The integrated ecology, biogeochemistry, and hydrology of the terrestrial biosphere – an earth system model perspective

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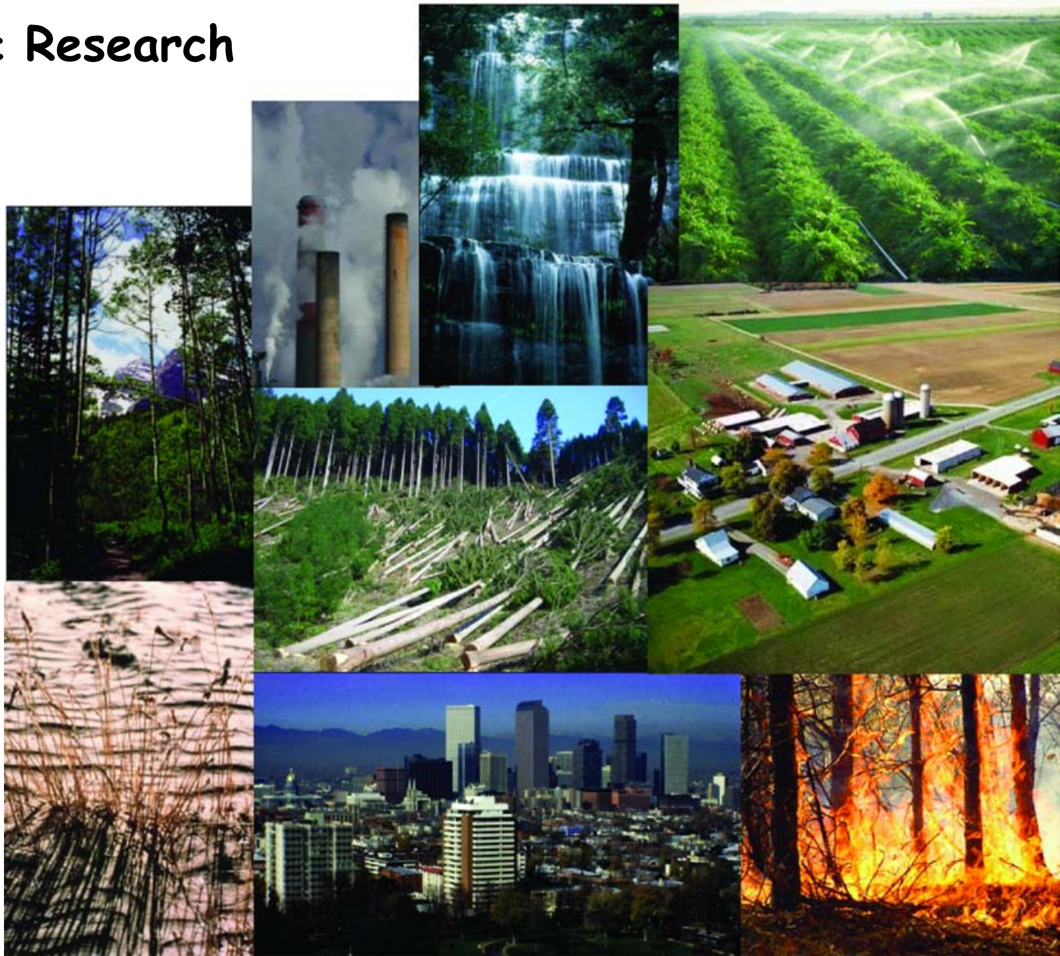
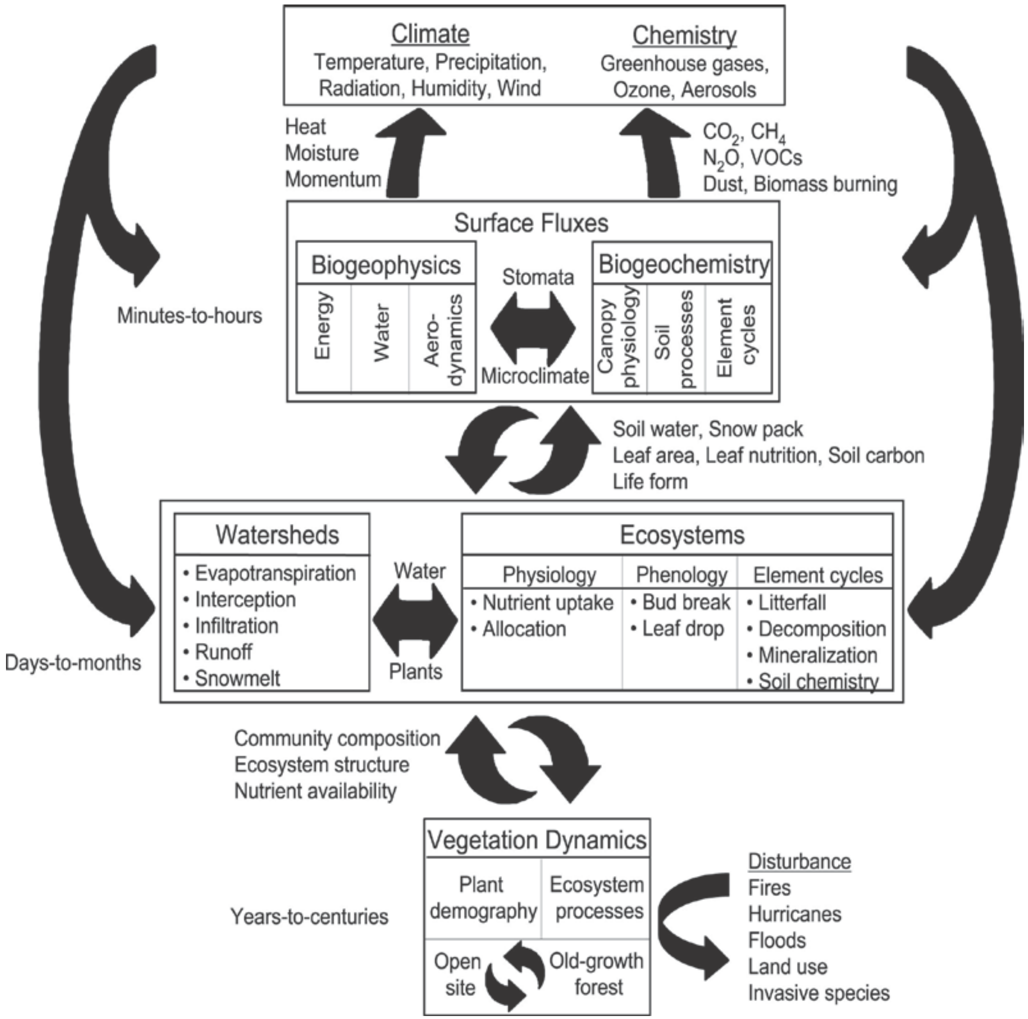


1 March 2011
1st INTERFACE Workshop
Captiva Island, Florida

NCAR is sponsored by the National Science Foundation

Multi-disciplinary science



Bonan (2008) Ecological Climatology, 2nd ed (Cambridge Univ. Press)

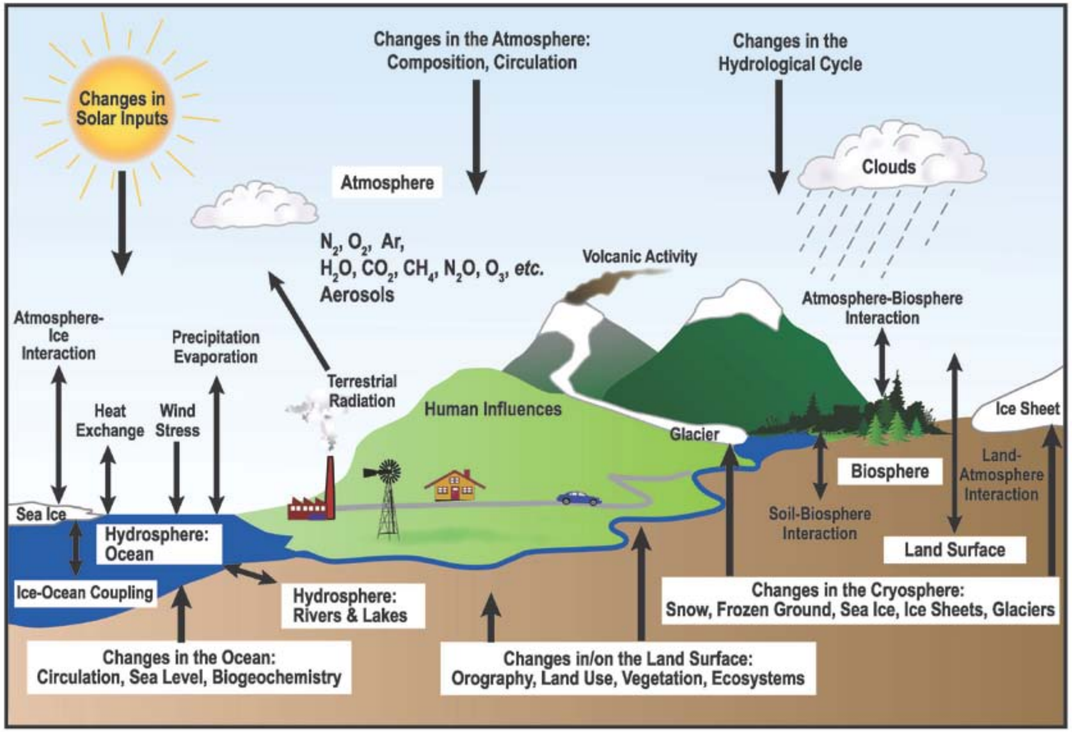
Terrestrial ecosystems influence climate through physical, chemical, and biological processes that affect planetary energetics, the hydrologic cycle, and atmospheric composition

Earth system science spans traditional disciplines

Three examples

- ❑ Anthropogenic land cover change
- ❑ Photosynthesis-transpiration
- ❑ Leaf area index

The Community Earth System Model



(IPCC 2007)

Earth system models use mathematical formulas to simulate the **physical**, **chemical**, and **biological** processes that drive Earth's atmosphere, hydrosphere, biosphere, and geosphere

A typical Earth system model consists of coupled models of the **atmosphere**, **ocean**, **sea ice**, and **land**

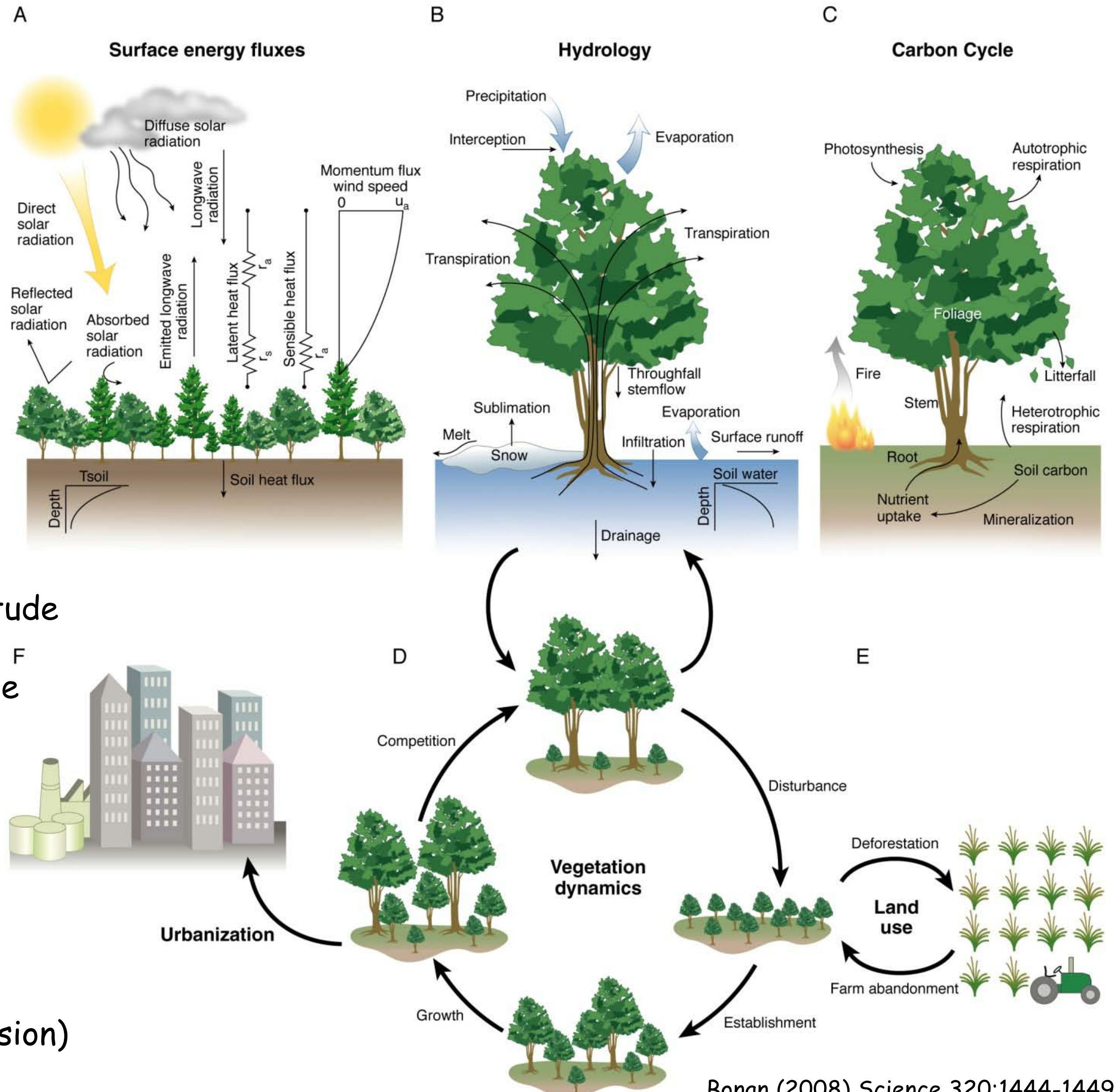
Land is represented by its **ecosystems**, **watersheds**, **people**, and **socioeconomic** drivers of environmental change

The model provides a comprehensive understanding of the processes by which people and ecosystems **feed back**, **adapt to**, and **mitigate** global environmental change

The Community Land Model (CLM4)

Fluxes of energy, water, and carbon and the dynamical processes that alter these fluxes

Oleson et al. (2010) NCAR/TN-478+STR
Lawrence et al. (2011) JAMES, in press



Spatial scale

- 1.25° longitude × 0.9375° latitude (288 × 192 grid)
- 2.5° longitude × 1.875° latitude (144 × 96 grid)

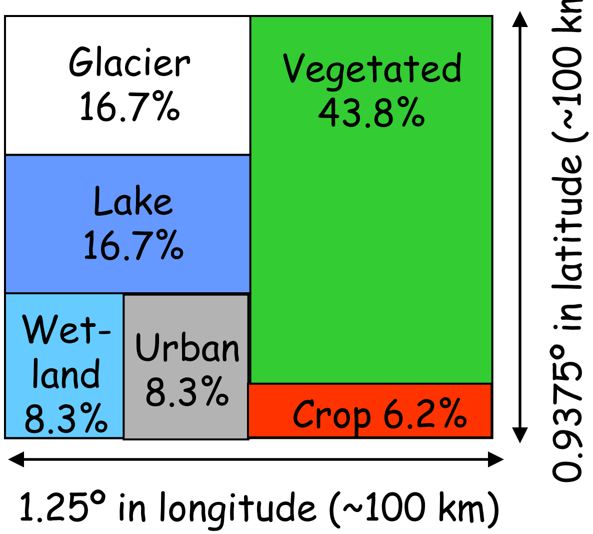
Temporal scale

- 30-minute coupling with atmosphere
- Seasonal-to-interannual (phenology)
- Decadal-to-century climate (disturbance, land use, succession)
- Paleoclimate (biogeography)

Bonan (2008) Science 320:1444-1449

Land surface heterogeneity

Subgrid land cover and plant functional types



CLM represents a model grid cell as a mosaic of up to 6 primary land cover types. Vegetated land is further represented as a mosaic of plant functional types

Bonan et al. (2002) GBC, 16, doi:10.1029/2000GB001360

Integrate ecological studies with earth system models

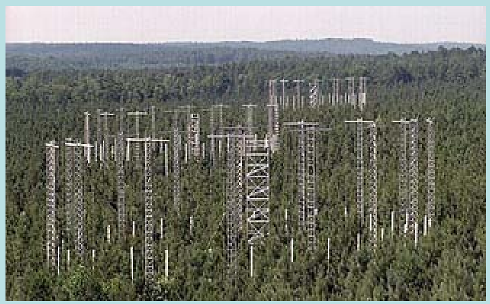
Environmental Monitoring

Eddy covariance flux tower
(courtesy Dennis Baldocchi)

Hubbard Brook
Ecosystem Study

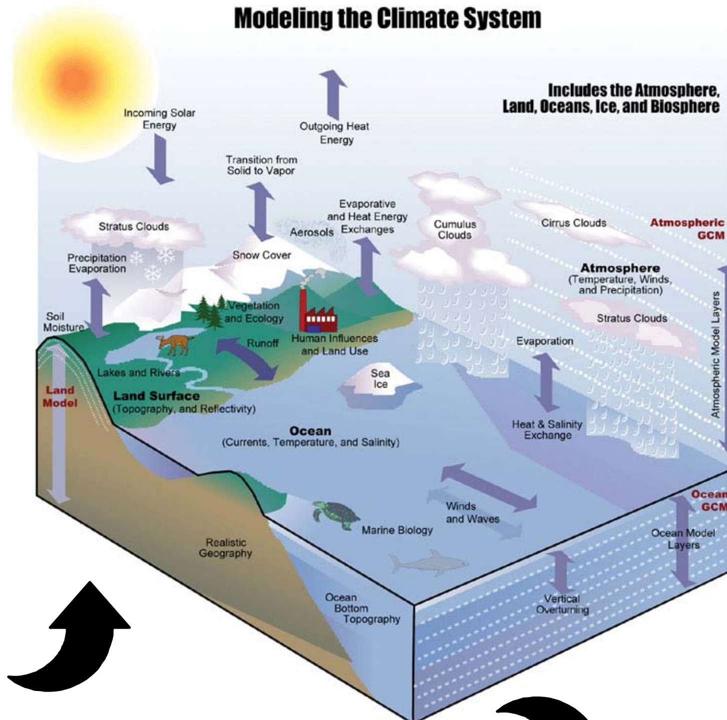
Experimental Manipulation

Soil warming, Harvard Forest



CO_2 enrichment, Duke Forest

CO_2 × N
enrichment,
Cedar Creek

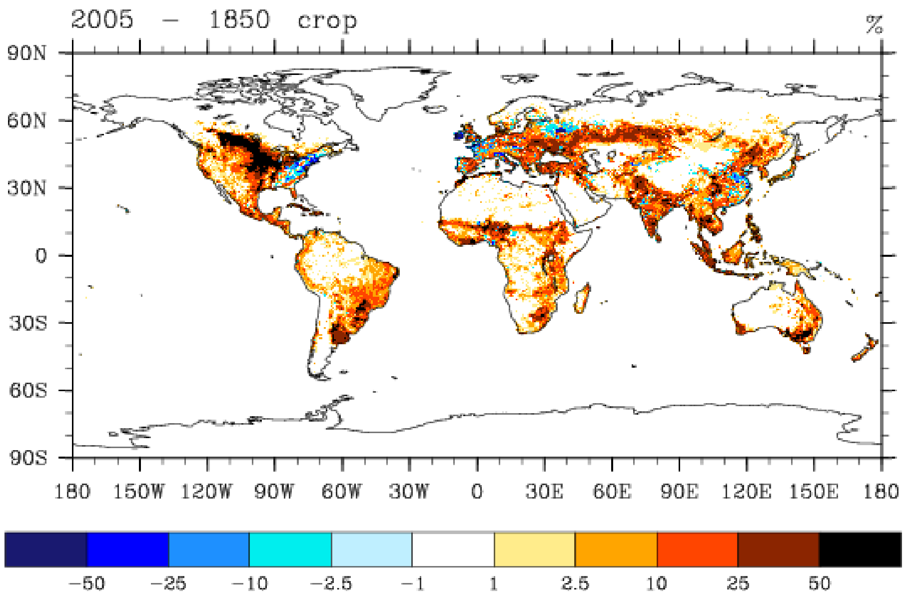


Planetary energetics
Planetary ecology
Planetary metabolism

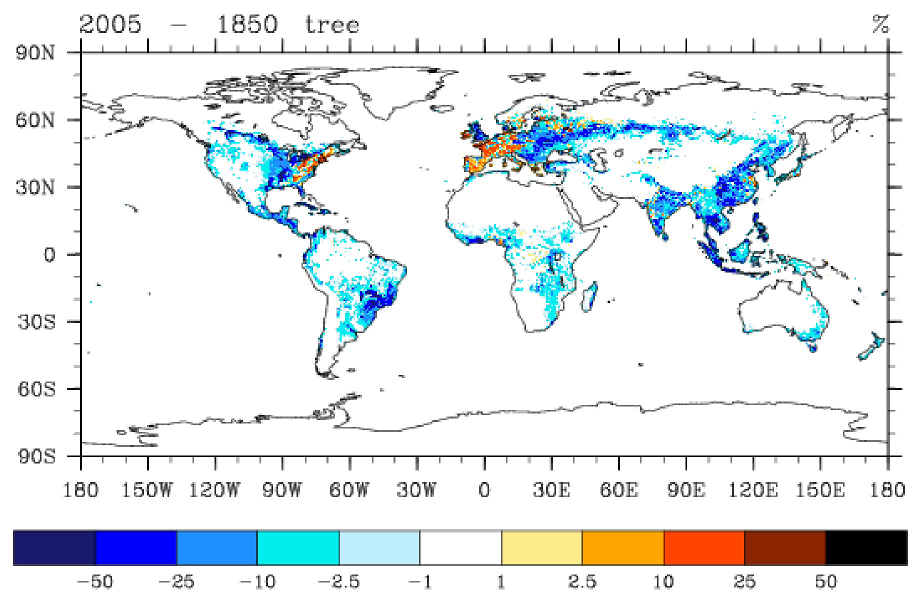
Test model-generated hypotheses of earth system functioning with observations

Historical land cover change, 1850 to 2005

Crop PFT



Tree PFTs



Lawrence et al. (2011) J. Climate, in prep.

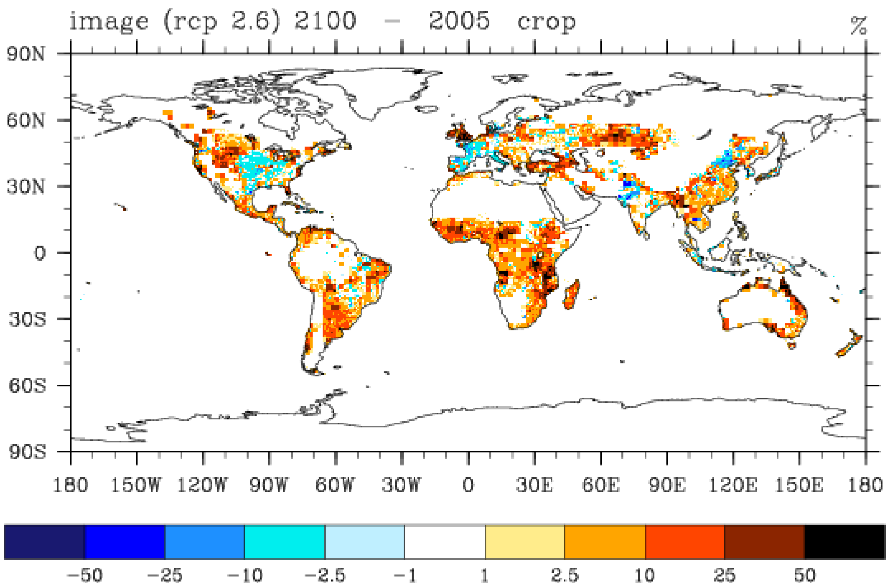
Prevailing paradigm

- ❑ Anthropogenic land cover change cools mid-latitude climate, primarily from increased surface albedo
- ❑ Land use carbon emissions warms climate

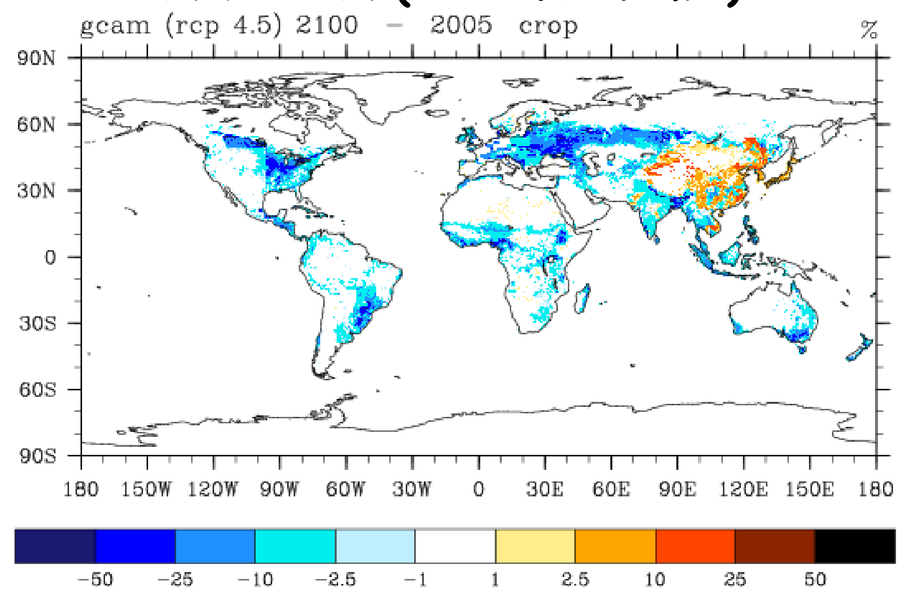
How does this understanding depend on hydrology?

Future land cover change, 2005 to 2100

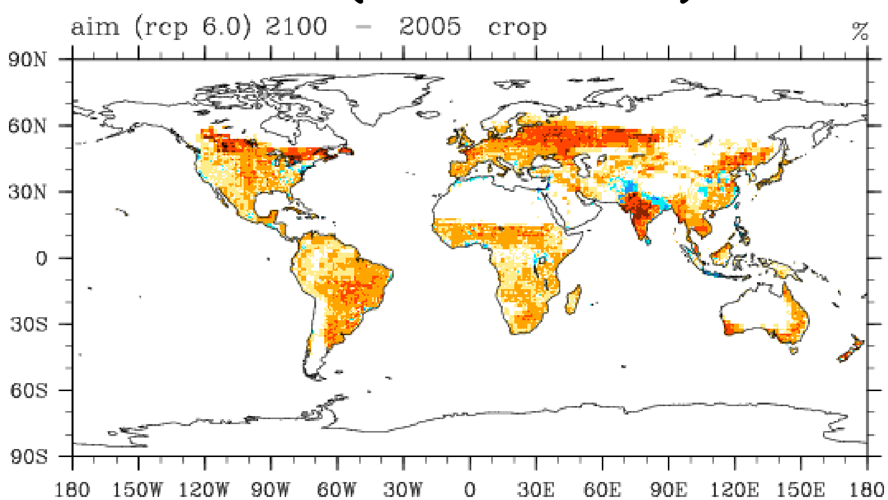
IMAGE (RCP 2.6 W m^{-2})



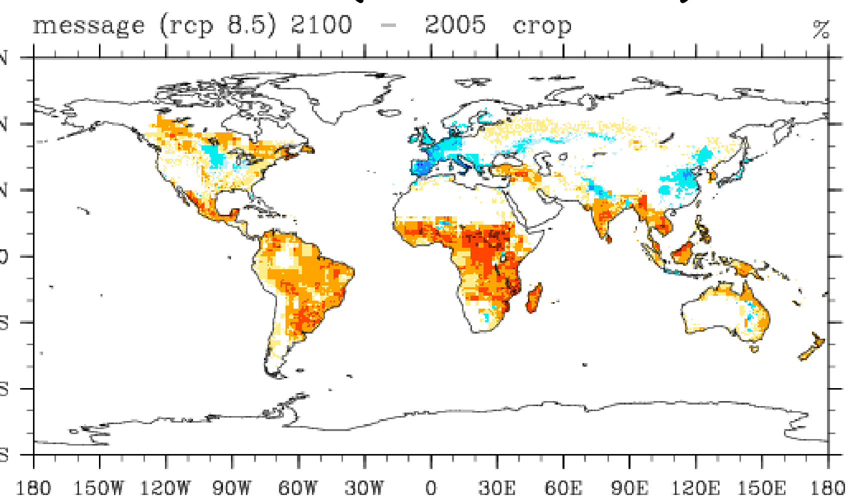
MINICAM (RCP 4.5 W m^{-2})



AIM (RCP 6.0 W m^{-2})



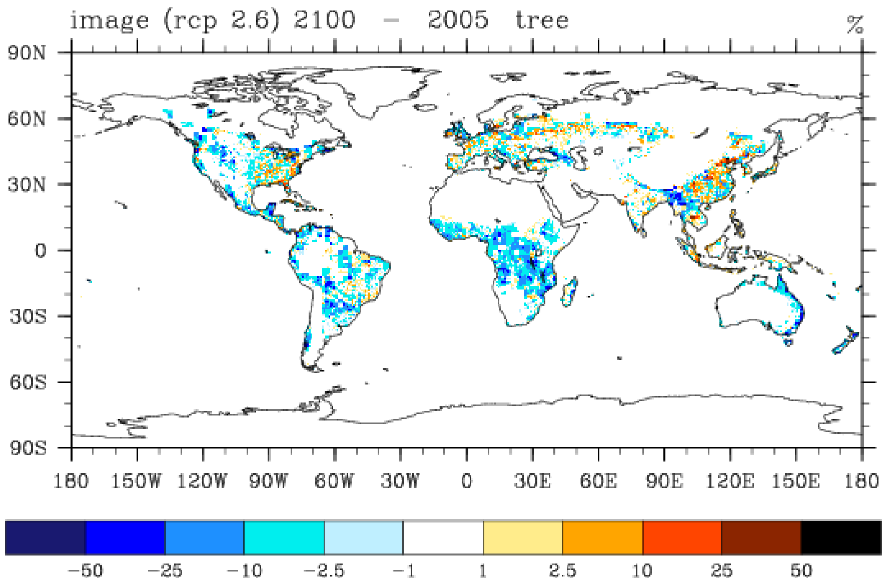
MESSAGE (RCP 8.5 W m^{-2})



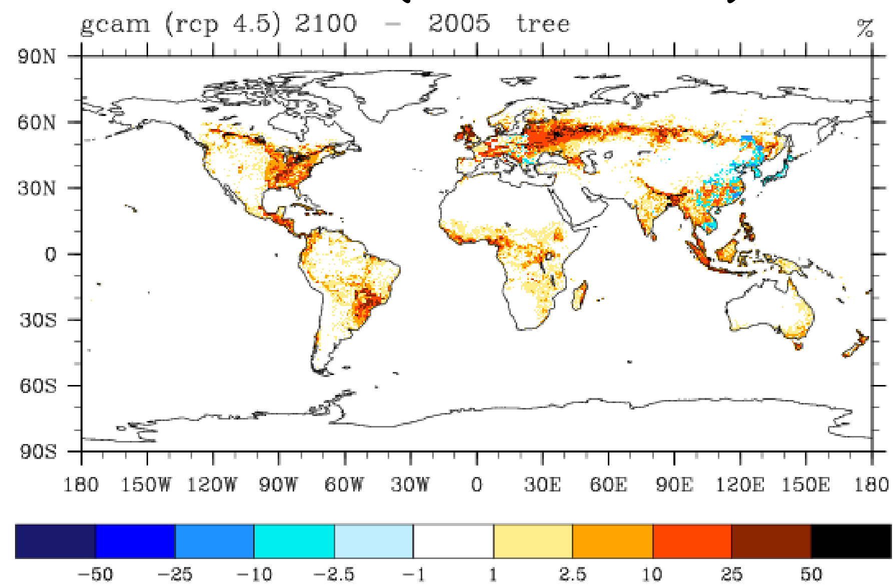
Lawrence et al. (2011) J. Climate, in prep.

Future land cover change, 2005 to 2100

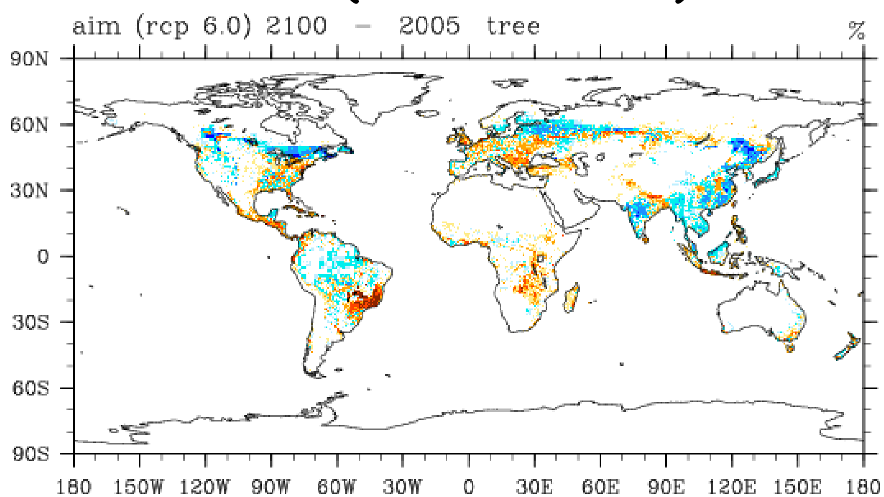
IMAGE (RCP 2.6 W m^{-2})



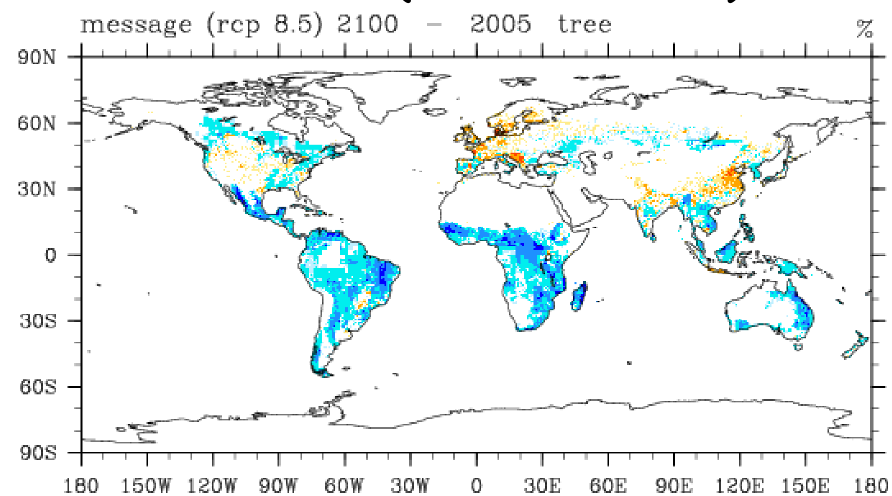
MINICAM (RCP 4.5 W m^{-2})



AIM (RCP 6.0 W m^{-2})

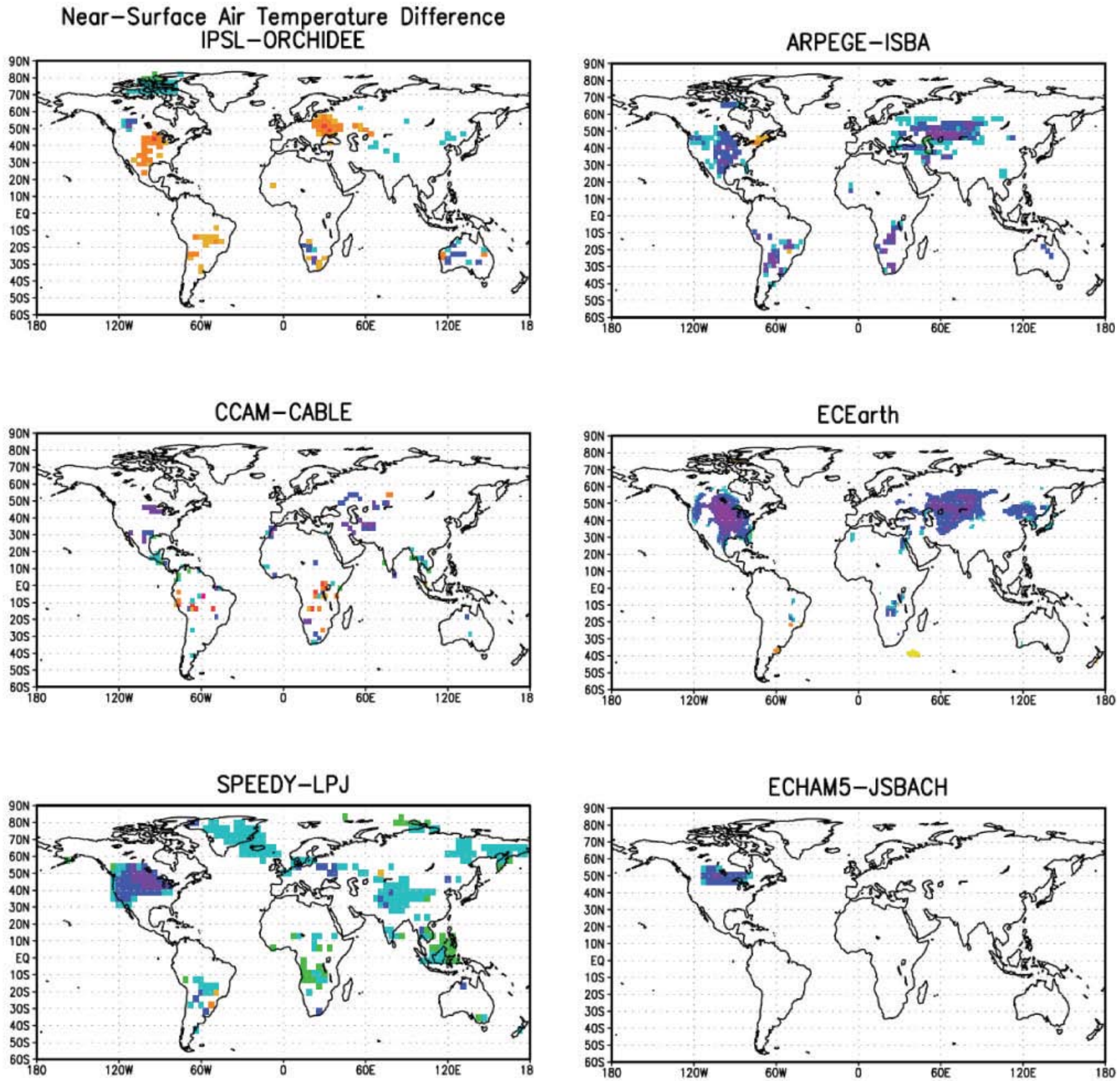


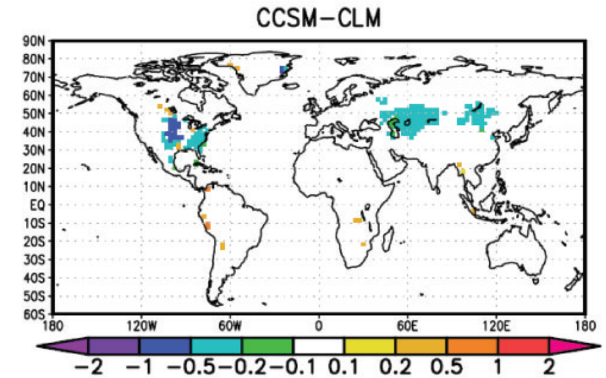
MESSAGE (RCP 8.5 W m^{-2})



Lawrence et al. (2011) J. Climate, in prep.

The LUCID intercomparison study

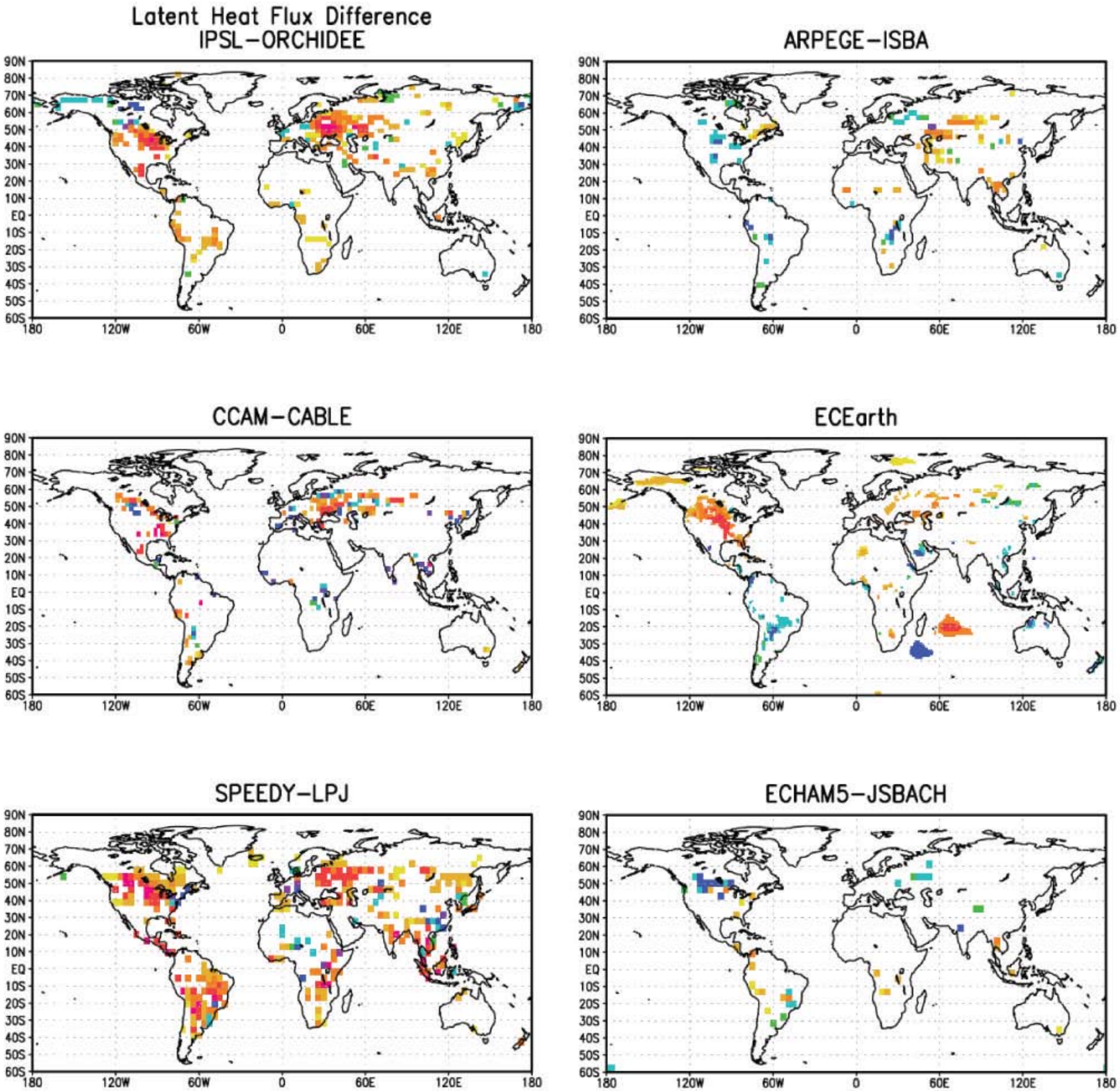


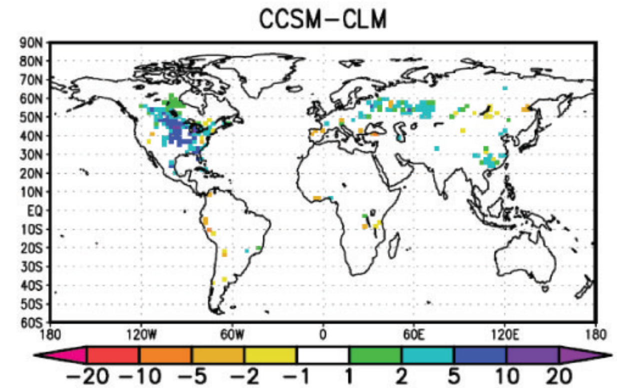


Change in JJA near-surface air temperature (°C) resulting from land cover change (PD – PDv)

Pitman, de Noblet-Ducoudré, et al. (2009) GRL, 36, doi:10.1029/2009GL039076

The LUCID intercomparison study





Change in JJA latent heat flux (W m^{-2}) resulting from land cover change (PD – PDv)

CLM – Crops vs trees

- ❑ Higher albedo and g_s
- ❑ Lower z_0, LAI, and SAI
- ❑ Root profile not important
  Soils are wet; no deep roots or hydraulic redistribution
- ❑ Latent heat flux increases, mostly in soil evaporation

Pitman, de Noblet-Ducoudré, et al. (2009) GRL, 36, doi:10.1029/2009GL039076

Land cover change and evapotranspiration

Prevailing model paradigm

Crops

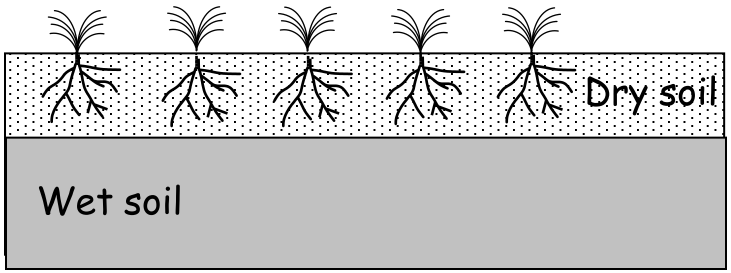
Low latent heat flux because of:

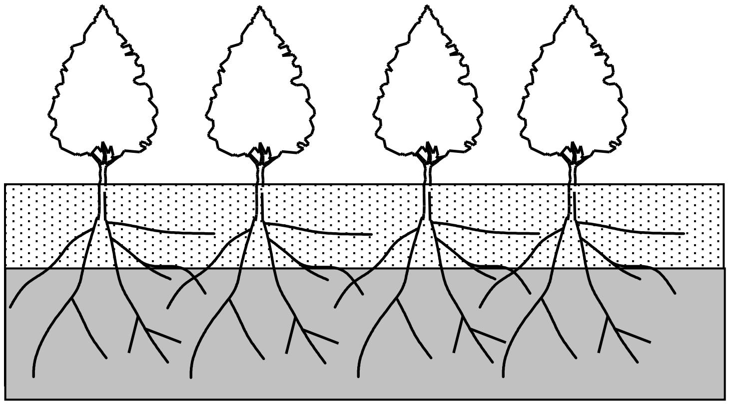
- Low roughness
- Shallow roots decrease soil water availability

Trees

High latent heat flux because of:

- High roughness
- Deep roots allow increased soil water availability





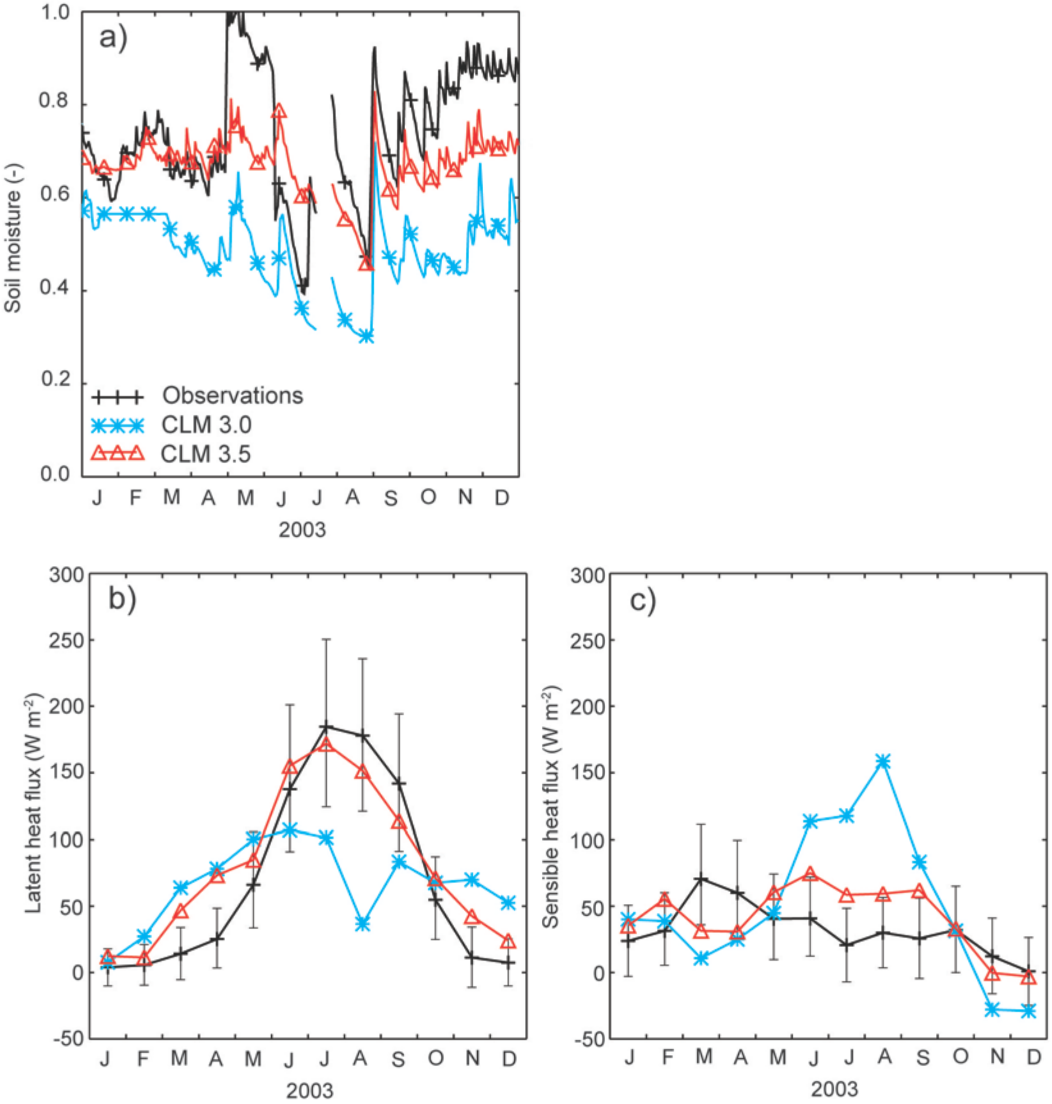
Tropical forest – cooling from higher surface albedo of cropland and pastureland is offset by warming associated with reduced evapotranspiration

Temperate forest - higher albedo leads to cooling, but changes in evapotranspiration can either enhance or mitigate this cooling

Bonan (2008) Science 320:1444-1449

Flux tower measurements – temperate deciduous forest

Morgan Monroe State Forest, Indiana

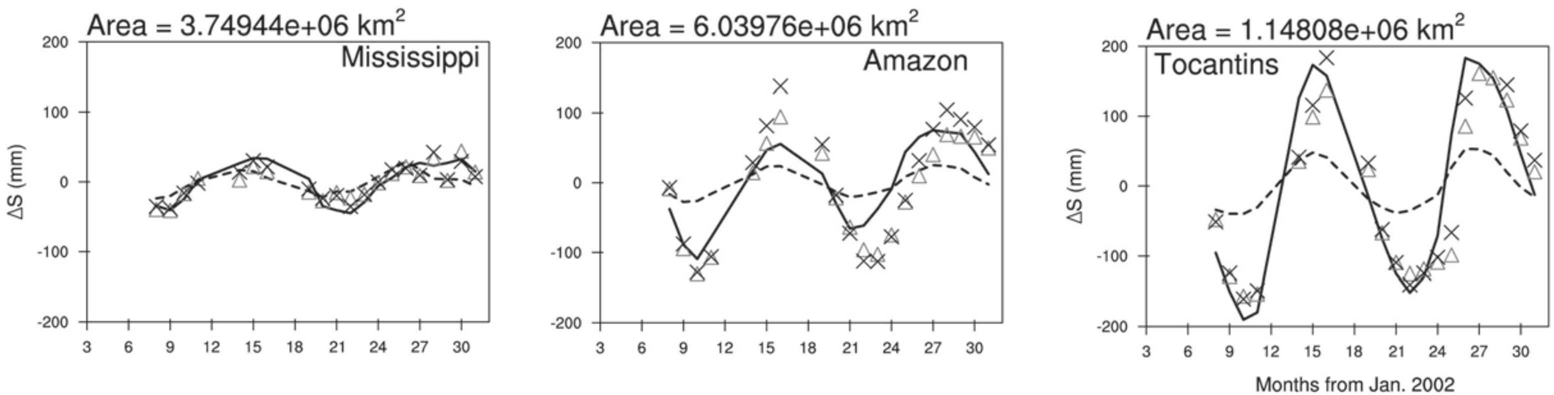


CLM3.0 – dry soil, low latent heat flux, high sensible heat flux
CLM3.5 – wetter soil and higher latent heat flux

Stöckli et al. (2008) JGR, 113, doi:10.1029/2007JG000562

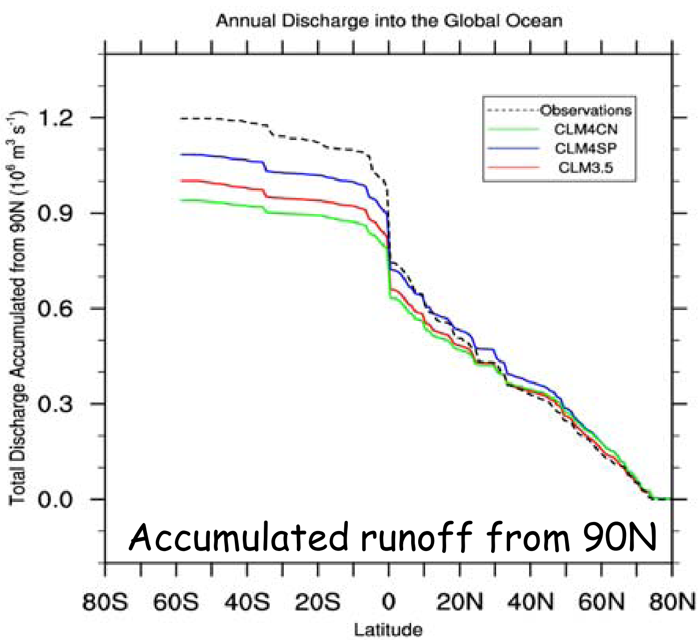
Large-scale hydrologic cycle

Basin-scale water storage



Oleson et al. (2008) JGR, 113, doi:10.1029/2007JG000563

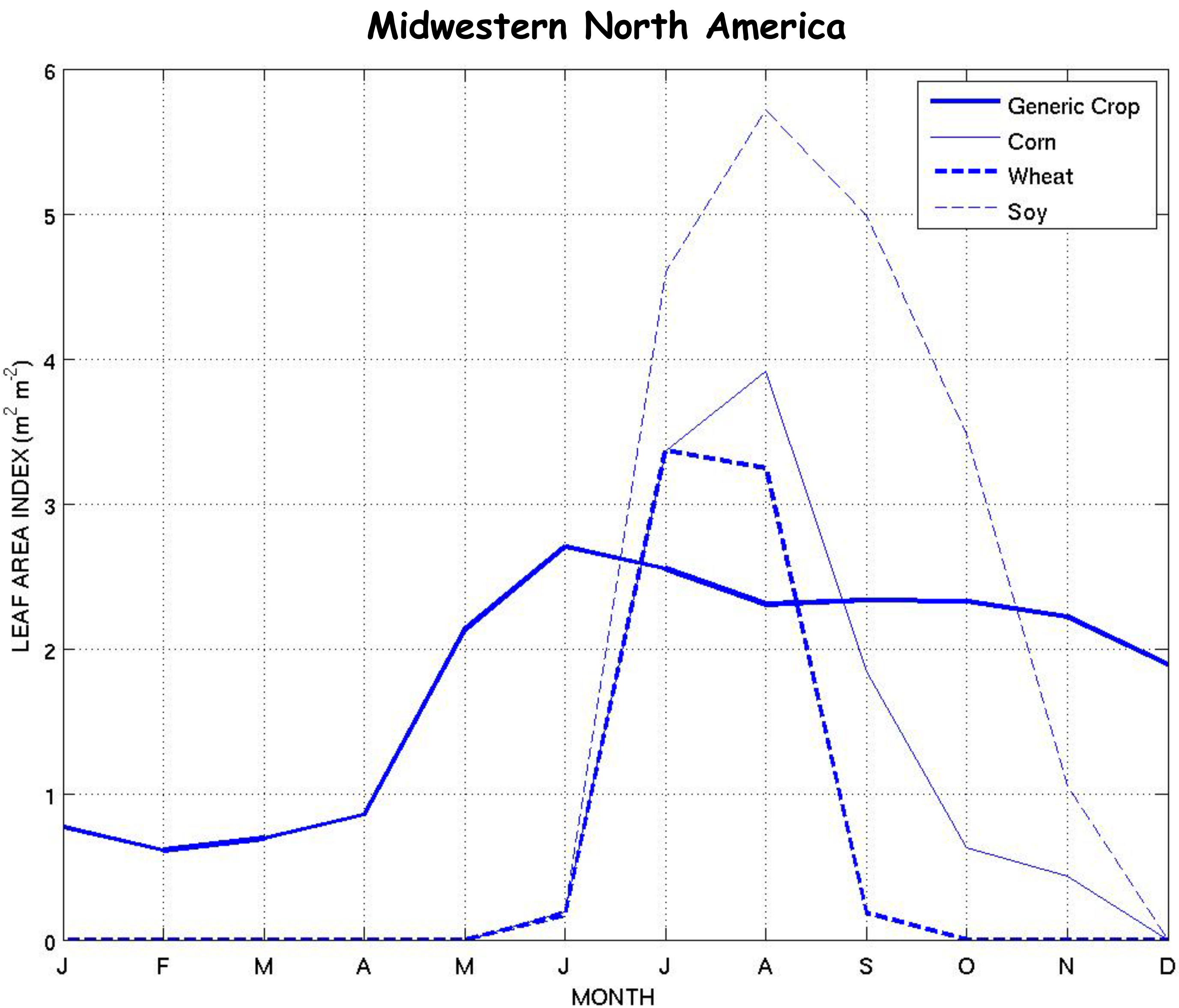
Global runoff



Lawrence et al (2011) JAMES, in press

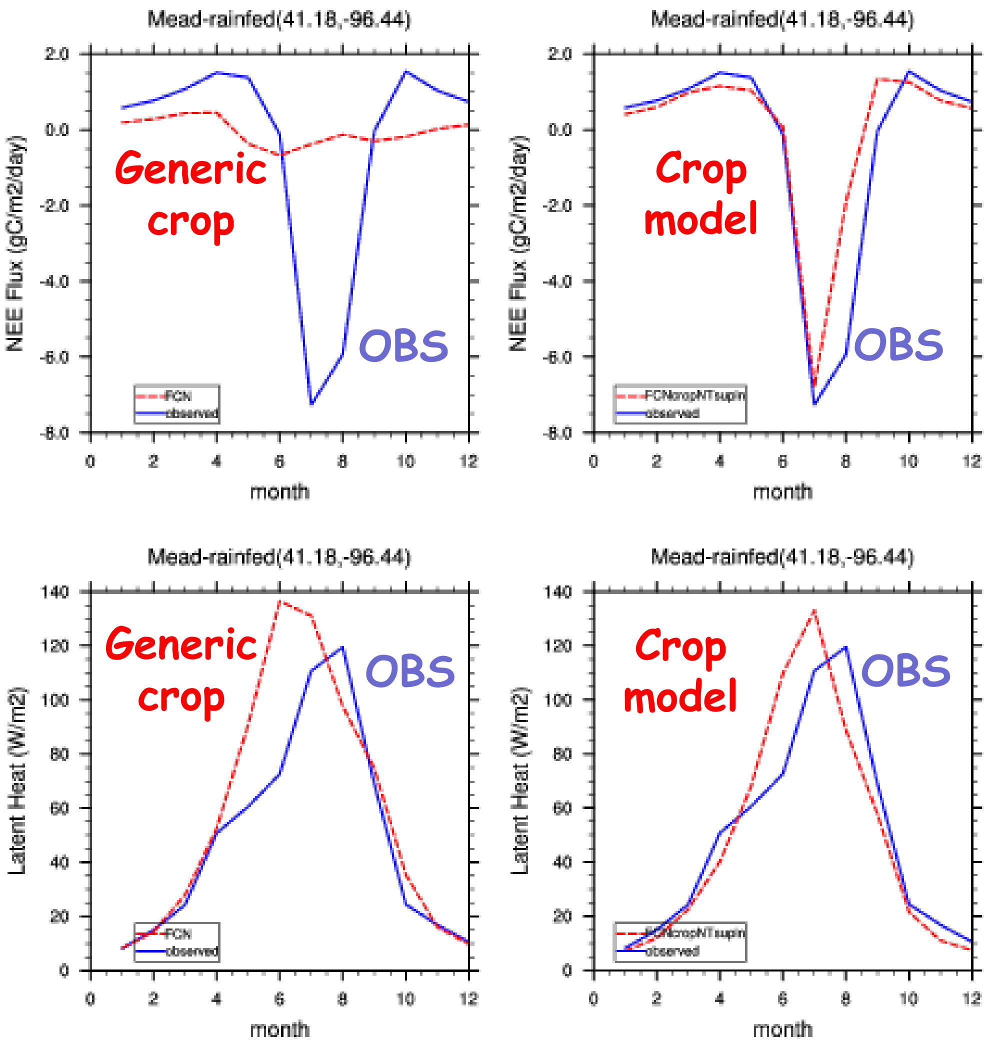
- ❑ CLM3.0 – dry, weak annual cycle of water storage
- ❑ CLM3.5 – wet, stronger annual cycle of water storage, high ET
- ❑ CLM4 – reduced ET and greater runoff

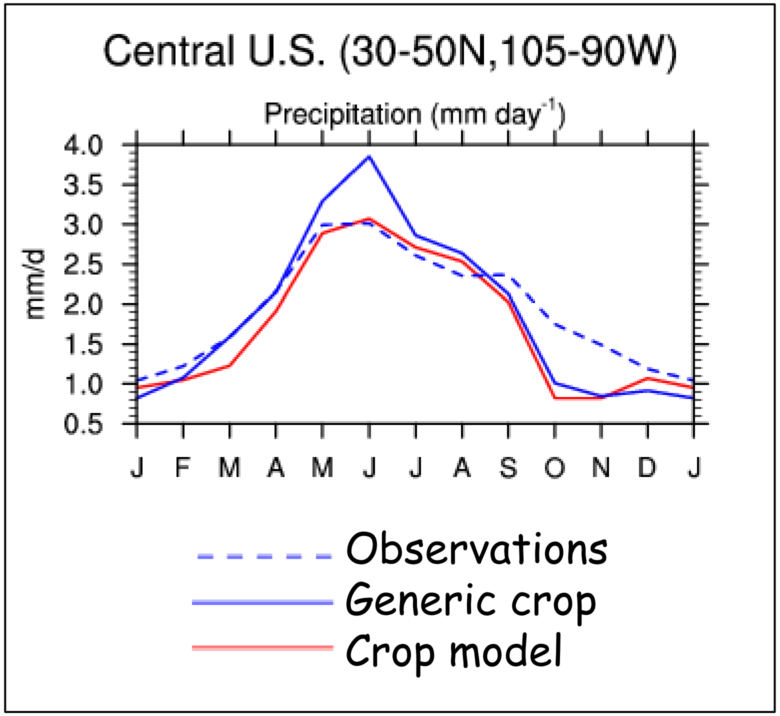
Crop model improves leaf area phenology



Levis & Bonan (2011) J. Climate, in prep.

Crop model improves surface fluxes and climate

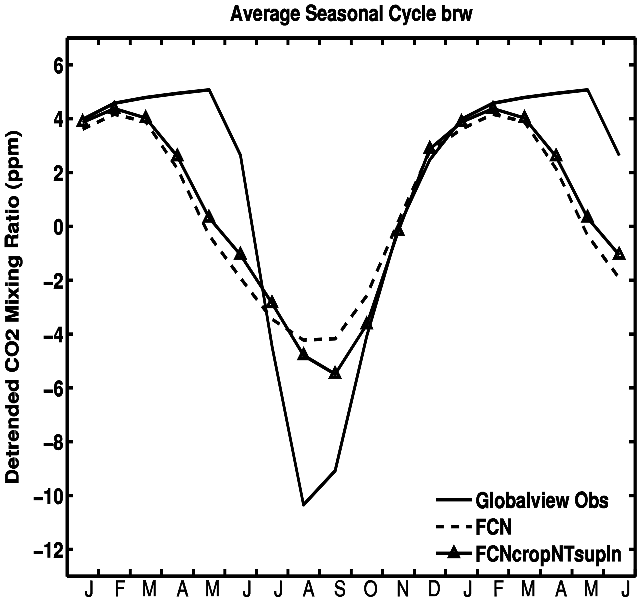




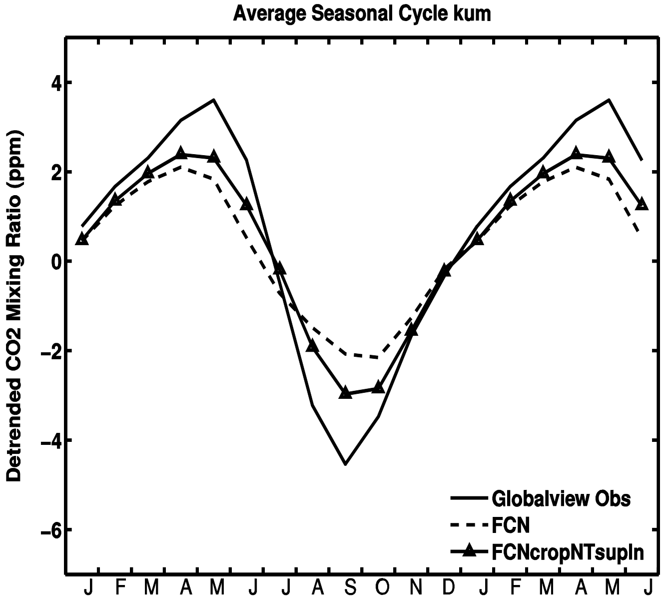
Levis & Bonan (2011) J. Climate, in prep.

Crop model improves annual CO_2 cycle

Barrow, Alaska

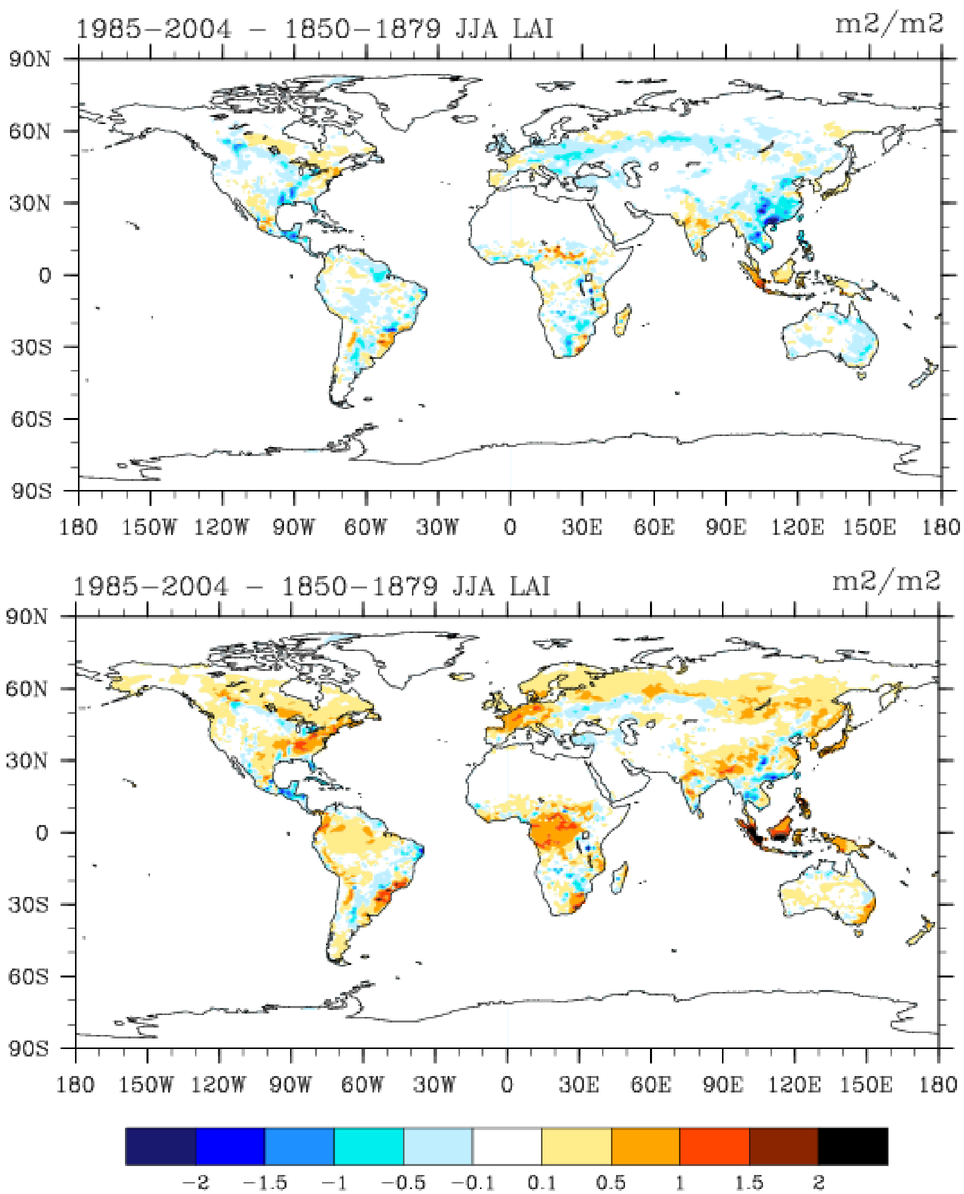


Kumakahi, Hawaii



Levis & Bonan (2011) J. Climate, in prep.

Opposing trends in vegetation



Simulated leaf area index

(Present-day – Pre-industrial)

Single forcing simulation

Land cover change only

Loss of leaf area, except where reforestation

All forcing simulation

CO_2

Climate

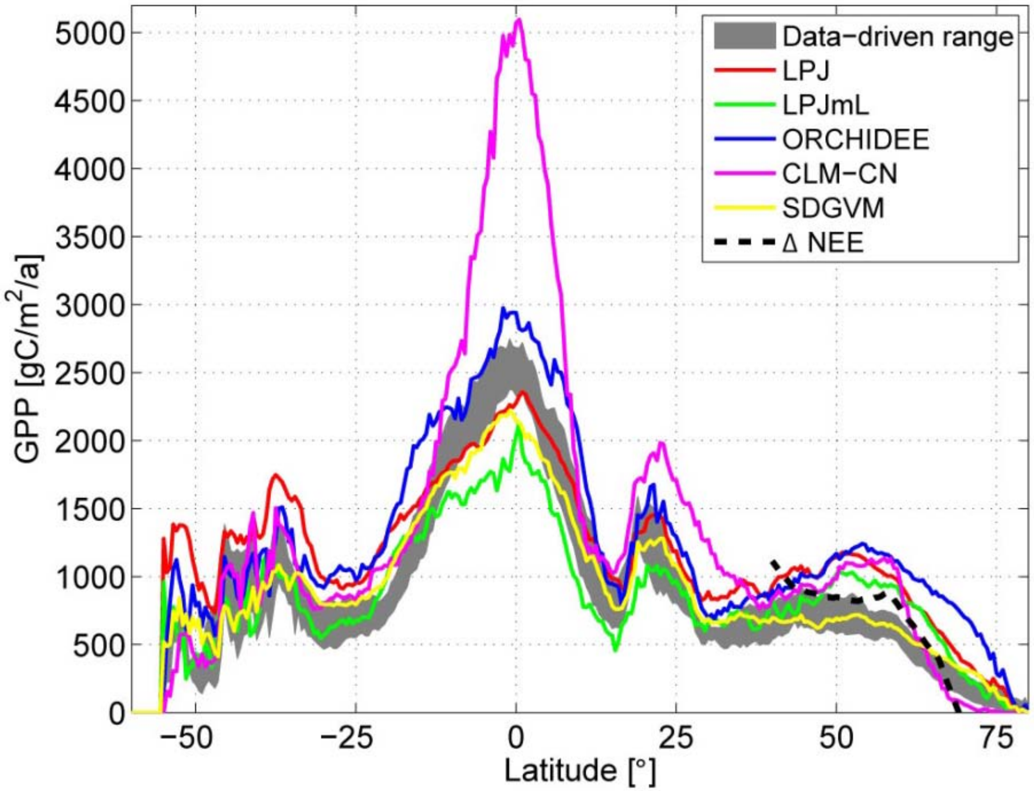
Nitrogen deposition

Land cover change

Increase in leaf area, except where agricultural expansion

Gross primary production biases

CLM4 (purple line) overestimates annual gross primary production (GPP) compared with data-driven estimates and other models



Beer et al. (2010) Science 329:834-838

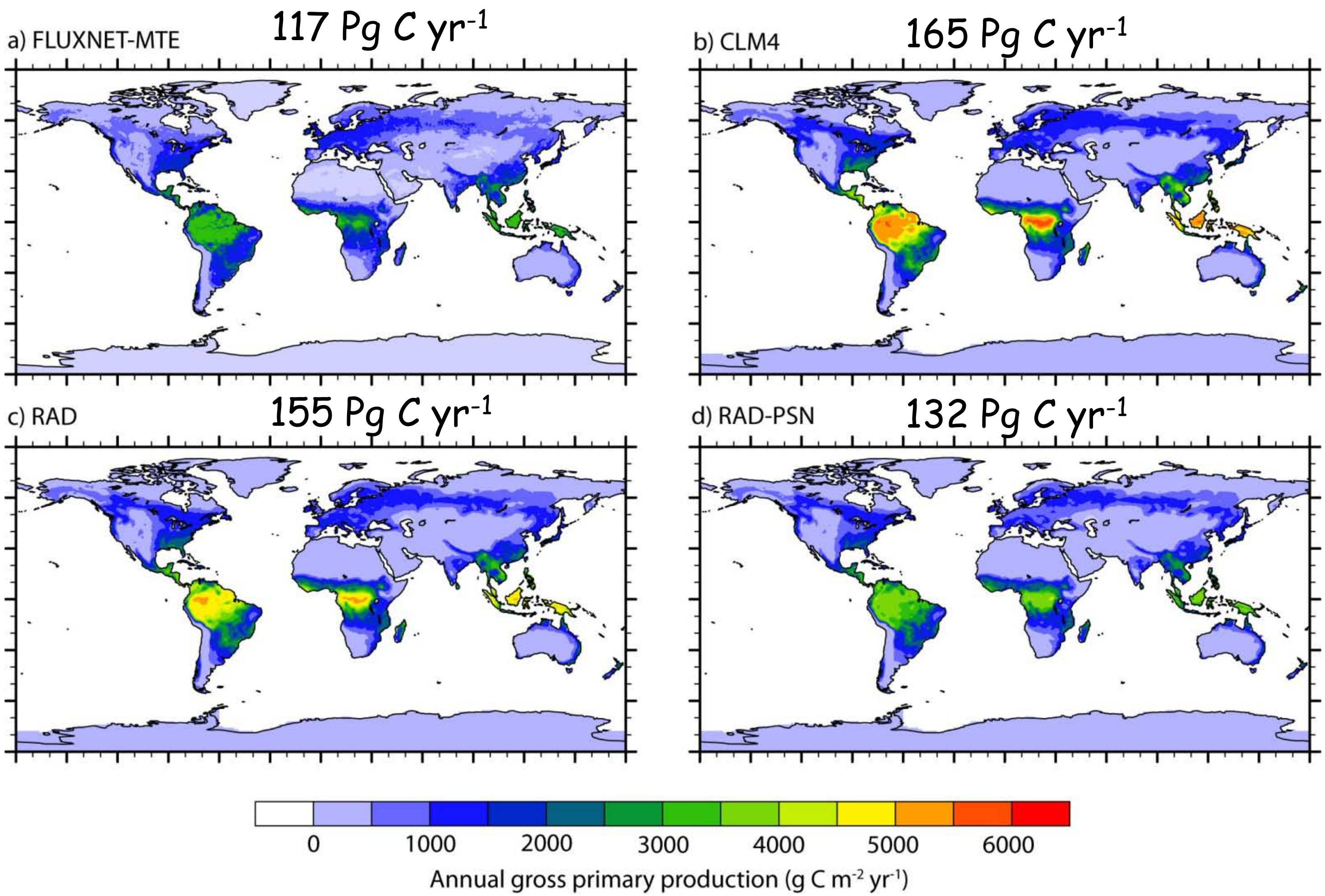
Causes of GPP bias

Model structural error
Canopy radiative transfer
Photosynthesis-stomatal conductance
Canopy integration

Model parameter uncertainty
Vcmax

Bonan et al. (2011) JGR, doi:10.1029/2010JG001593, in press

Gross primary production bias reduction (1982-2004)



Control

Radiative transfer

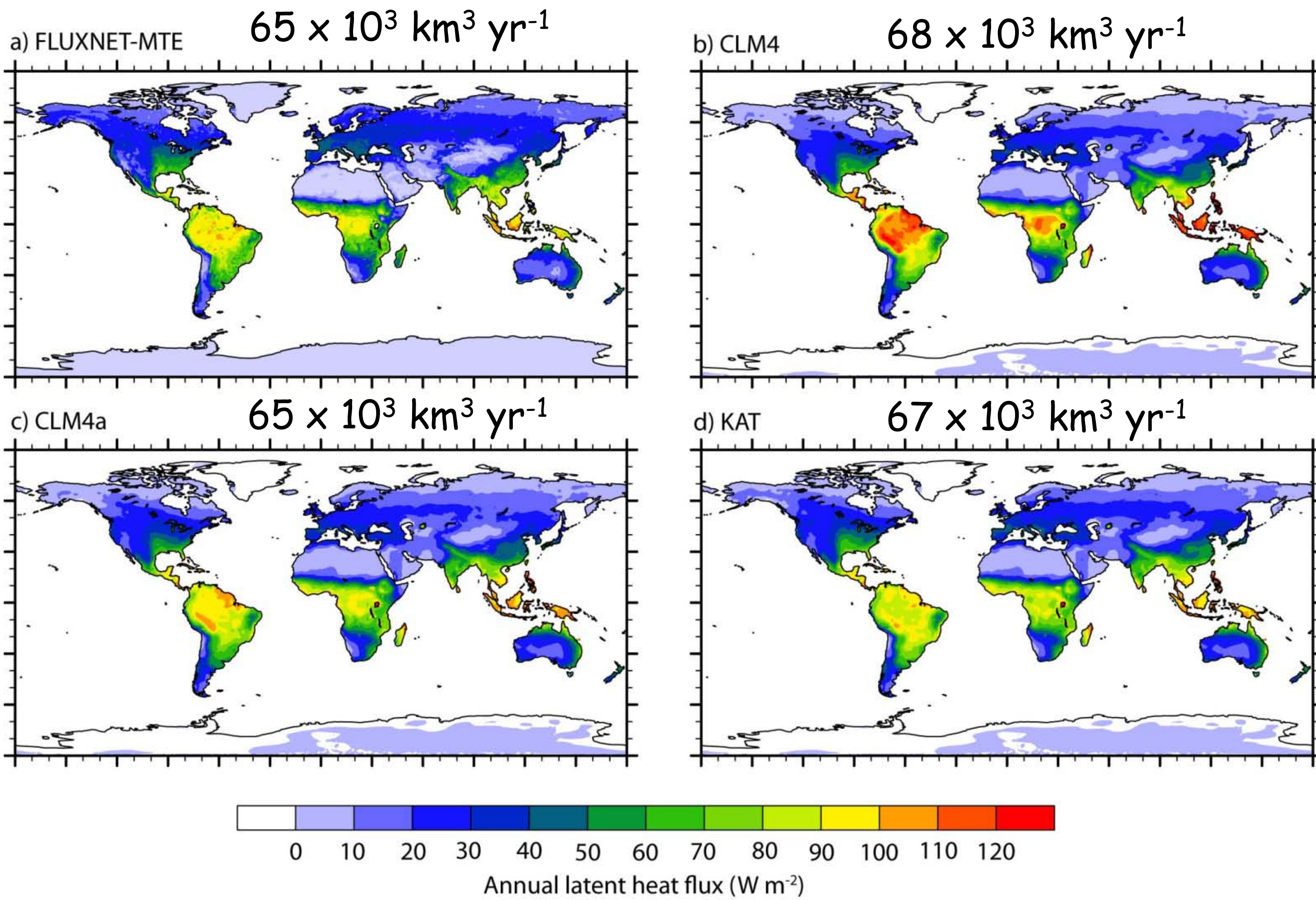
Radiative transfer and photo-synthesis

Model improvements (RAD-PSN [CLM4a]) reduce annual GPP biases in tropics and extra-tropics compared with CLM4. Similar improvements are seen in monthly fluxes.

FLUXNET-MTE data from Martin Jung and Markus Reichstein (M-P-I Biogeochemistry)

Bonan et al. (2011) JGR, doi:10.1029/2010JG001593, in press

Improved annual latent heat flux



Vcmax sensitivity

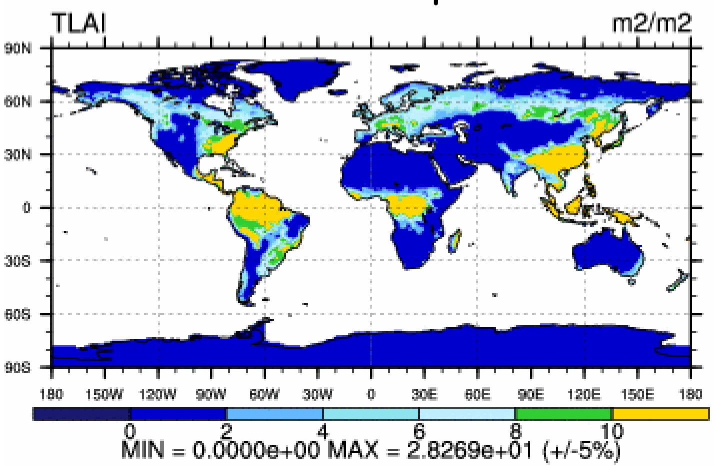
Model improvements (CLM4a) reduce ET biases, especially in tropics, and improve monthly fluxes

Bonan et al. (2011) JGR, doi:10.1029/2010JG001593, in press

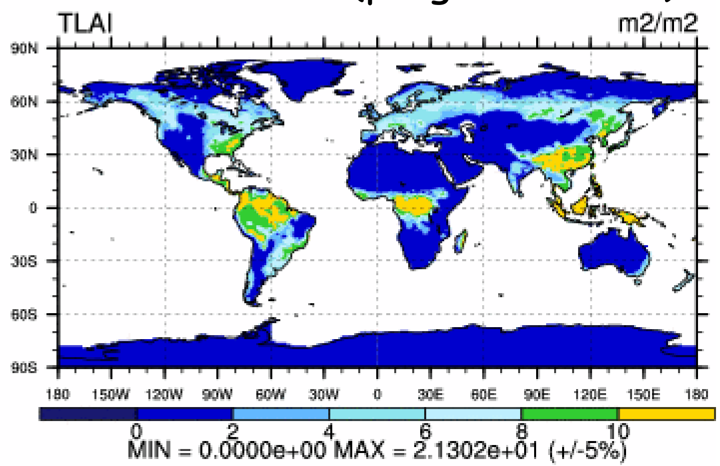
Is the model not obviously wrong?

Simulated leaf area index (Jun, Jul, Aug)

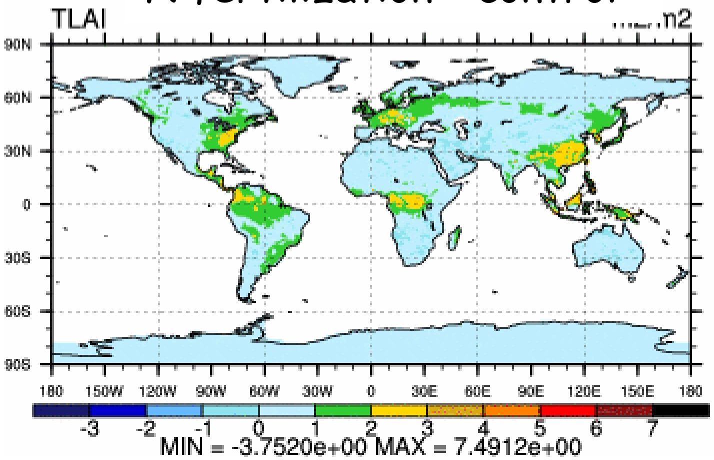
N fertilization experiment

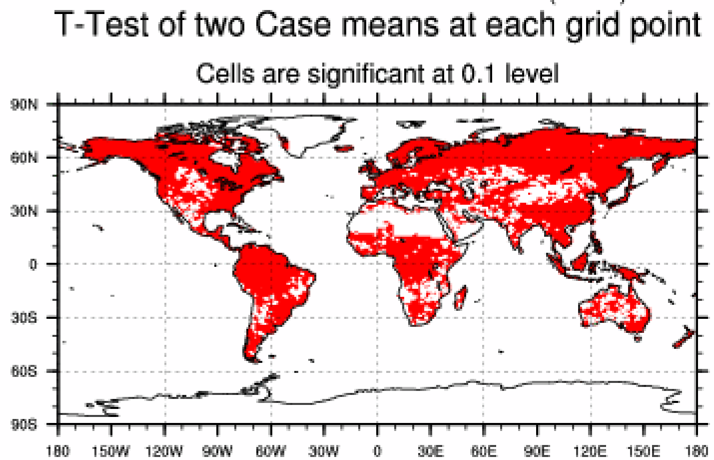


CLM4 control (prognostic LAI)



N fertilization - control

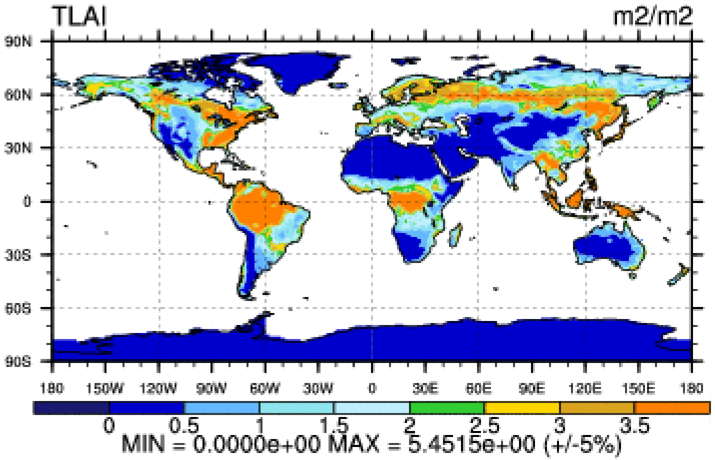




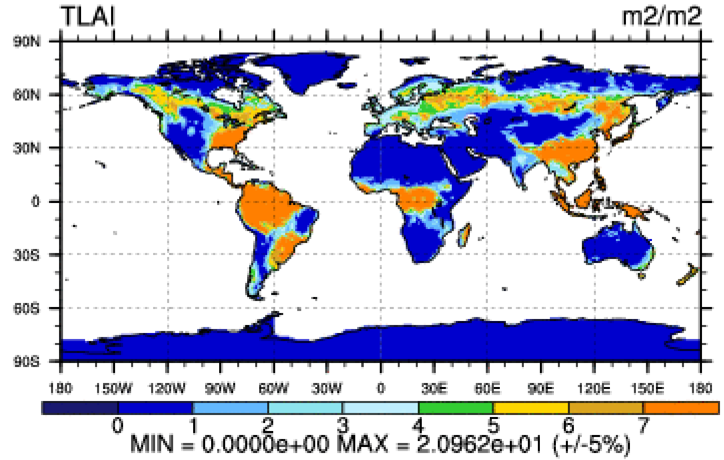
Is the model obviously better?

Satellite LAI

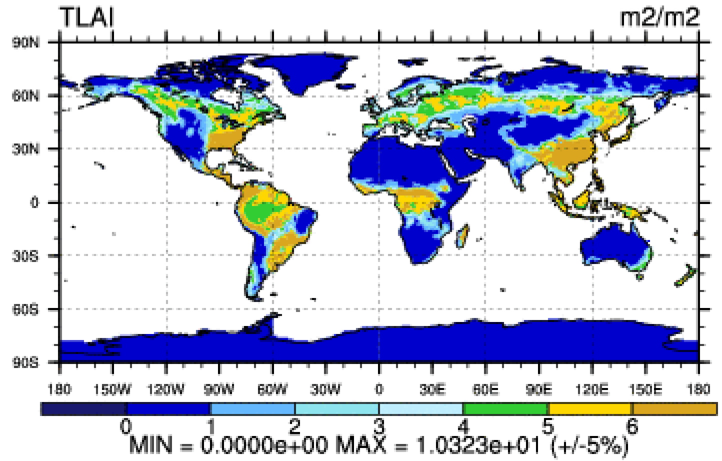
CLM4 MODIS LAI



CLM4 control (prognostic LAI)



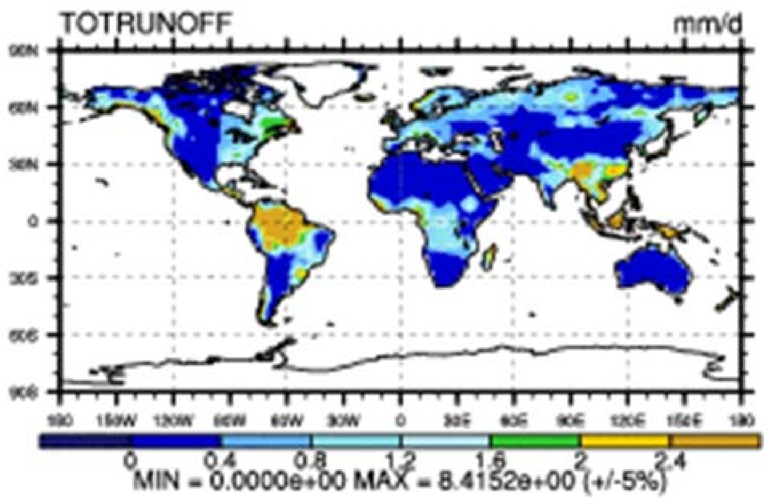
CLM4 – improved canopy



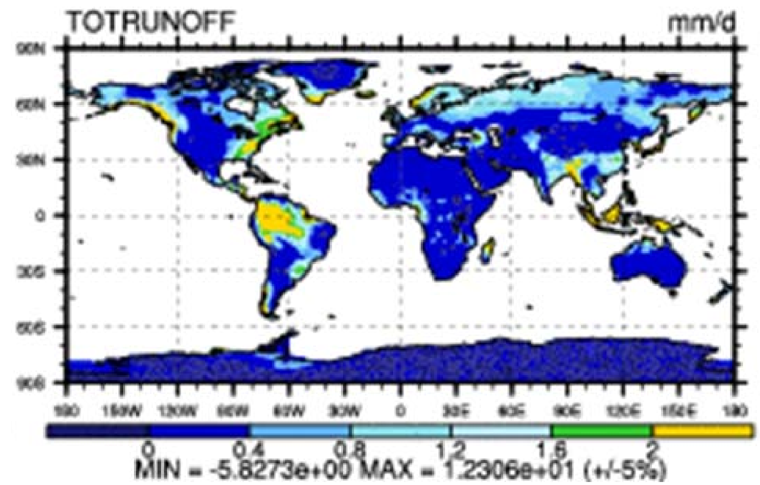
Prognostic LAI

Better LAI leads to improved hydrology

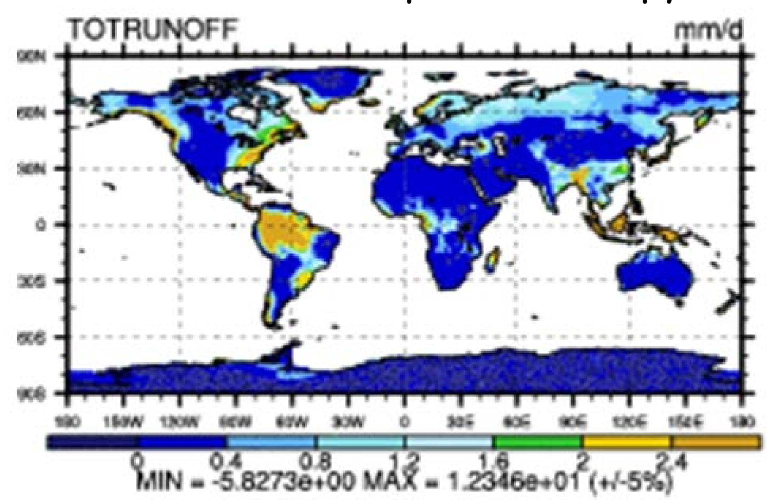
GRDC



CLM4 control



CLM4 – improved canopy



- CLM4 – High LAI leads to high ET and low runoff
- Improved canopy – Lower LAI leads to less ET and more runoff

Conclusions

Integrated ecology, biogeochemistry, and hydrology

Cannot evaluate the carbon cycle independent of the hydrologic cycle, or vice versa, and must also consider N (and P) cycles

How do we further advance earth system models?

Move beyond model experimentation that diagnoses model behavior and towards parameterization or structural experimentation to understand model responses

Do not just report how a model responds to a perturbation; report why it responds as it does

To do this requires:
Model structure and parameterizations grounded in theory
Strong understanding of the consequences of different theories
Key model experiments and datasets to critically assess the model