A dynamic boundary: The impacts & feedbacks of land cover change on atmospheric moisture and energy

Justin Bagley
November 30, 2011

Why study land cover change?

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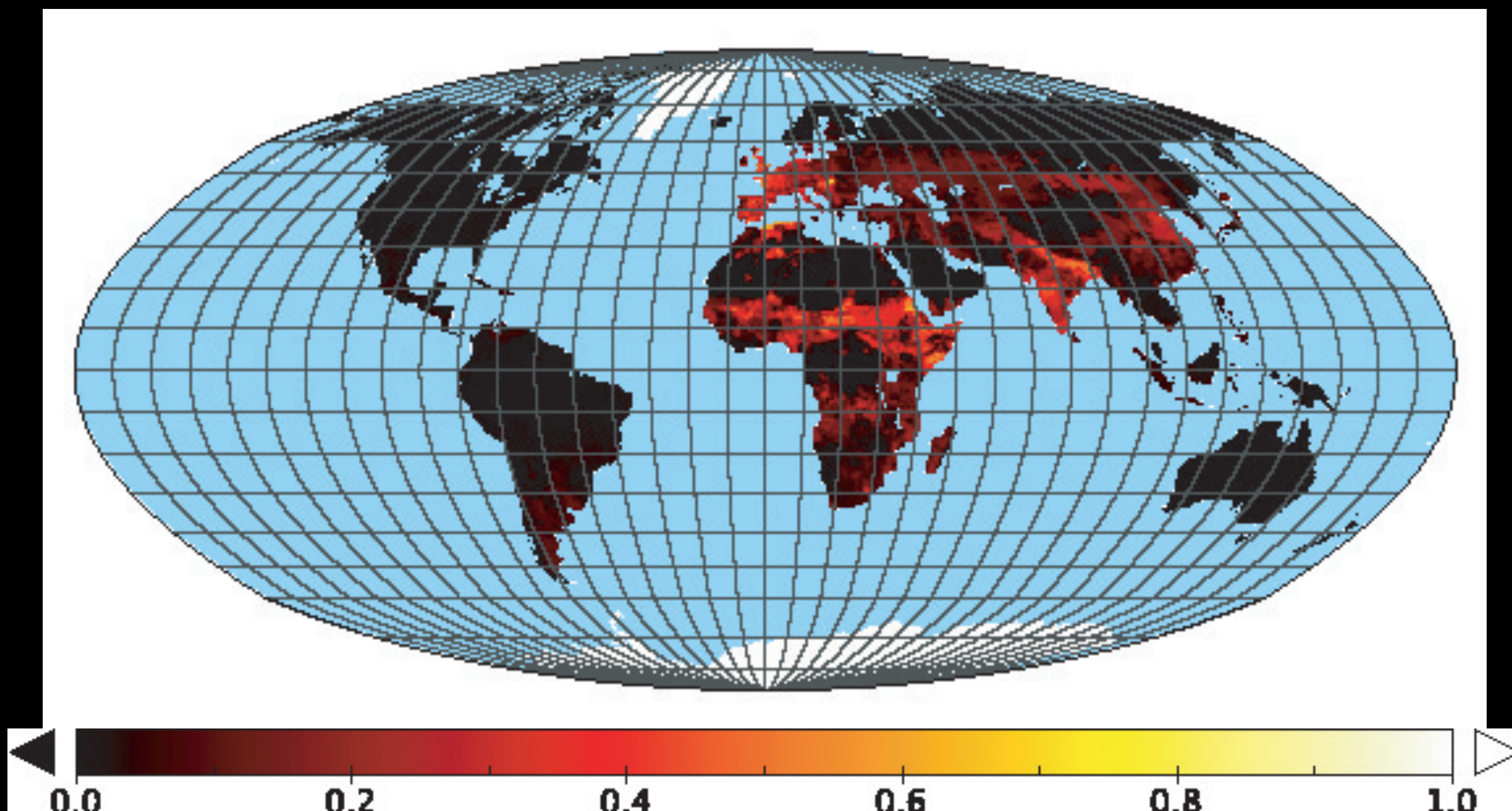
BHAS:

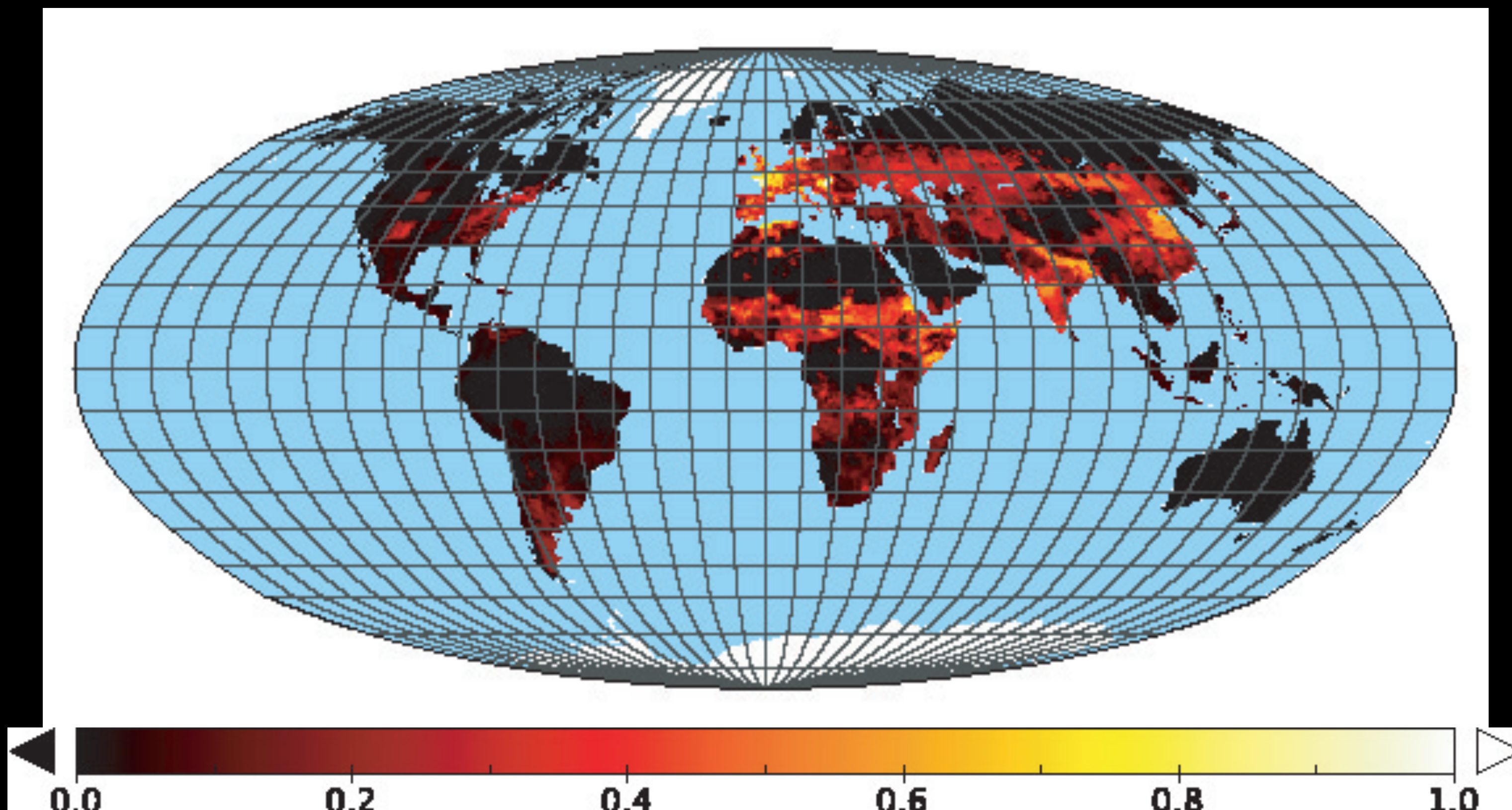
Agriculture and the land cover change that accompanies it, has had and continues to have the single largest environmental impact of any human endeavor

How have we changed the earth's surface?



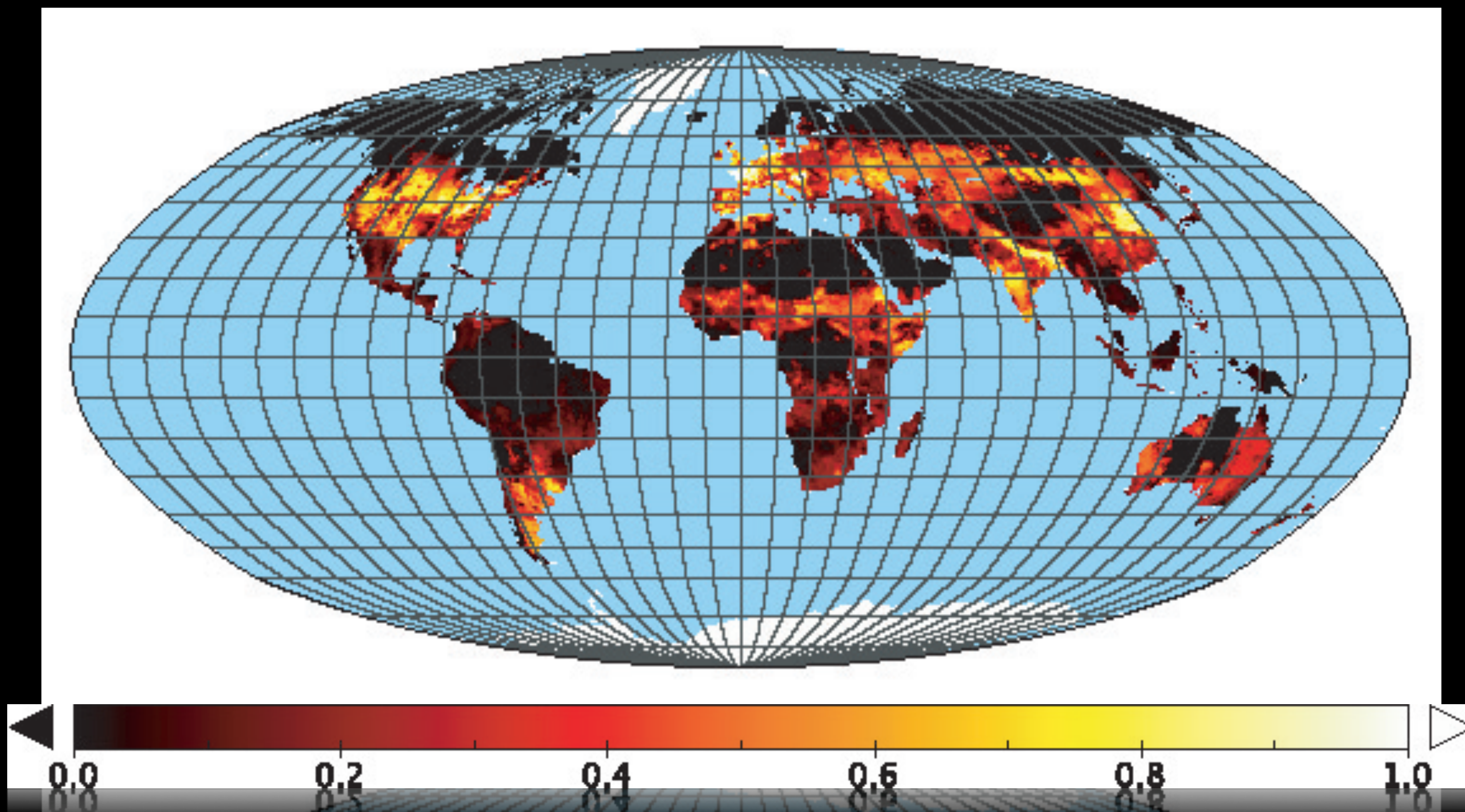
1700

How have we changed the earth’s surface?



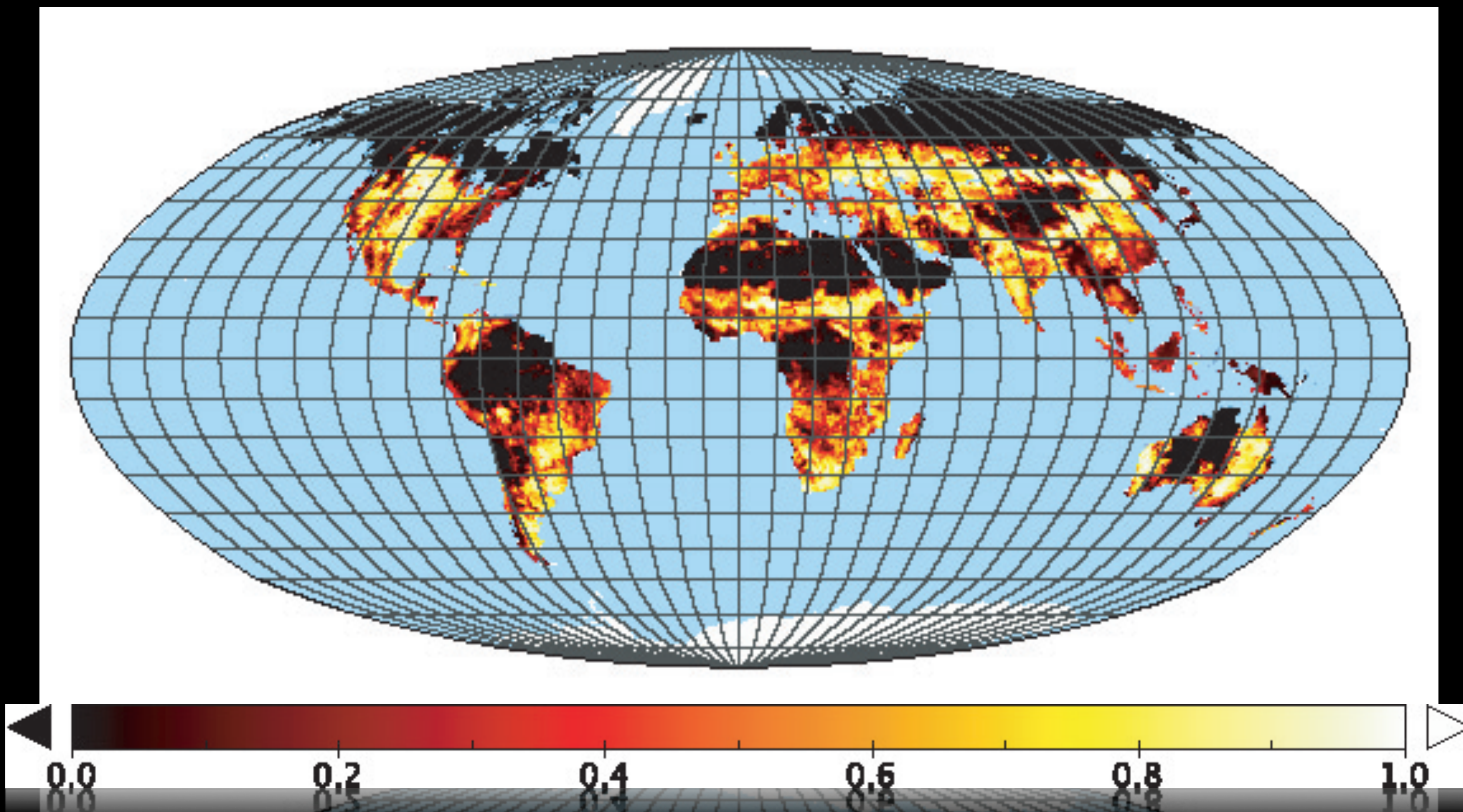
1800

How have we changed the earth's surface?



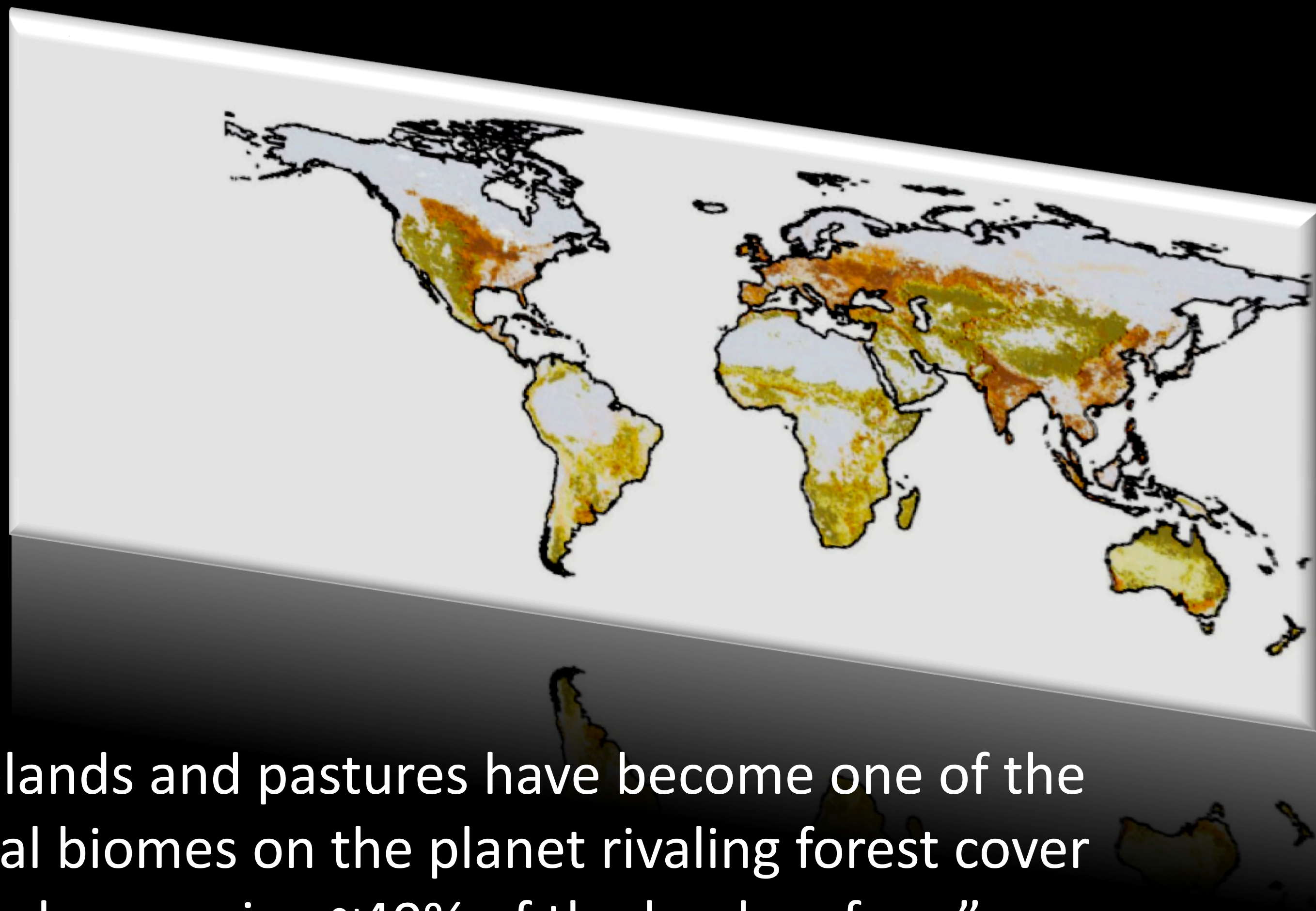
1900

How have we changed the earth's surface?



2000

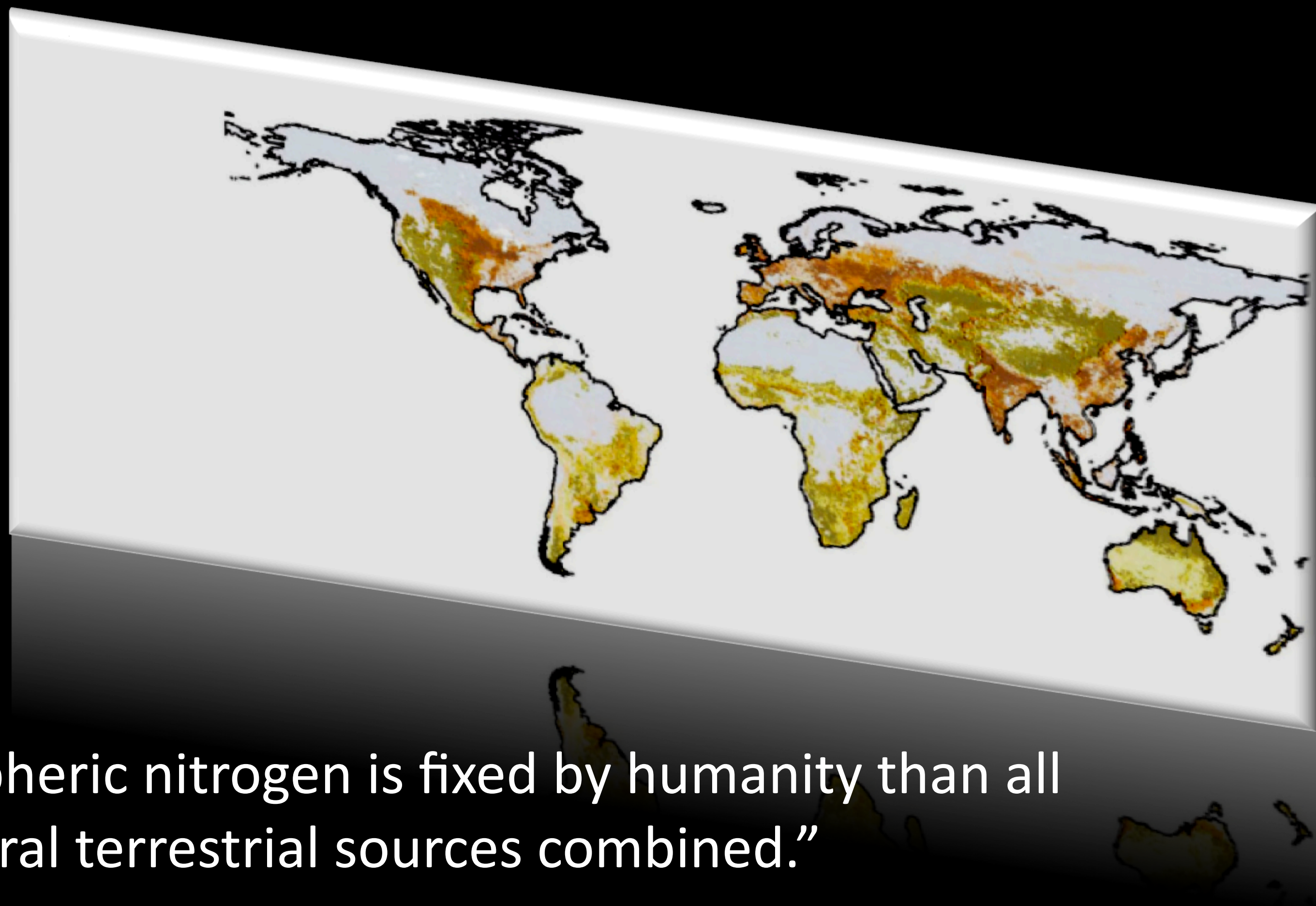
How extensive is our current management of ecosystems?



"Together, croplands and pastures have become one of the largest terrestrial biomes on the planet rivaling forest cover in extent and occupying ~40% of the land surface."

Foley et al. 2005

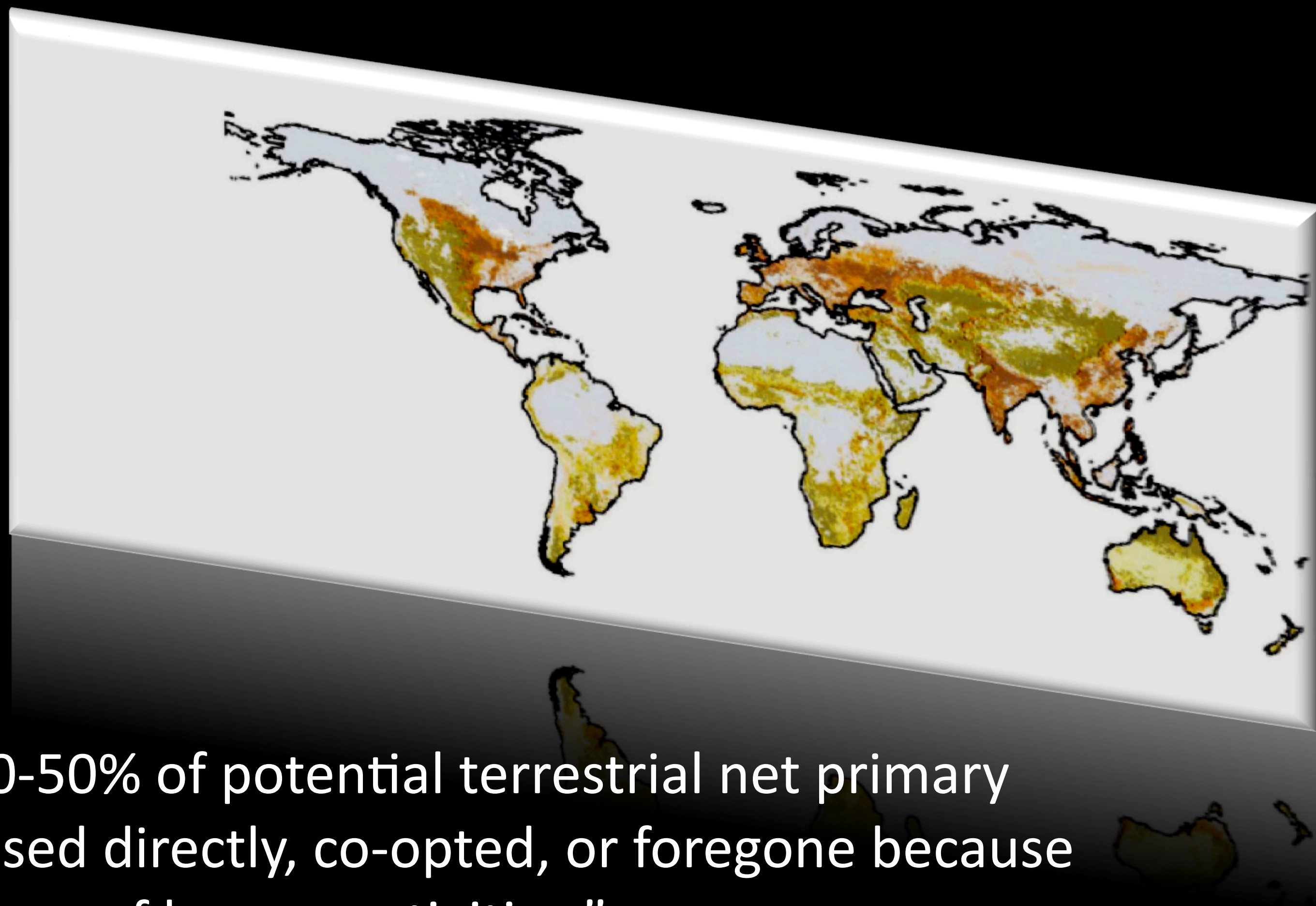
How extensive is our current management of ecosystems?



"More atmospheric nitrogen is fixed by humanity than all natural terrestrial sources combined."

Vitousek et al. 1997

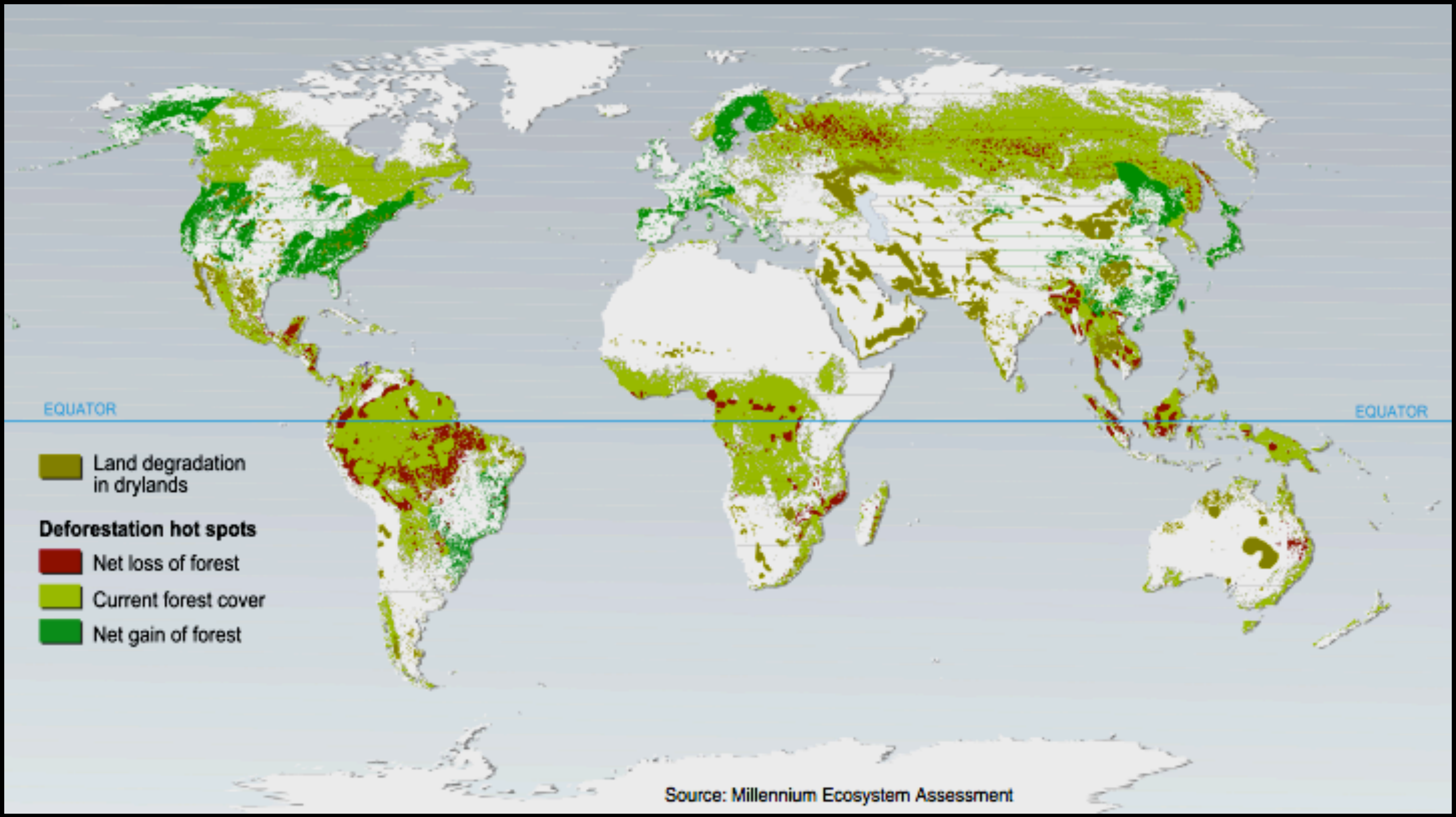
How extensive is our current management of ecosystems?



"Between 30-50% of potential terrestrial net primary production is used directly, co-opted, or foregone because of human activities."

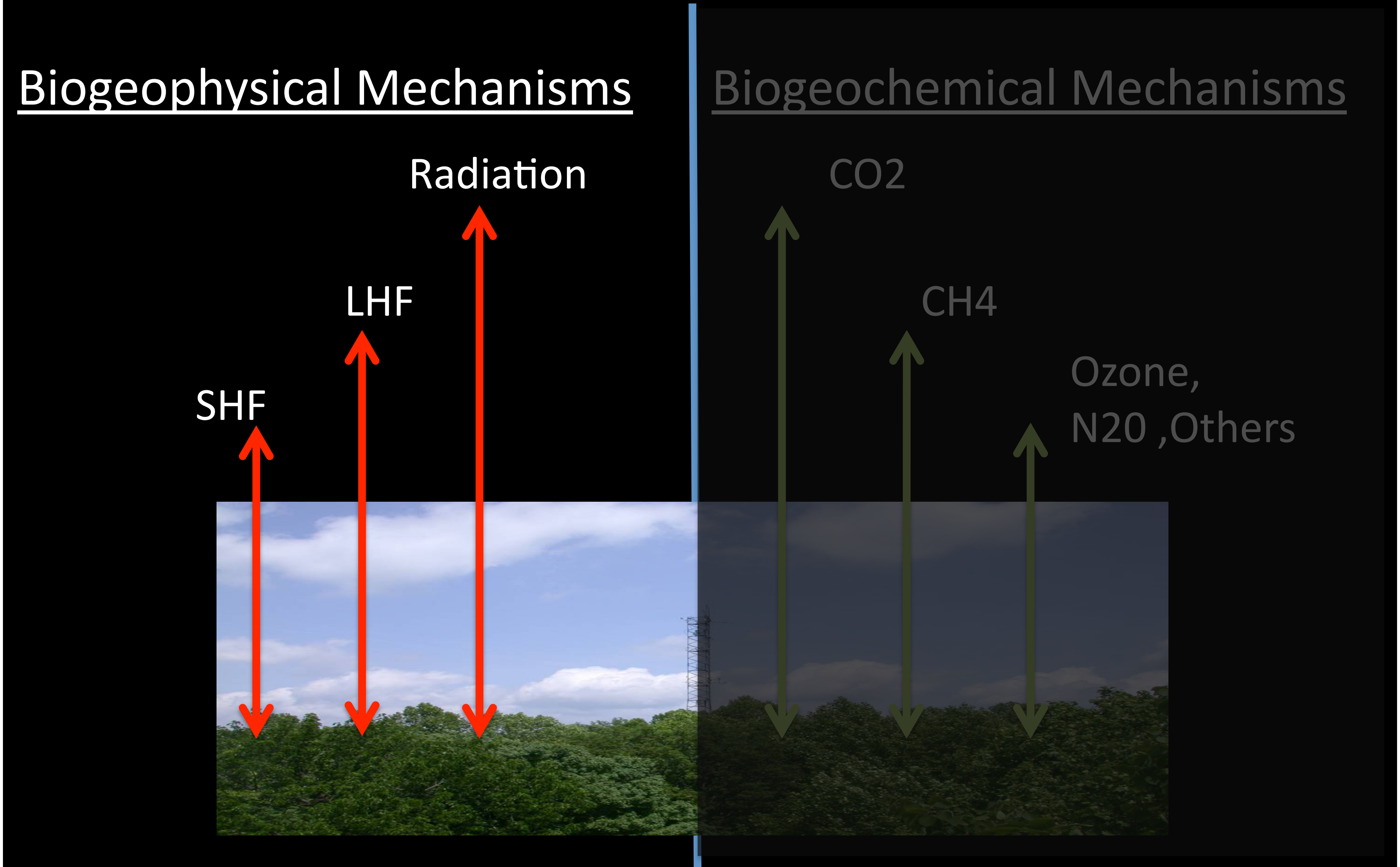
Vitousek et al. 1986

How is the land currently changing?



How do these changes impact the atmosphere?

How does land use/cover impact the atmosphere and local climate?



Specific study questions

1. **To what extent does vegetation** *regulate* **local climate?**

Specific study questions

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2. **What are the impacts of tropical deforestation on *hydrology* under natural variability?**

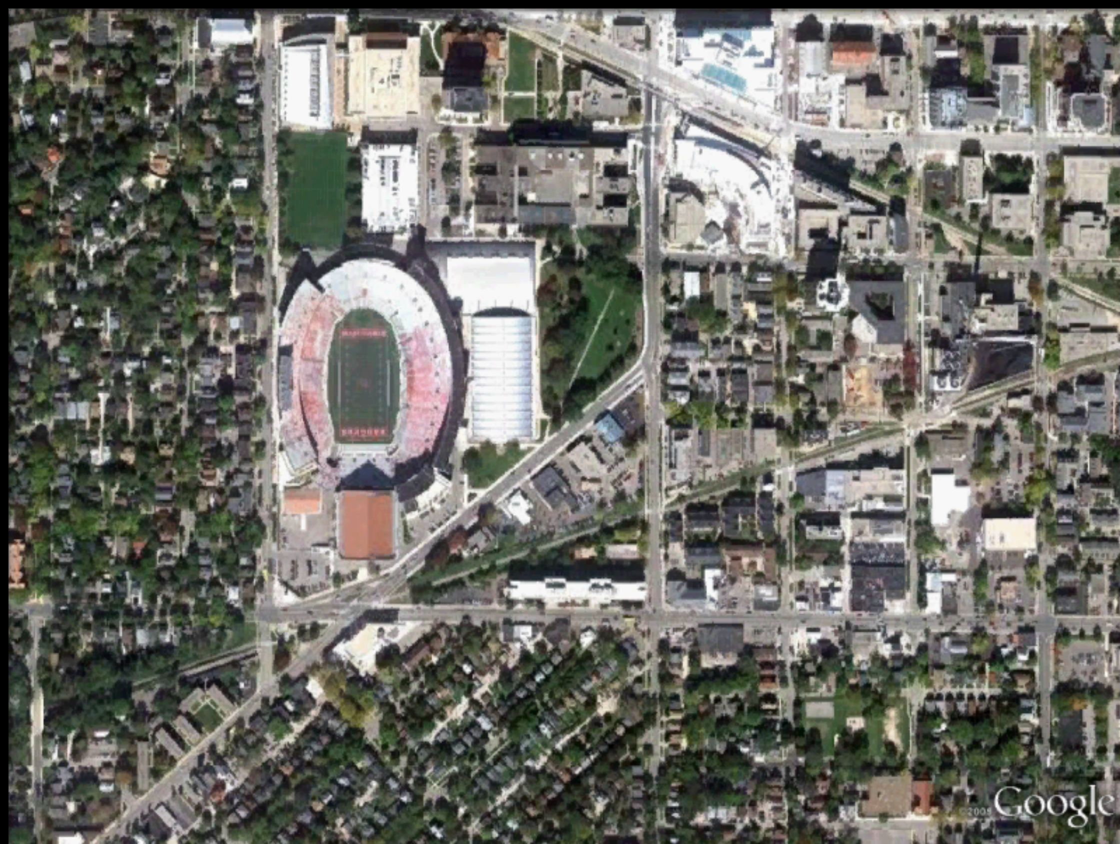
Specific study questions

1. To what extent does vegetation *regulate* local climate?

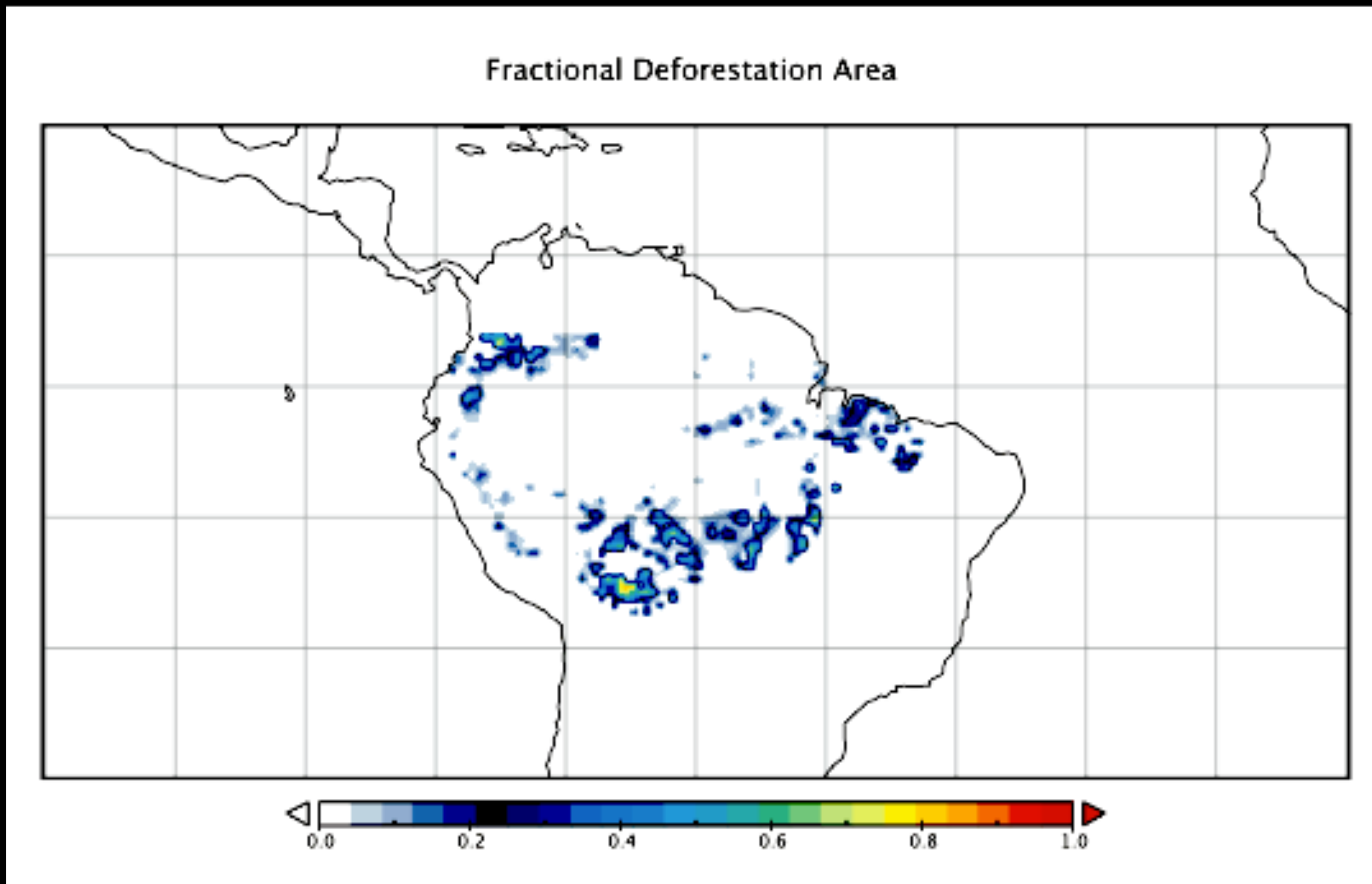
2. What are the impacts of tropical deforestation on *hydrology* under natural variability?

3. **What is the potential impact of land cover change on *precipitation* and *crop yield* in the world's breadbaskets?**

Let’s begin by taking a trip to the Amazon



Current extent of tropical deforestation in Amazon



Deforestation

Question:

How does deforestation impact moisture and energy in the region?

Haven't I heard about that one before???

Xu, L., et al. (2011), Widespread decline in greenness of Amazonian vegetation due to the 2010 drought, Geophys. Res. Lett., 38, L07402, doi:10.1029/2011GL046824.

Anderson, R. G., *et al.* (2010), Biophysical considerations in forestry for climate protection, *Frontiers in Ecology and the Environment*.

Yoon, J. H. and N. Zeng (2010), An Atlantic influence on Amazon rainfall, *Clim. Dyn., 34,* 249-264.

Aragão, Luiz Euardo O. C., et al. (2007), Spatial patterns and fires response of recent Amazonian droughts, *Geo. Res. Let., 34,* doi:10.1029/2006GL028946.

Walker, R., et al. (2009), Protecting the Amazon with protected areas, *PNAS, 106,* 10582-10586.

Baidya Roy, S., and R. Avissar (2002), Impact of land use/ land cover change on regional hydrometeorology in Amazonia, *J. of Geophys. Res., 107,* DOI 10.1029/2000JD000266.

Bala, G., et al. (2007), Combined climate and carbon-cycle effects of large-scale deforestation, *Proceedings of the National Academy of Sciences, 104*, 6550-6555.

Coe, M. T., E. M. Latrubesse, M. E. Ferreira and M.L. Amsler (2011), The effects of deforestation and climate variability on the streamflow of the Araguaia River, Brazil. *Biogeochemistry*, DOI 10.1007/s10533-011-9582-2

Snyder, P., et al. (2004), Evaluating the influence of different vegetation biomes on the global climate, *Climate Dynamics, 23,* 279-302.

Saleska, S. R., et al. (2007), Amazon forests green-up during 2005 drought, *Science, 318*, 612, doi:10.1126/science.1146663.

Costa, M. H., and J. A. Cardille (2003), Effects of large-scale changes in land cover on the discharge of the Tocantins River, southeastern Amazonia. *J. Hydrol., 283,* 206-217.

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Culf, A., *et al.* (1996), Radiation, temperature and humidity over forest and pastures in Amazonia., in *Amazonian Deforestation and Climate*, edited by J. Gash, *et al.*, pp. 175-192, John Wiley & Sons, Chichester.

Marengo, J. A. (2004), Interdecadal variability and trends of rainfall across the Amazon basin, *Theor. Appl. Cliatol., 78,* 79-96.

D'almeida, C., et al., (2007), The effects of deforestation on the hydrological cycle in

Important fact

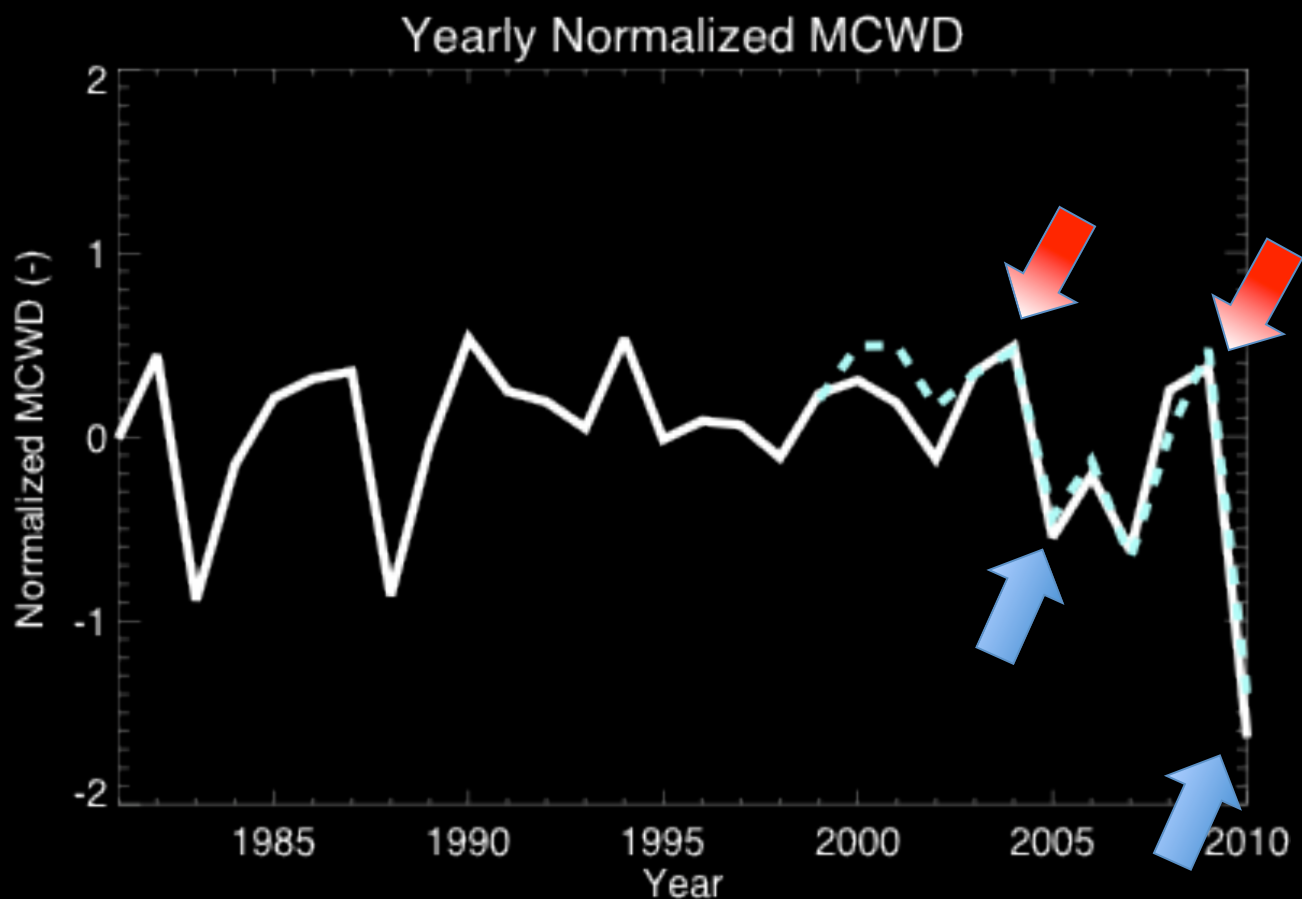
The Southern Amazon has experienced two “once in a century” level droughts in the last decade, and one major flood.



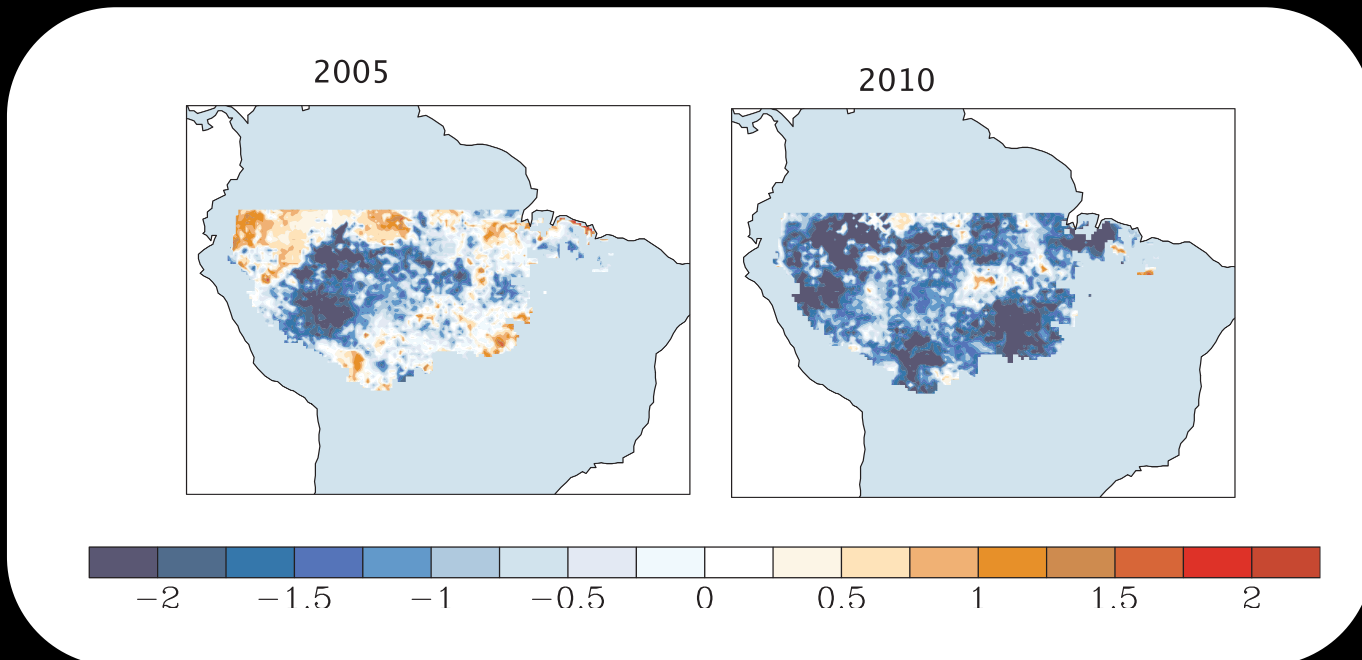

Revised question:

How does the impact of deforestation on moisture and energy in the Amazon region change under varied precipitation regimes?

A history of drought and floods in the Southern Amazon



Spatial patterns of droughts in the Southern Amazon

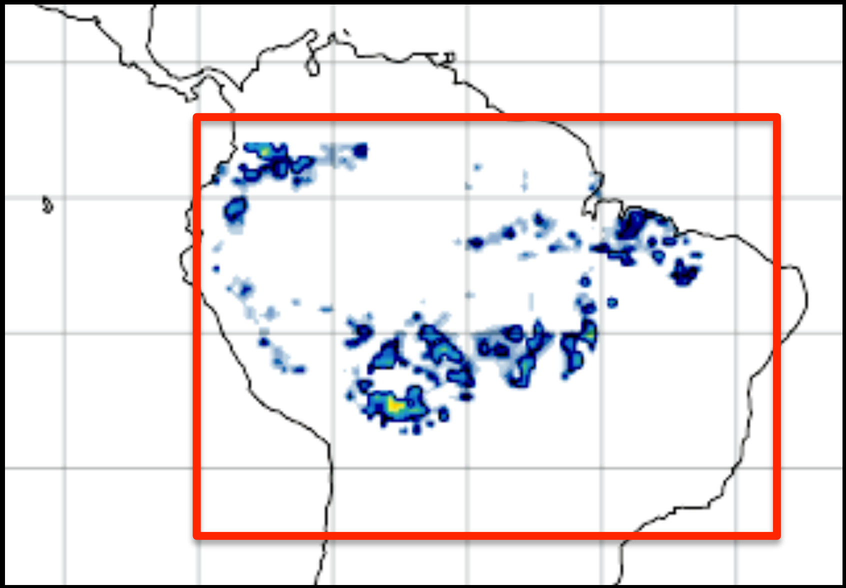


TRMM observed normalized MCWD for drought years of 2005 and 2010

Basic Experimental Setup

Goal:	Determine how the impacts of deforestation differ in drought vs. pluvial years
Method:	Use high-res mesoscale model to simulate series of drought and pluvial years with and without modern deforestation
Primary Tool:	WRF-Noah model

WRF-Noah Setup



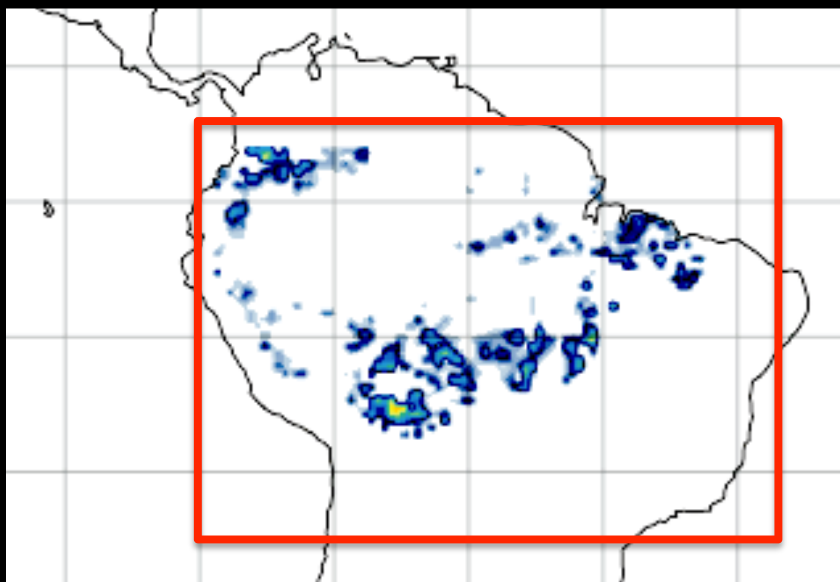
- Spatial Resolution: 20km x 20km

- Timestep: 60 seconds

- For 2003, 2004, 2005, 2007, 2009, and 2010 the model was run from March 15 – October 15 with and without deforestation

- Total of 12 seven-month simulations completed with hourly output

WRF-Noah Setup



- Gridpoints with land use > 50% converted to pasture
- Gridpoints with land use between 5%-50% converted to a forest pasture mix

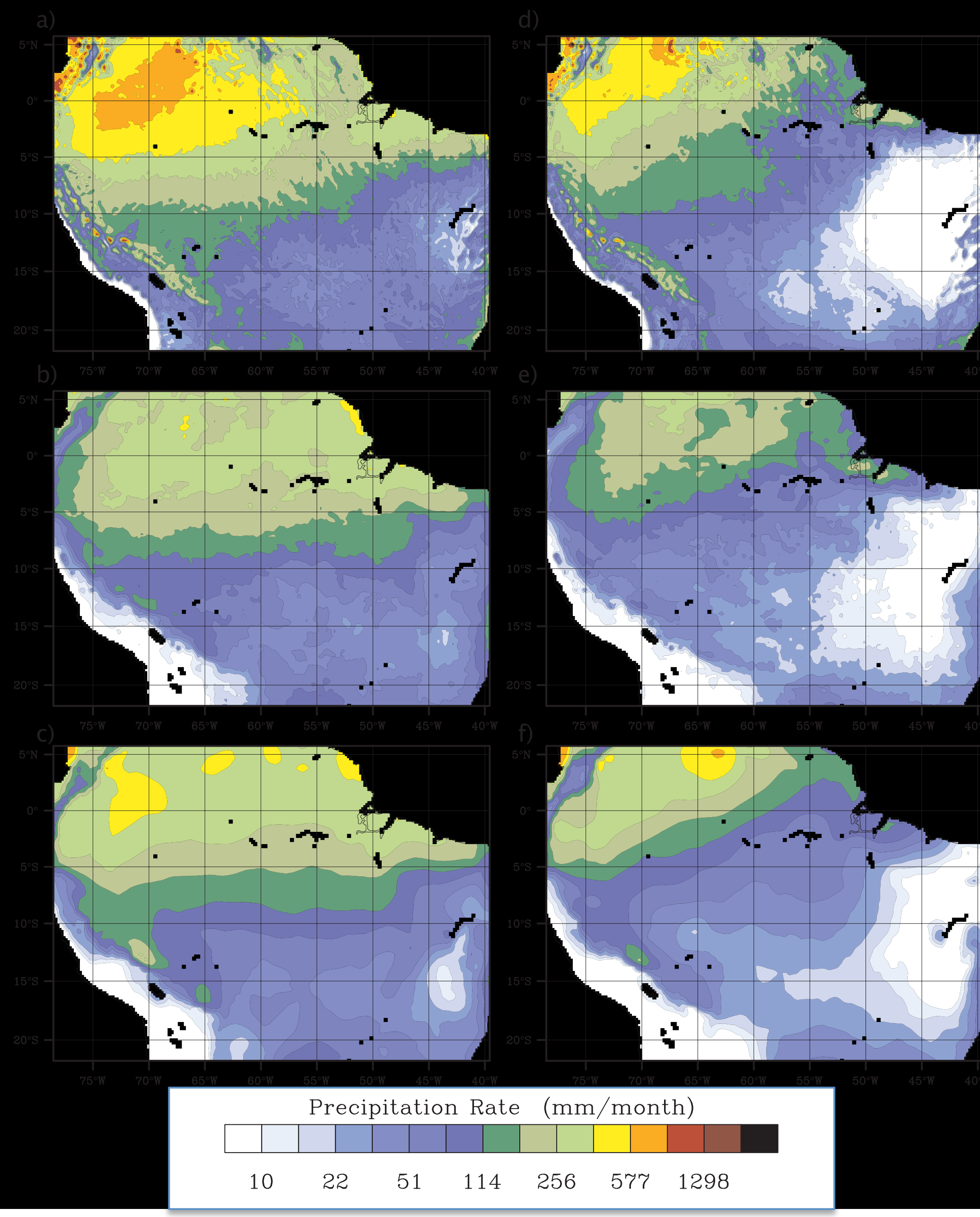
WRF Precip Verification

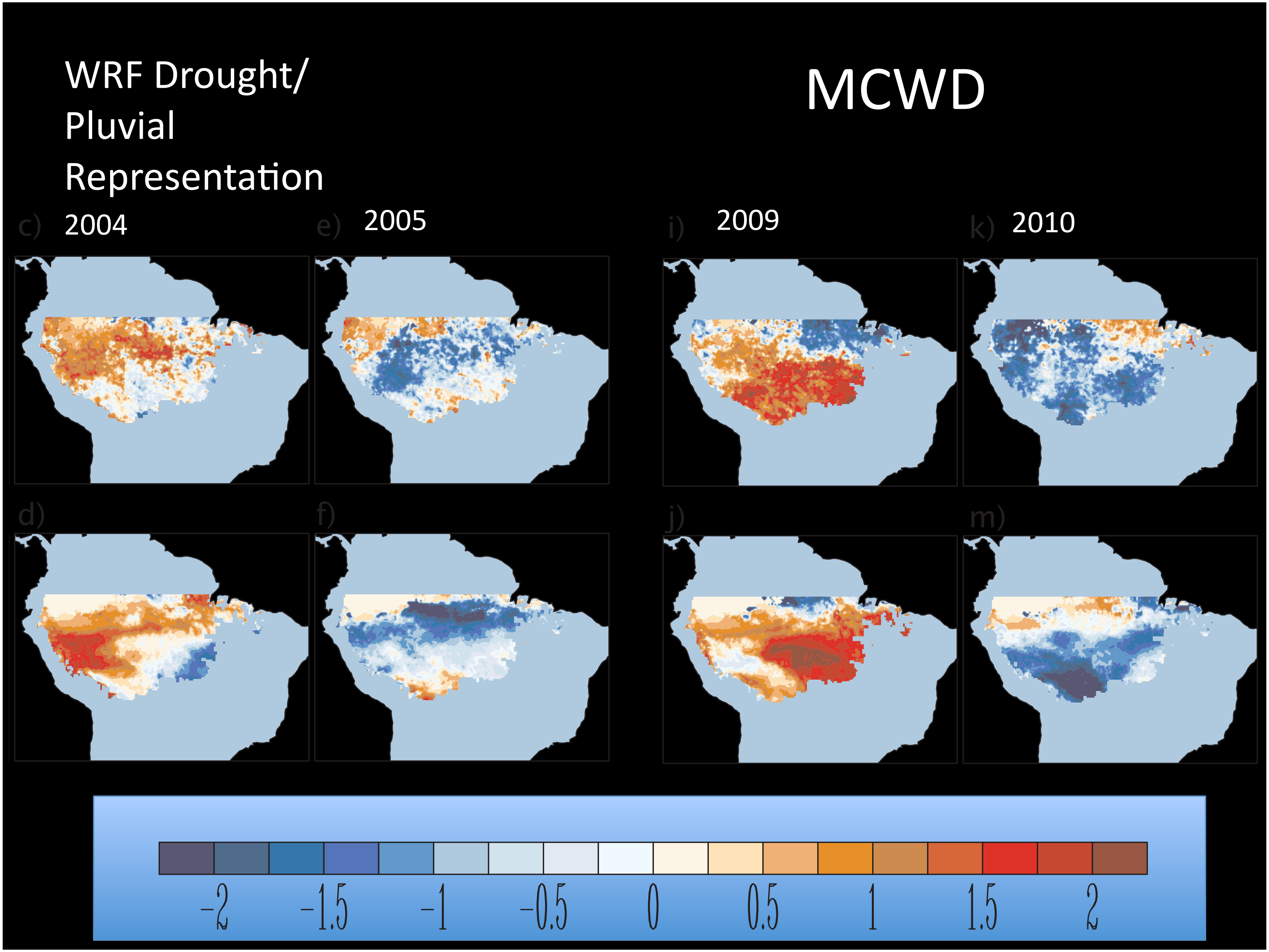
April- June | July - September

WRF-Noah

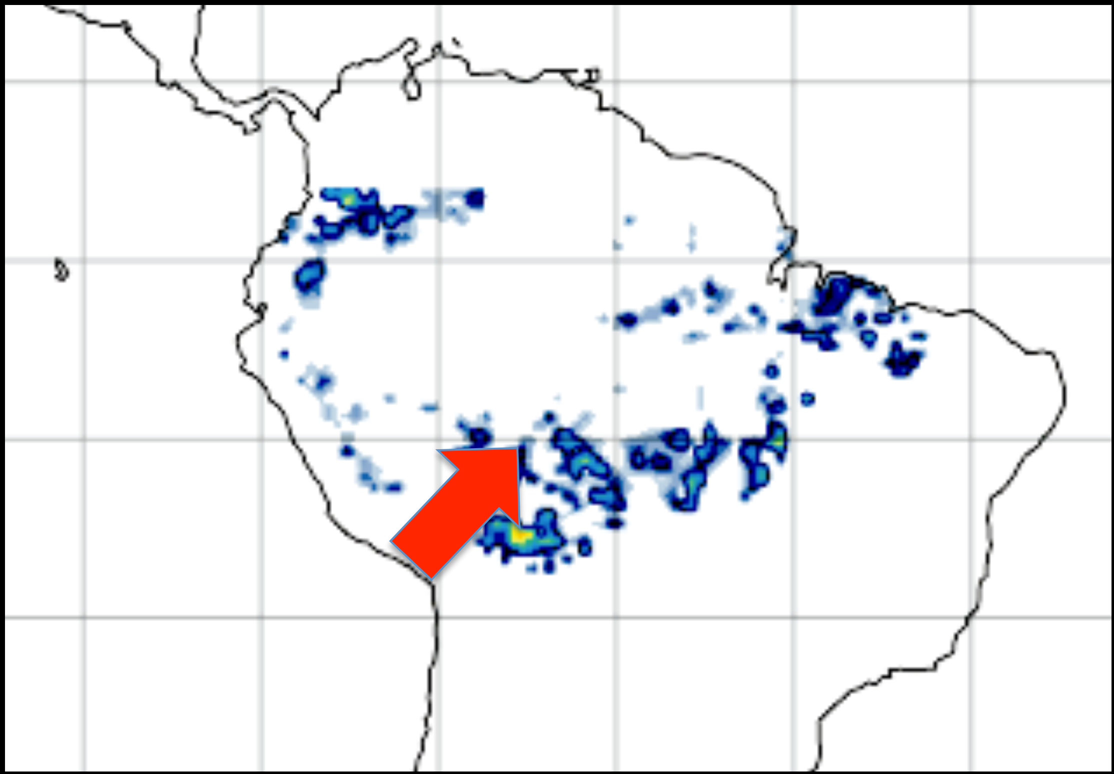
TRMM data

CRU data

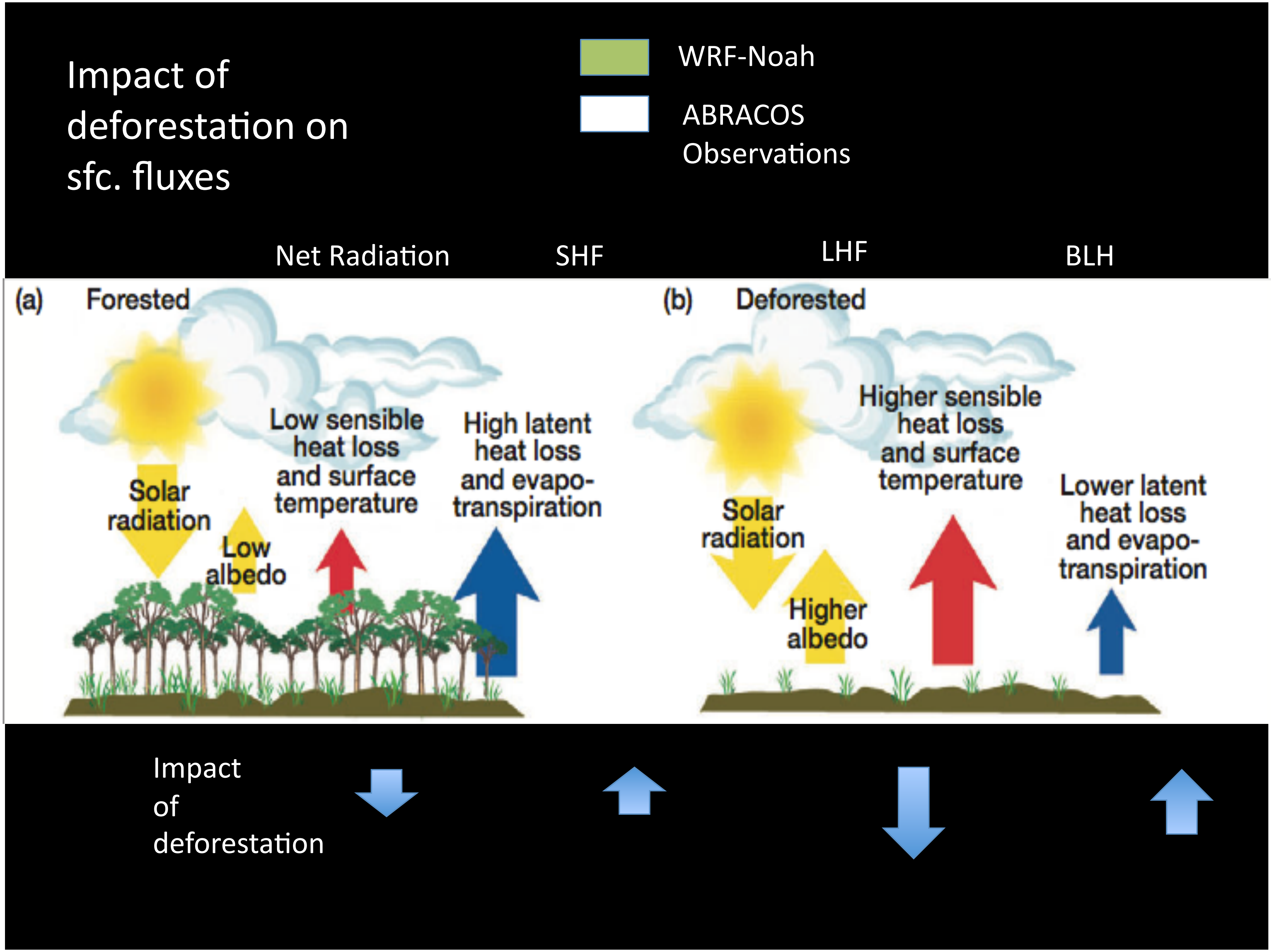



WRF Drought/
Pluvial
Representation
MCWD
c) 2004
e) 2005
i) 2009
k) 2010
d)
f)
j)
m)
−2
−1.5
−1
−0.5
0
0.5
1
1.5
2

Impact on surface fluxes

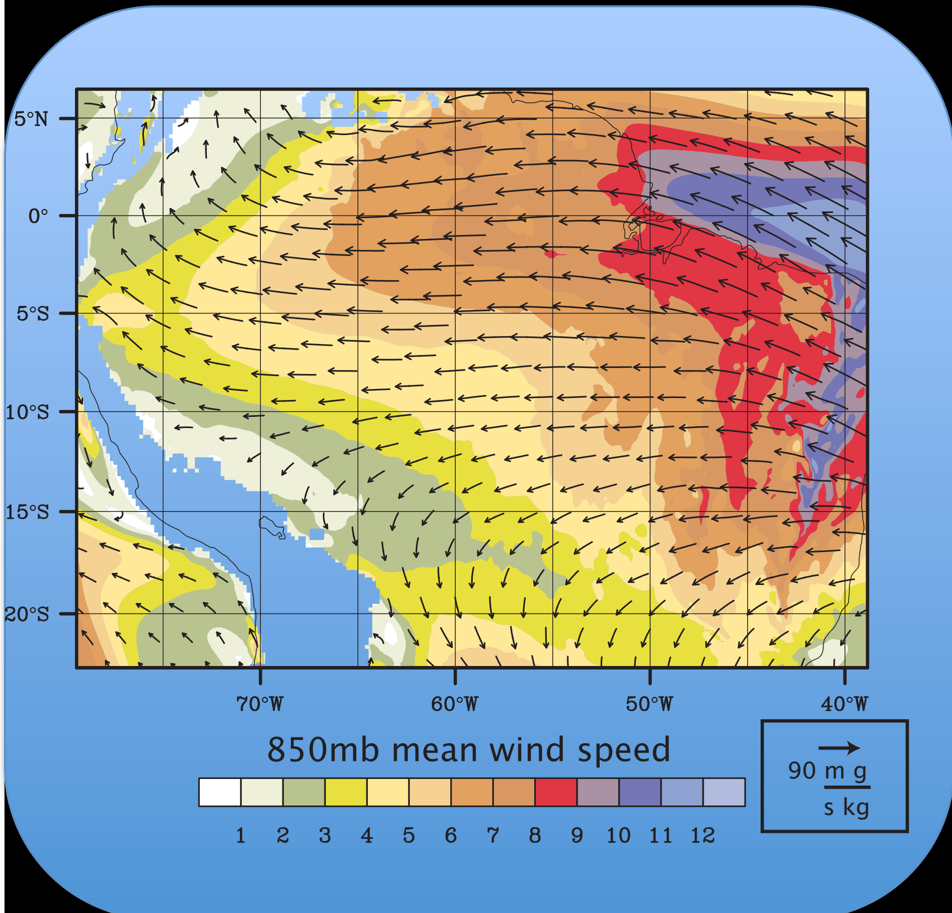


ABRACOS/LBA paired site comparison


Impact of deforestation on sfc. fluxes
WRF-Noah
ABRACOS Observations
Net Radiation
SHF
LHF
BLH
(a) Forested
Solar radiation
Low albedo
Low sensible heat loss and surface temperature
High latent heat loss and evapo-transpiration
(b) Deforested
Solar radiation
Higher albedo
Higher sensible heat loss and surface temperature
Lower latent heat loss and evapo-transpiration
Impact of deforestation

Dry Season Circulation Impacts

90 ms^{-1} gH_2O kg^{-1} Moisture flux reference size



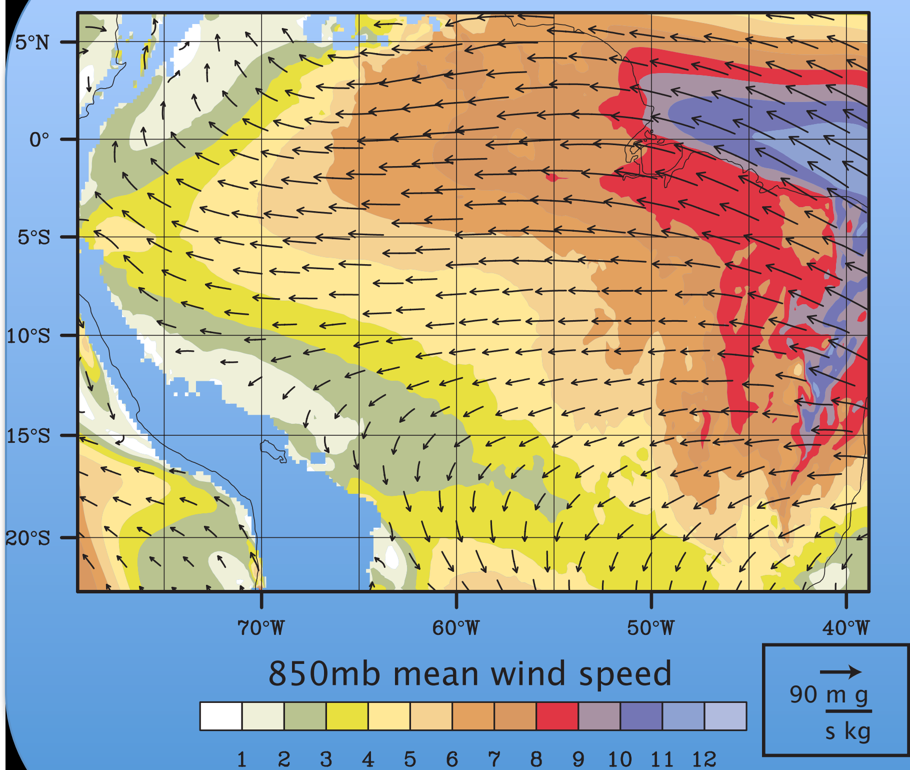
Mean moisture flux and wind speed

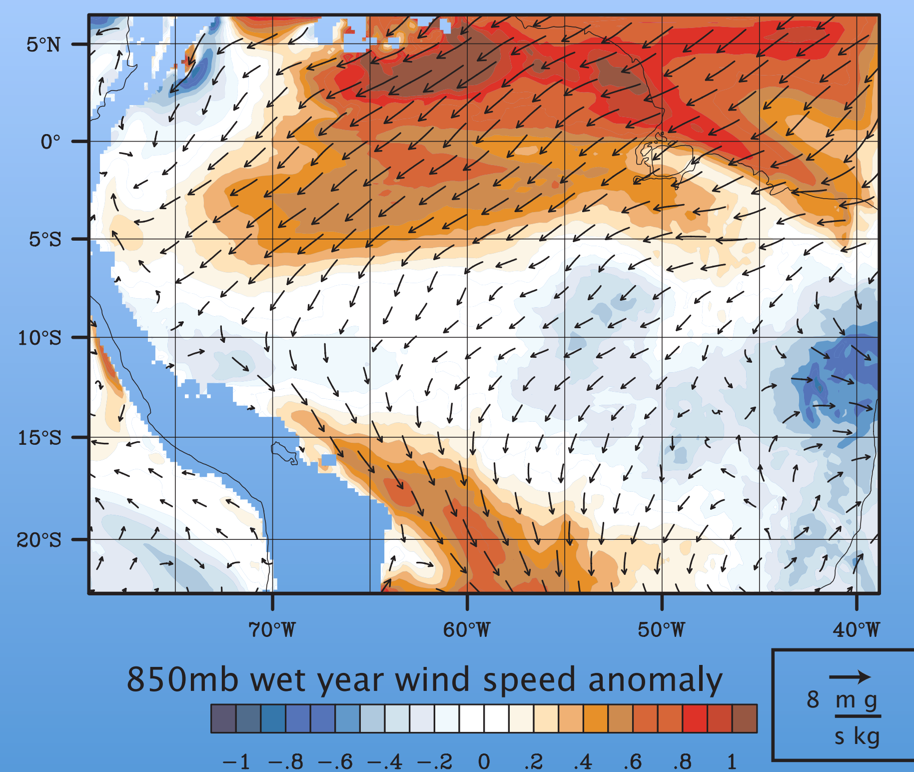
Dry Season Circulation Impacts

$90\ ms^{-1}\ gH_2O\ kg^{-1}$

Moisture flux reference size

$8\ ms^{-1}\ gH_2O\ kg^{-1}$



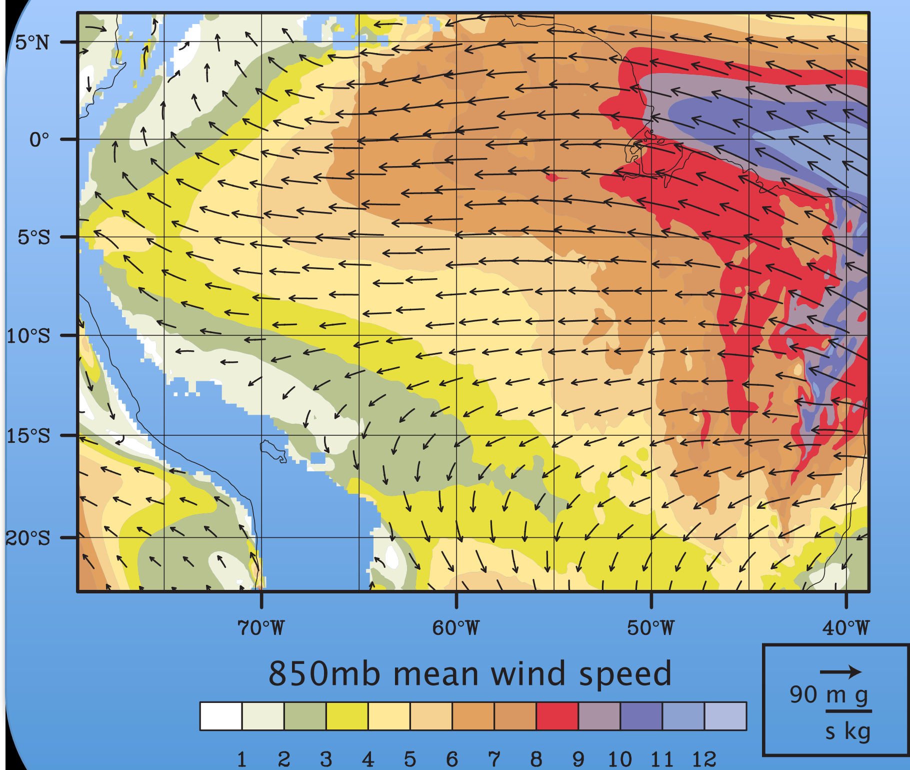


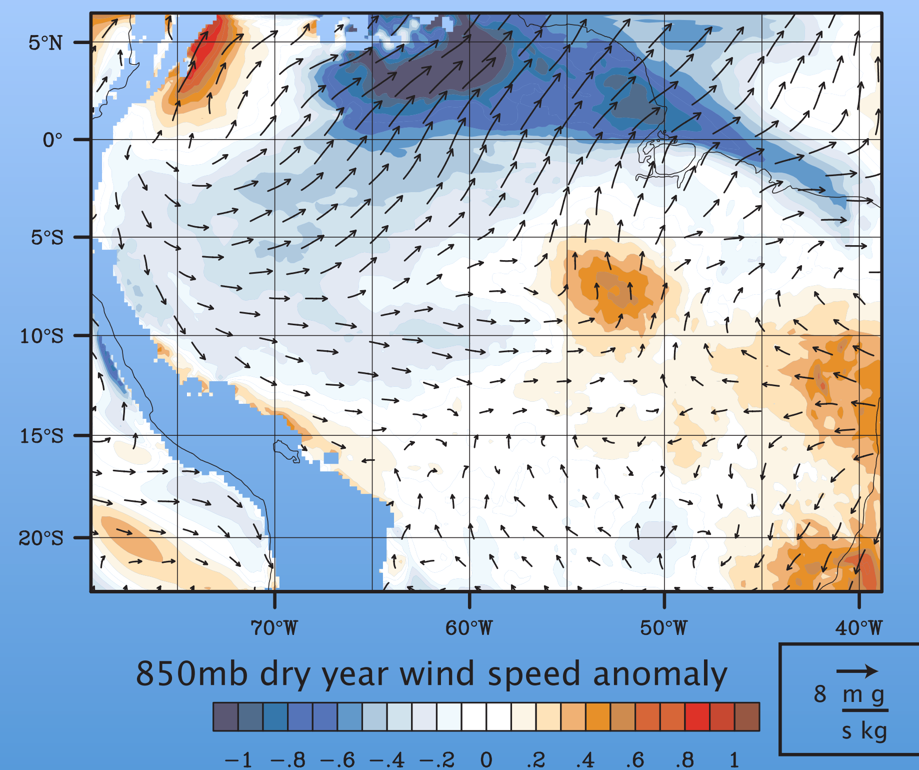
Mean moisture flux
and wind speed

Pluvial year anomaly

Dry Season Circulation Impacts

$90\ ms^{-1}\ gH_2O\ kg^{-1}$ Moisture flux reference size $8\ ms^{-1}\ gH_2O\ kg^{-1}$





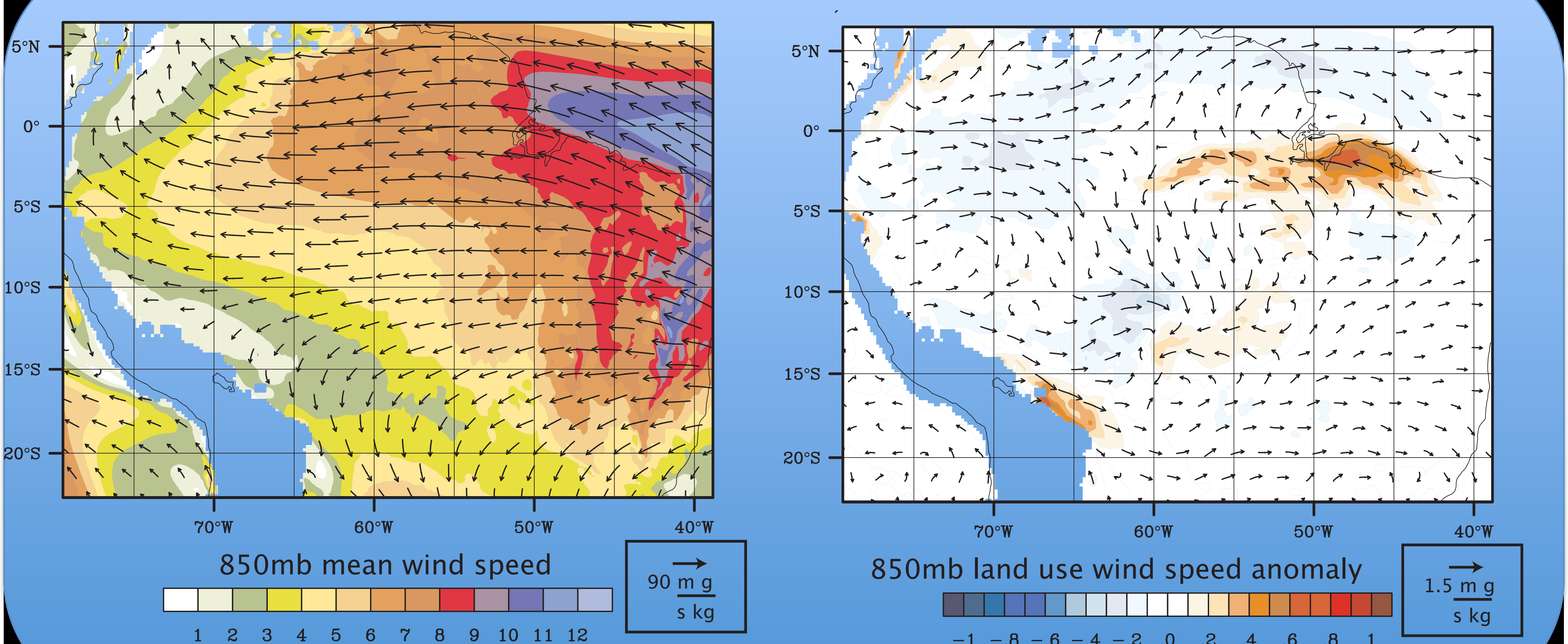
Mean moisture flux and wind speed

Drought year anomaly

Dry Season Circulation Impacts

Moisture flux reference size

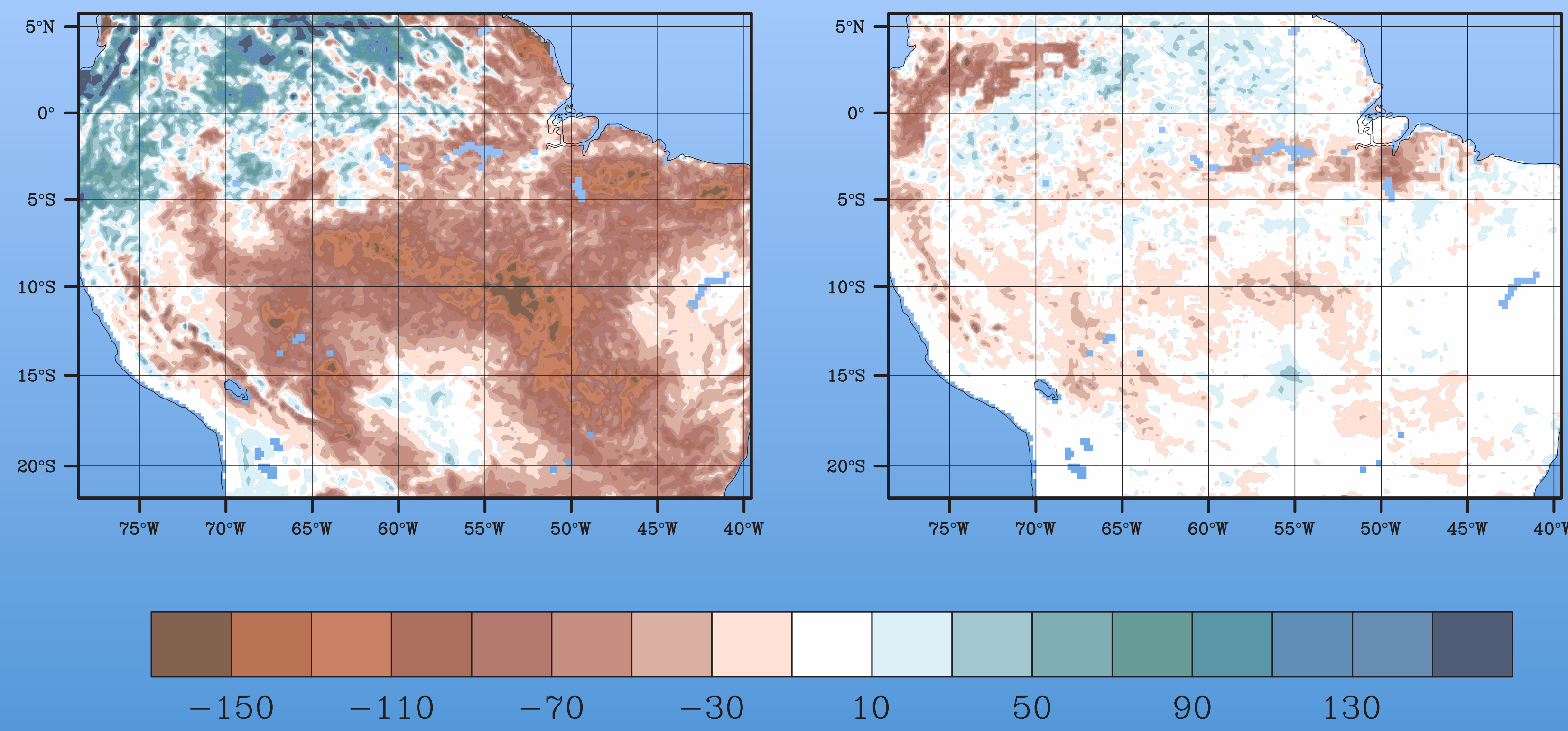
90 ms^{-1} gH_2O kg^{-1} 1.5 ms^{-1} gH_2O kg^{-1}



Mean moisture flux and wind speed

Deforestation perturbation

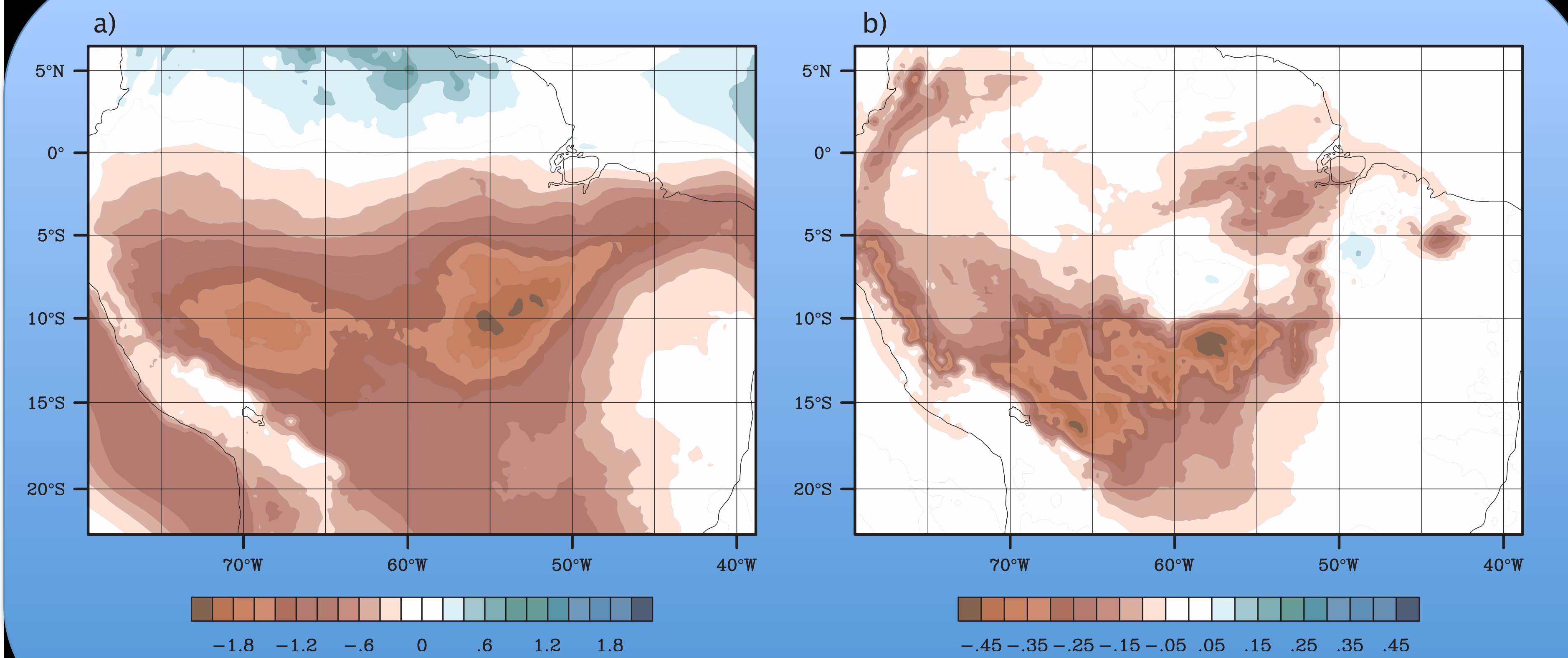
Precipitation Rate (mm/month)



Dry Season Anomaly

Deforestation perturbation

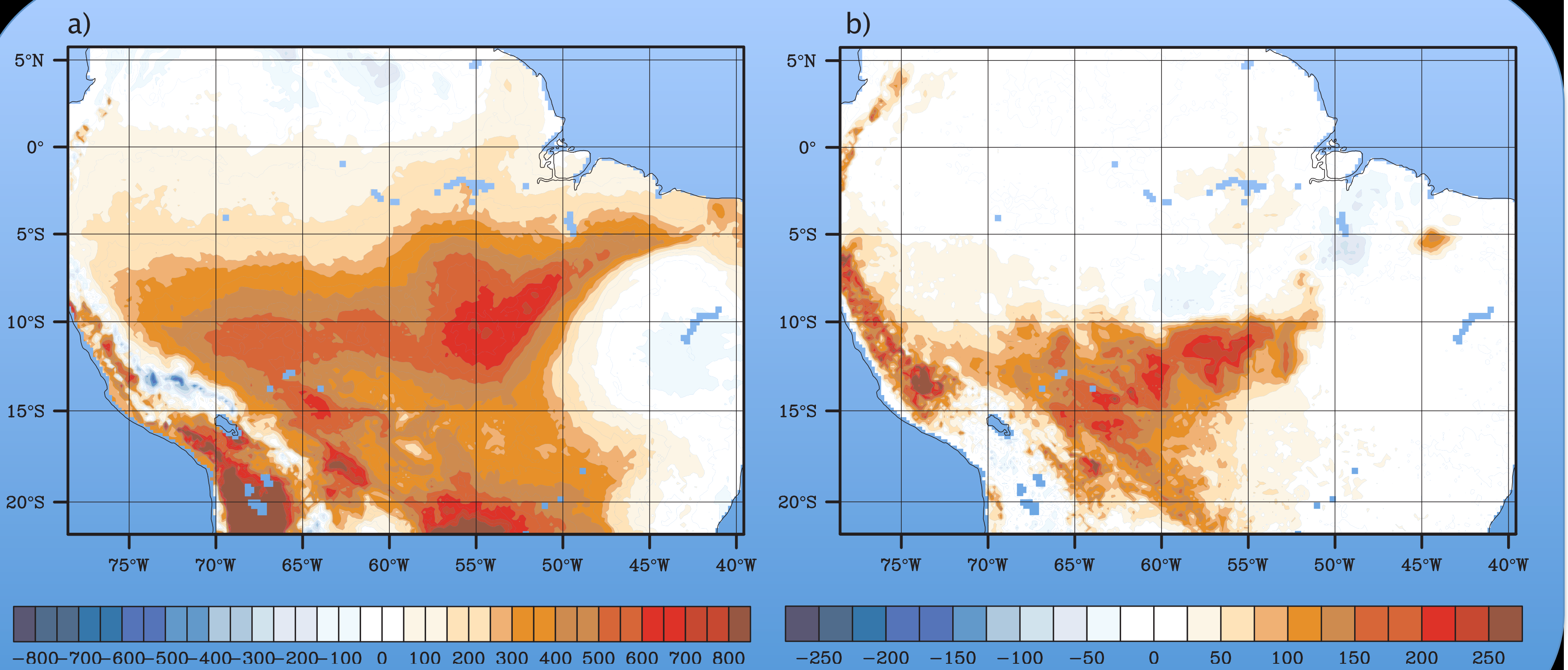
Precipitable Water



Dry Season Anomaly

Deforestation perturbation

Lifting Condensation Level



Dry Season Anomaly

Deforestation perturbation

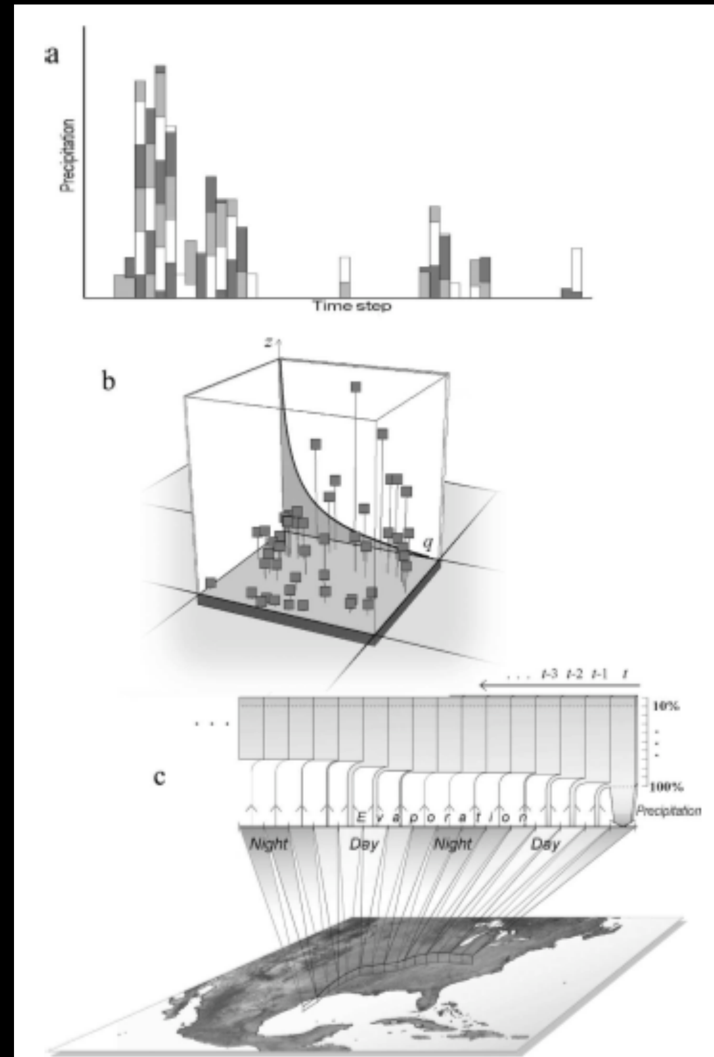
Deforestation impacts local and regional precipitation and climate.

Can we determine where the moisture evapotranspired by regions of deforestation actually goes, and how it changes with deforestation?

Back Trajectory
Analysis

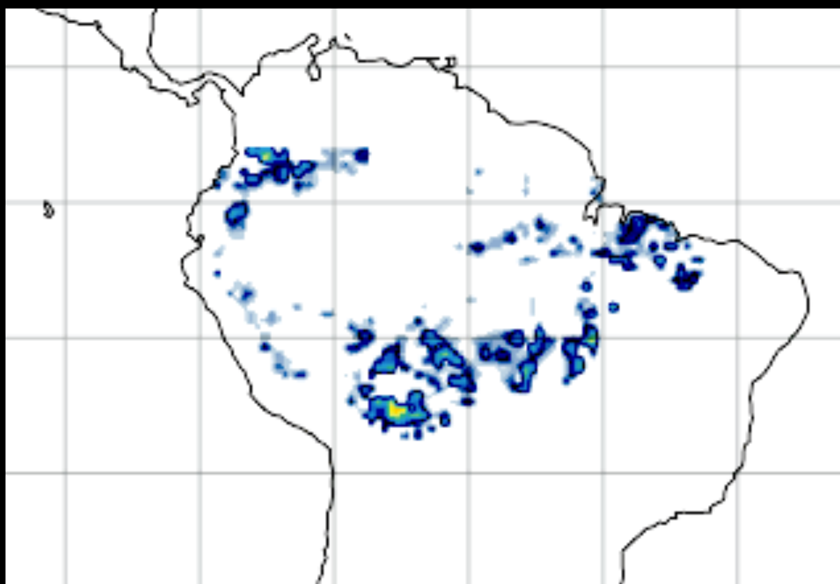
- Use model fields to track moisture that rains during a single event back in time to find where it last evaporated off of the earth's surface (evaporative source)

- Aggregated over many precipitation events can use evaporative source to determine where moisture that evaporates off a given location falls as precipitation (forward trajectory)

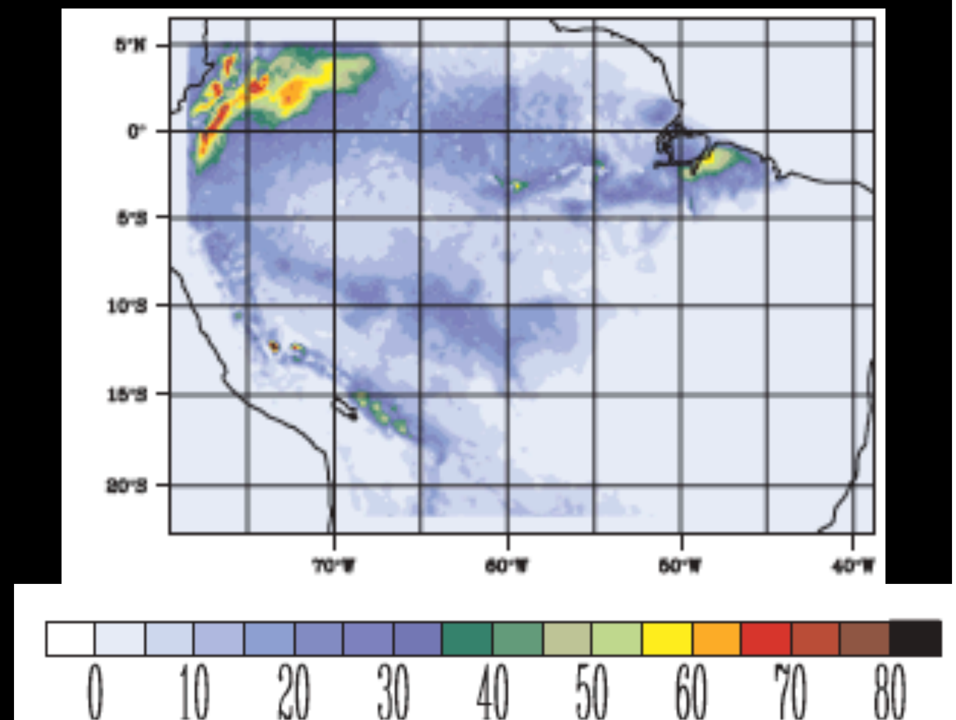


Precipitation, Recycling, and Land Memory: An Integrated Analysis (Dirmeryer 2009)

Moisture Trajectory Analysis

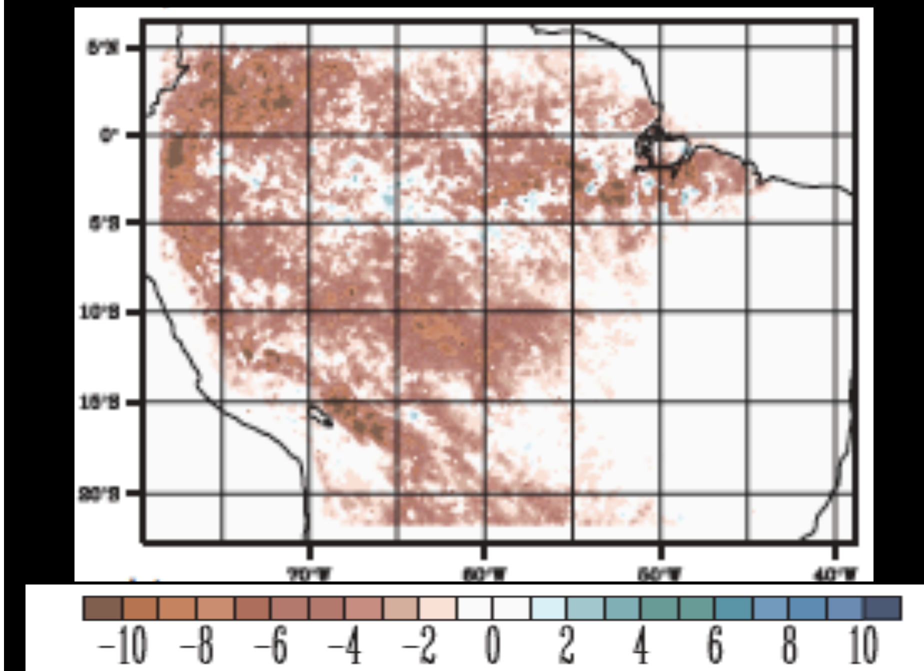


Deforested Regions

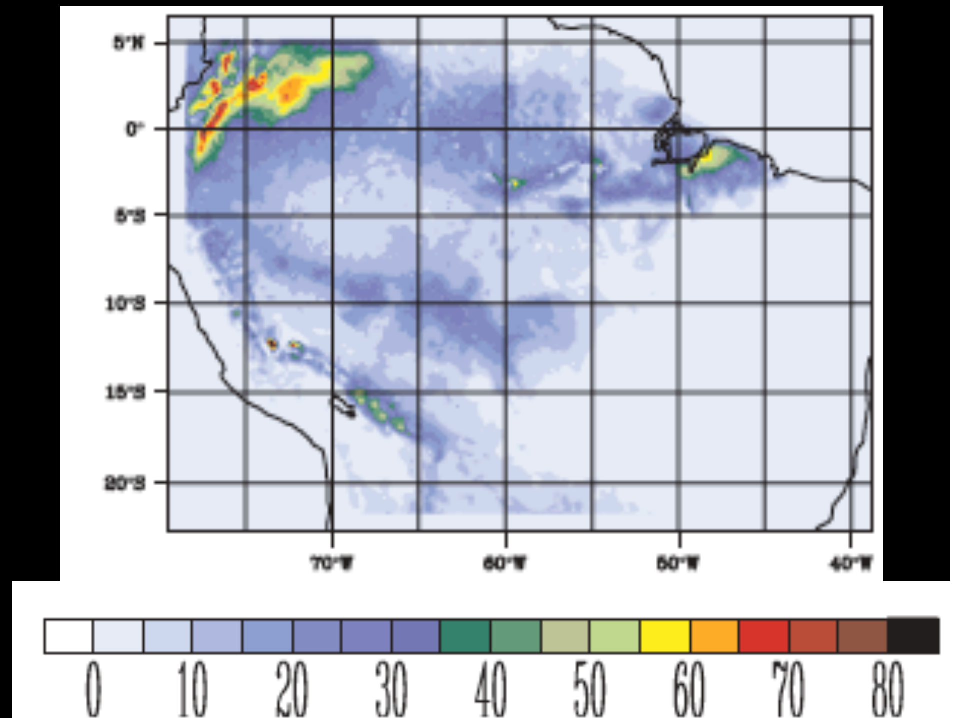


Mean forward trajectory precipitation rate from deforested points

Moisture Trajectory Analysis

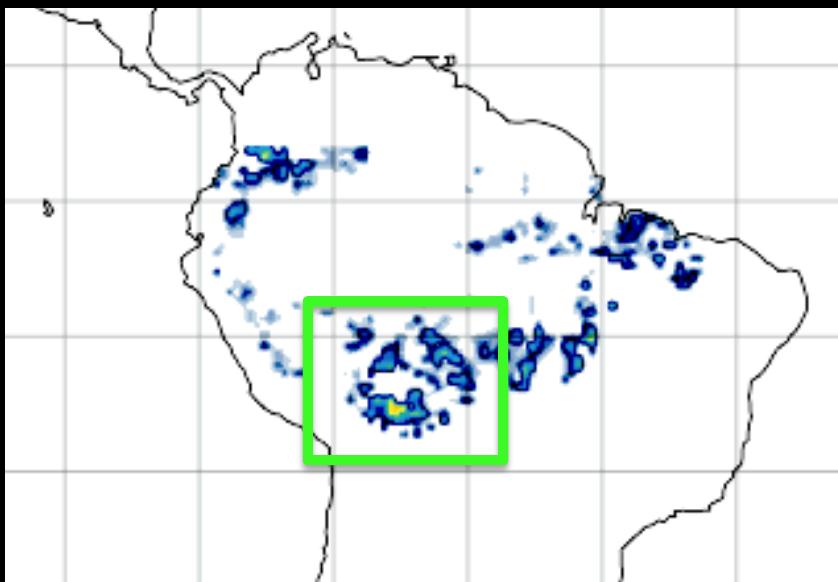


Impact of deforestation on precipitation rate from deforested points

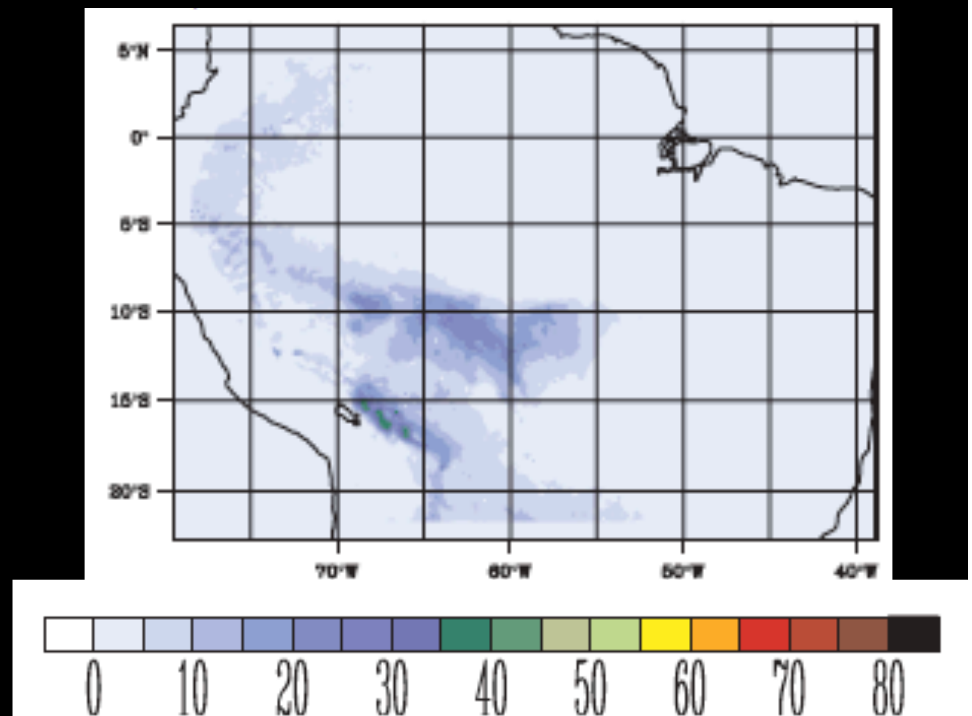


Mean forward trajectory precipitation rate from deforested points

Moisture Trajectory Analysis

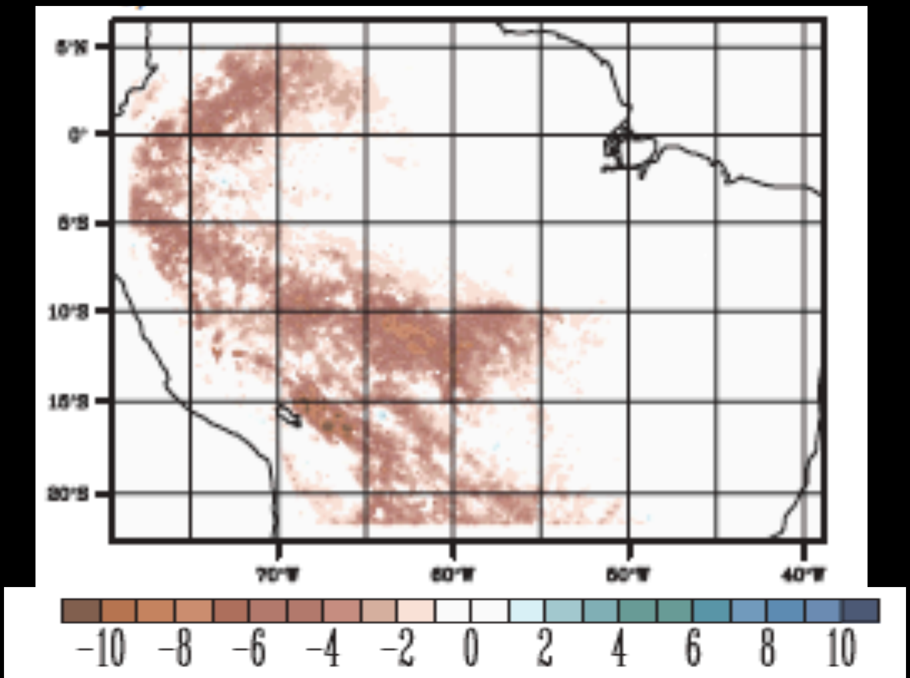


Source Region

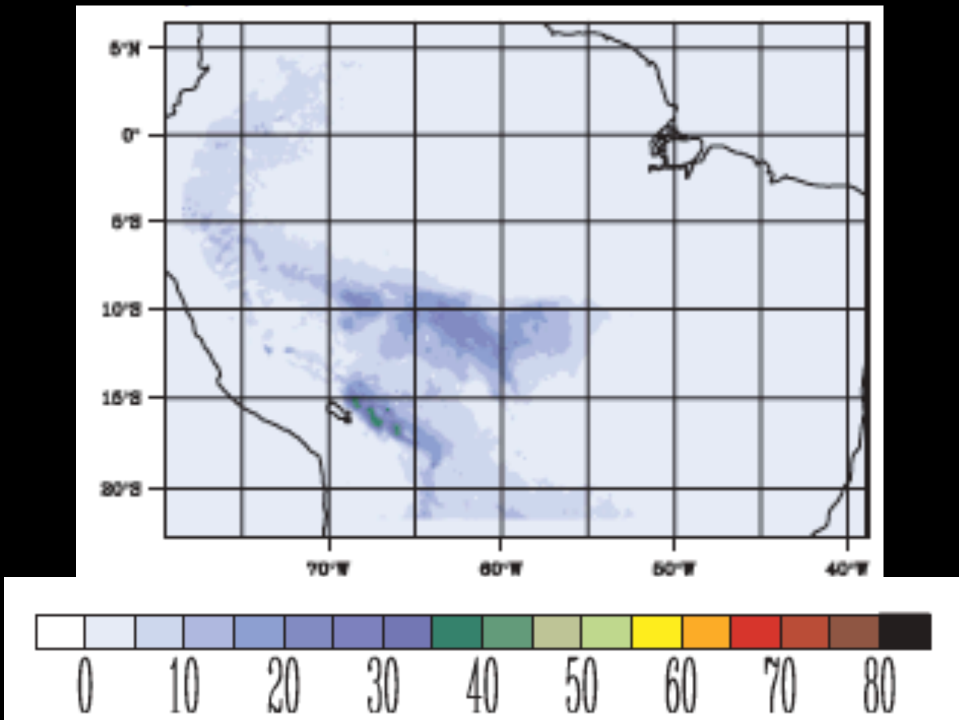


Mean forward trajectory precipitation rate from deforested points

Moisture Trajectory Analysis



Impact of deforestation on precipitation rate from deforested points



Mean forward trajectory precipitation rate from deforested points

Recycling Ratio
Description

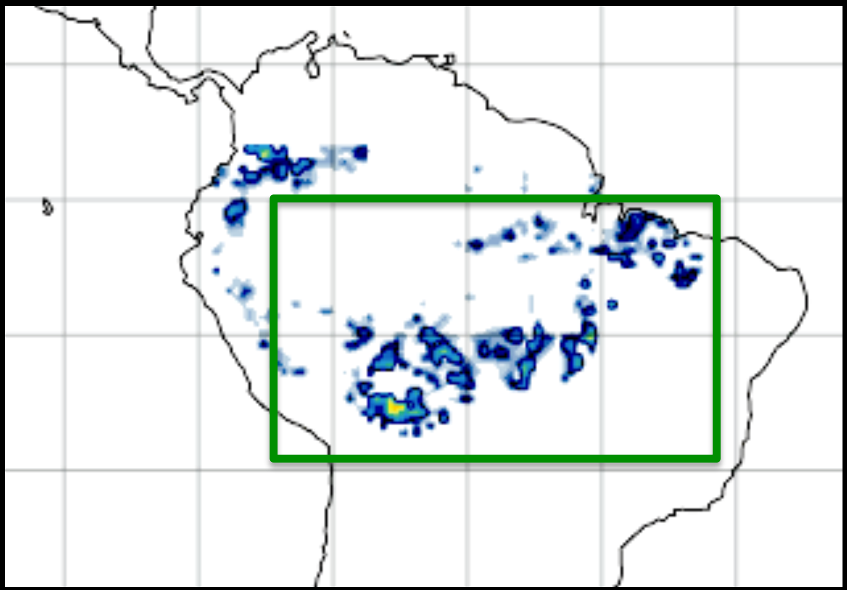
Recycling ratio is the fraction of precipitation in a given region that last evapotranspired from the region itself.

Using backtrajectory analysis this is trivially calculated.

$$R = \frac{P_{rec}}{P_{tot}}$$

The recycling ratio is an important estimate of land atmosphere coupling.

July Regional Recycling



Drought Year
Recycling Ratio

.850

Pluvial Year
Recycling Ratio

.694

Change in mean normalized MCWD with Deforestation

Change in MCWD during pluvial years	Change in MCWD during drought years
-.165	-.312

Amazon Rainforest Percent Changes with Deforestation

	July - September	
	Pluvial Years	Drought Years
% Δ Precipitation Rate	-4.99%	-5.93%
% Δ Sensible Heat Flux	+.48%	+4.28%
% Δ Latent Heat Flux	-3.63%	-5.57%
% Δ Net Surface Radiation	-2.41%	-2.70%
% Δ Boundary Layer Height	-.11%	+1.36%
% Δ Rel. Soil Moisture Top Layer	-3.00%	-4.38%
% Δ Rel. Soil Moisture Bot. Layer	+3.50%	+5.09%
% Δ 2m Specific Humidity	-.77%	-1.31%
% Δ Level of free convection	+2.62%	+.52%
% Δ Lifting condensation level	+1.29%	+3.94%

In nearly every measure the impact of deforestation is greater during drought years

Take home messages:

1. The impacts of deforestation appear to be amplified during drought conditions

2. Current levels of deforestation do not seem to alter large scale circulation appreciably, instead the impacts on precipitation appear to primarily occur through local changes in stability and reductions in surface moisture fluxes which are advected downstream.

But…

1. Limited by boundary conditions

2. WRF and backtrajectory analysis computationally expensive

3. Computational expense limits land use scenario possibilities

For many interesting scientific questions, the complexity and expense of simulating the full atmosphere is unnecessary and may decrease confidence when investigating scenarios of land cover change.

What can we do about this?

A new goal

Goal: A model that can quickly and simply estimate key climatological impacts of large numbers of land-use scenarios on the biosphere. Easily Implemented by interdisciplinary researchers.

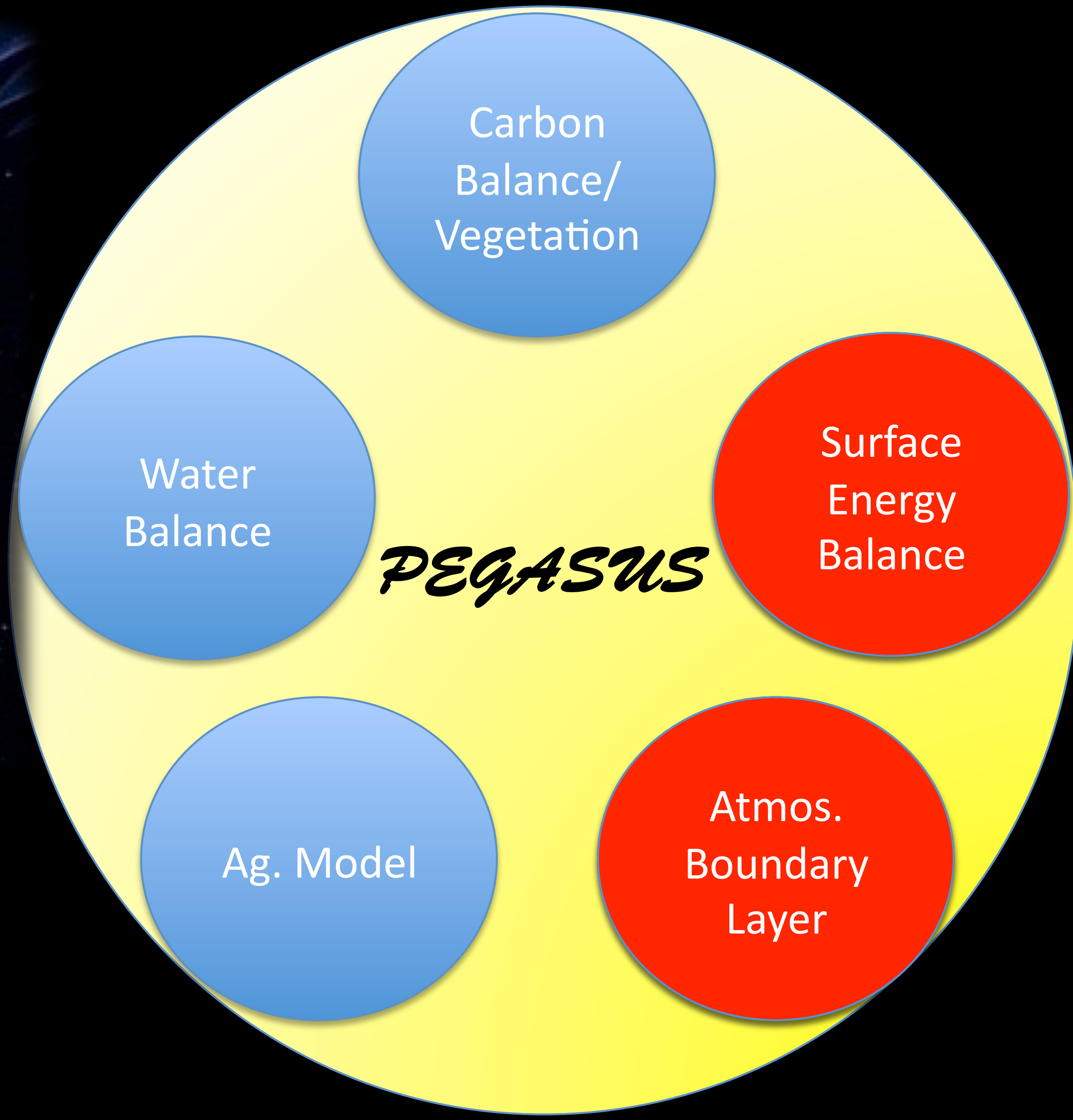
Problem: Models that are currently used for these types of problems are either highly complex and expensive GCMs/ LES models, or highly conceptual ecosystem models.

Solution: Developed the Predicting Ecosystem Goods and Services using Scenarios (PEGASUS) model of soil-veg-boundary layer system

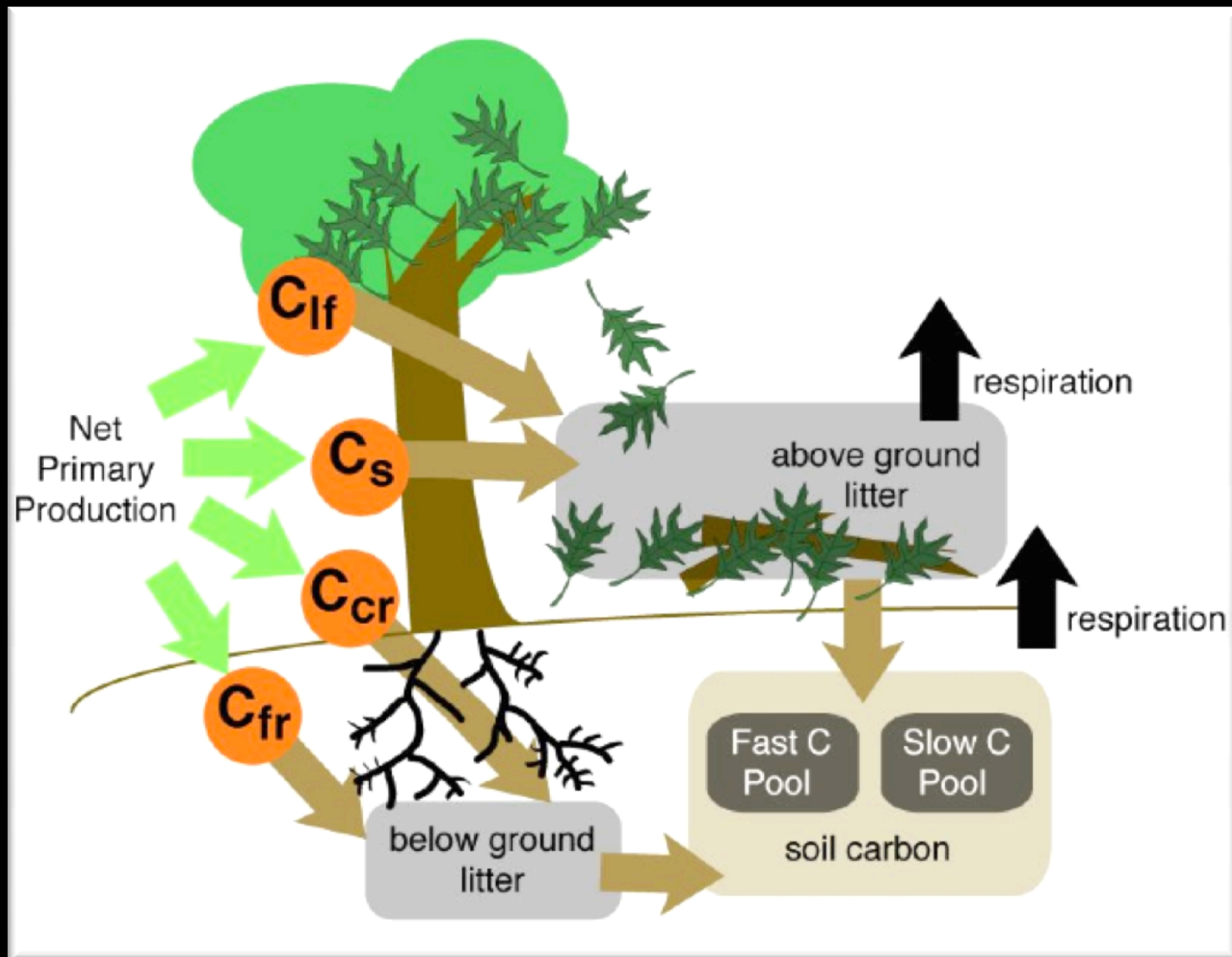
PEGASUS- Basic Model Properties

Time Resolution:	Daily timestep*
Spatial Resolution:	10 minute
Input Datasets:	Driven by 30-year mean CRU temp., prec., and cloud cover datasets (New et al. 2000). Also uses soil available water capacity dataset (Batjes 2006)

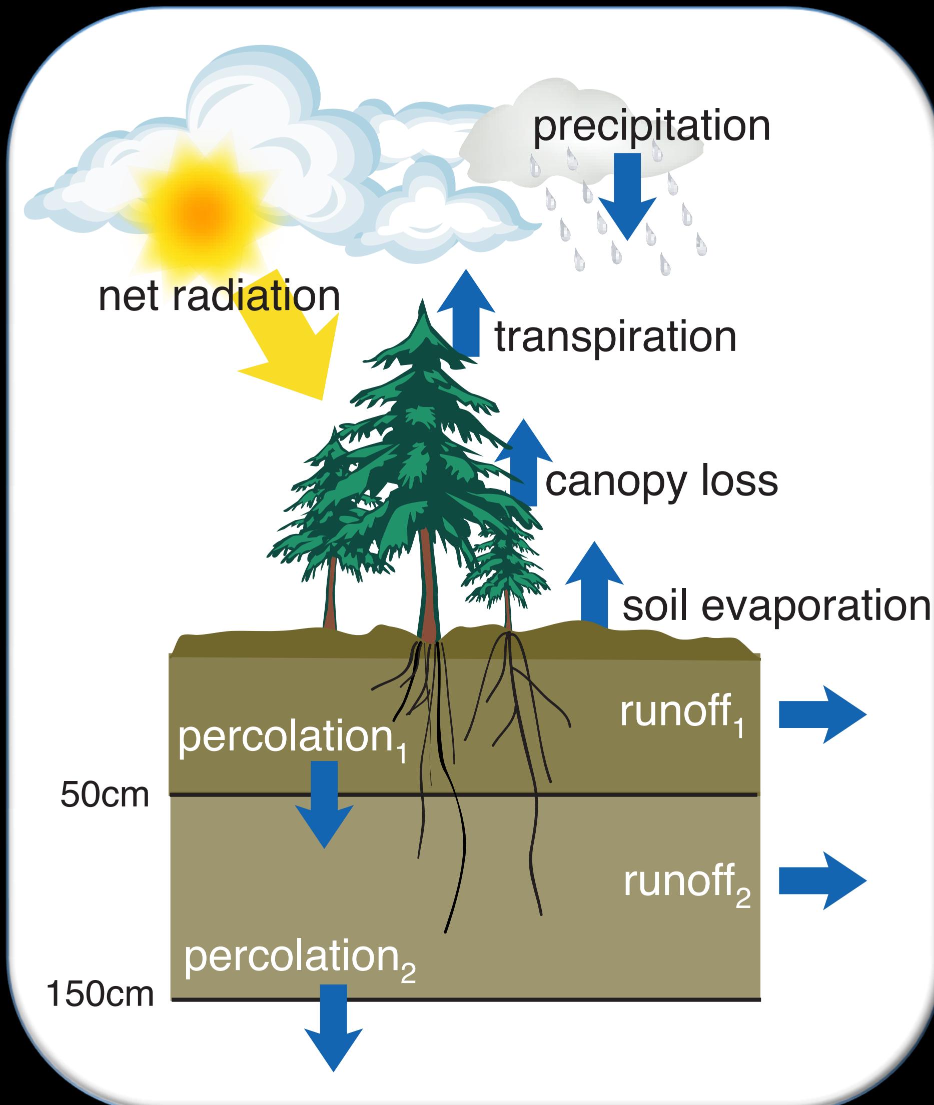
The PEGASUS model



Carbon Balance/ Vegetation Model



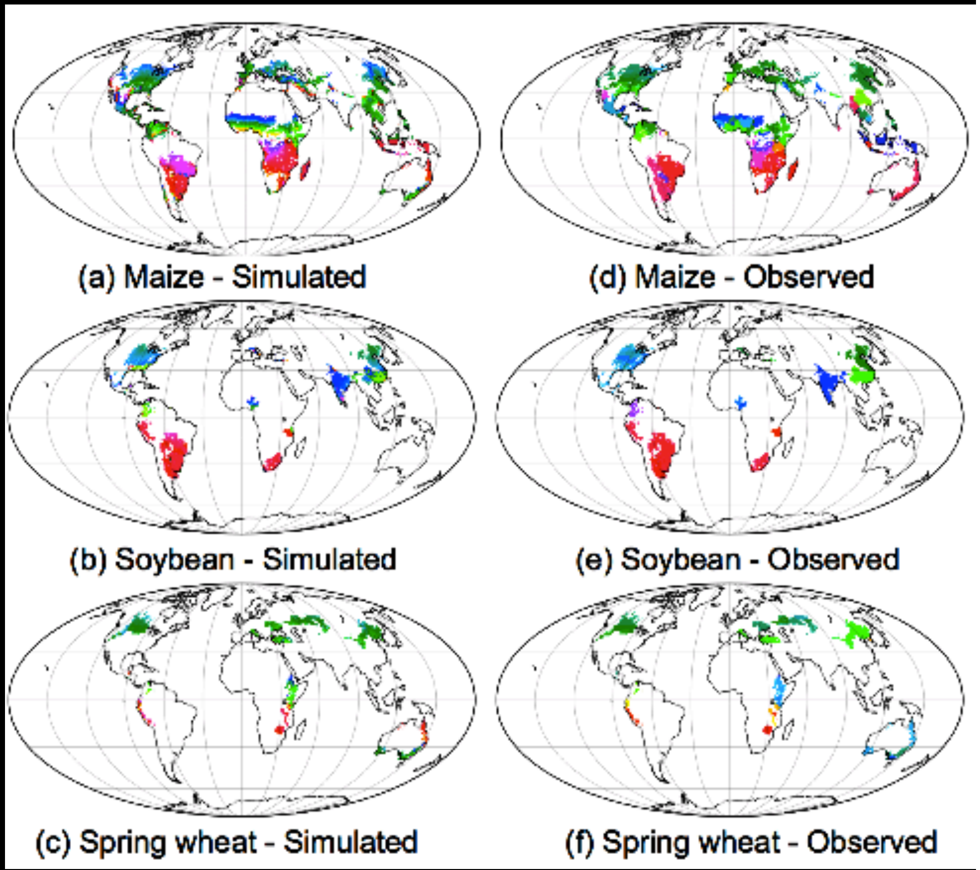
Water Balance Model



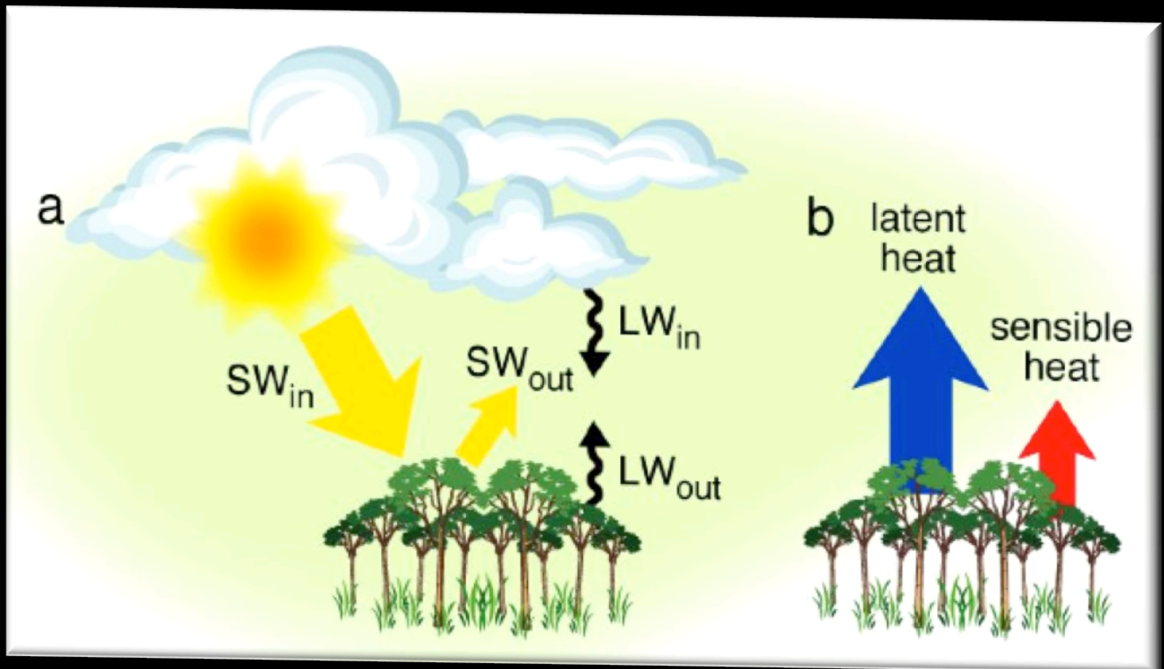
Agriculture Model

- Integrates climate, the effect of planting and harvesting decisions, irrigation, and fertilizer application on crop yield for maize, soybean, and spring wheat

- Uses data on crop planting/harvesting dates, crop-specific irrigation area, a global analysis of yield gaps, and harvested area of major crops as model input or calibration data



Surface Energy Balance Model

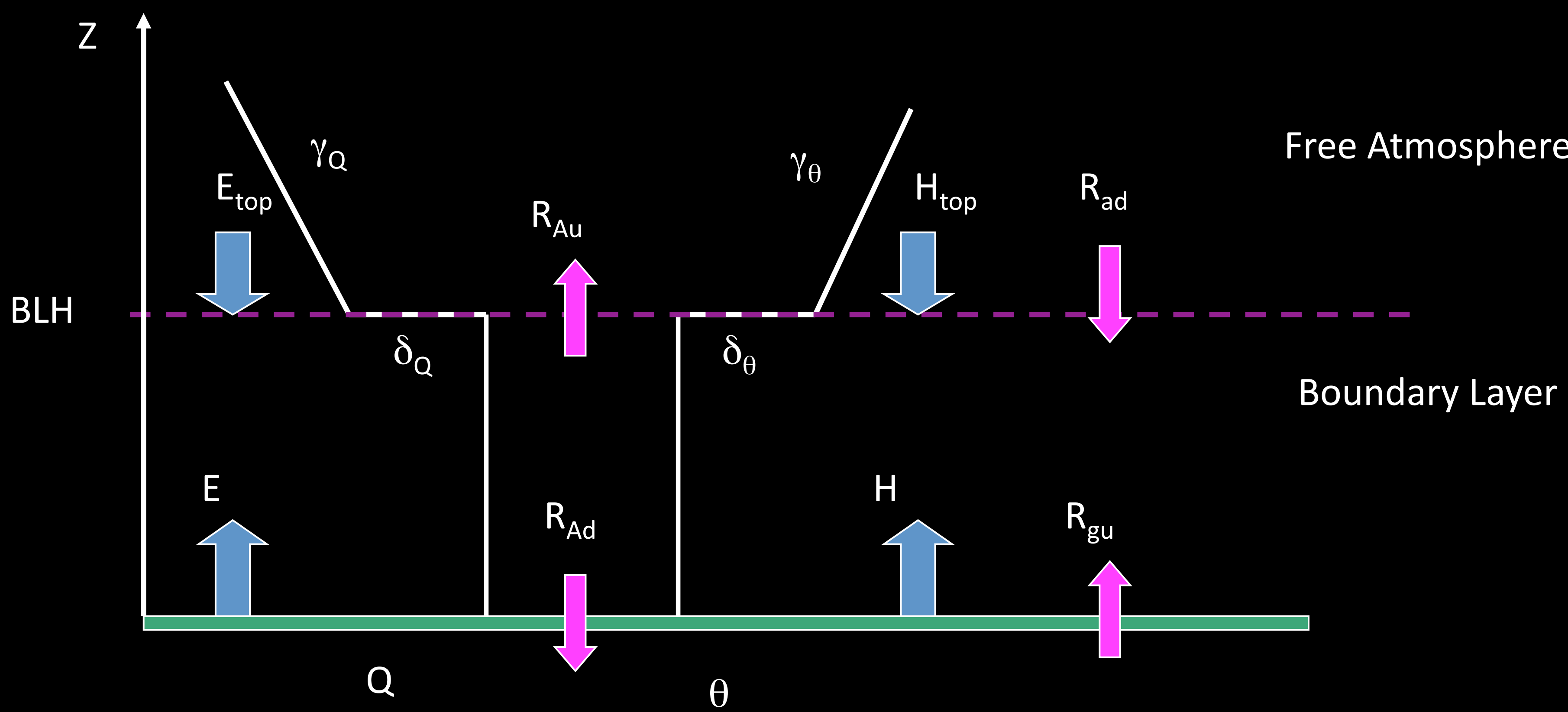


•Albedo calculated from literature derived values and plant phenology (and snow cover)

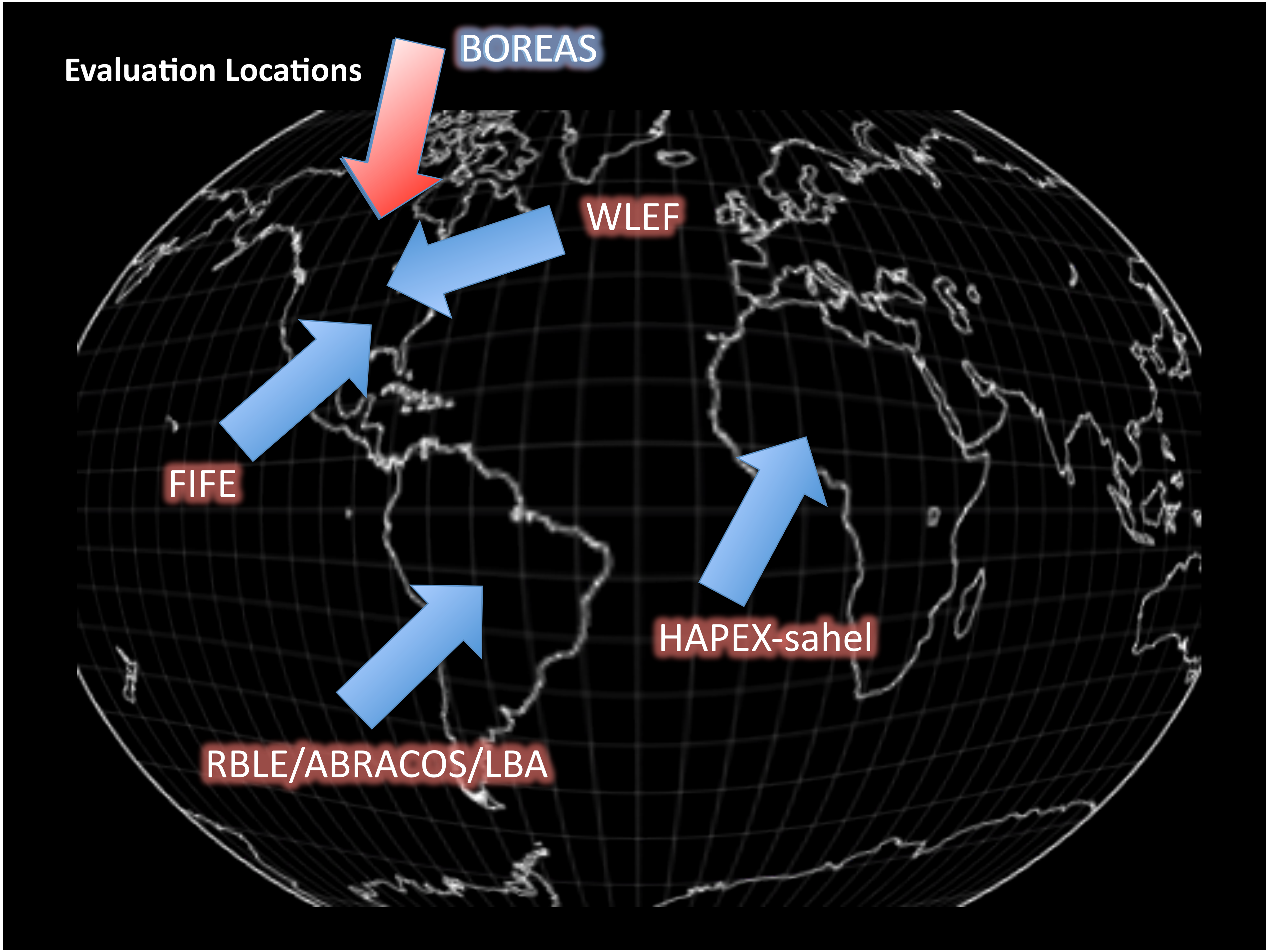
•Daily net LW radiation a function of temperature and cloudiness

•Sensible heat flux calculated as residual of surface energy balance.

Atmospheric Bulk Boundary Layer Model



Strengths	Weaknesses
Model is fast	Driven by climatology
High spatial resolution	Boundary layer advection and stability
Limited input parameters	No ground water transport
Specifically designed to model changes in ecosystem services due to scenarios of land use change	Initial boundary layer free atmosphere and “jump” conditions.


Evaluation Locations
BOREAS
WLEF
FIFE
RBLE/ABRACOS/LBA
HAPEX-sahel

June BOREAS results

Surface Fluxes

Net Rad.

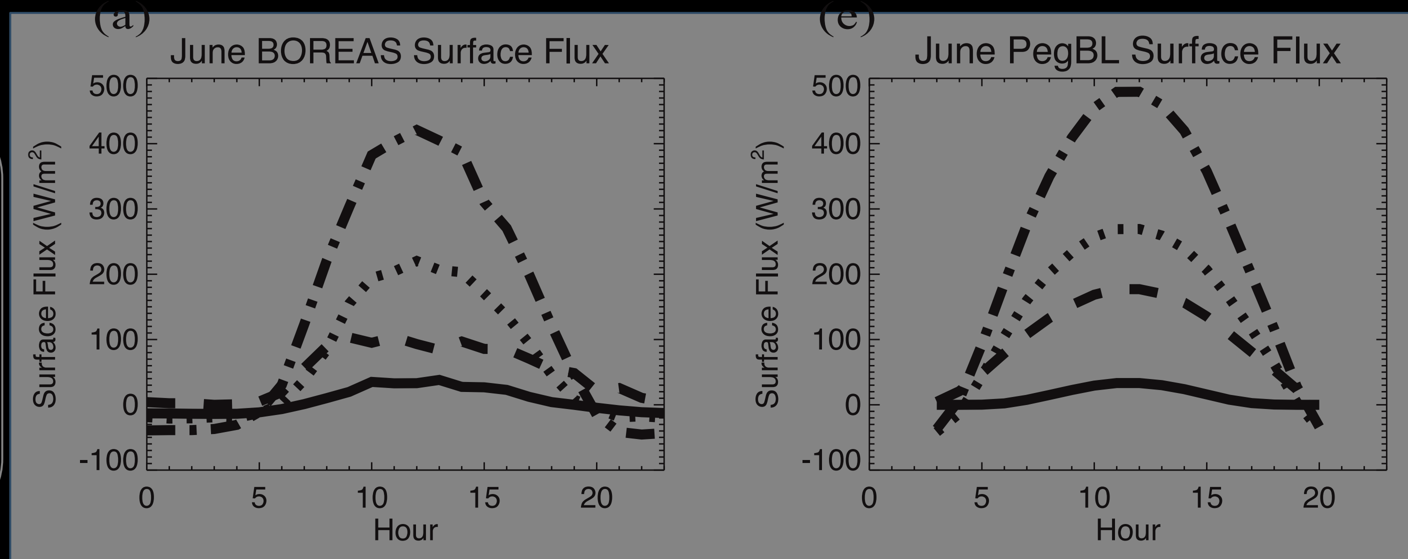
SHF

LHF

Sfc. Heat Storage

Observed sfc. fluxes

Modeled sfc. fluxes

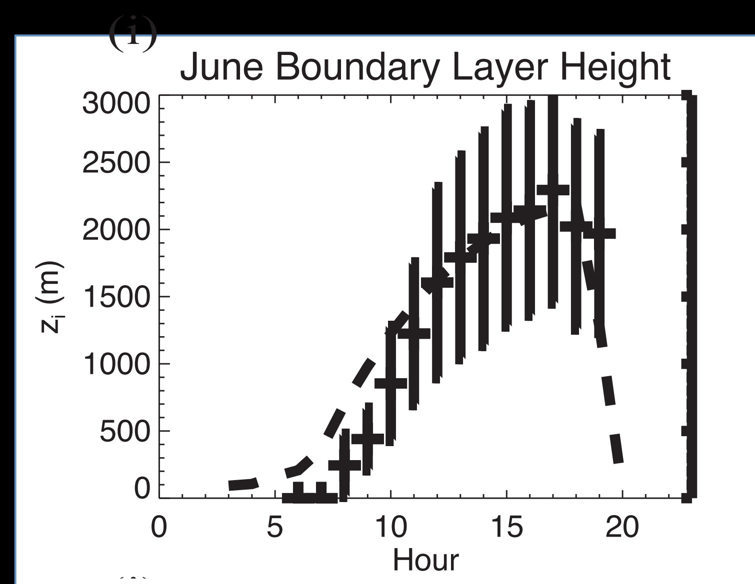


BLH

Modeled:

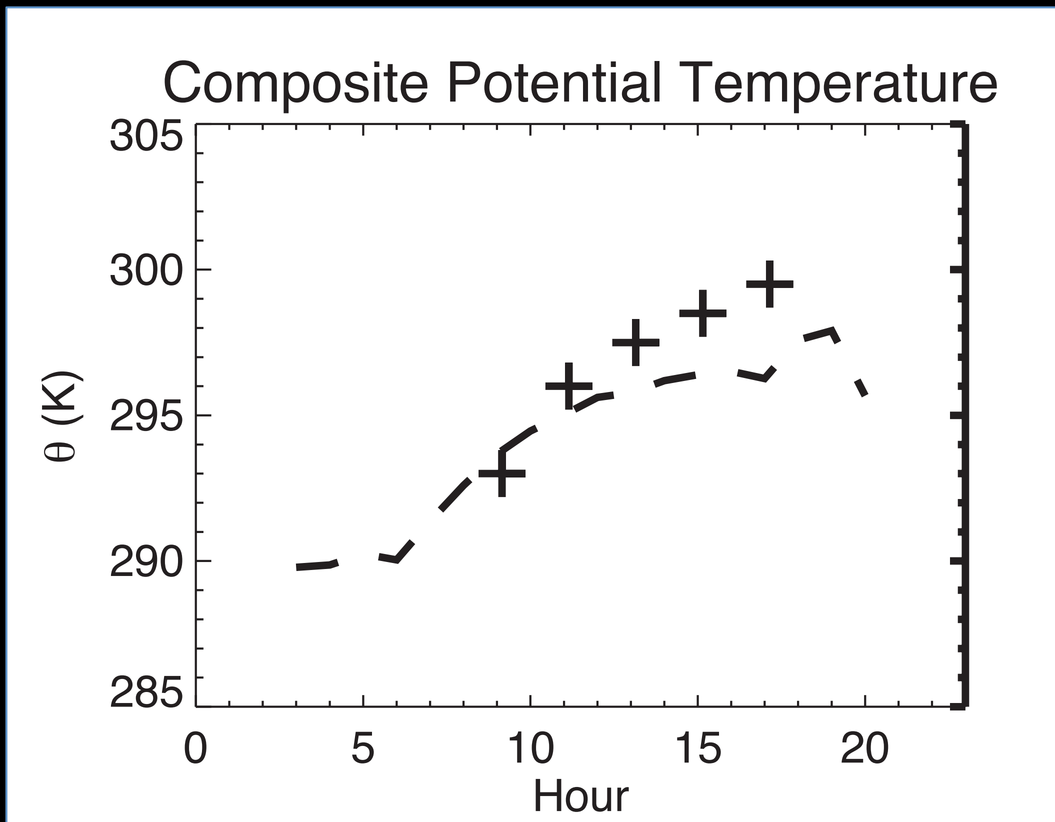
Observed:

Observed & modeled BLH:



Composite
Boundary Layer
BOREAS results

Observed
Composites from
Barr and Betts (1997)



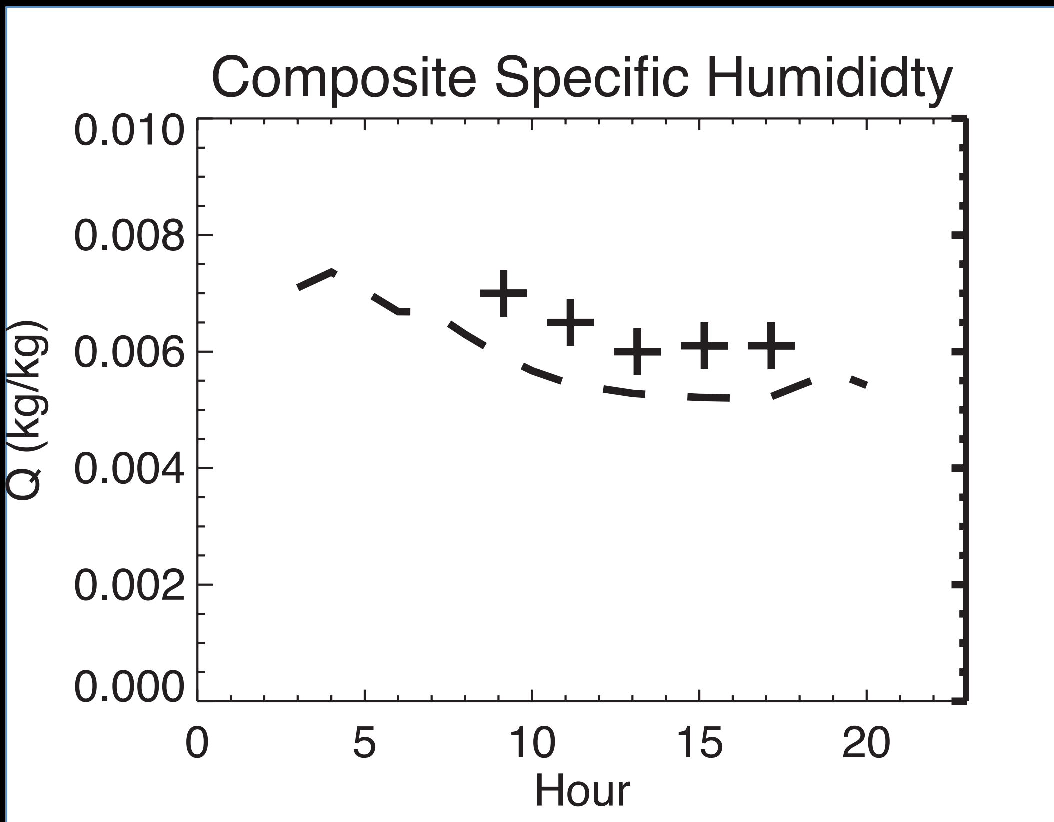
Modeled: – – – –

Observed: +

Boundary Layer Potential
Temperature

Composite
Boundary Layer
BOREAS results

Observed composites from Barr and Betts (1997)



Modeled:

Observed:

Boundary Layer Specific Humidity

ABRACOS/RBLE comparison

ABRACOS/WRF/ PEGASUS

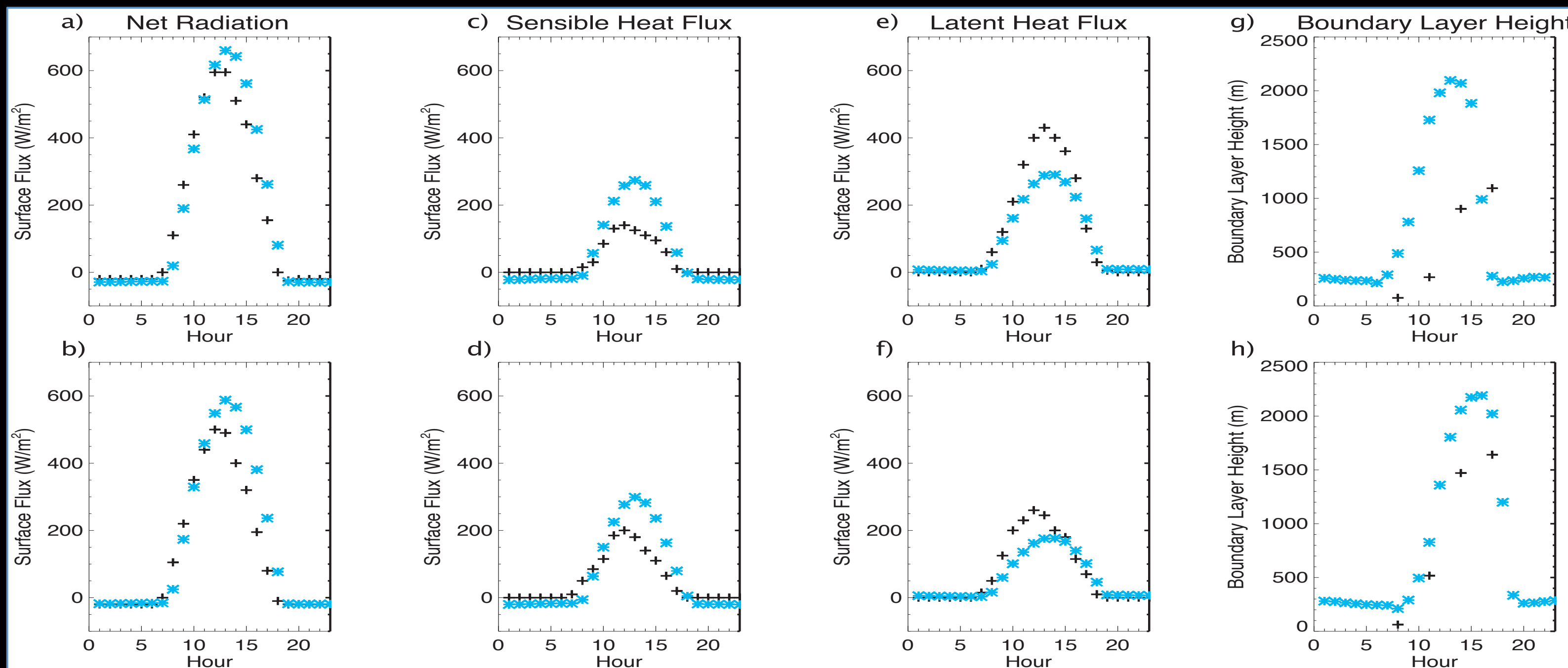
* WRF-Noah

+ ABRACOS Observations

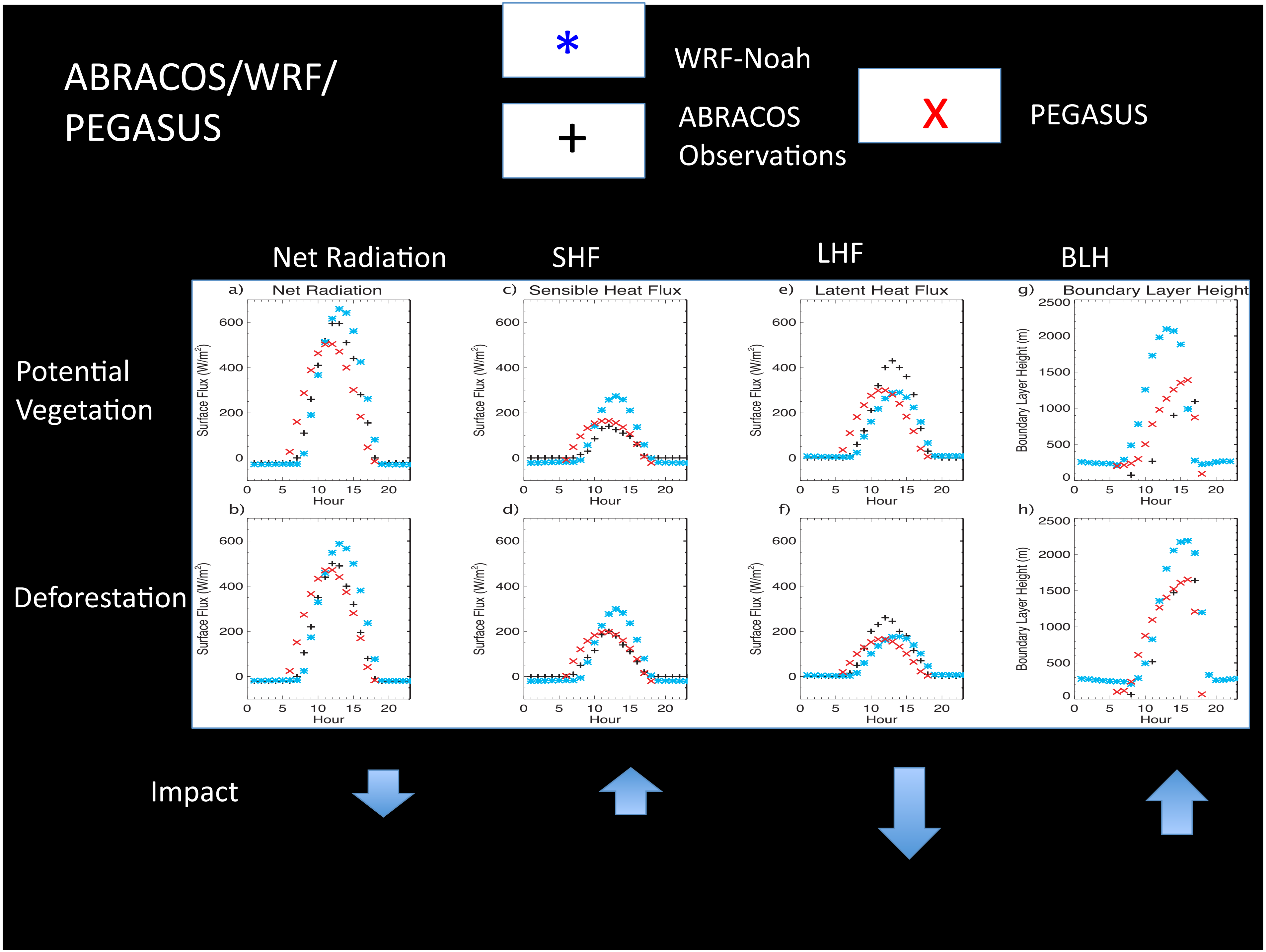
Net Radiation | SHF | LHF | BLH

Potential Vegetation

Deforestation



Impact


ABRACOS/WRF/
PEGASUS
*
WRF-Noah
+
ABRACOS
Observations
X
PEGASUS
Net Radiation
SHF
LHF
BLH
Potential
Vegetation
Deforestation
a) Net Radiation
c) Sensible Heat Flux
e) Latent Heat Flux
g) Boundary Layer Height
b)
d)
f)
h)
Surface Flux (W/m²)
Boundary Layer Height (m)
Hour
Impact

Overview of Evaluations

- Modeled surface energy balance and boundary layer variables generally compared well with observations
- Performed best in boreal, tropical, and Sahel regions

- Relatively poor flux reproduction where conditions significantly different than climatology (FIFE, WLEF)
- Poor fluxes led to poor boundary layer simulation

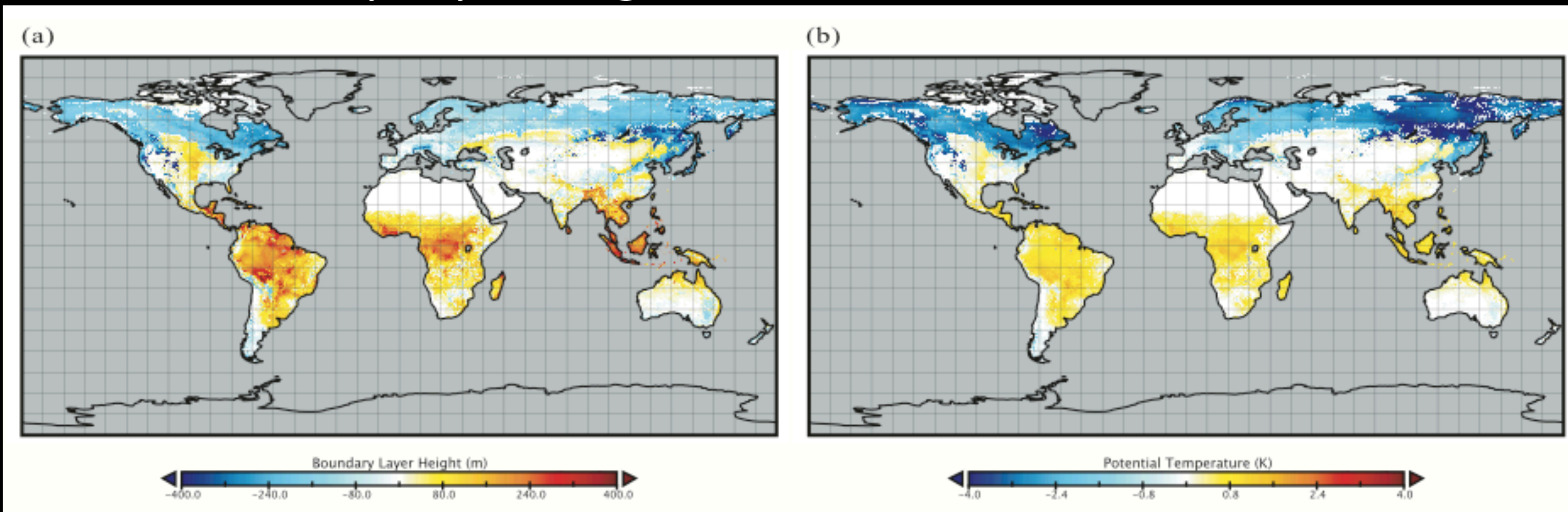
Application:

To what extent is local climate regulated by surface fluxes and vegetation relative to advected energy and moisture?

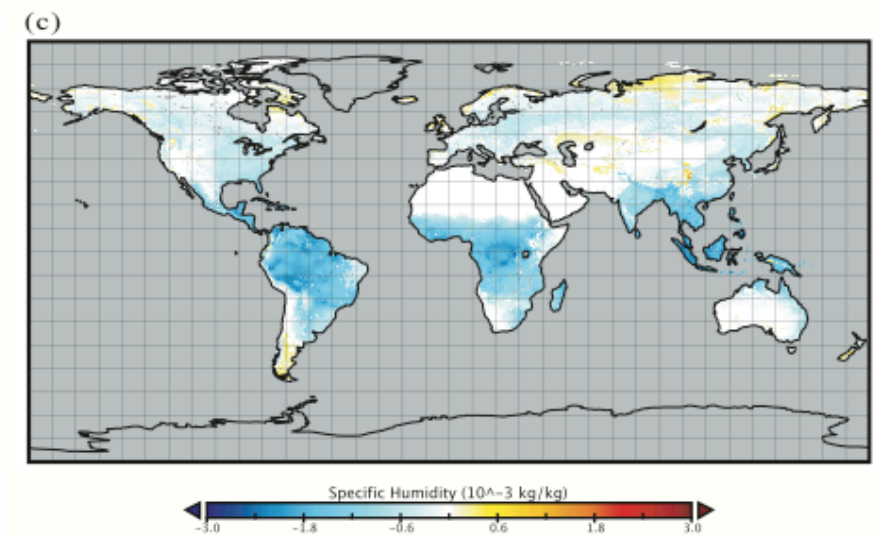
Local regulation of boundary layer climate by vegetation

Δ Boundary Layer Height

Δ Potential Temperature



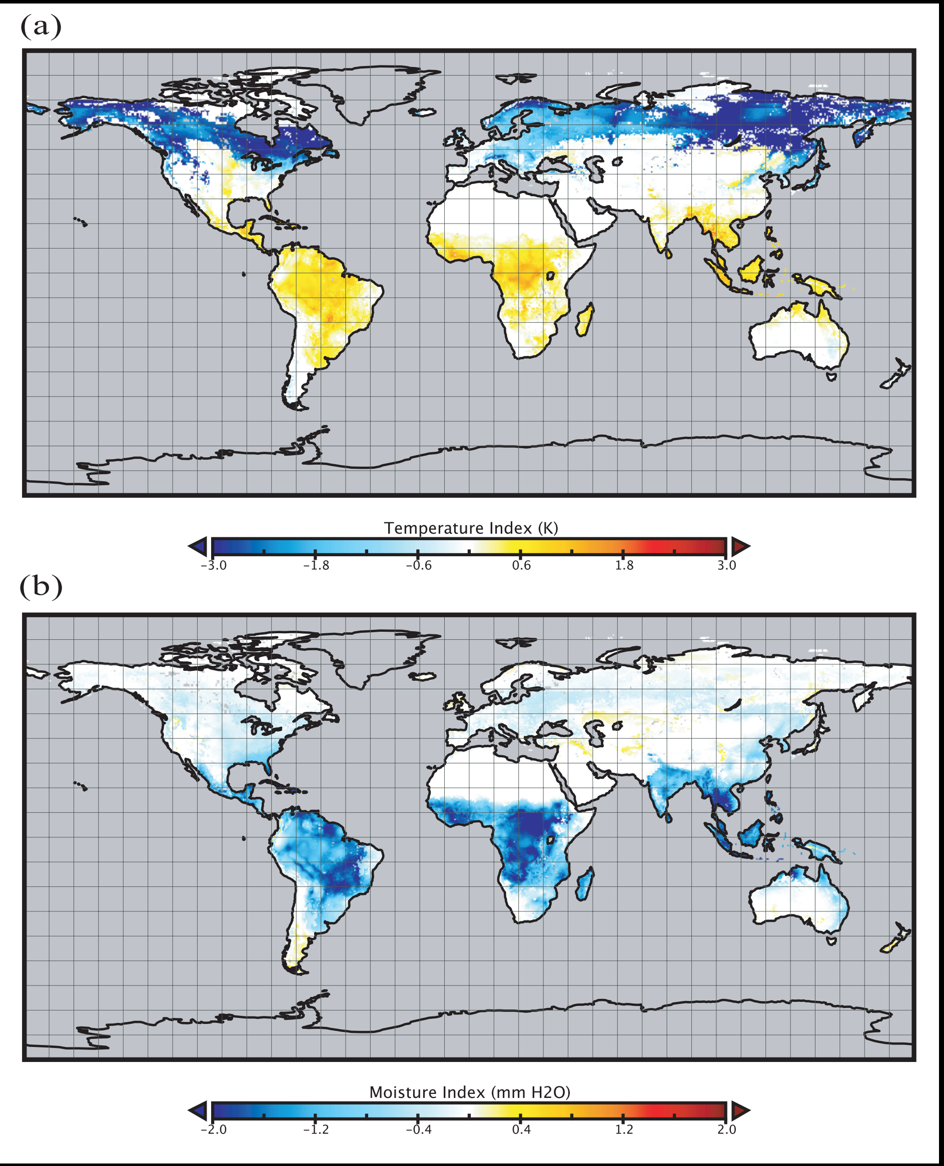
Δ Specific Humidity



Local regulation of surface climate by vegetation

$$H\_reg\_index = \Delta H \frac{|\Delta H|}{|\Delta H| + |H_{adv}|}$$

$$Q\_reg\_index = \Delta Q \frac{|\Delta Q|}{|\Delta Q| + |Q_{adv}|}$$



Take home messages:

1. The PEGASUS model is a *new model* capable of accurately simulating the land surface and lower atmosphere for large numbers of scenarios with limited parameters and computational requirements

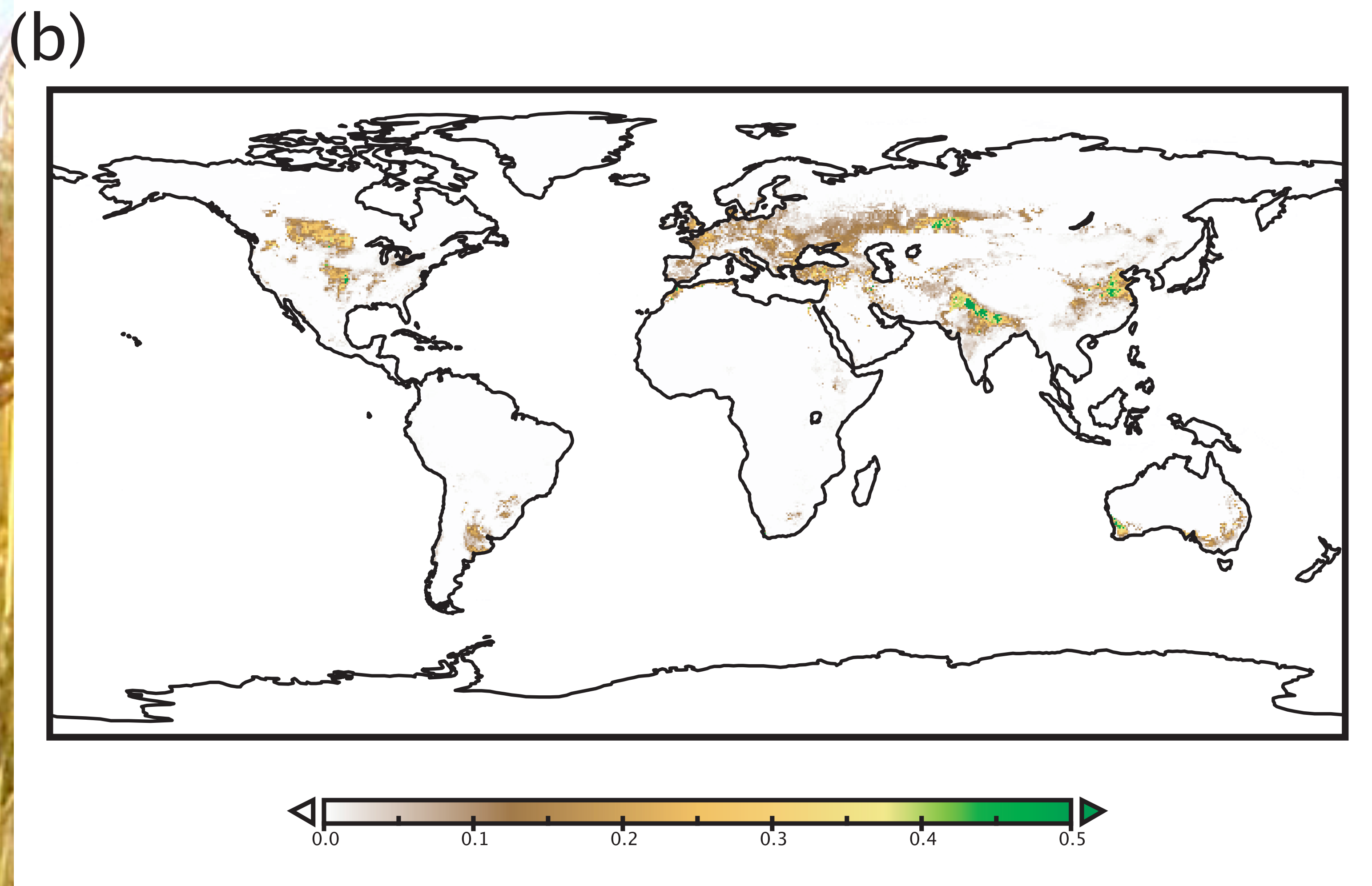
2. Vegetation most strongly regulates local climate in the *boreal* and *tropical* forest regions

Given what we have learned so far and using the tools we have developed I'll end this talk with an application that has been on everyone's mind…

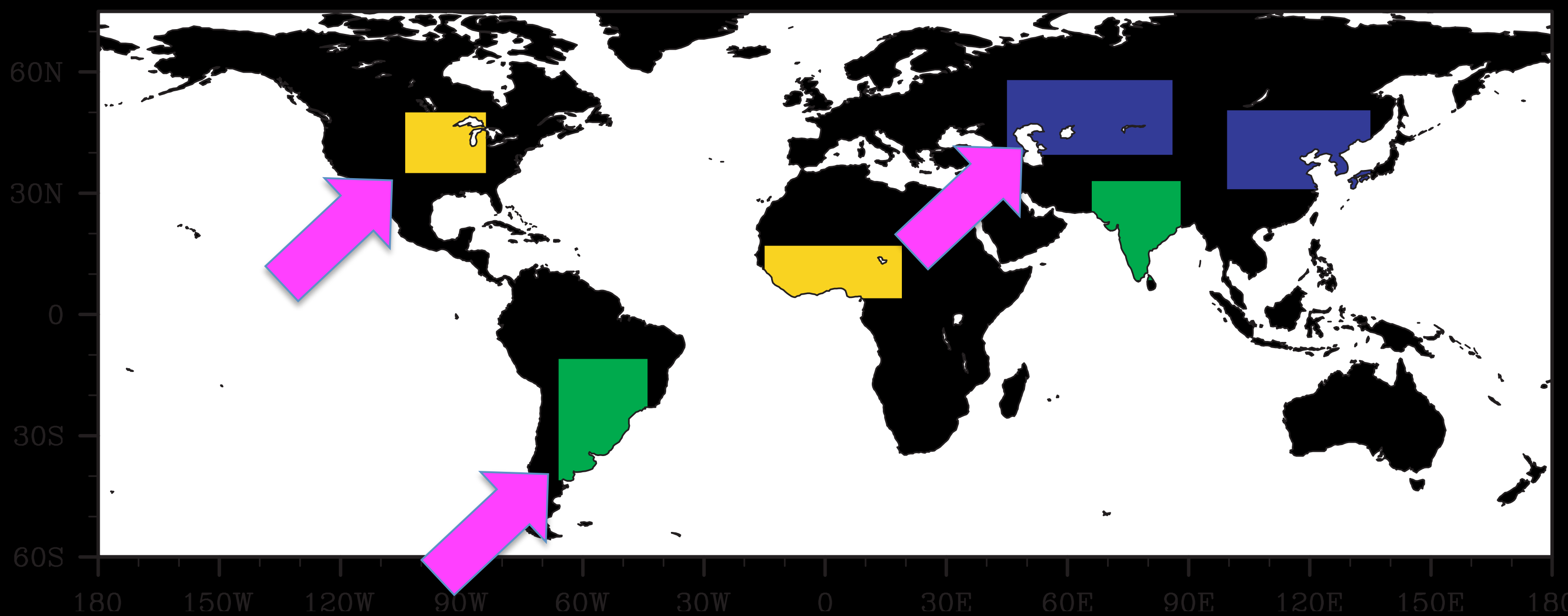
Important Fact:

Despite the widespread nature of current food production, a *disproportionate* amount of the world's calories come from a few relatively small areas. These represent the earth's *breadbaskets*.

Observed Wheat



Breadbasket Regions



Maize

Wheat

Soybeans

Breaking News:

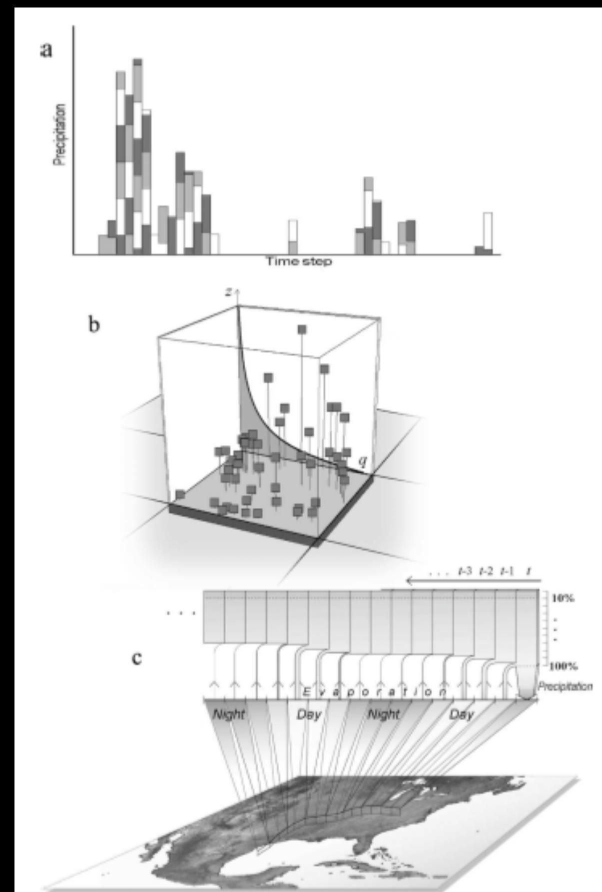
A study released *today* in PNAS estimates that by 2050 we will need *double* our current food production to feed the earth's population, unless we change our eating habits and/or population growth (Tillman et al. 2011).

Question:

Where does the moisture necessary for breadbasket food production come from, and to what extent can this be impacted by land cover change?

Climatological back trajectory analysis

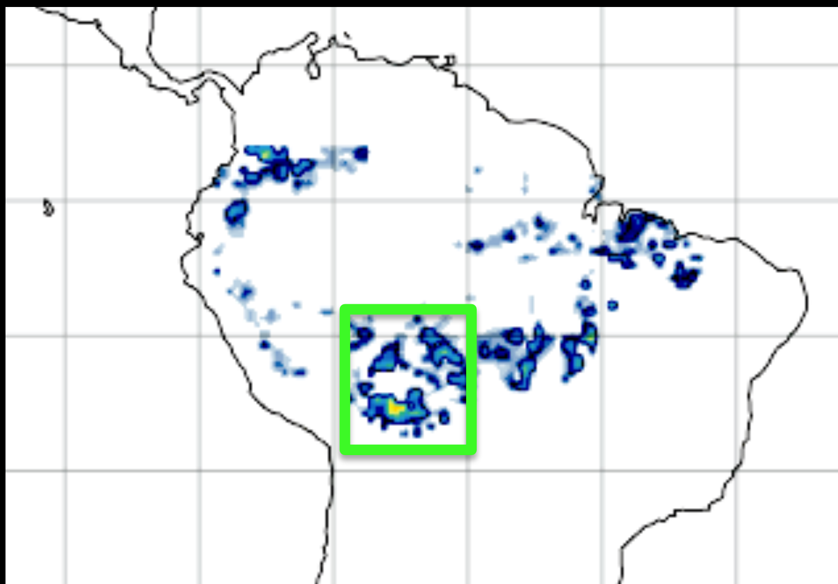
Precipitation, Recycling, and Land Memory: An Integrated Analysis (Dirmeryer 2009)

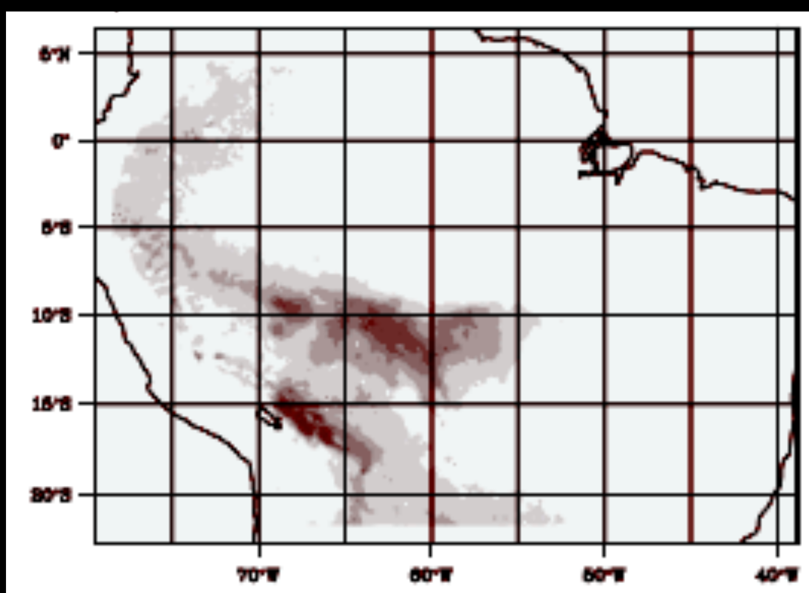


In the Amazon study we found that moderate levels of land cover change did not extensively alter regional circulation.

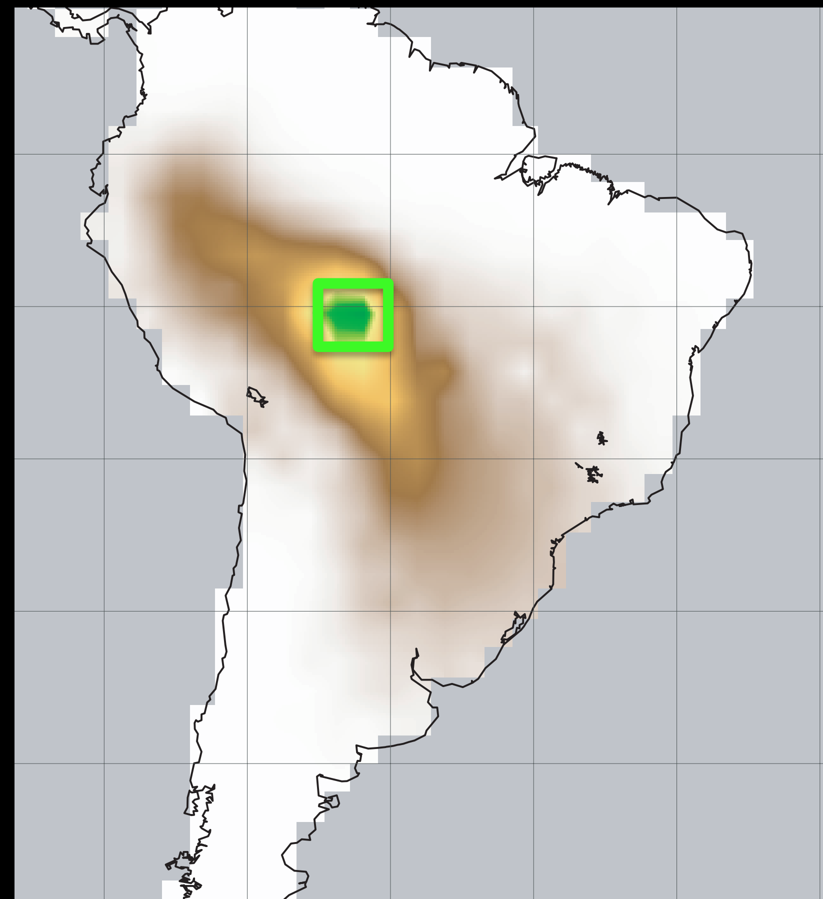
Here we assume circulation and stability does not change with land cover change, and use climatological estimates of evaporative source

WRF-Noah Analysis

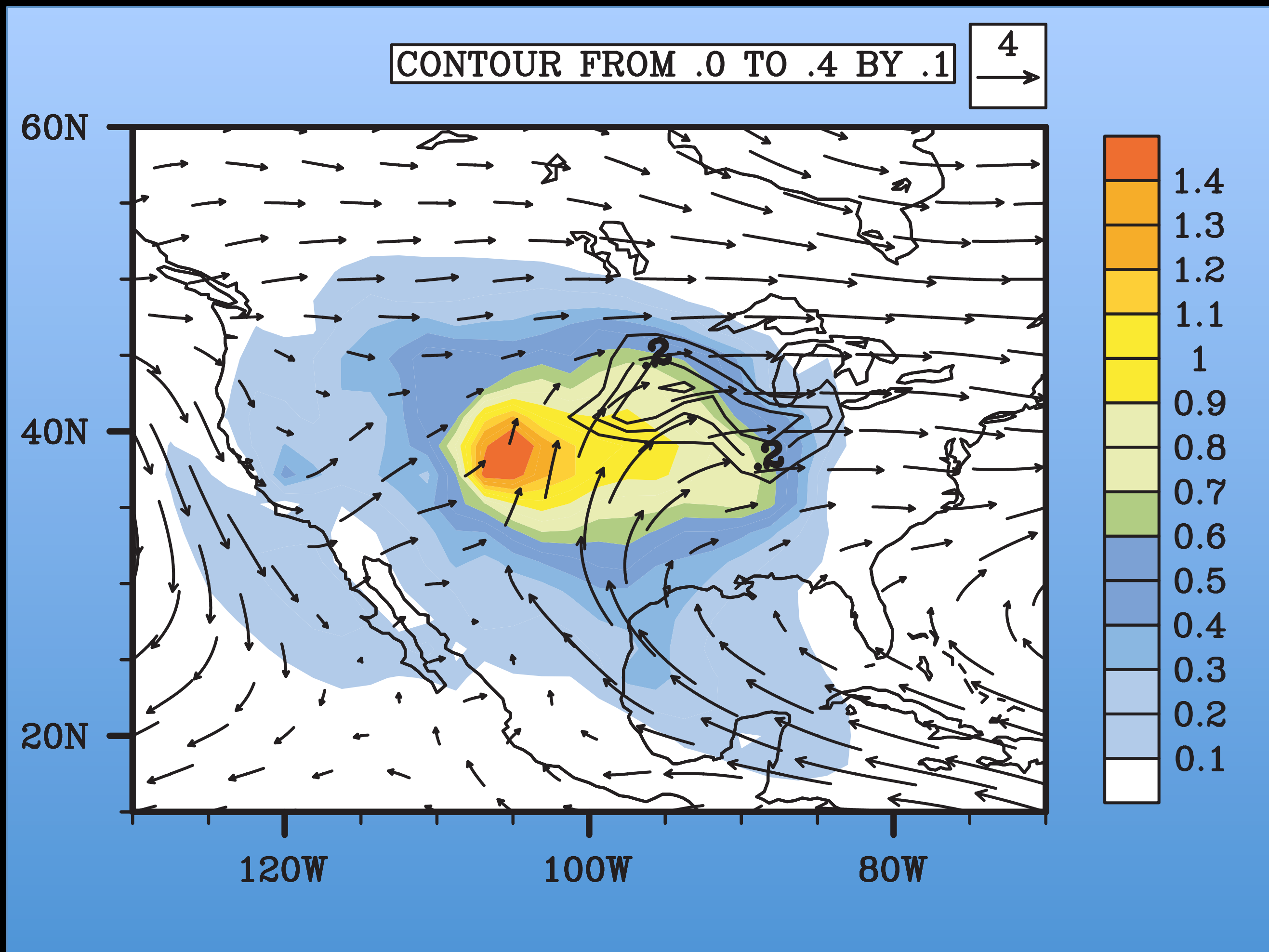




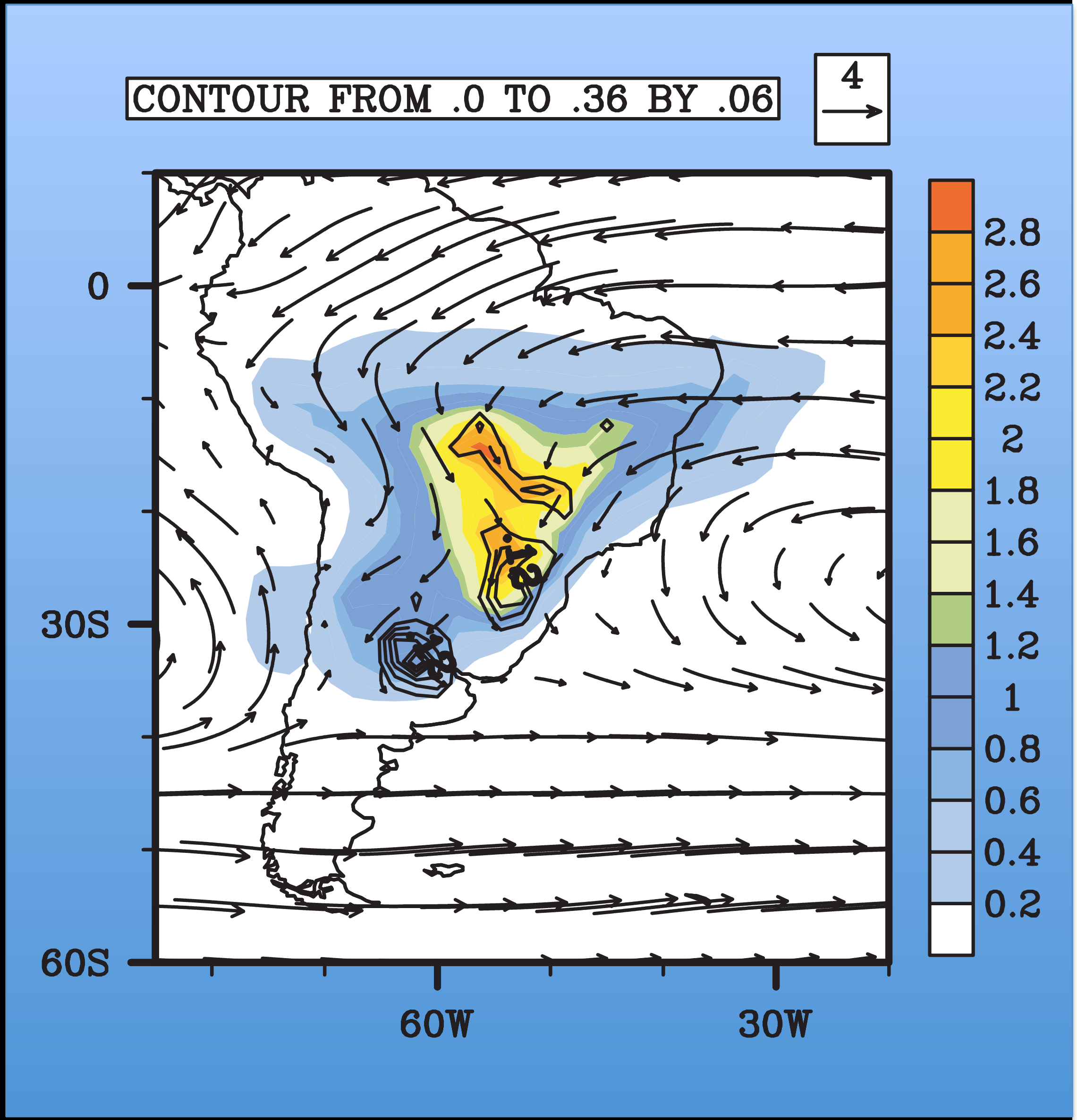
PEGASUS-linear model



North American Maize Evaporative Source

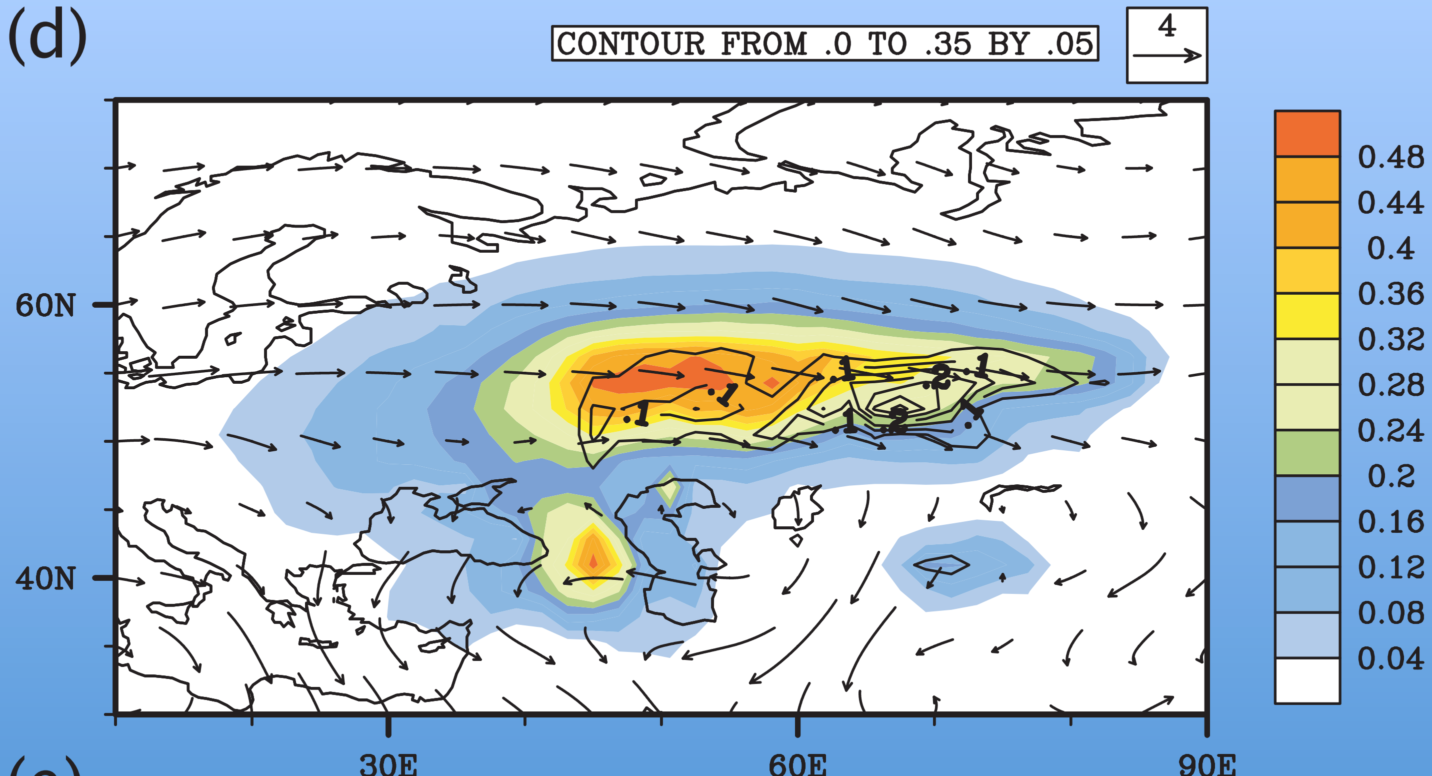


South American Soybeans
Evaporative Source



Central Asian Wheat Evaporative Source

(d)



(e)

How can land cover change within the evaporative source footprint of the breadbasket regions, alter the water available for crop precipitation?

Assumptions of land cover change

1. Pristine regions (LCC = 0) are assumed to be inaccessible to agriculture and remain unchanged.

2. Areas that are already crops or pastureland remain so.

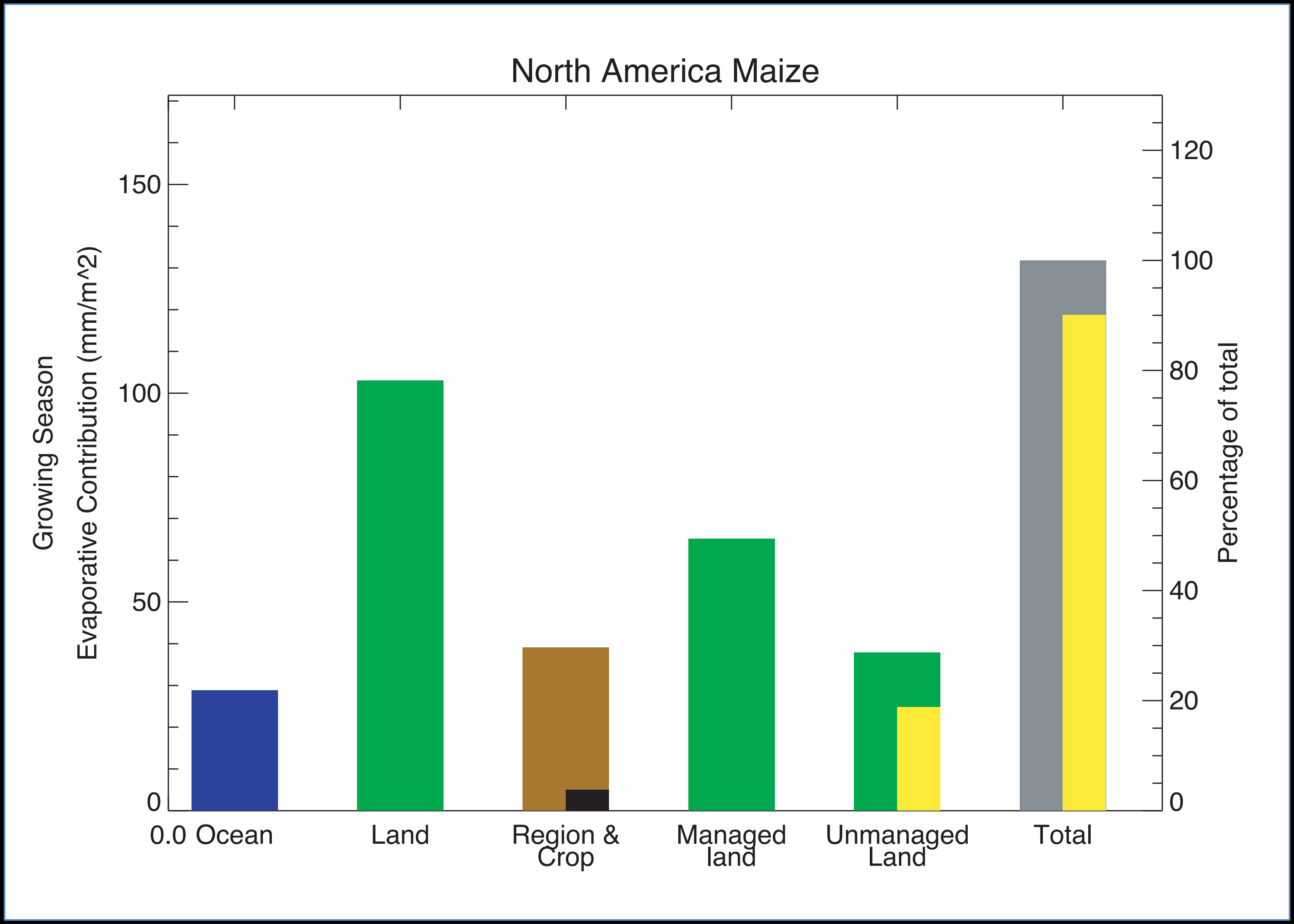
3. Points with large amounts of land cover change and are closest to the breadbasket regions are converted first.

4. Points further than 3000km from a breadbasket region are unchanged.

5. Land cover removal scenarios proceeded in 5% increments of the total possible

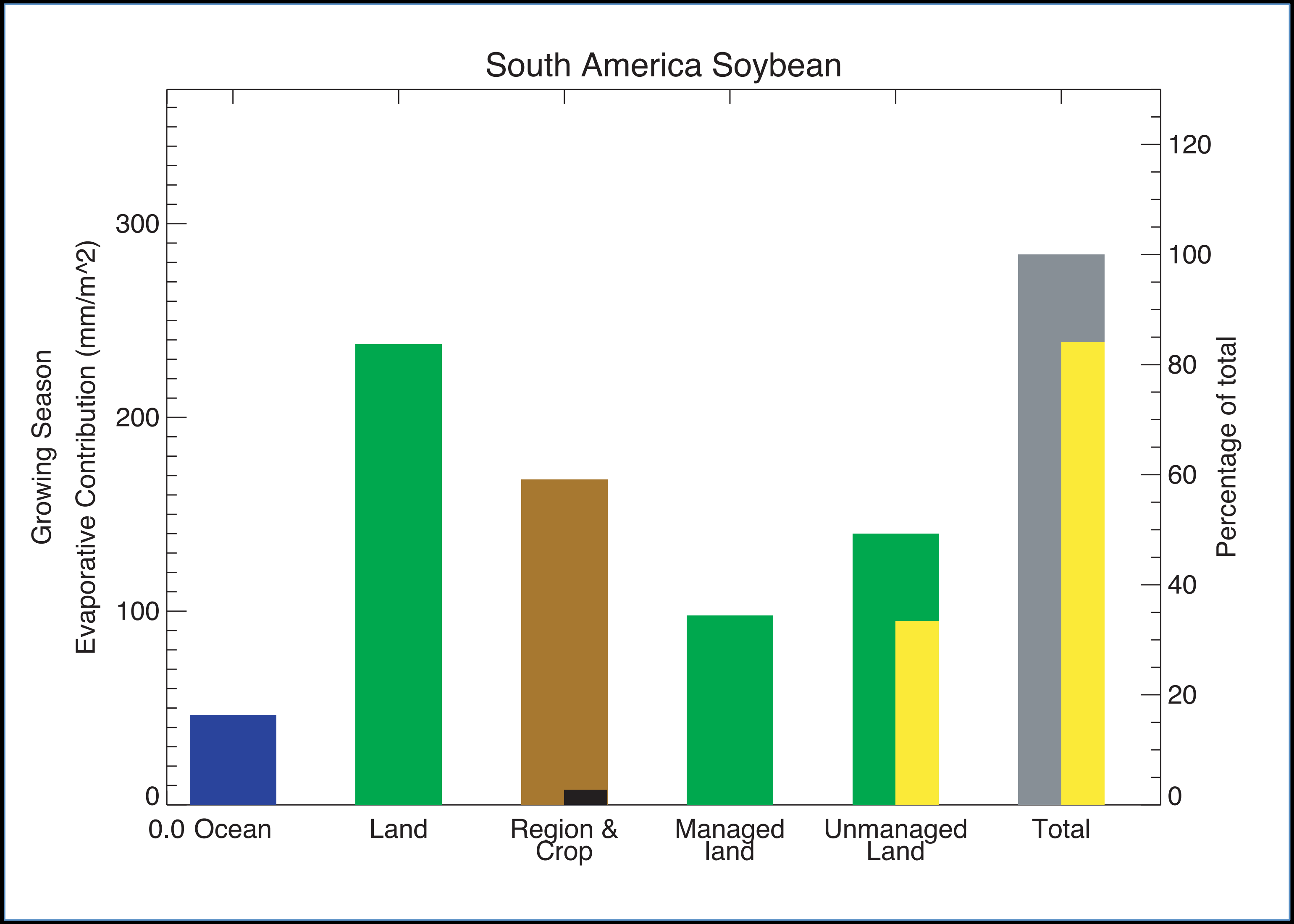
Potential Impact of Land Cover Change on Precipitation

North America Maize



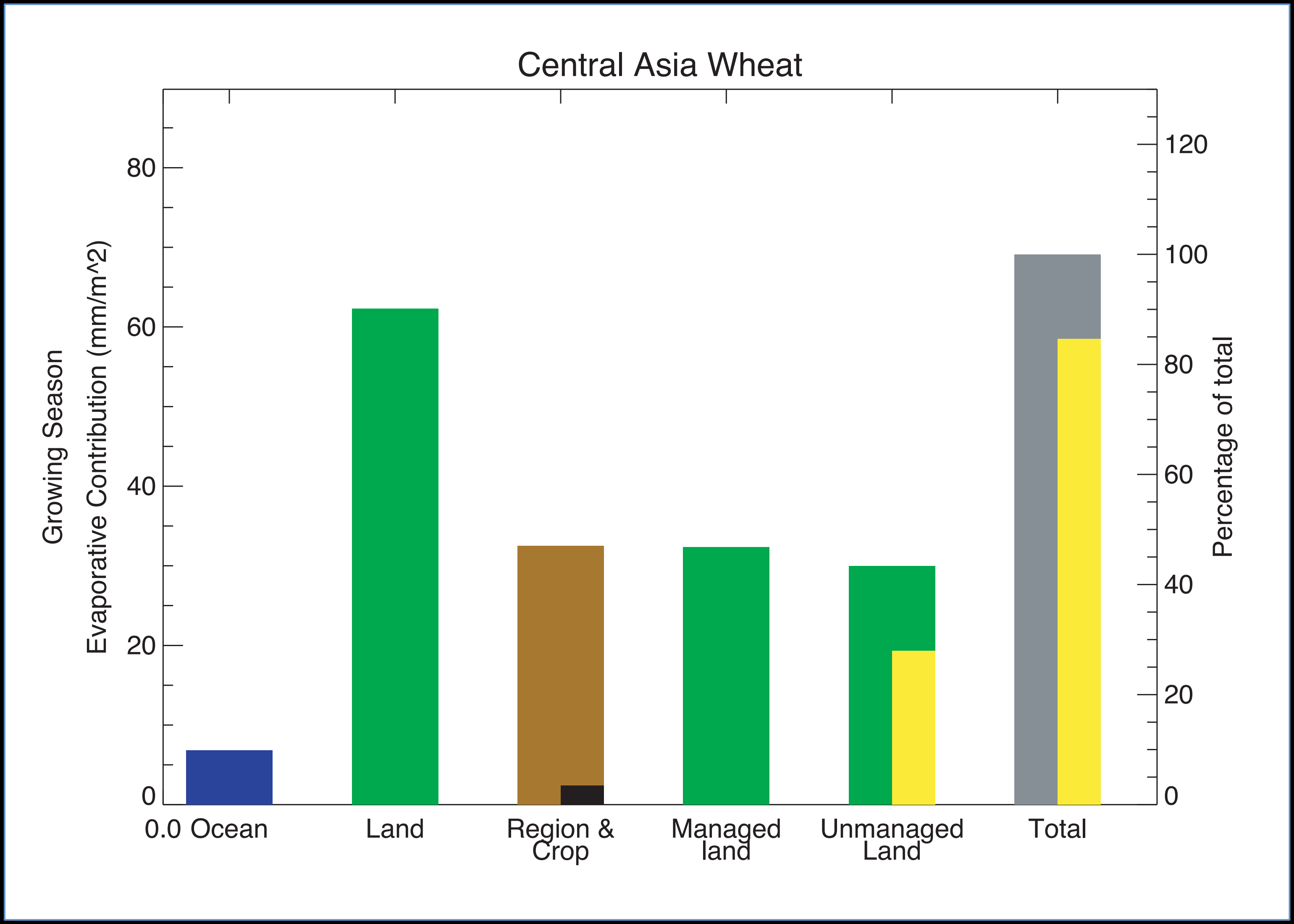
Potential Impact of Land Cover Change on Precipitation

S. America Soybeans



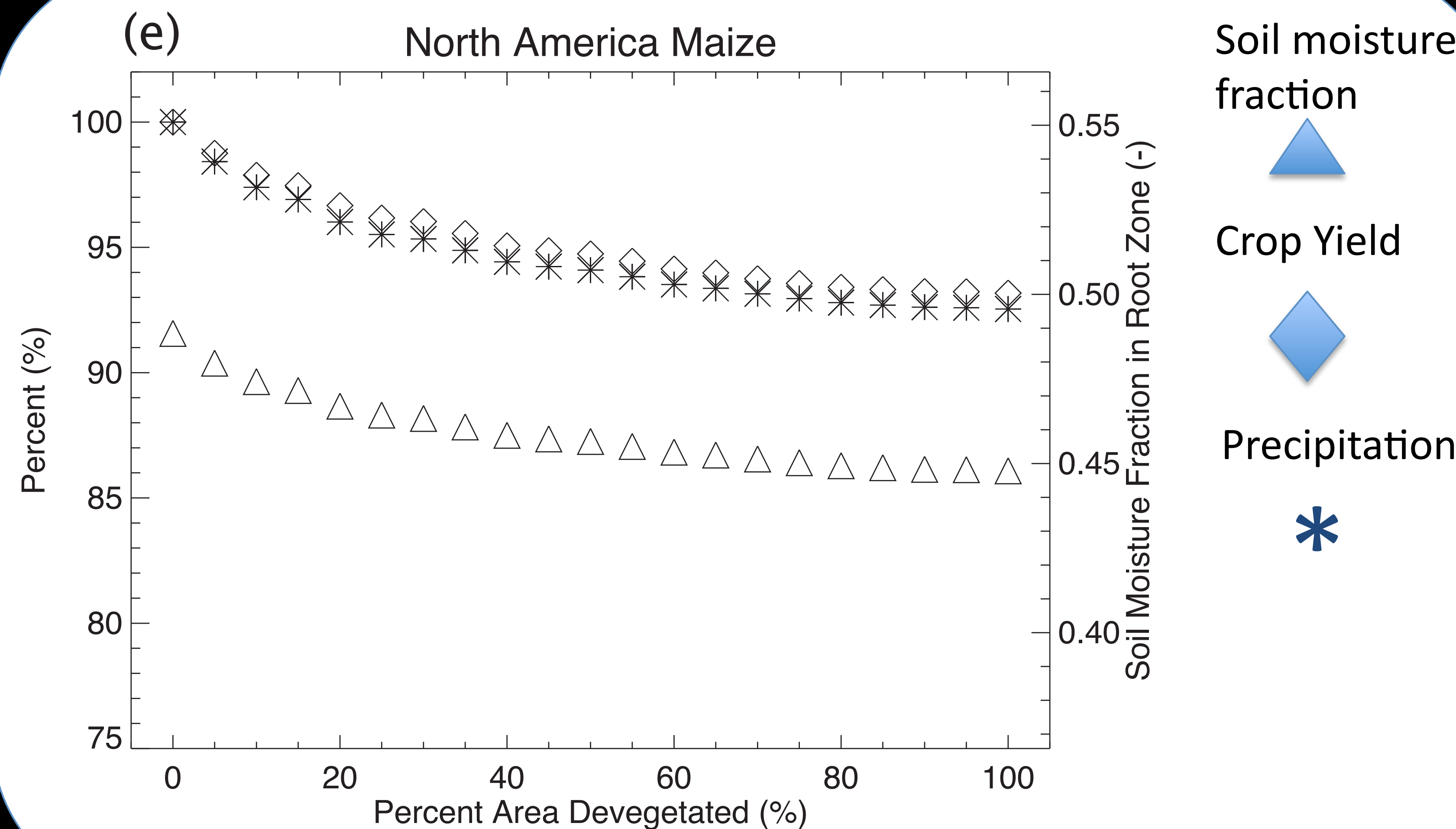
Potential Impact of Land Cover Change on Precipitation

Central Asian Wheat



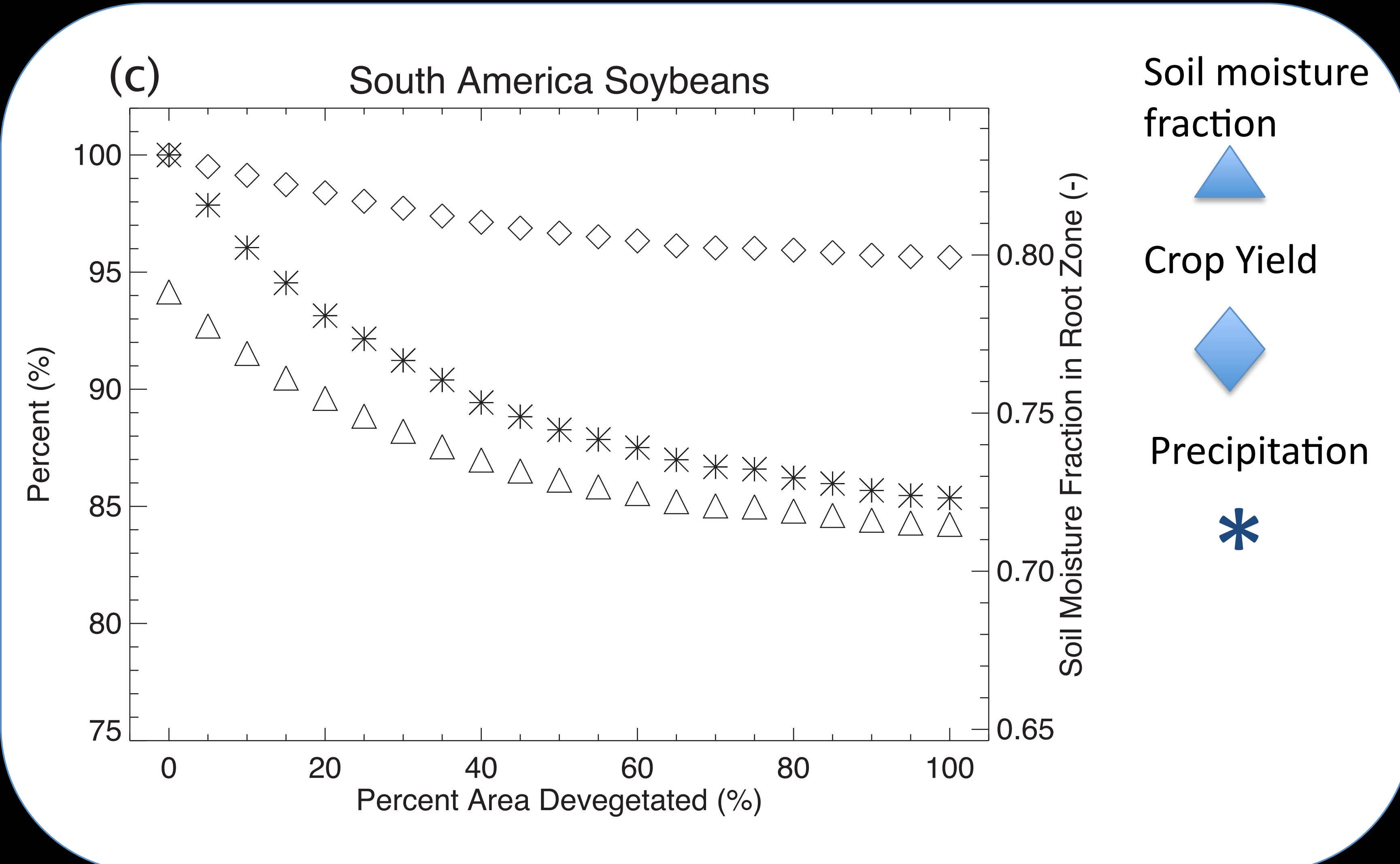
Potential Impact of Land Cover Change on Crop Yield

N. America Maize



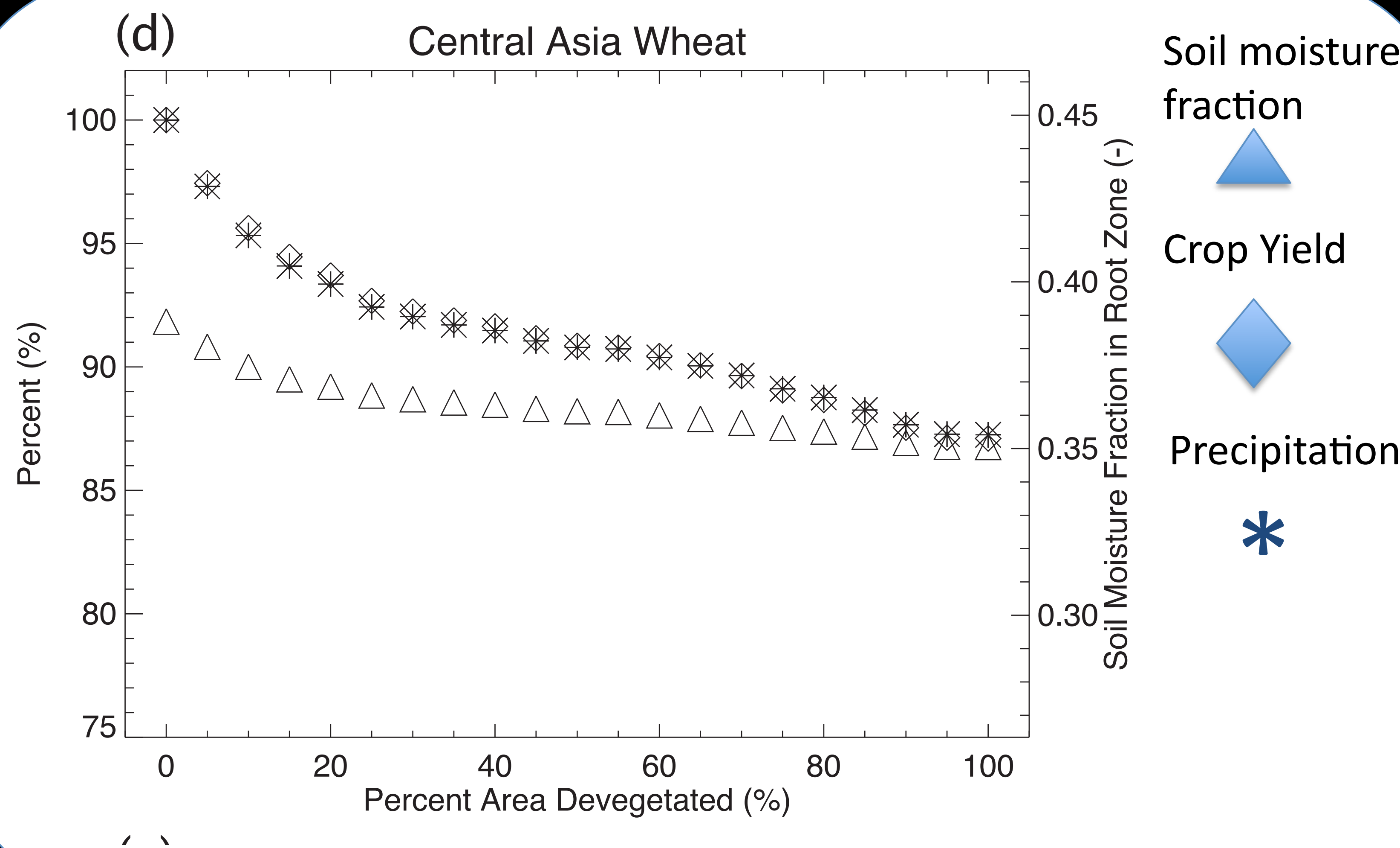
Potential Impact of Land Cover Change on Crop Yield

S. America Soybeans



Potential Impact of Land Cover Change on Crop Yield

Central Asian Wheat



Take home messages:

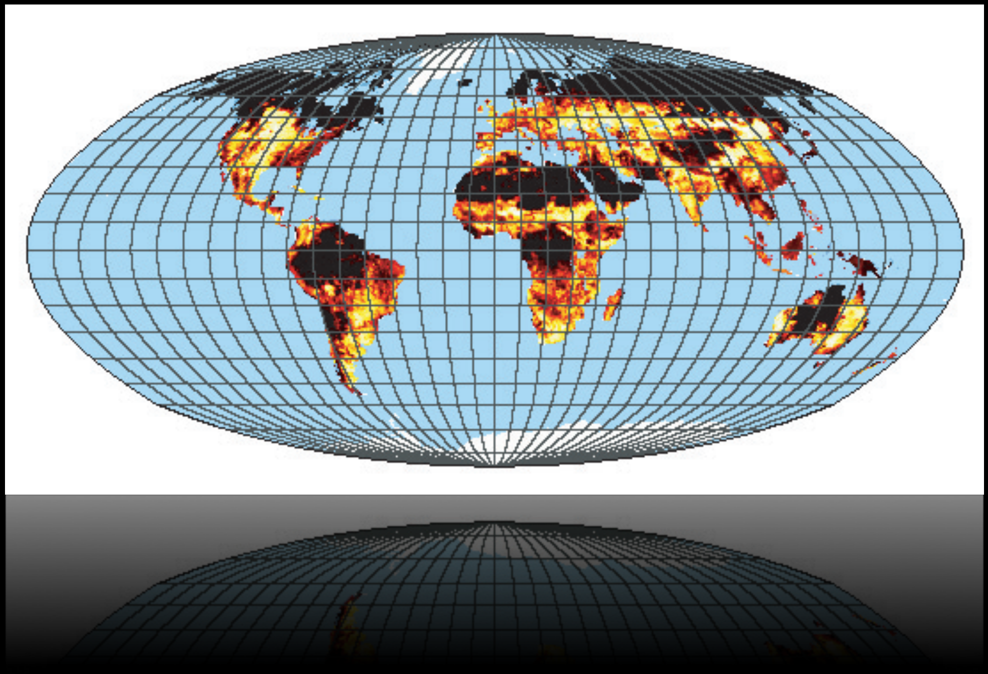
1. Much of the moisture that precipitates over breadbasket regions is *terrestrial* in origin and potentially subject to alterations from land cover change.

2. Land cover change has the potential to *reduce precipitation* over breadbasket crops between 6-17%.

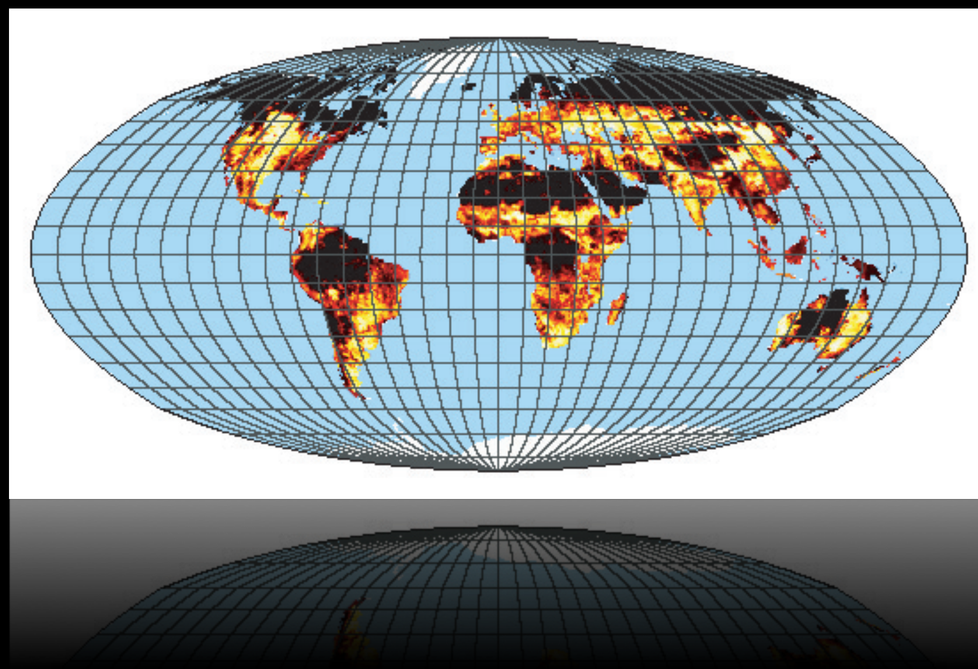
3. Crop yields respond differently to altered precipitation. Depending on the region we found the reduction crop yield reduction to be between 1-17% (similar mag. as climate change).

4. This study would have been prohibitively expensive to complete with full GCM's or regional models.

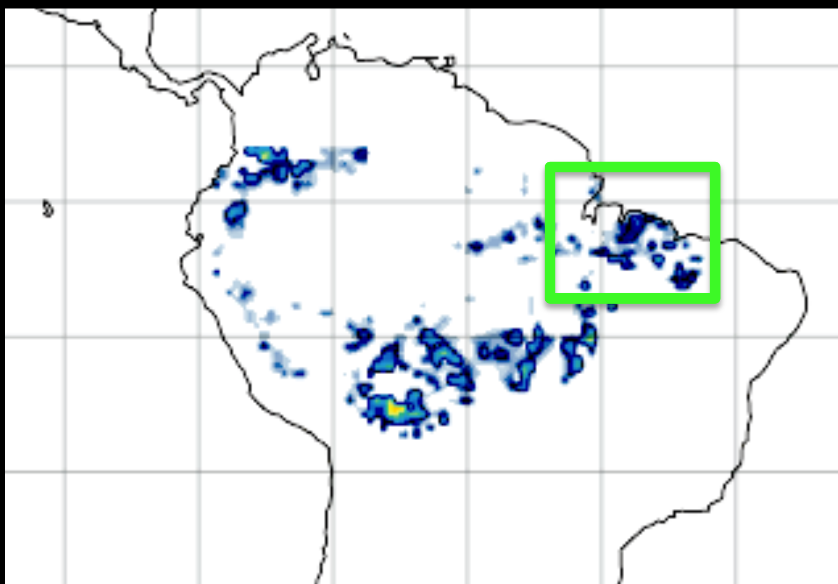
Acknowledgements



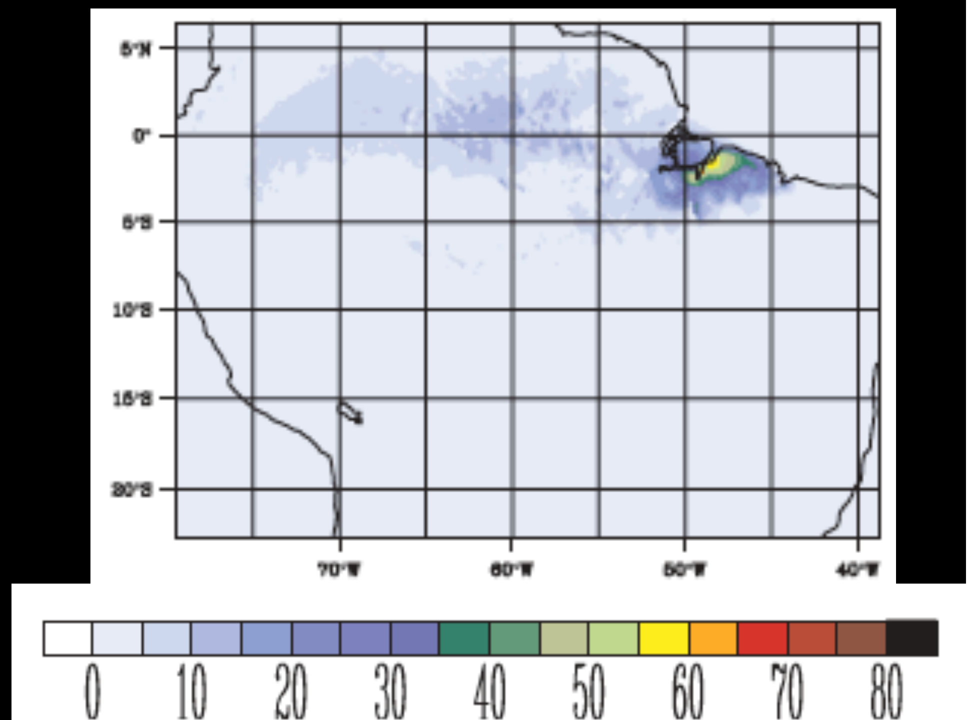
Questions?



Moisture Trajectory Analysis

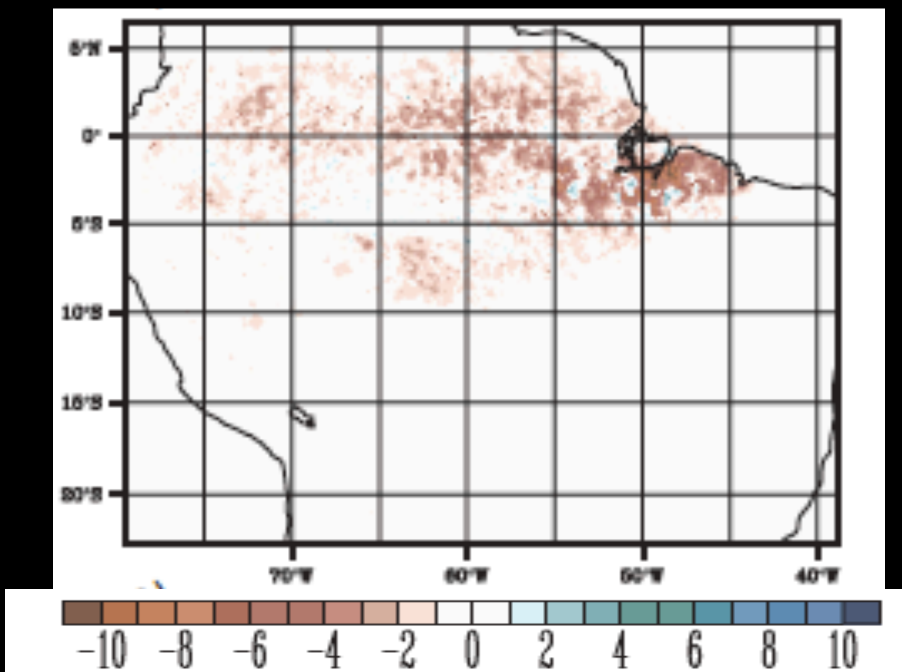


Source Region

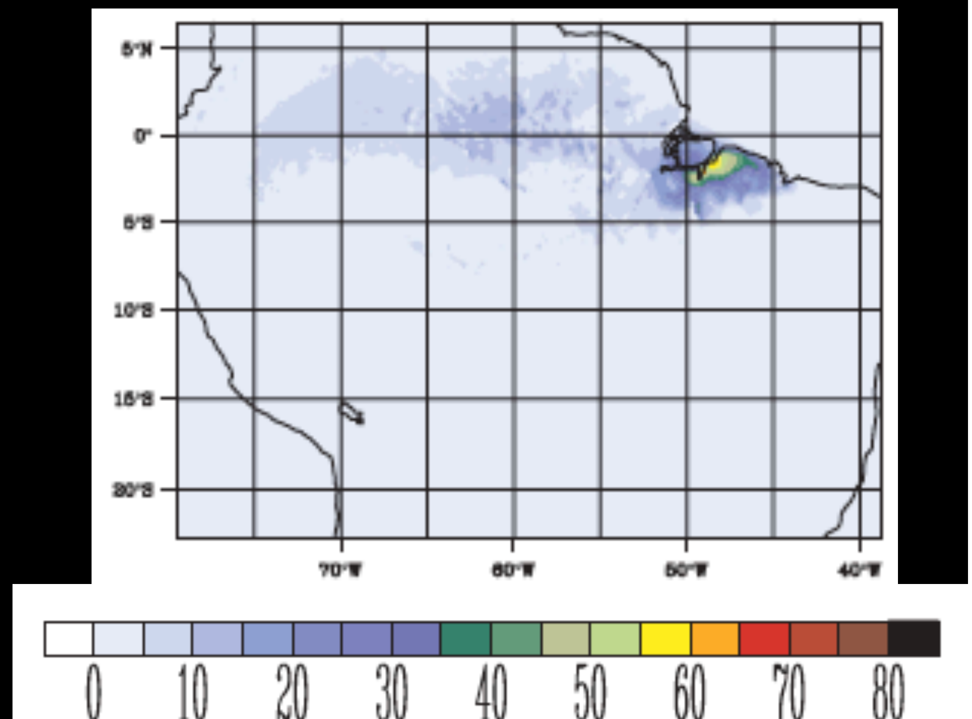


Mean forward trajectory precipitation rate from deforested points

Moisture Trajectory Analysis



Impact of deforestation on precipitation rate from deforested points

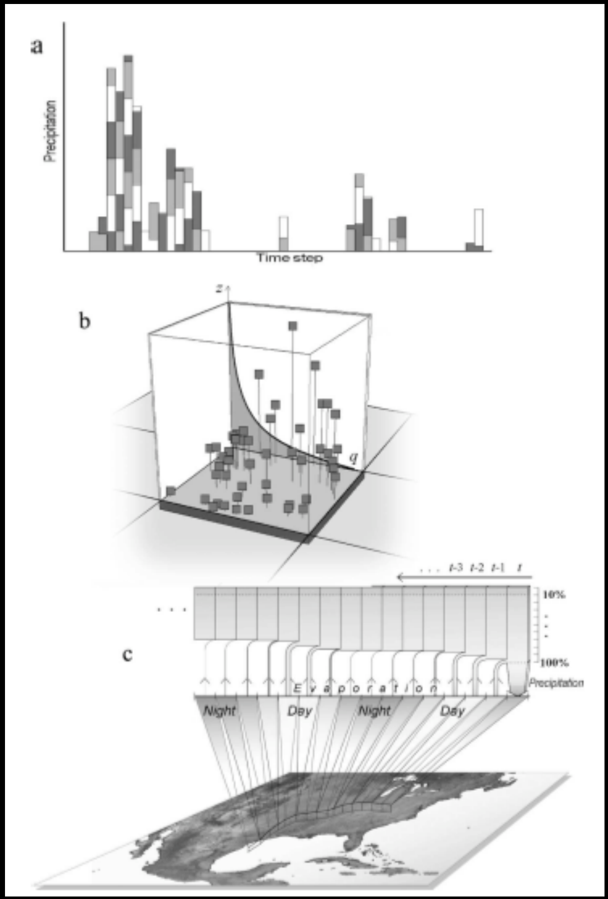


Mean forward trajectory precipitation rate from deforested points

Back Trajectory Analysis Description

Precipitation, Recycling, and Land Memory: An Integrated Analysis (Dirmeryer 2009)

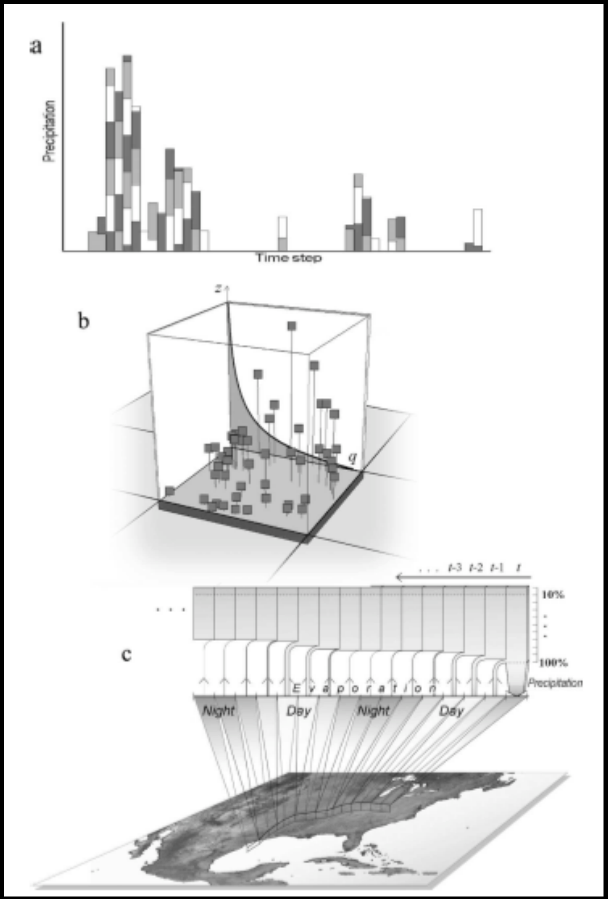
1. Identify precipitation event
2. Initialize 100 parcels at grid cell of precipitation at pseudo-random heights
3. Generally following isentropic lines follow parcels 14 days backward in time or until the parcel intersects the surface
4. As it passes over adjacent gridpoints assume the a portion of its moisture is given to it by the evapotranspiration occurring at that point
5. Aggregate parcels to get evaporative source of precipitation event



Back Trajectory
Analysis Description

Precipitation, Recycling, and Land Memory: An Integrated Analysis
(Dirmeryer 2009)

By compiling this information across all the precipitation events, we can invert the backtrajectories to determine where moisture evaporated from a given point tends to rain out of the atmosphere



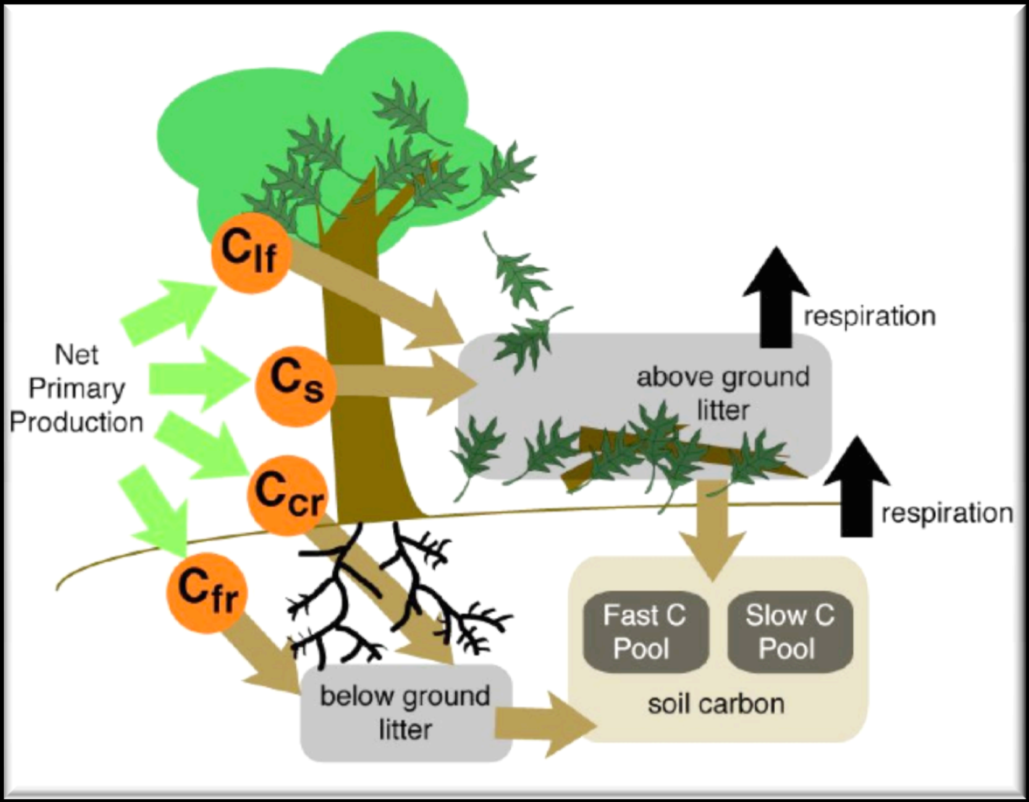
Carbon Balance/ Vegetation Model

- Calculates NPP on daily timestep as ftn. of LAI, PAR, LUE, temp., and soil water.

- NPP partitioned into several stocks based on biome specific allocation constants

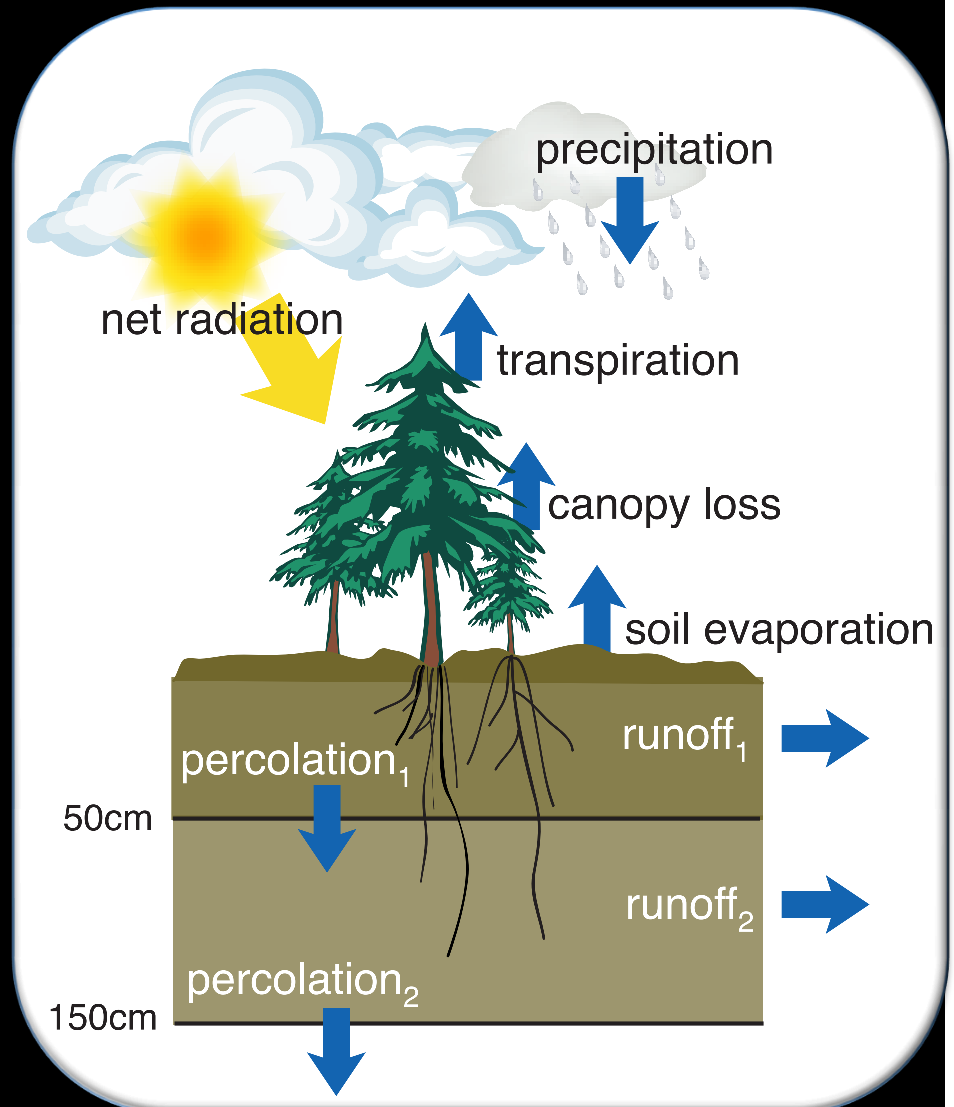
- Carbon loss estimated from climate, plant phenology, and size of carbon stocks

- Carbon remaining after respiration is separated into fast and slow carbon pools



Water Balance Model

- AET calculated using Priestley-Taylor approach
- Canopy evap. a ftn of precip, veg. cover, and temperature
- Snow fall calculated using formula of Legates and Bogart (2009)
- Soil moisture of two layers calculated by water balance
- Runoff calculated as residual after evaporation and percolation as well as percolation below 150cm



Composite
Boundary Layer
BOREAS results

Observed
Composites from
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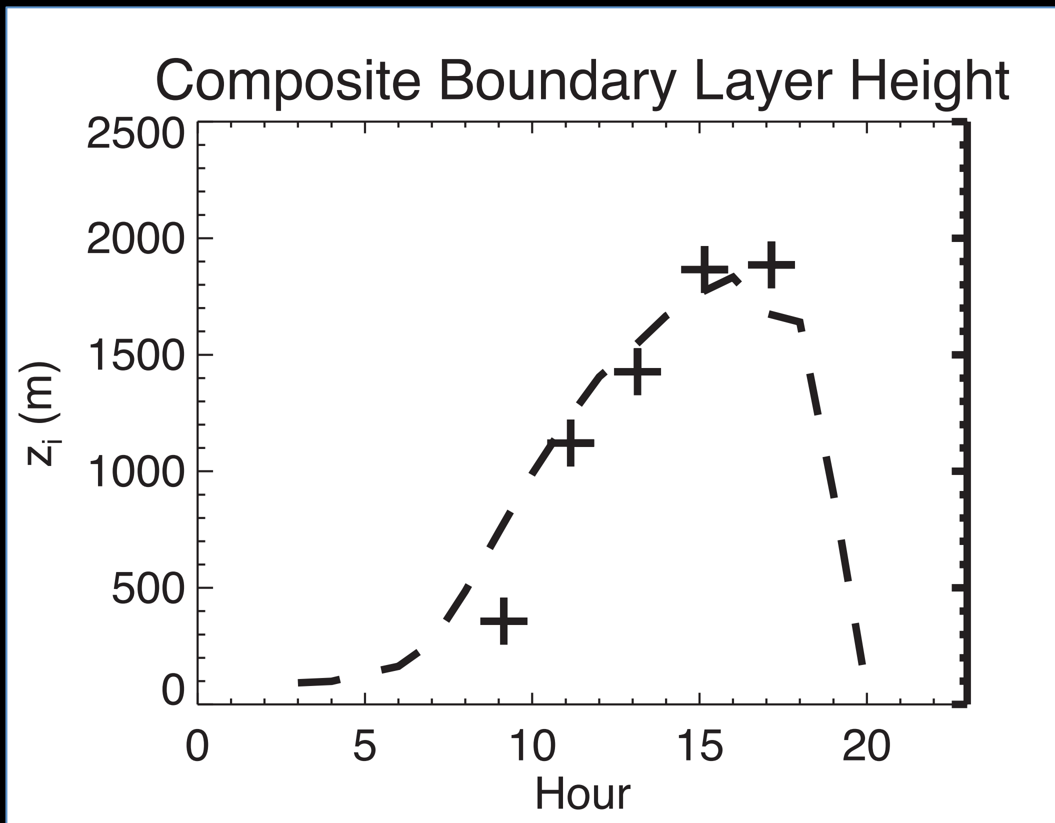
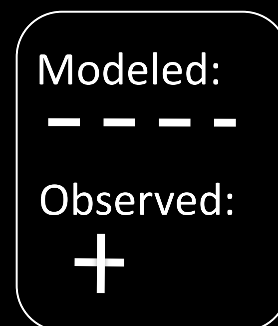
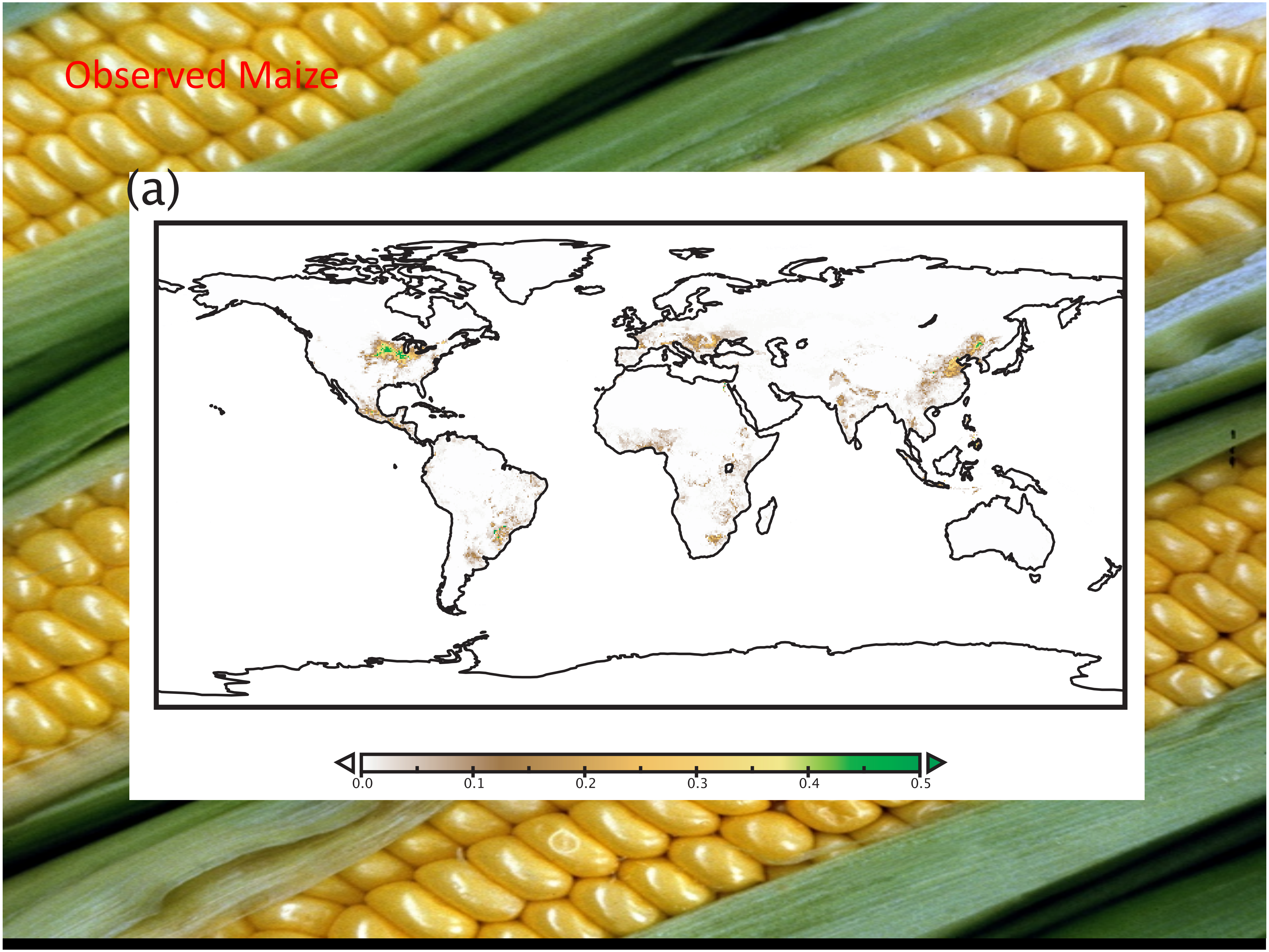
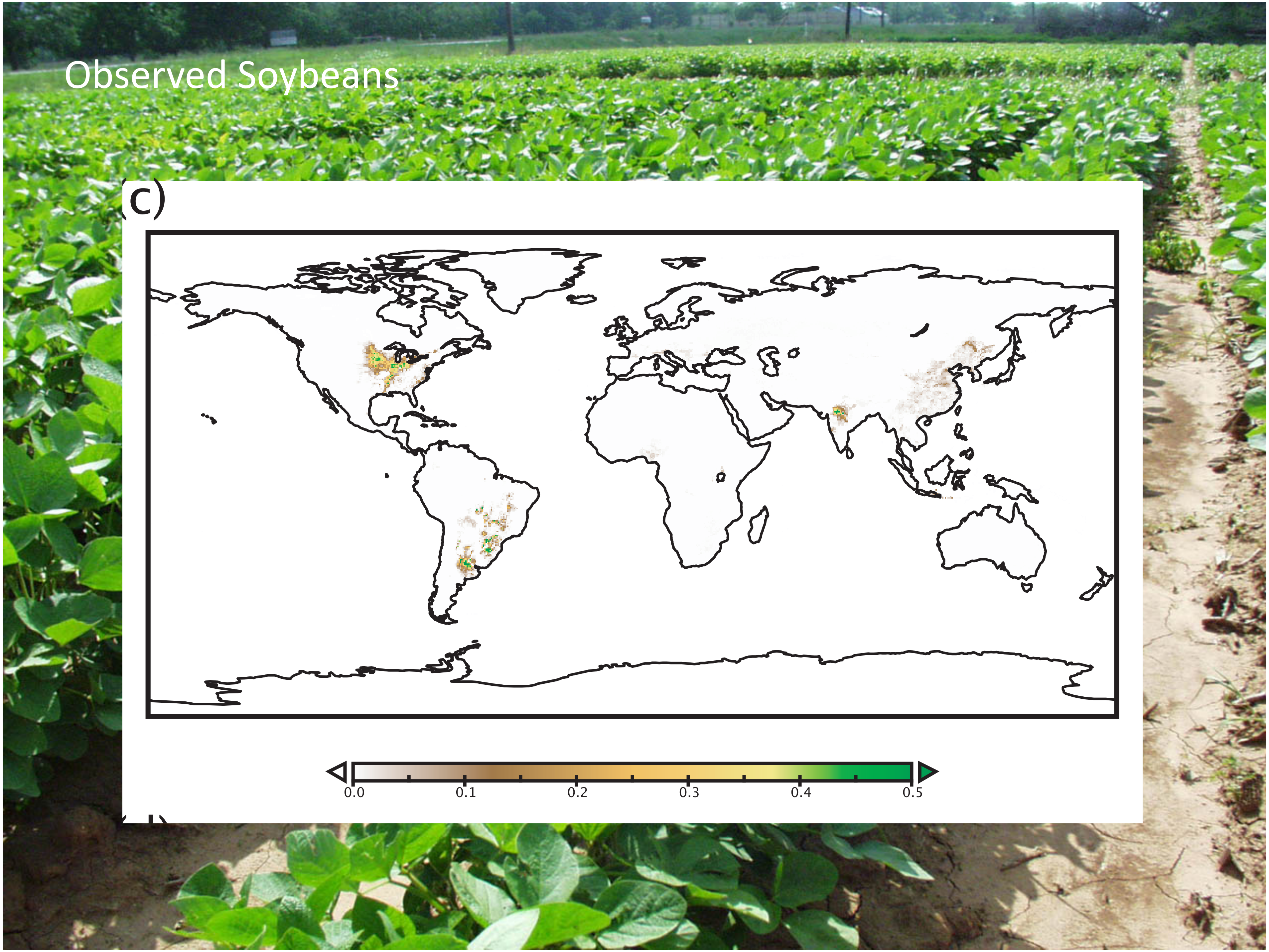




Boundary Layer Height


Observed Maize
(a)
0.0
0.1
0.2
0.3
0.4
0.5


Observed Soybeans
(c)
0.0
0.1
0.2
0.3
0.4
0.5