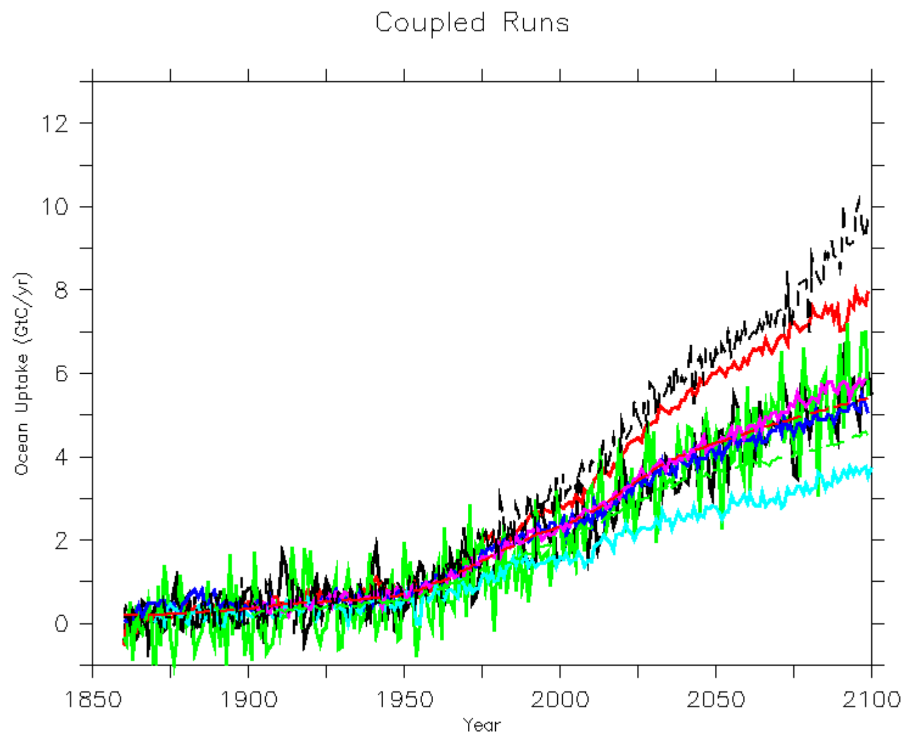
Models have large uncertainty in simulated atmospheric CO_2 at 2100

- > 1000 ppm
- < 750 ppm

Courtesy of Pierre Friedlingstein

C4MIP – Climate and carbon cycle





Uncertainty arises from differences in terrestrial fluxes

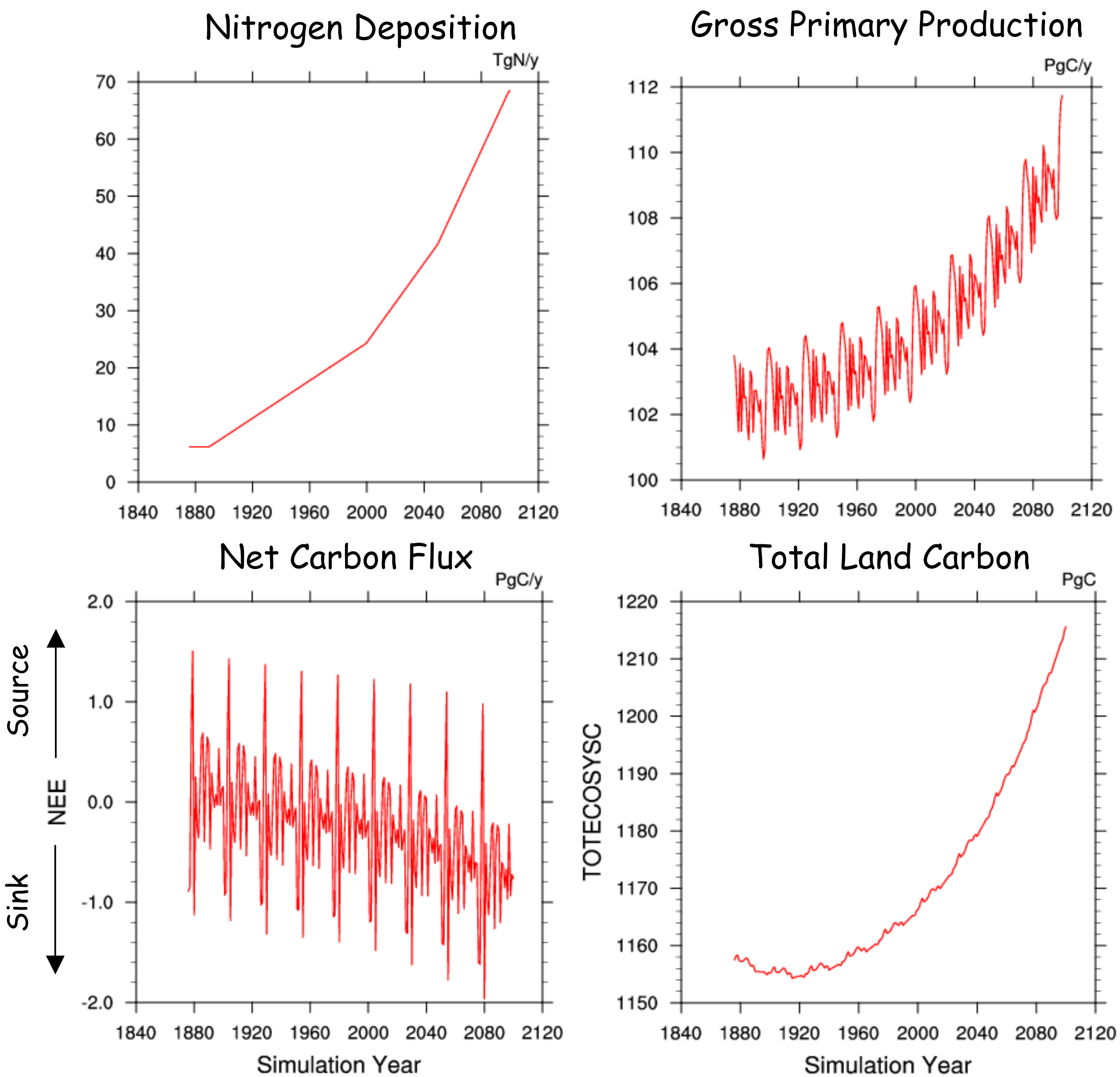
- One model simulates a large source of carbon from the land
- Another simulates a large terrestrial carbon sink
- Most models simulate modest terrestrial carbon uptake

Figures courtesy of Pierre Friedlingstein

<u>Conclusion</u>

- Terrestrial carbon cycle can be a large climate feedback
- Considerable more work is needed to understand this feedback
- How will carbon cycle science be advanced? Is there a tradeoff between more complexity (e.g., N, wildfire) and understanding?

Carbon-nitrogen interactions



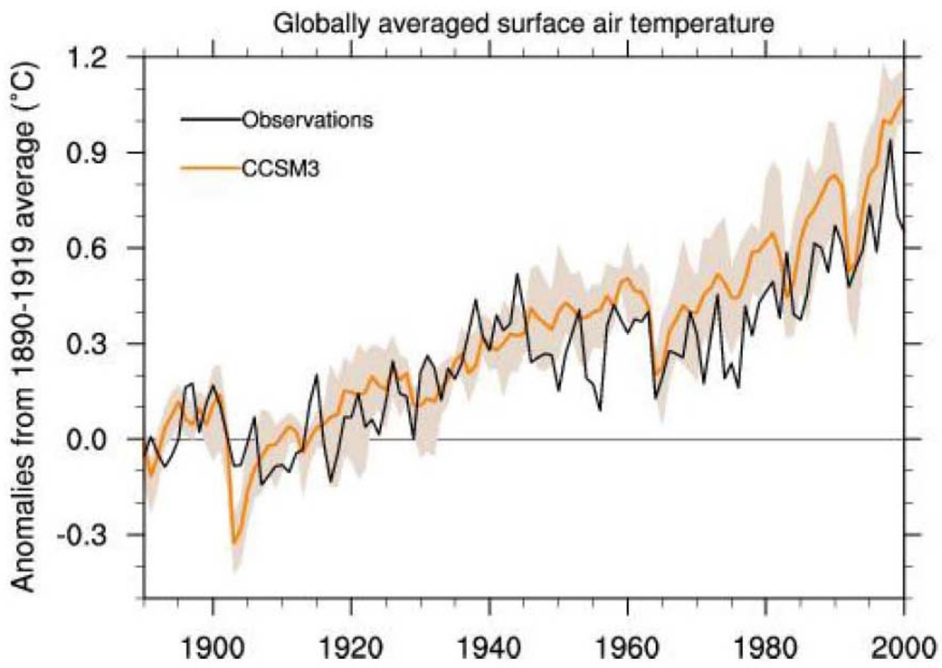
CLM-CN simulation forced with:

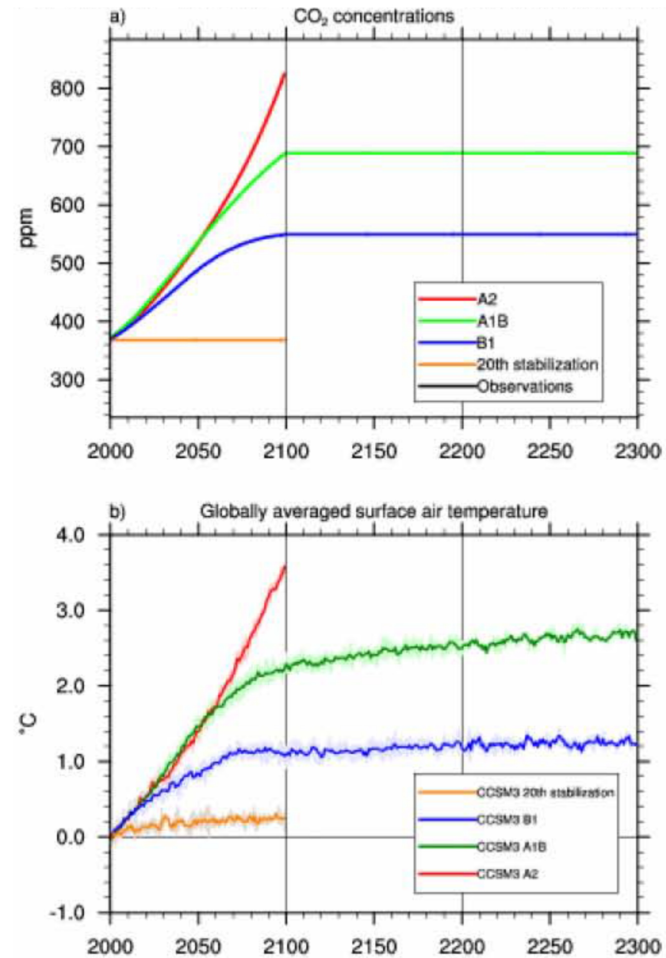
- Atmospheric data for 1870 (CAM3)
- Transient N-deposition

<u>Result</u>
N-deposition increases carbon uptake on land

Thornton, Lamarque, et al., unpublished

Climate of the 20th and 21st centuries





<u>Climate Forcings</u>

Greenhouse gases	Ozone
Solar variability	Sulfate aerosols
Volcanic aerosols	Black carbon aerosols

Meehl et al. (2005) J. Climate, CCSM special issue

What is the vegetation forcing of climate?

How do we distinguish the **biogeochemical** processes (e.g., CO_2) from the **biogeophysical** processes that affect radiative forcing, turbulent fluxes, and the hydrologic cycle?

How do we distinguish the direct effects of the carbon cycle (atmospheric CO_2) from indirect effects (community composition, leaf area, phenology, stomatal conductance)?

How do we gain confidence in our simulation of the vegetation forcing?

Quantify and understand vegetation forcing of climate

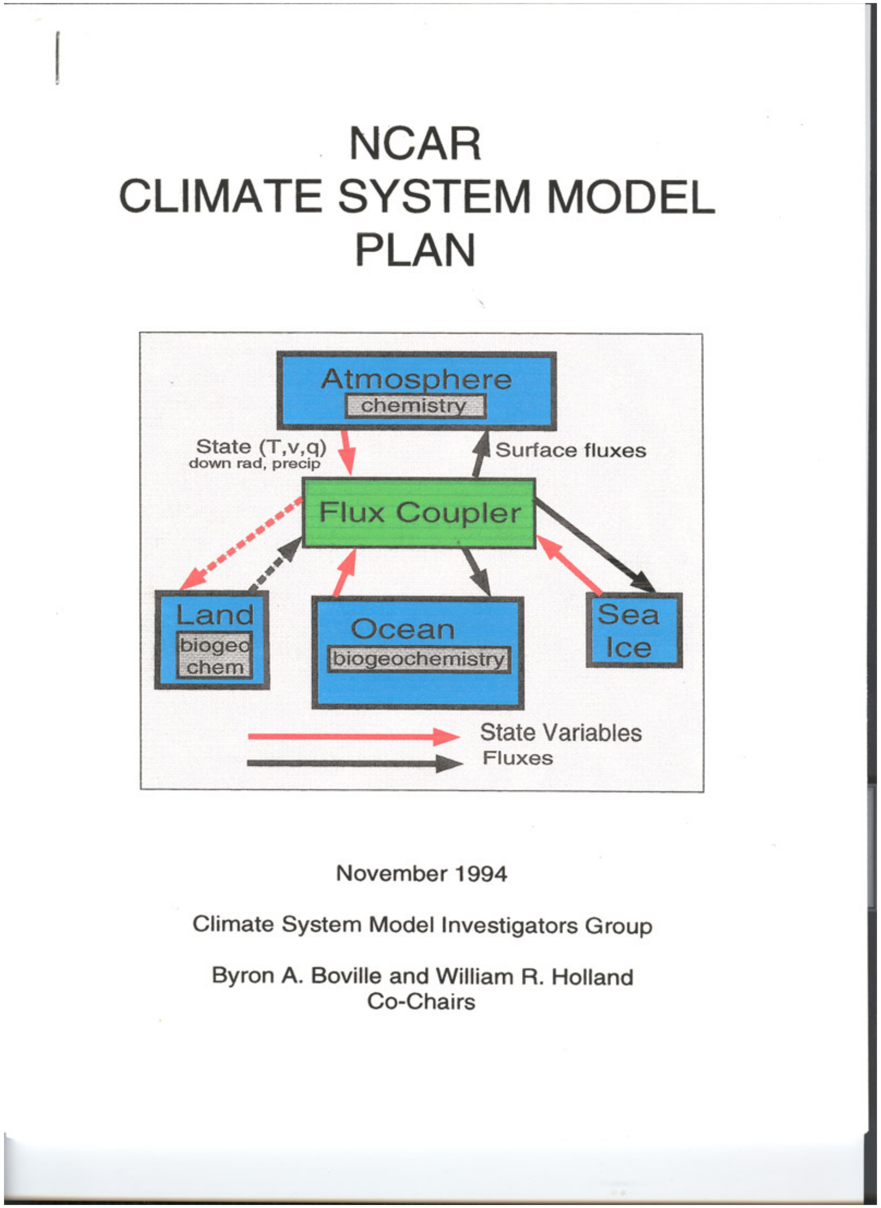
Vegetation affects climate through human perturbations to the land surface and through feedbacks

Human forcings	**Vegetation feedbacks**
Land use	Stomata – CO2 fertilization
• Cropland	Phenology – Changing growing season length
• Pastureland	Vegetation dynamics
• Irrigation	• Leaf area
• Urbanization	• Plant community composition
	• Biogeography
N deposition	Wildfire

Its not just biogeochemistry …

These affect climate through **biogeochemical** processes (e.g., CO_2, dust) and through **biogeophysical** processes that affect radiative forcing, turbulent fluxes, and the hydrologic cycle

Lessons learned from 10 years of CCSM?



The past ten years of CCSM development and application have greatly advanced our ability to model vegetation feedbacks on climate and our understanding of the importance of vegetation for climate simulation. Why?

- **Compelling science cannot be denied** - The CCSM plan called out the importance of vegetation, especially biogeochemistry, from the start
- **Do not over plan** - Just do it!

The next ten years of CCSM need to see focused studies of land-atmosphere coupling

- More study of precipitation over land
- More thorough analysis of the terrestrial hydrologic cycle. Carbon cycle and dynamic vegetation are essentials diagnostics
- Need to unify BGC (2) and DGVM (2) models
- No guarantee that coupled model will perform well. How do we 'live' with model biases?
- Numerous well-posed climate sensitivity experiments to unravel vegetation forcing