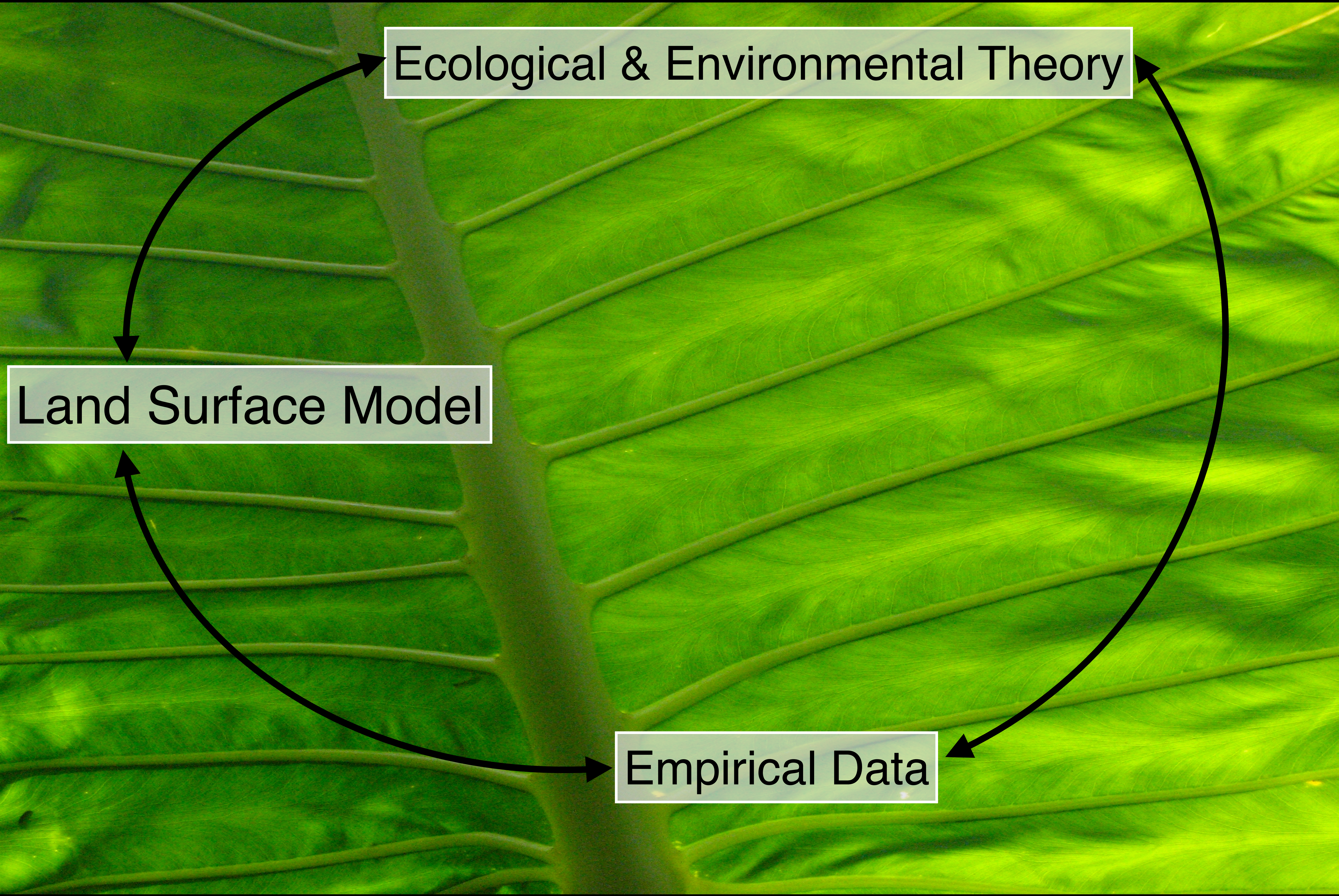
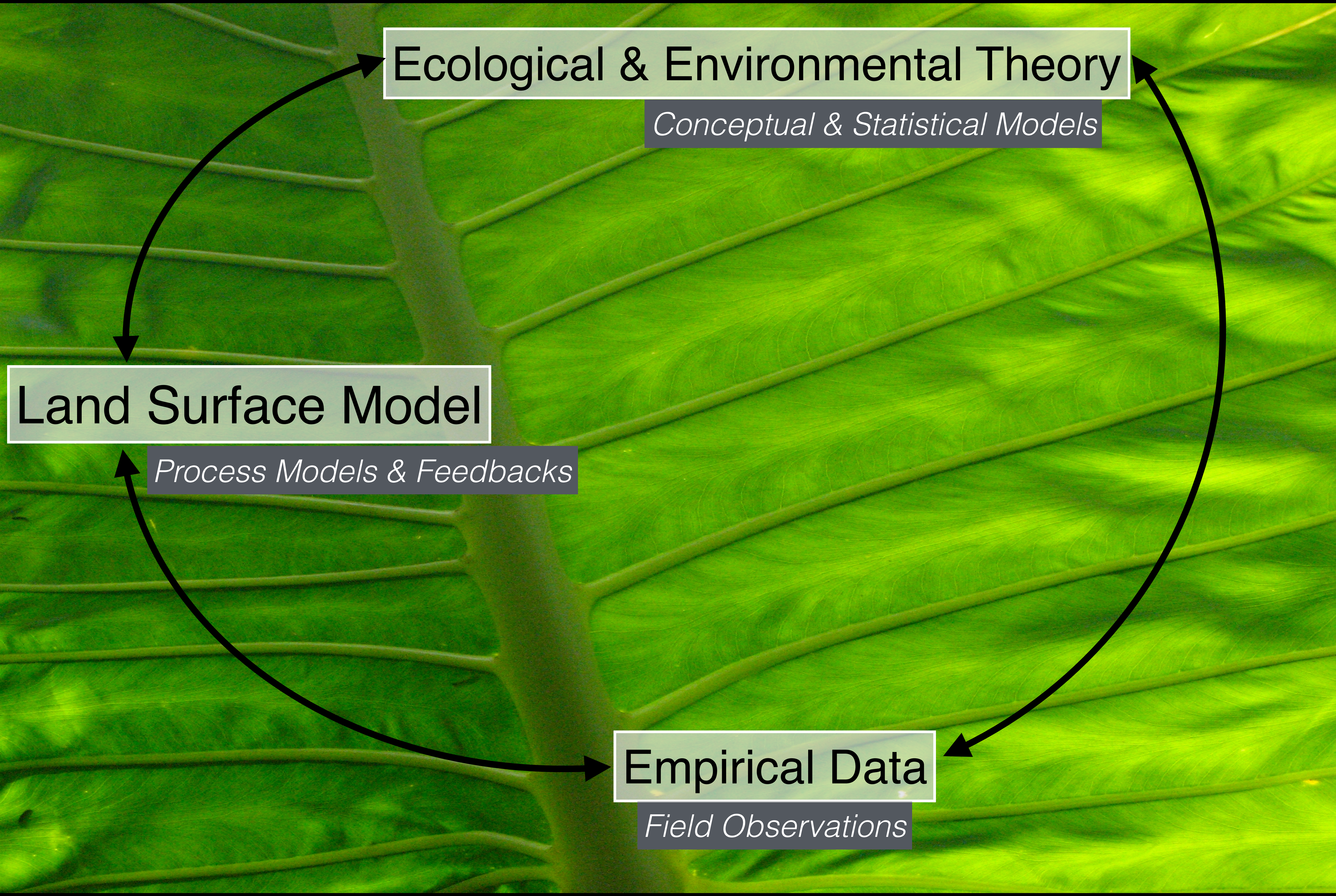
Modeling Terrestrial Processes in an ESM

Danica Lombardozzi
National Center for Atmospheric Research


Ecological & Environmental Theory
Land Surface Model
Empirical Data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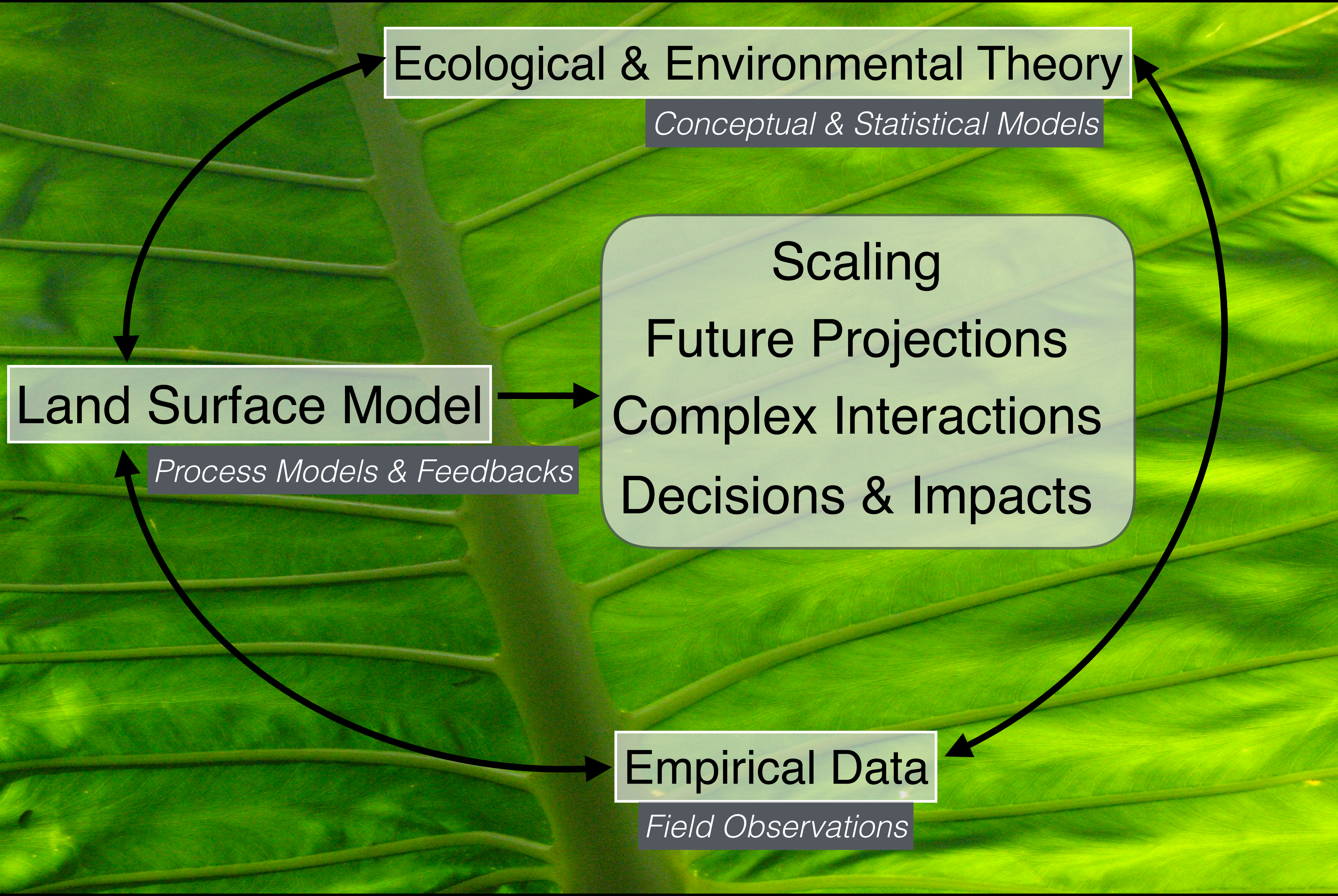
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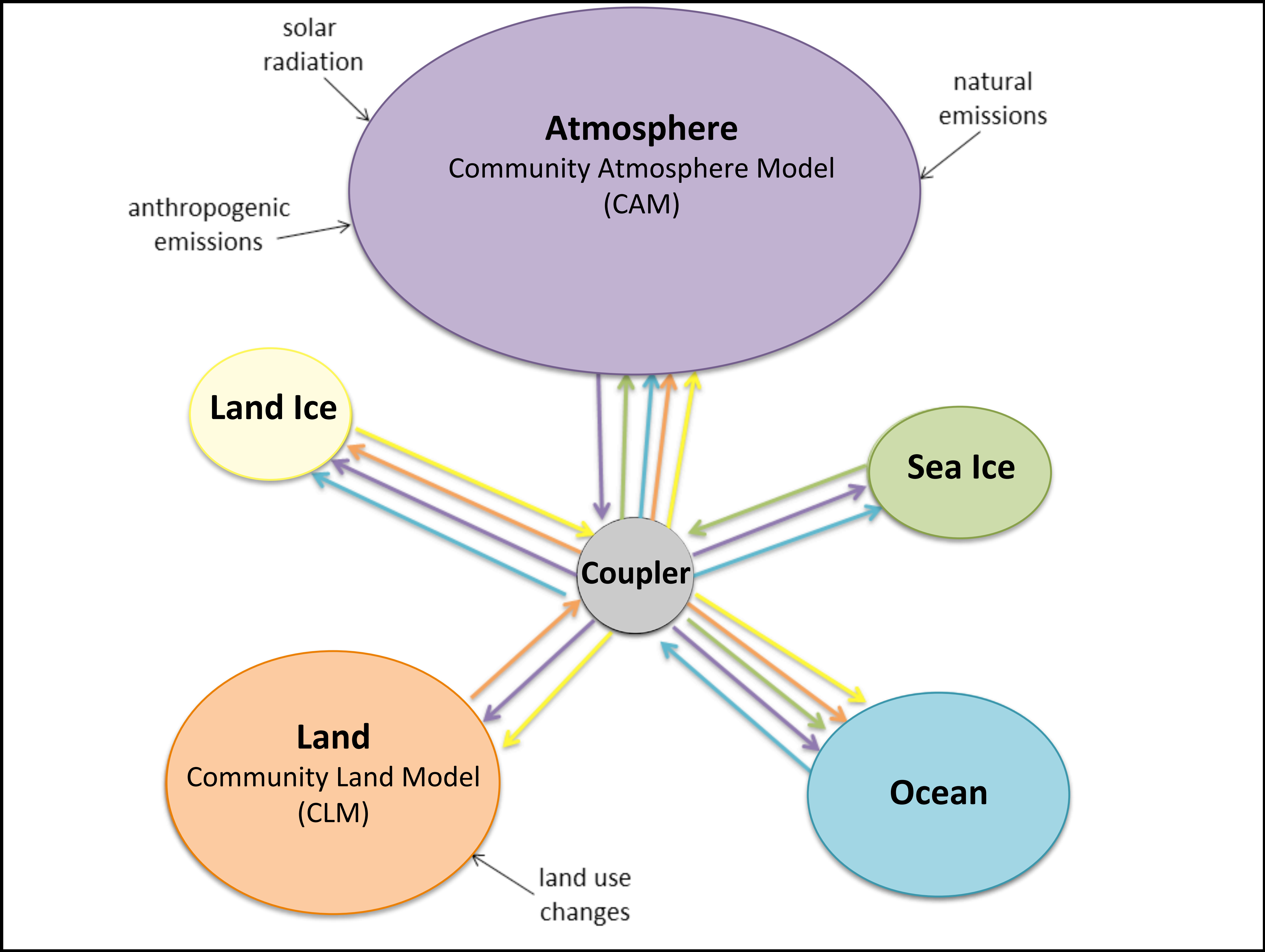
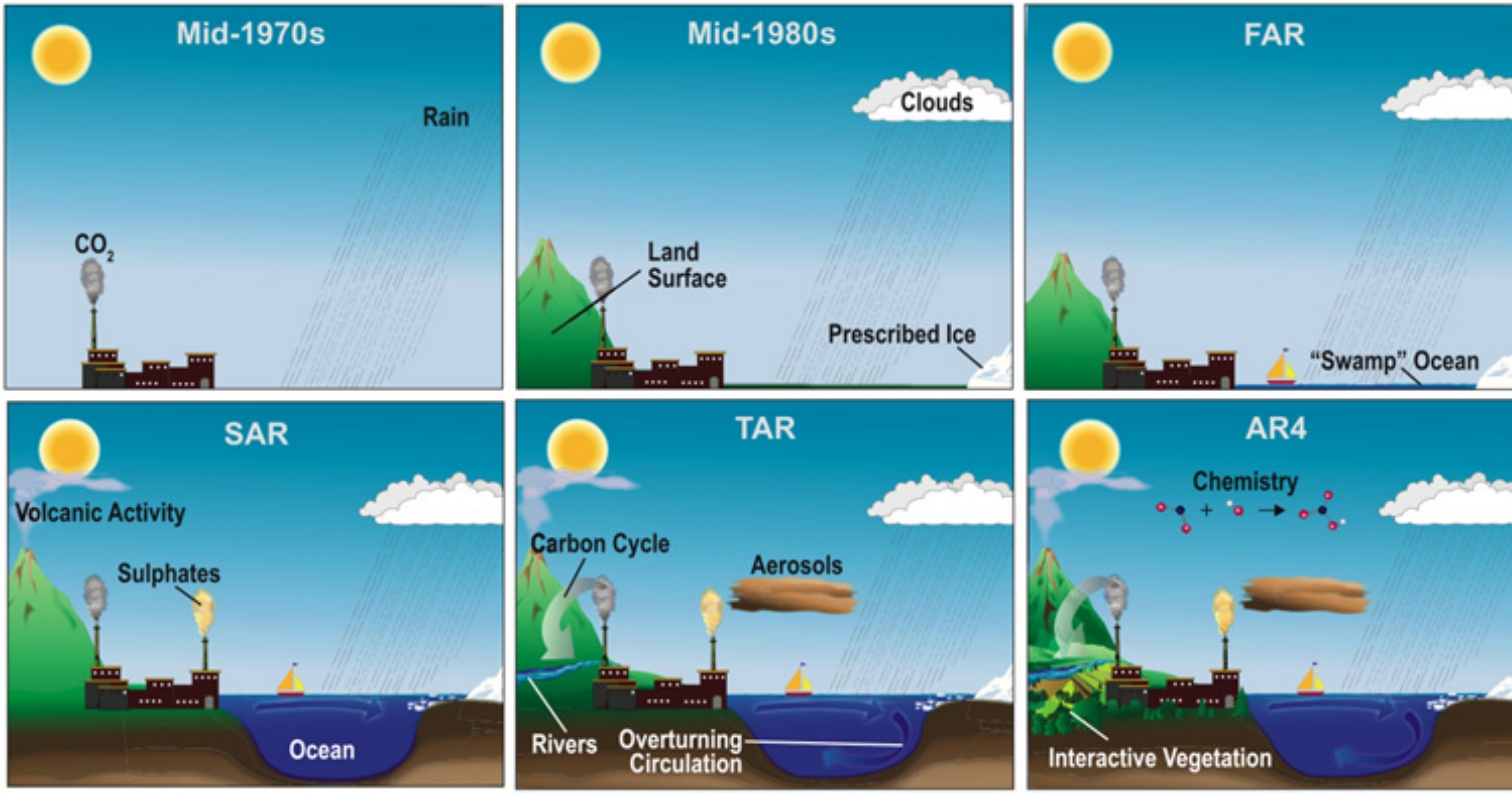
Outline

1. Why the land surface matters
2. Primary components of terrestrial energy balance
3. Primary components of hydrology
4. Primary components of the terrestrial carbon cycle

Community Earth System Model

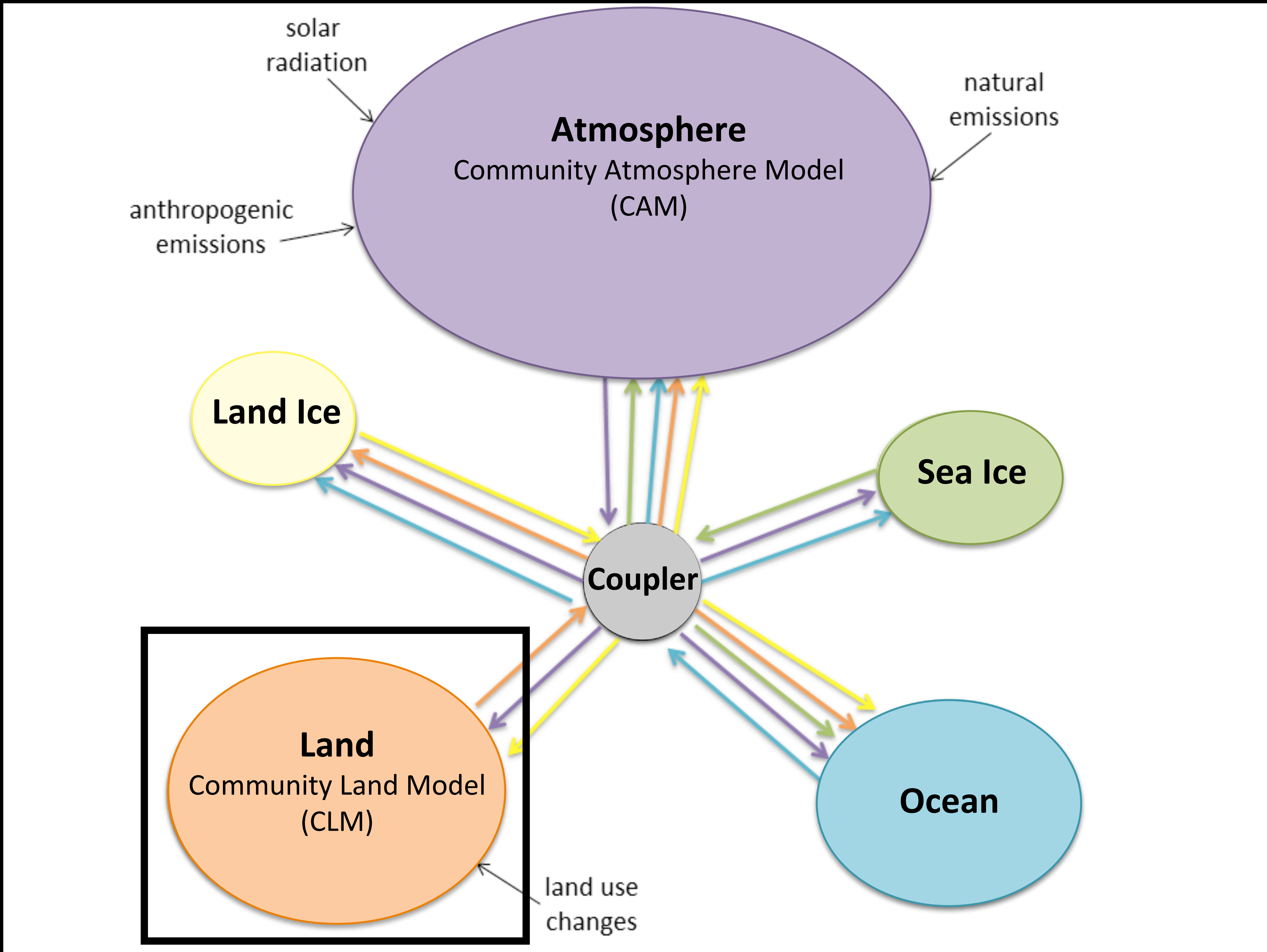


The World in Global Climate Models

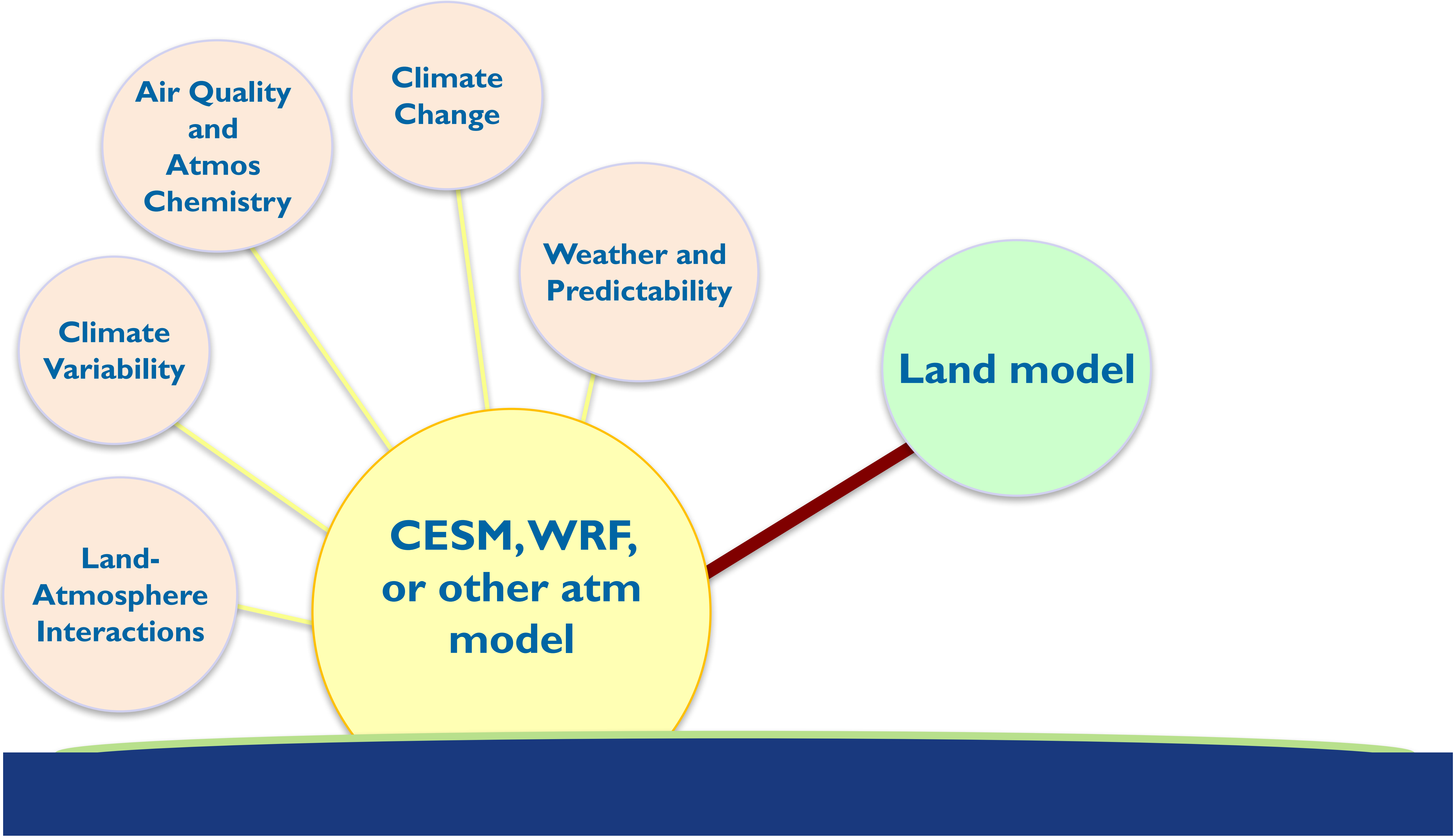


IPCC AR4

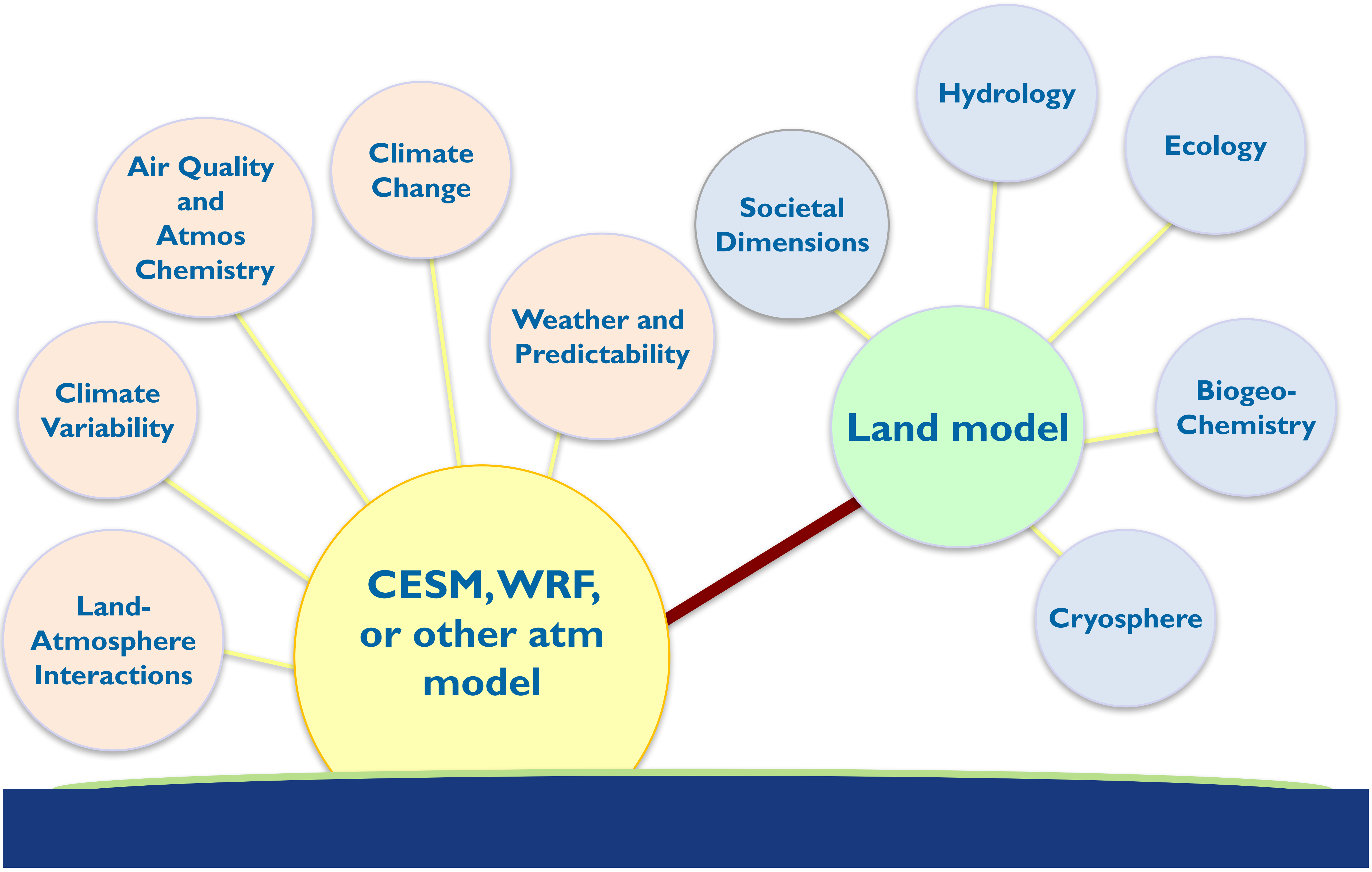
Community Earth System Model



Land models for Earth System prediction



Land models for Earth System prediction

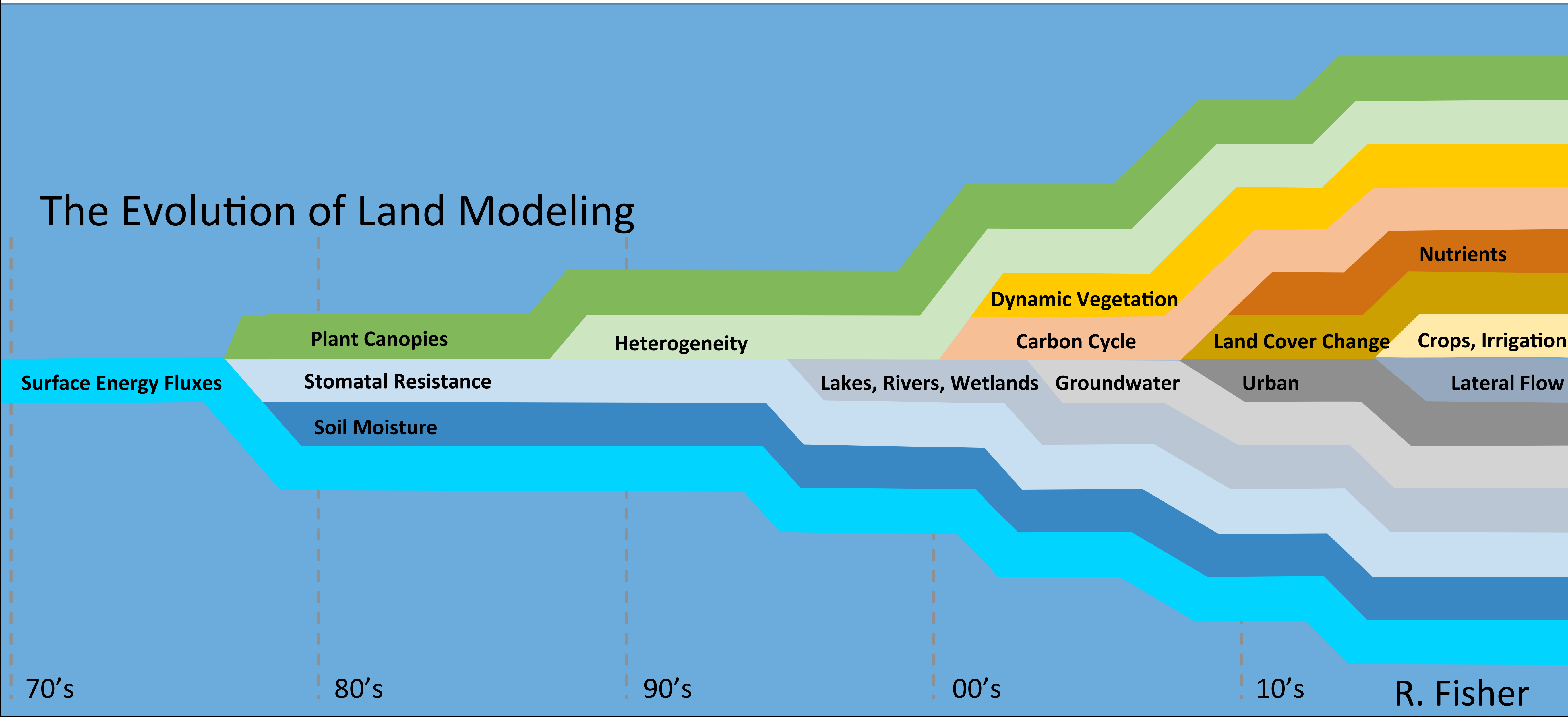


The interdisciplinary evolution of land models

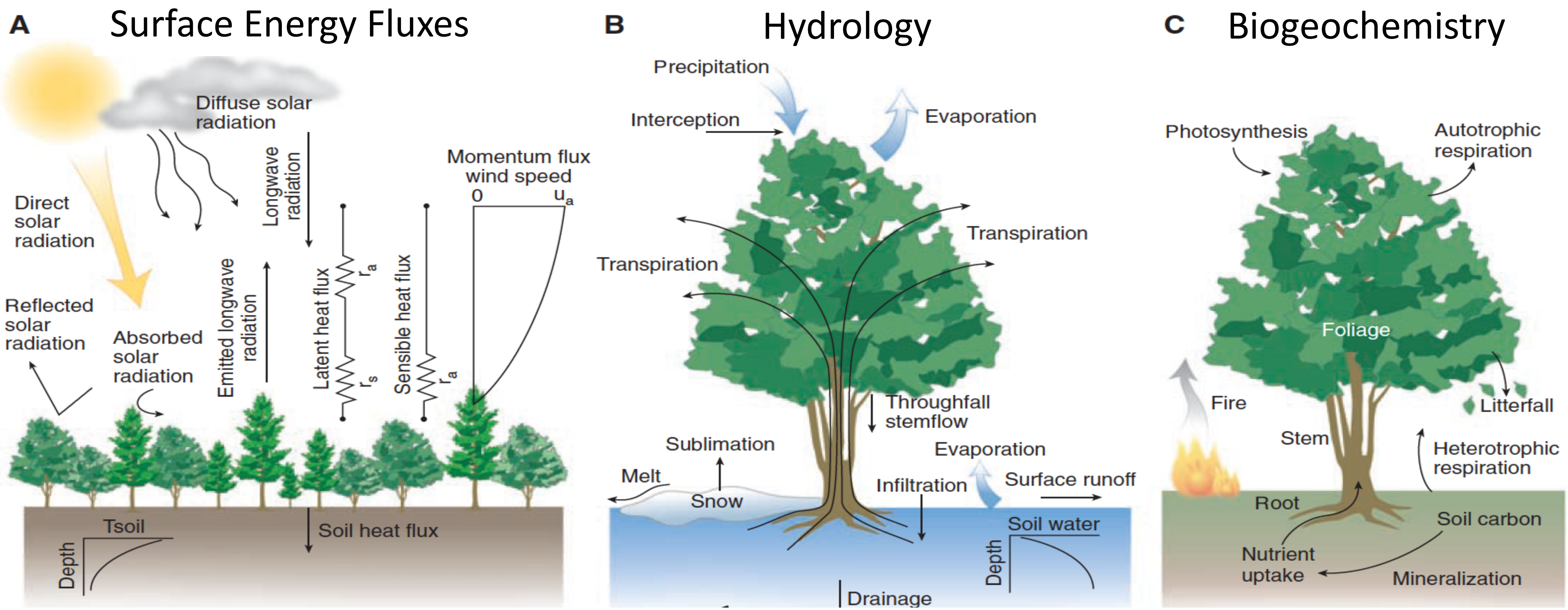
Land as a lower boundary to the atmosphere → **Land as an integral component of the Earth System**

Focus on land-atmosphere energy fluxes → *Mechanistic modeling of land processes* → *Simulate the dynamics of change (e.g., dynamic vegetation)*

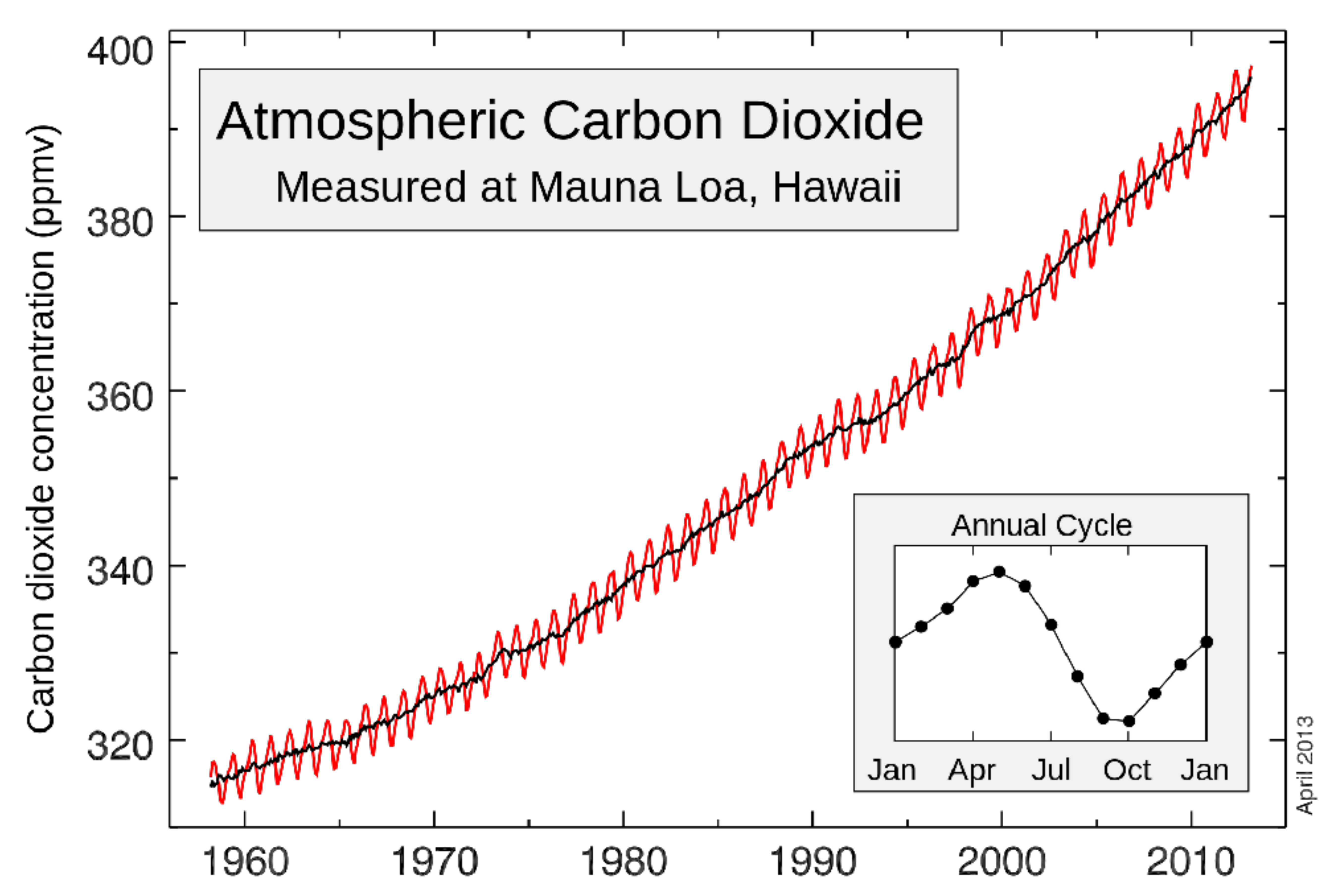
Limited representation of land processes & feedbacks → *Properties define processes (focus on short-term fluxes)* → *Processes define properties (feedbacks and interactions across time scales)*



The Community Land Model



Why land?



Atmospheric Carbon Dioxide
Measured at Mauna Loa, Hawaii
Carbon dioxide concentration (ppmv)
400
380
360
340
320
1960
1970
1980
1990
2000
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Annual Cycle
Jan
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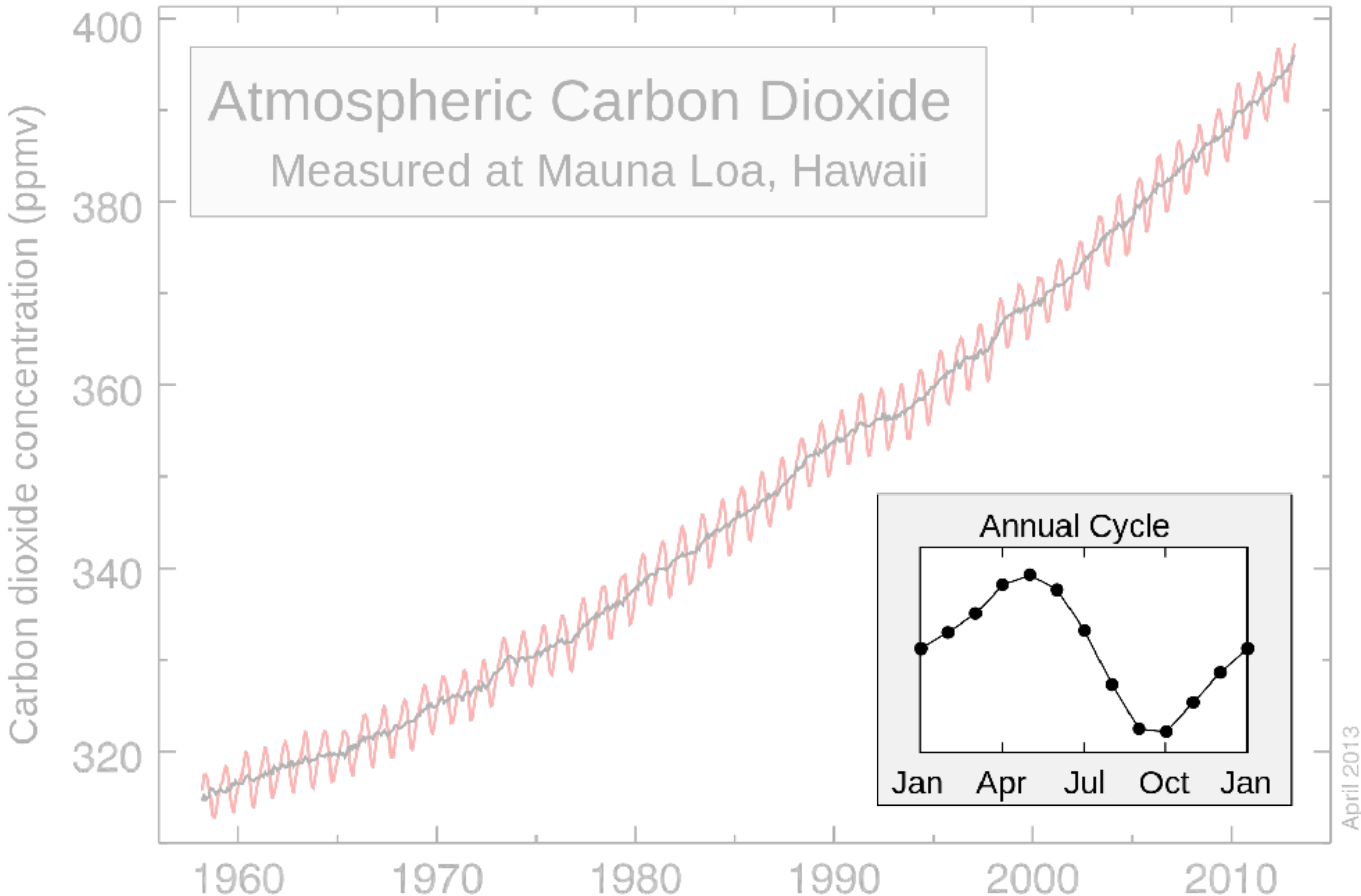

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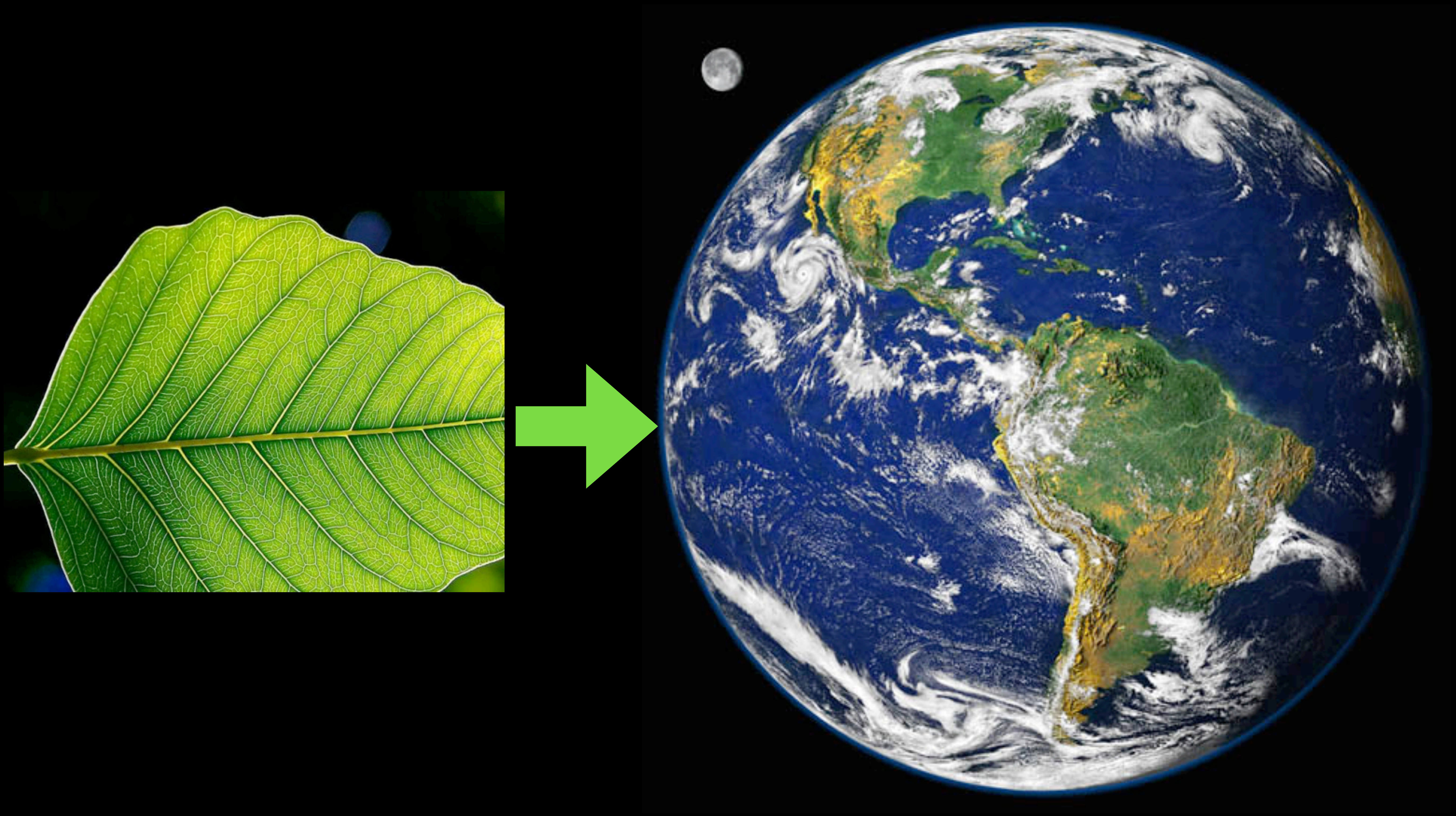
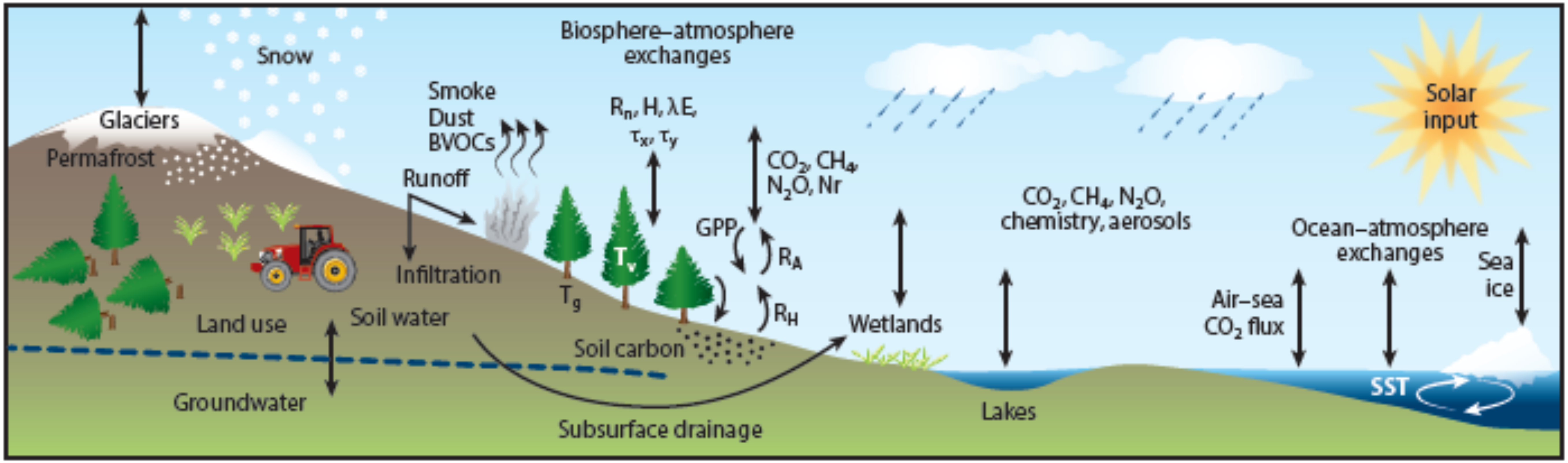


Earth System Models



Bonan (2016) Ecological Climatology, 3rd ed (Cambridge Univ. Press)
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Prominent terrestrial feedbacks:

- Snow cover and climate
- soil moisture-evapotranspiration-precipitation
- land use and land cover change
- carbon cycle
- reactive nitrogen
- chemistry-climate (BVOCs, O_3, CH_4, aerosols)
- Biomass burning

The role of a land model in an ESM

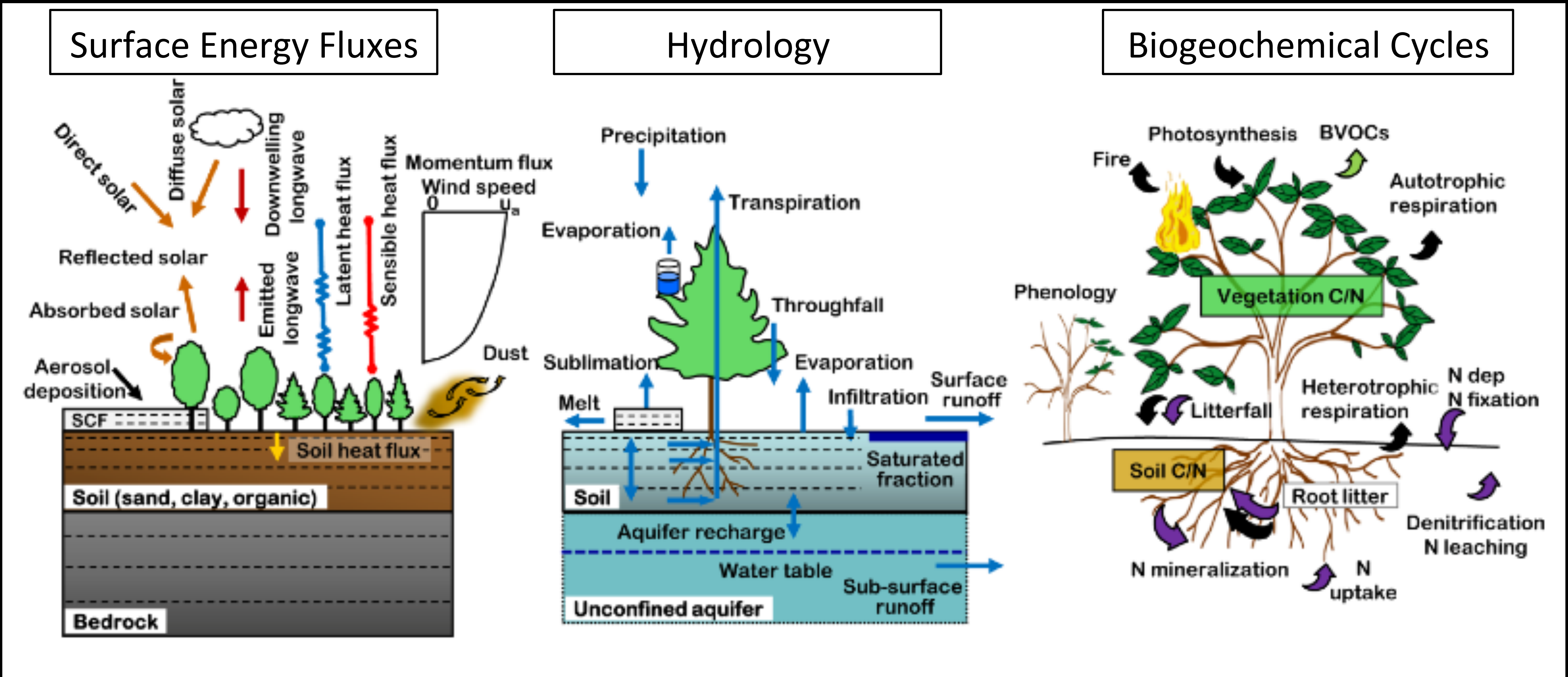
Land-atmosphere exchanges: energy, water vapor, CO_2, dust, trace gases, etc.

Land surface states: soil moisture, soil temperature, canopy temperature, snow water equivalent, C and N stocks

Land surface characteristics: soil texture, surface roughness, albedo, emissivity, vegetation type, leaf area index, etc.

Ultimately, we need to move energy, moisture, and gases between the land surface and the atmosphere while conserving each.

Community Land Model



The land surface model solves

Surface Energy Balance

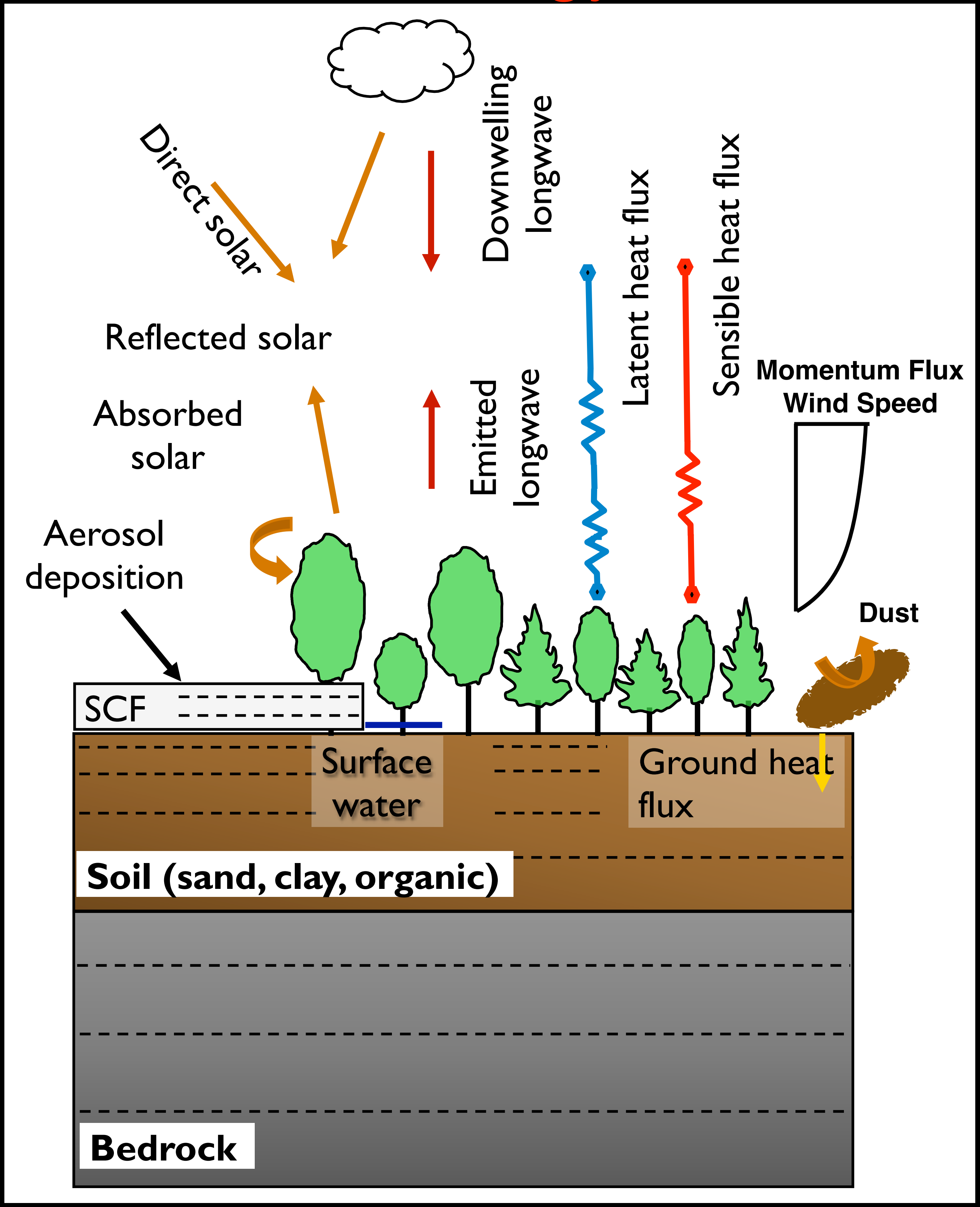
Surface Water Balance

Carbon Balance

at each model timestep

Community Land Model

Surface Energy Fluxes



Surface Energy Balance

$$S^{\downarrow} + L^{\downarrow} = S^{\uparrow} + L^{\uparrow} + \lambda E + H + G + \text{Energy Change}$$

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Inputs or Forcings

Surface Energy Balance

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Inputs or Forcings

$S^{\downarrow}$ = incoming shortwave (solar)

$L^{\downarrow}$ = incoming longwave (infrared)

Surface Energy Balance

$$S^{\downarrow} + L^{\downarrow} = S^{\uparrow} + L^{\uparrow} + \lambda E + H + G \text{ +Energy Change}$$

Response Fluxes

Surface Energy Balance

$$S^{\downarrow} + L^{\downarrow} = S^{\uparrow} + L^{\uparrow} + \lambda E + H + G + \text{Energy Change}$$

$S^{\uparrow}$ = outgoing shortwave (reflected solar, due to albedo)

$L^{\uparrow}$ = outgoing longwave (emitted infrared, $\varepsilon\sigma T^4$)

$S^{\downarrow} - S^{\uparrow} + L^{\downarrow} - L^{\uparrow}$ = net radiation

Surface Energy Balance

$$S^{\downarrow} + L^{\downarrow} = S^{\uparrow} + L^{\uparrow} + \lambda E + H + G \text{ +Energy Change}$$

$S^{\uparrow}$ = outgoing shortwave (reflected solar, due to albedo)

$L^{\uparrow}$ = outgoing longwave (emitted infrared, $\varepsilon\sigma T^4$)

λE = latent heat flux (evapotranspiration)

H = sensible heat flux

G = ground heat flux

Surface Energy Balance

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Energy change = the change in energy of some reservoir (canopy, soil, etc.)

Surface Energy Balance

Often, we think of the land surface as affecting the energy balance through three properties/processes:

a. Albedo
b. Surface Roughness
c. Evapotranspiration

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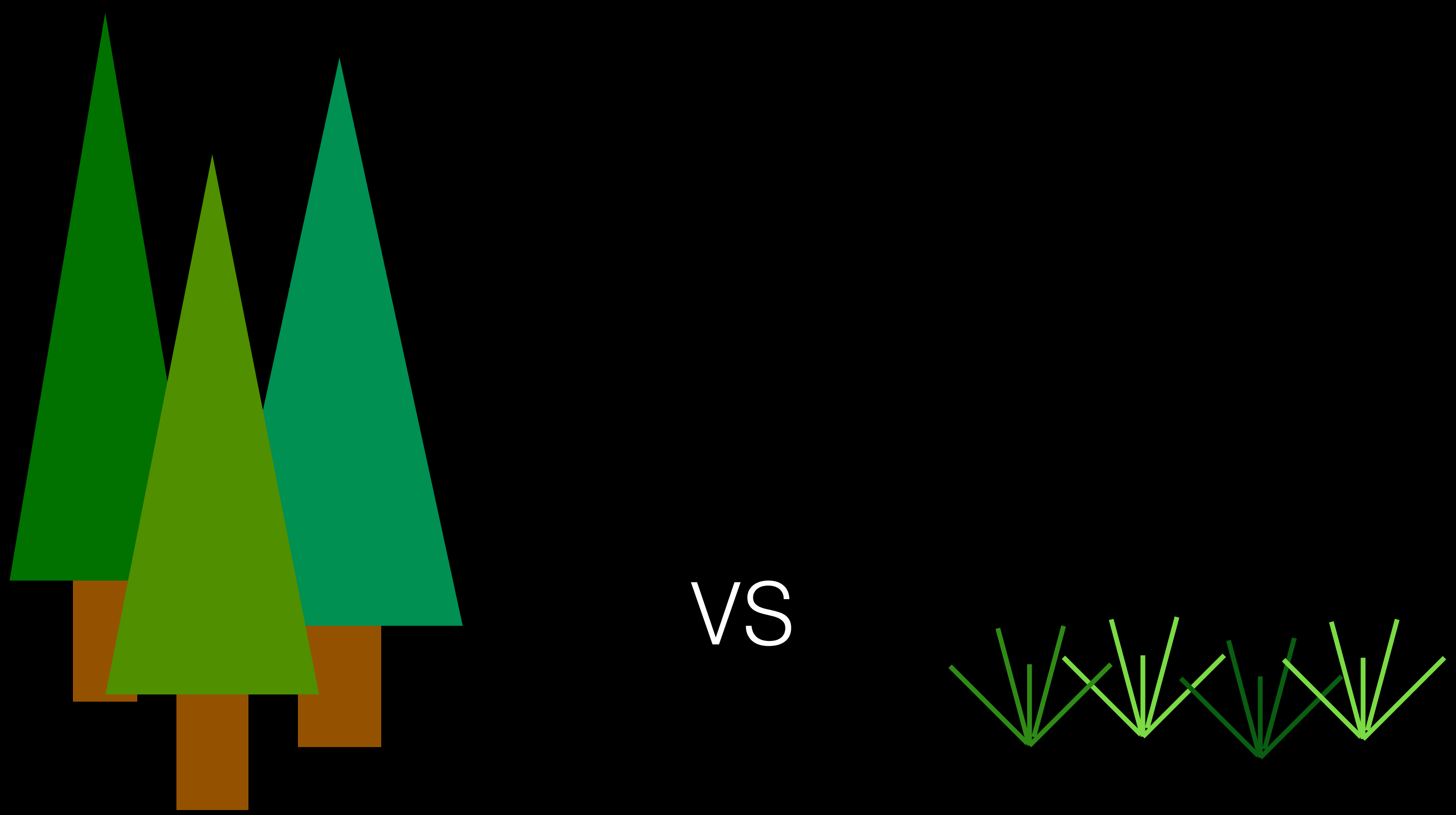

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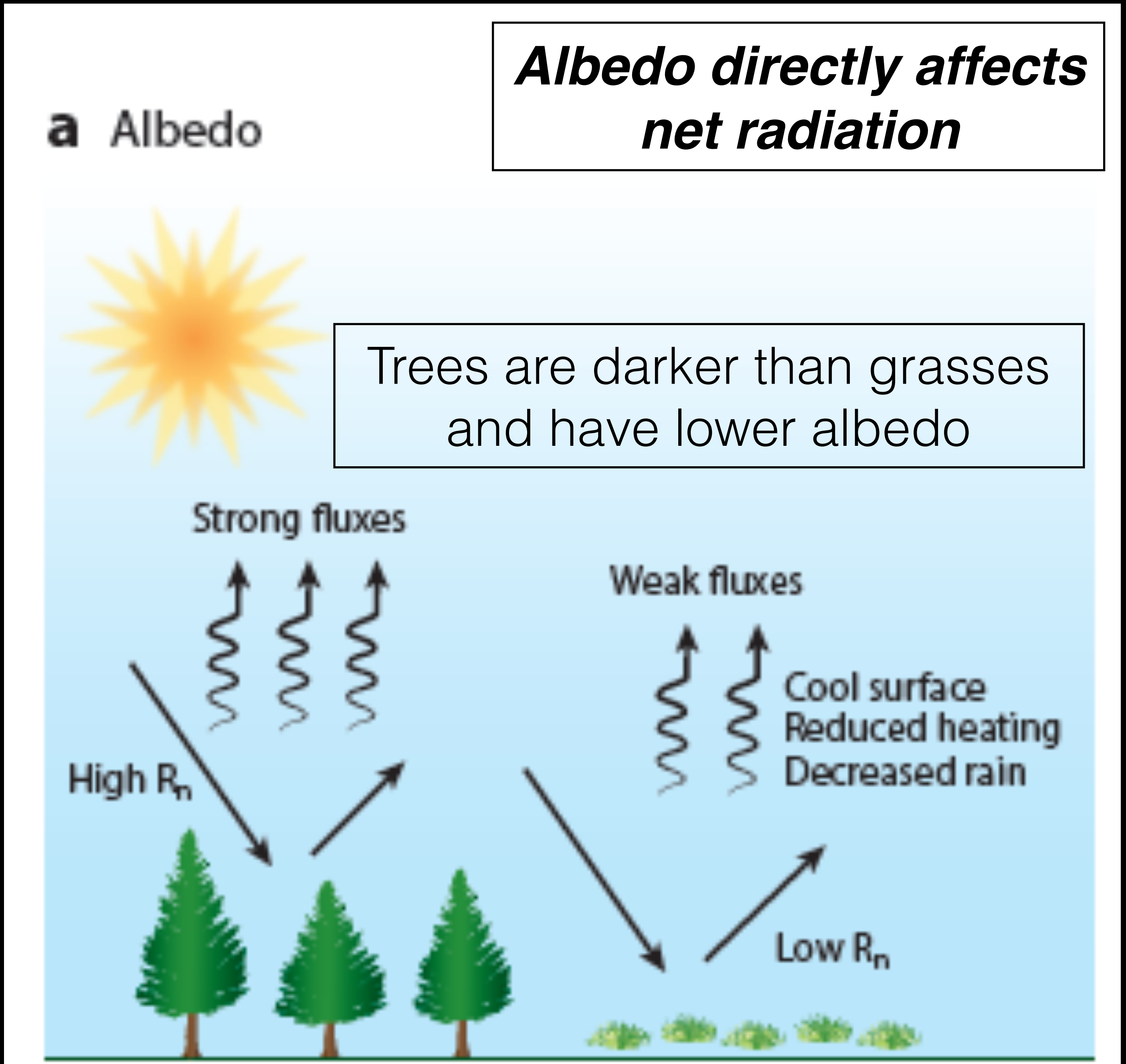

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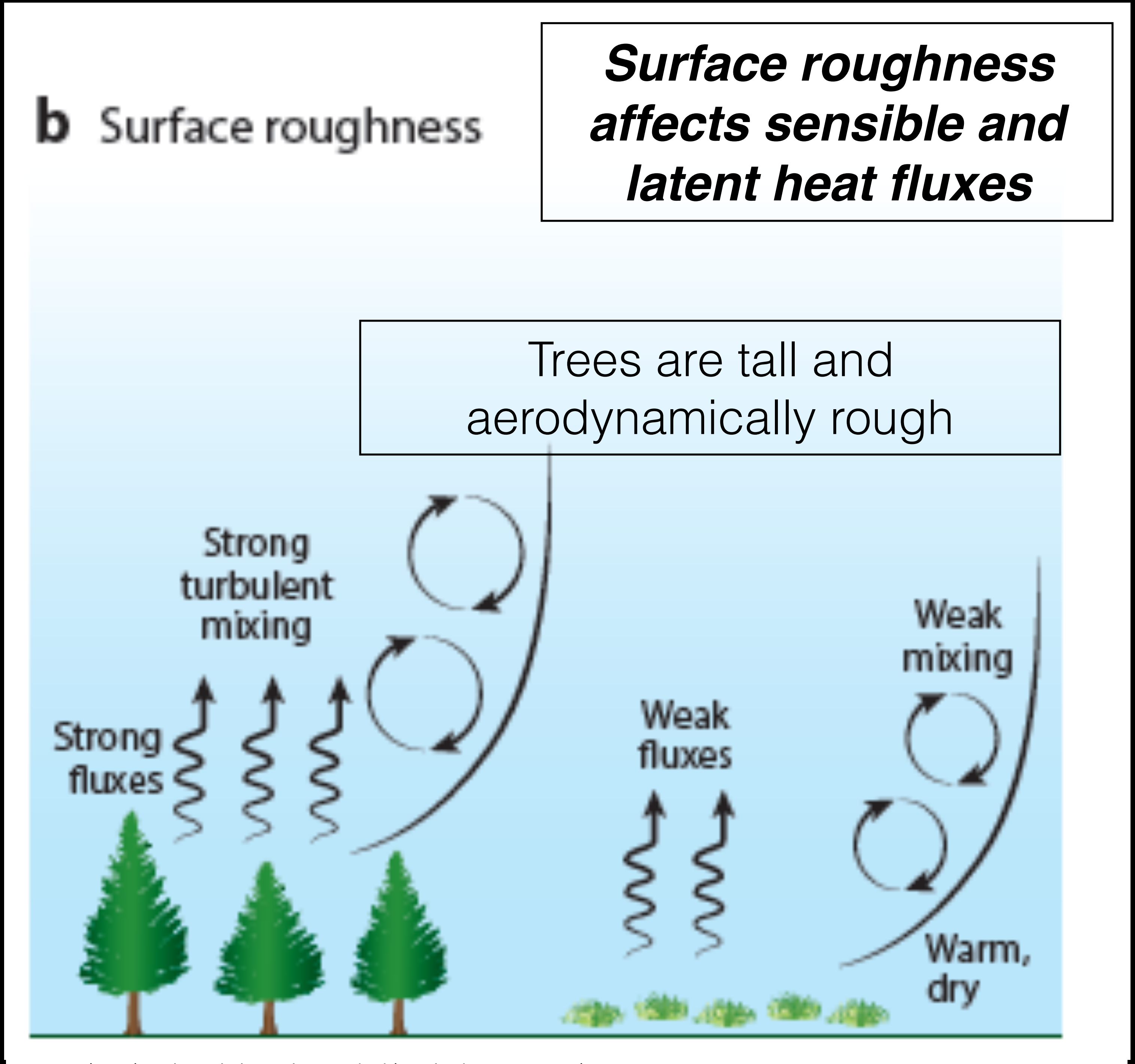

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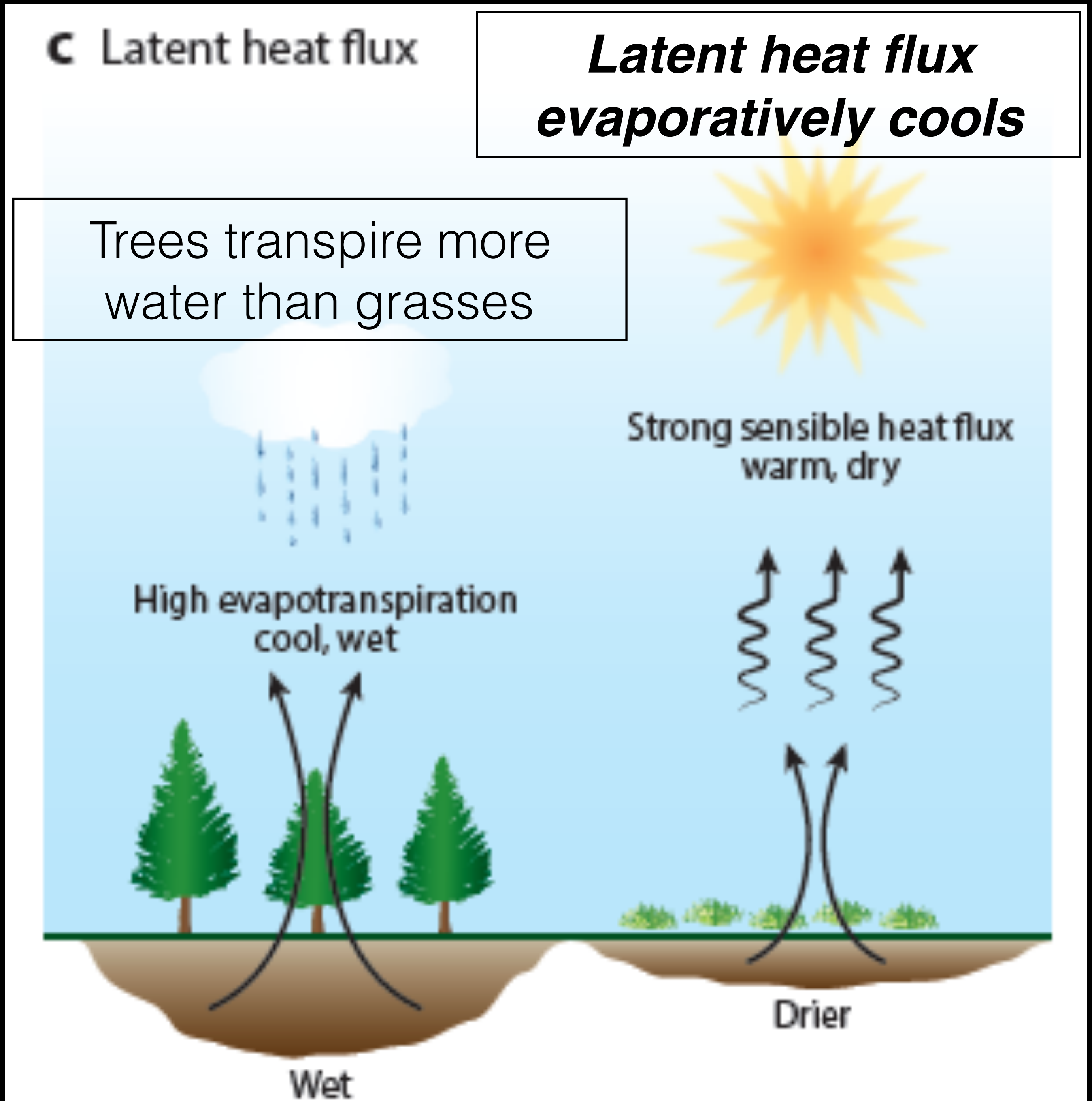

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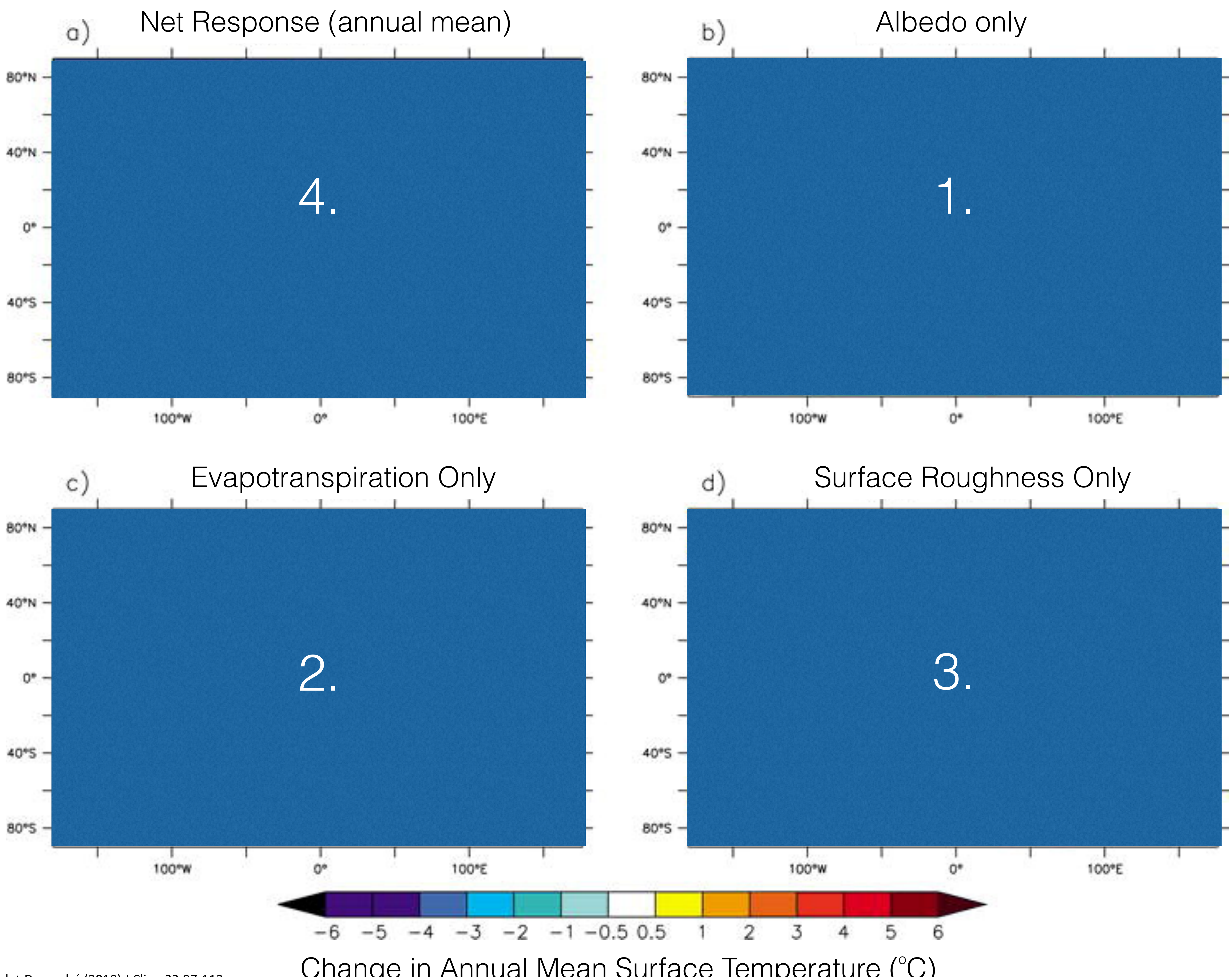
How does deforestation affect Earth's temperature?

a. Increase
b. Decrease
c. Neither
d. Both

Influence of deforestation on climate



Davin & de Noblet-Ducoudré (2010) J Clim. 23:97-112

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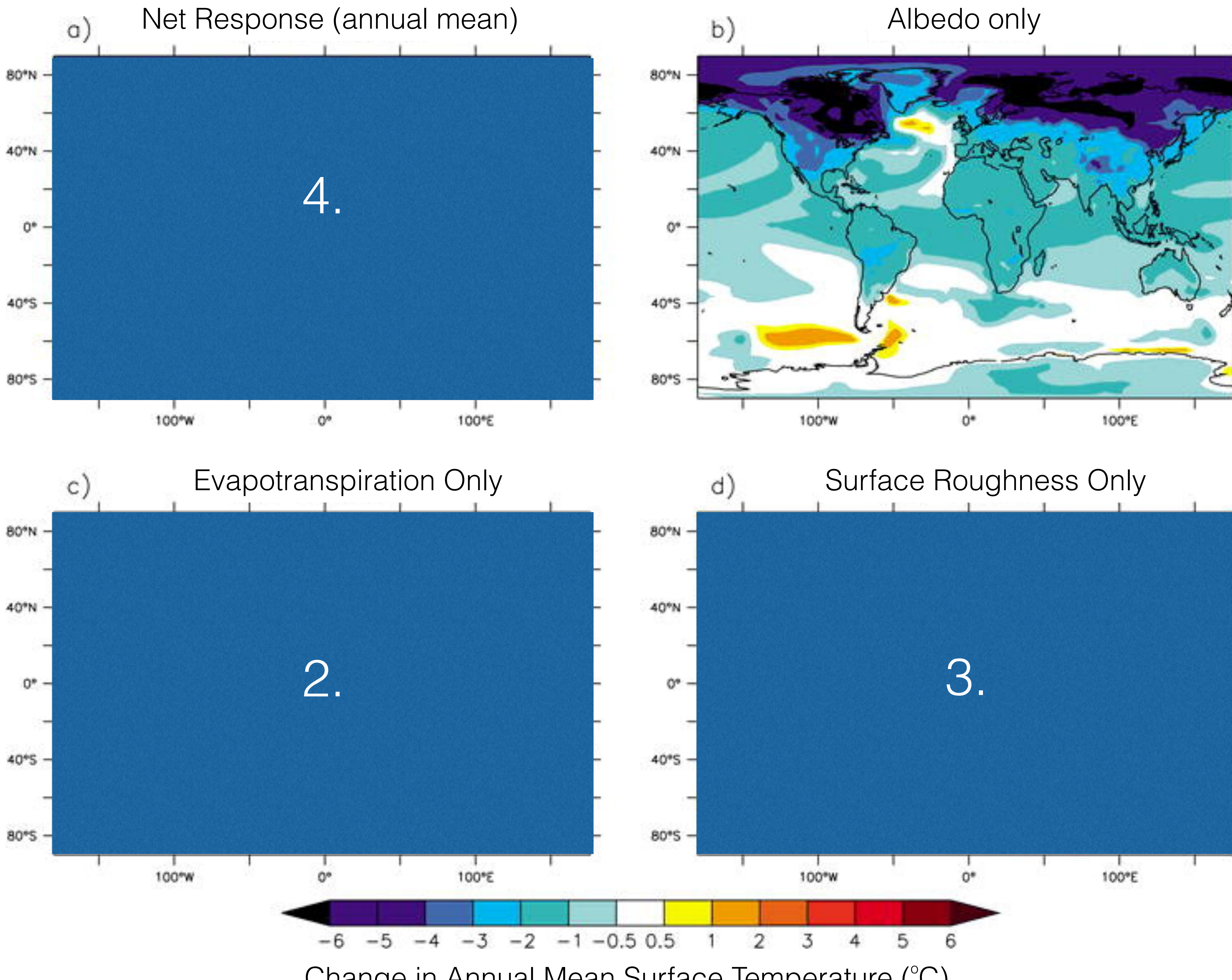

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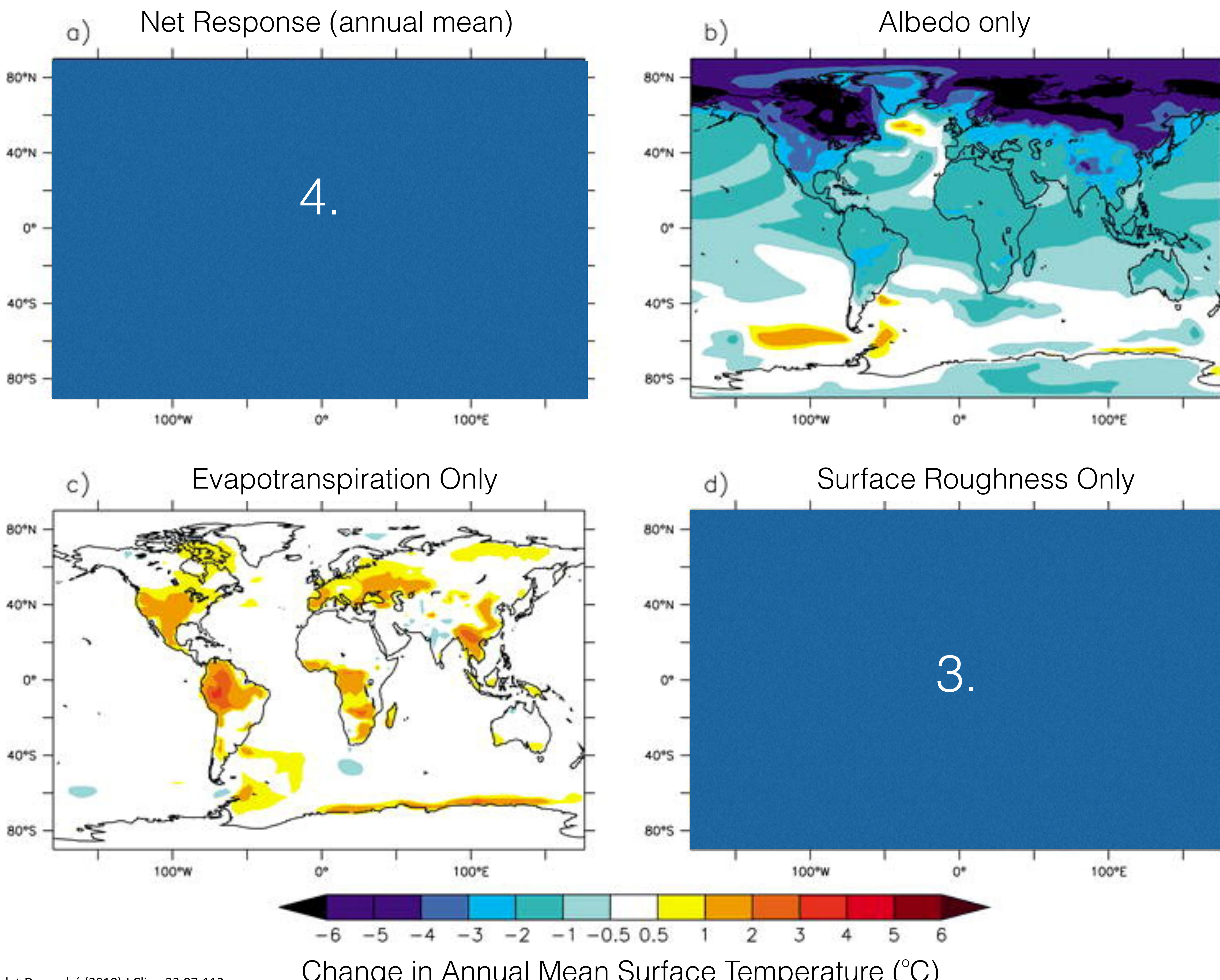

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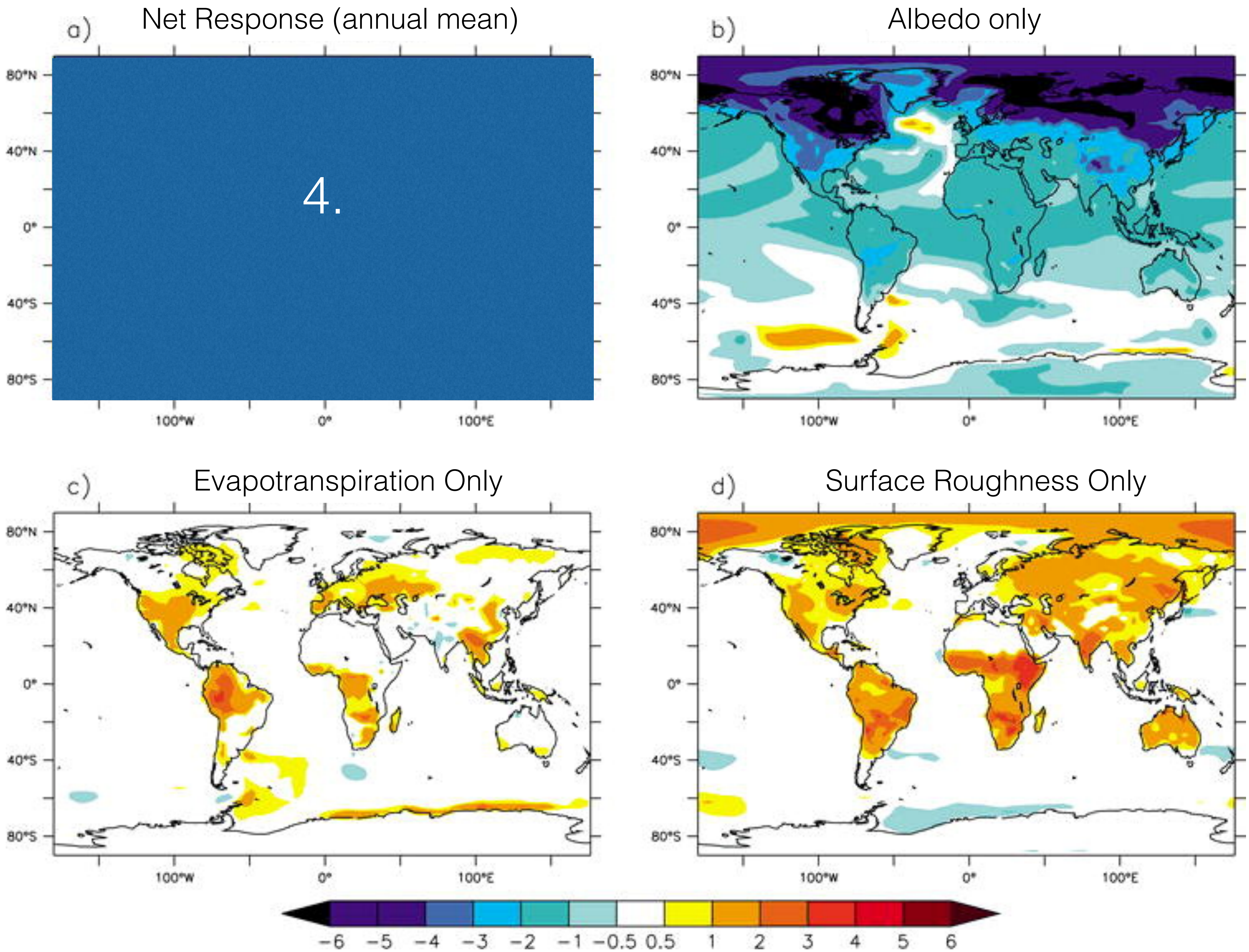

Change in Annual Mean Surface Temperature (°C)

Davin & de Noblet-Ducoudré (2010) J Clim. 23:97-112

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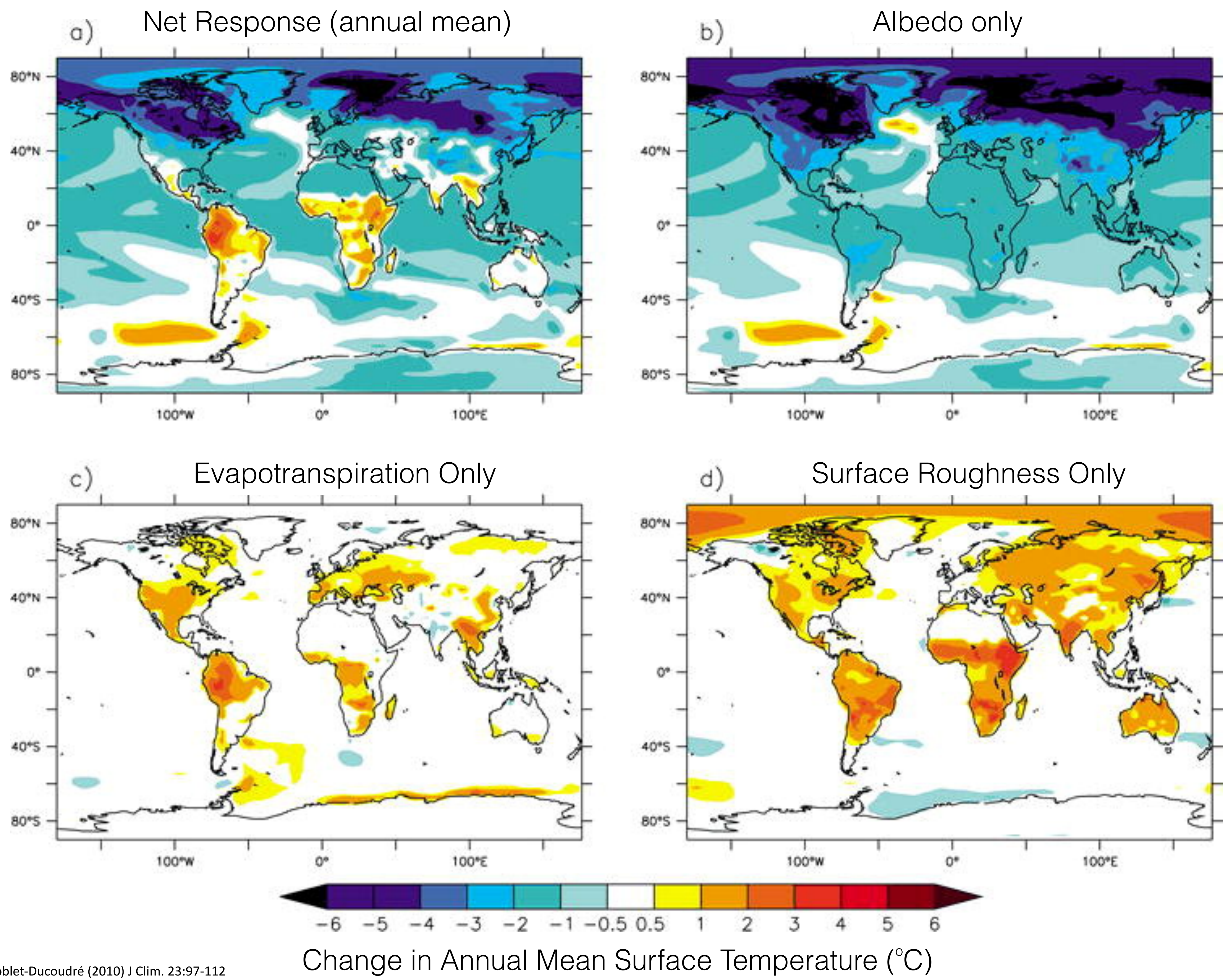

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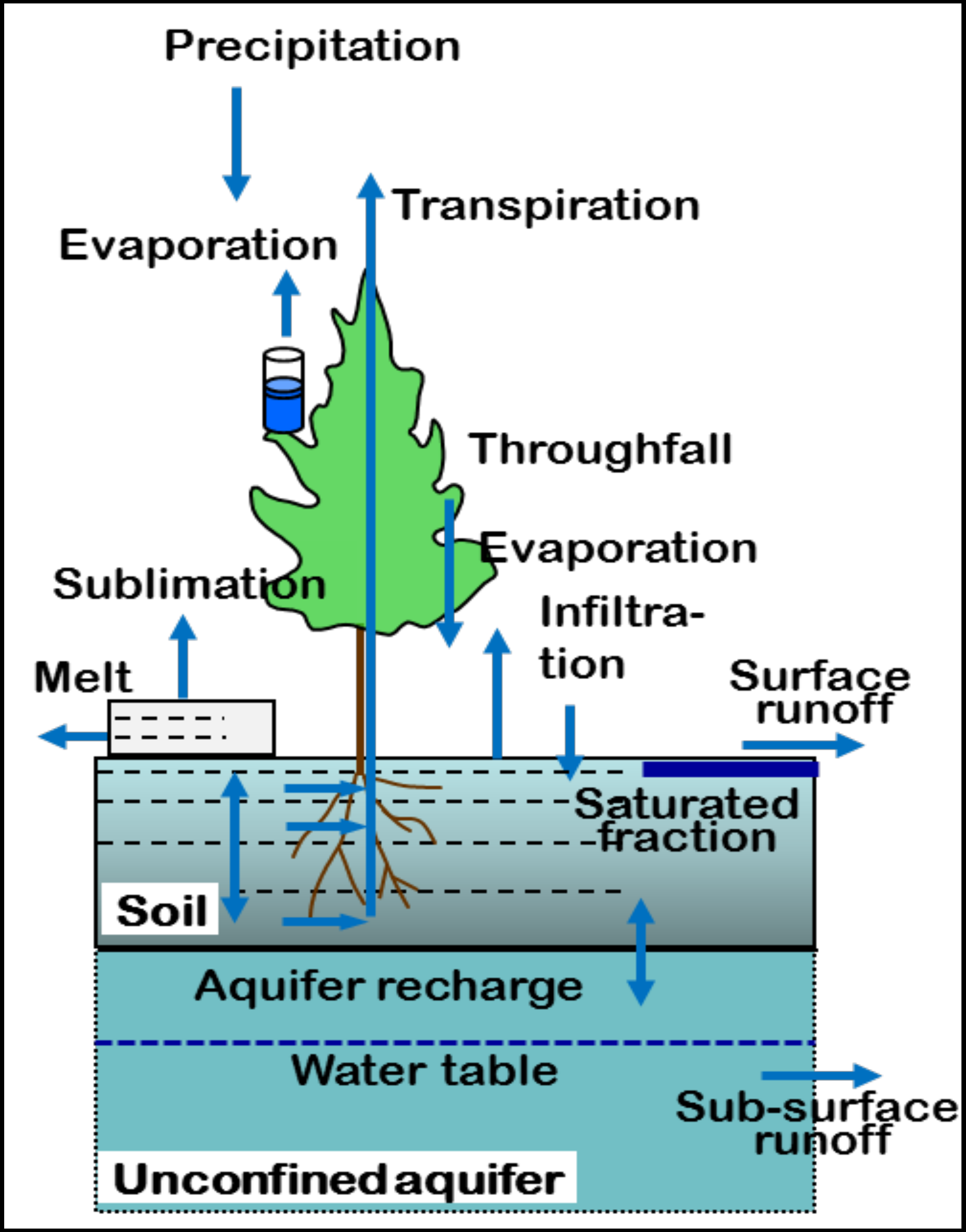
Based on this study, the effect depends on the region. Deforestation cools higher latitudes but warms tropical latitudes.

Note that this is an active area of research, so this is not the final word on the impact of deforestation on climate.

Community Land Model

Surface Water Balance



Surface Water Balance

(and other water balances such as snow and soil water)

$$P = (E_s + E_t + E_c) + (R_{surf} + R_{sub\text{-}surf}) + \Delta SM/\Delta t$$

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↑

P = rainfall

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$$P = (E_s + E_t + E_c) + (R_{surf} + R_{sub\text{-}surf}) + \Delta SM/\Delta t$$

Evapotranspiration ($E_s + E_t + E_c$)

P = rainfall

E_s = soil evaporation

E_t = transpiration

E_c = canopy evaporation

Surface Water Balance

(and other water balances such as snow and soil water)

$$P = (E_s + E_t + E_c) + (R_{surf} + R_{sub\text{-}surf}) + \Delta SM/\Delta t$$

Evapotranspiration — Total Runoff

P = rainfall

E_s = soil evaporation
E_t = transpiration
E_c = canopy evaporation

R_{surf} = surface runoff
$R_{sub\text{-}surf}$ = sub-surface runoff

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Evapotranspiration | Total Runoff

P = rainfall

E_s = soil evaporation
E_t = transpiration
E_c = canopy evaporation

R_{surf} = surface runoff
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$\Delta SM/\Delta t$ = change in soil moisture over a time step

How does a decrease in transpiration affect runoff?

Assume precipitation is a forcing that does not change

a. Increase
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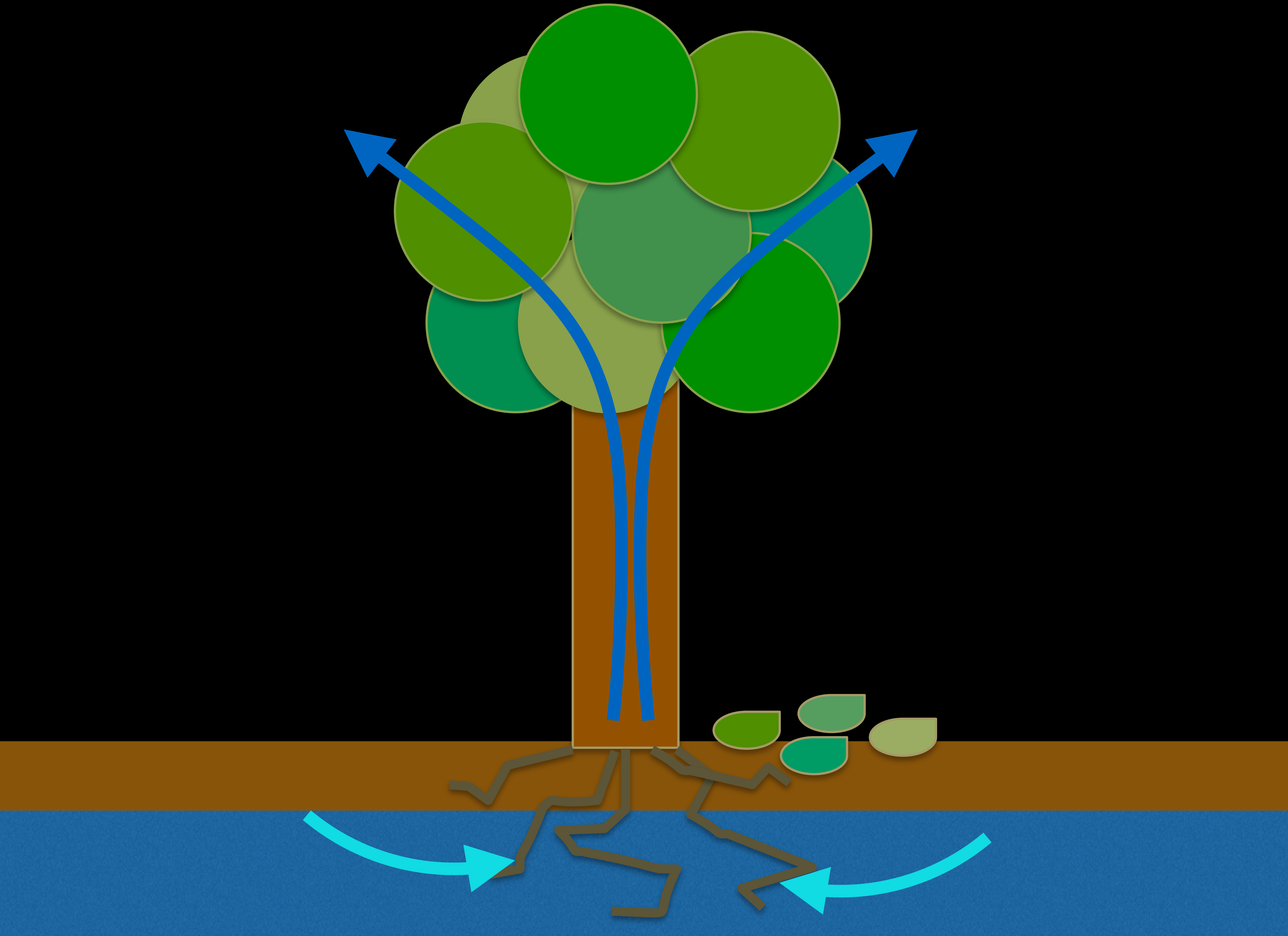
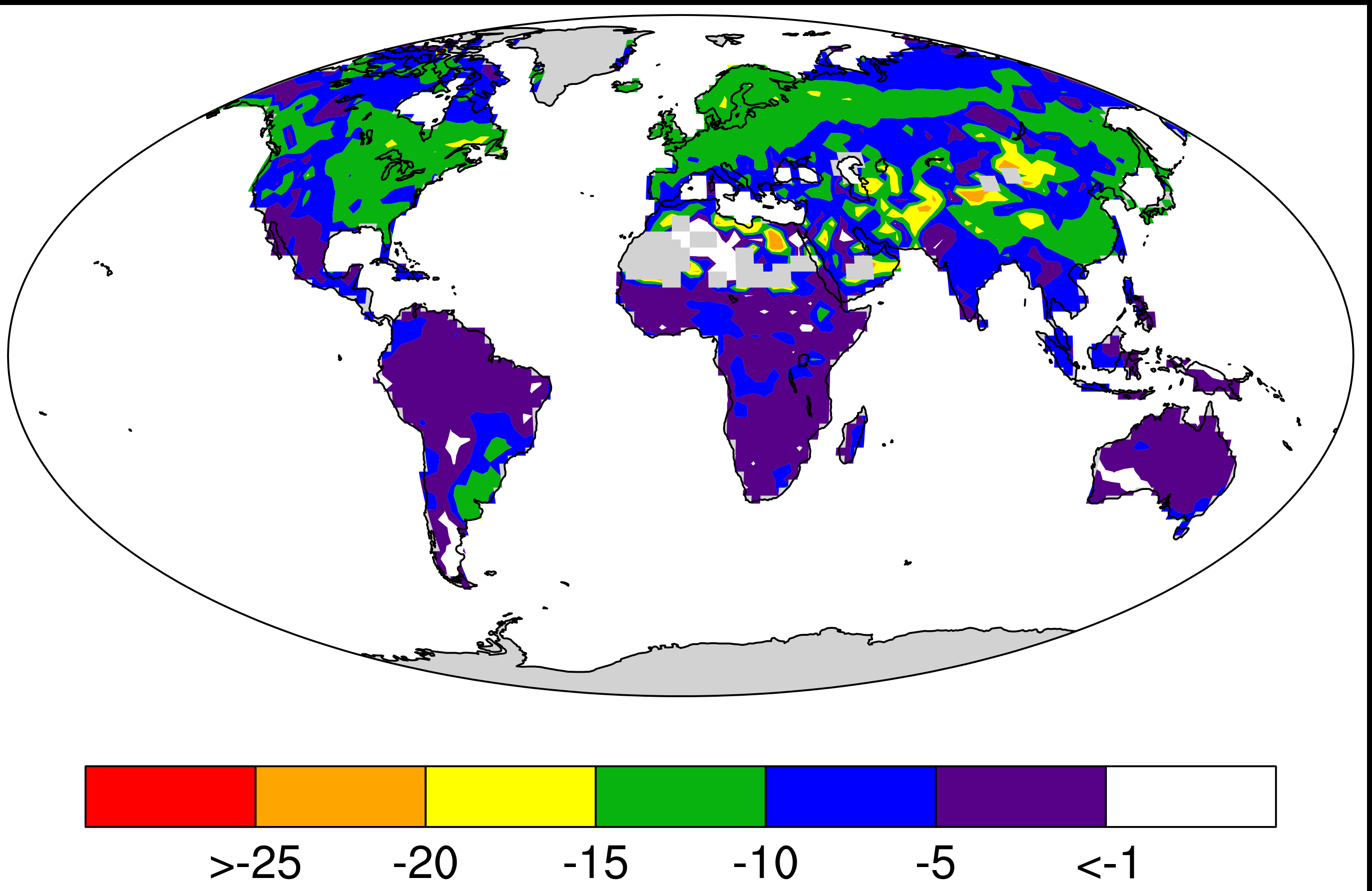


% Change in Transpiration



Lombardozzi et al. 2015 *J. Climate*

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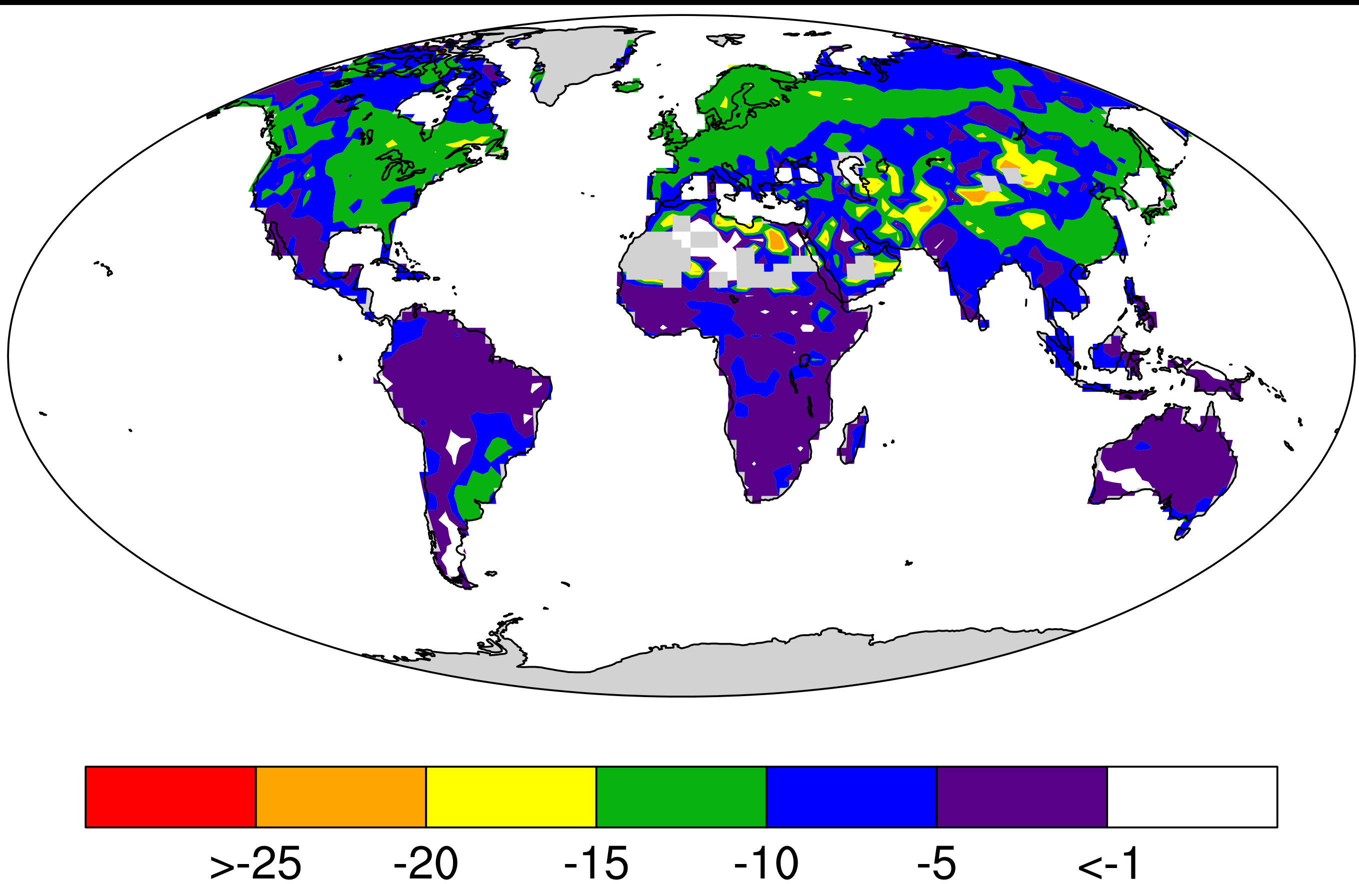
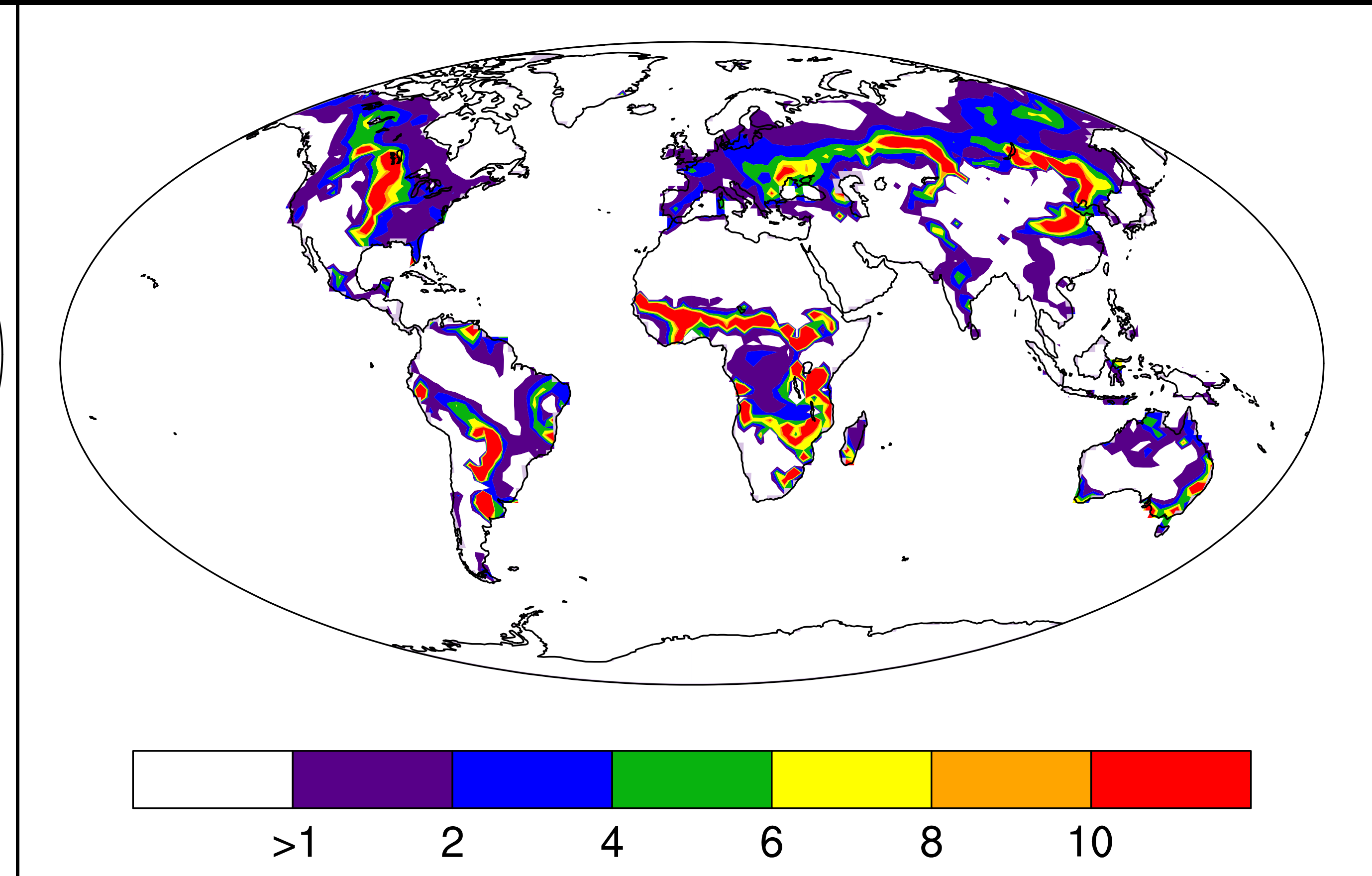


% Change in Runoff



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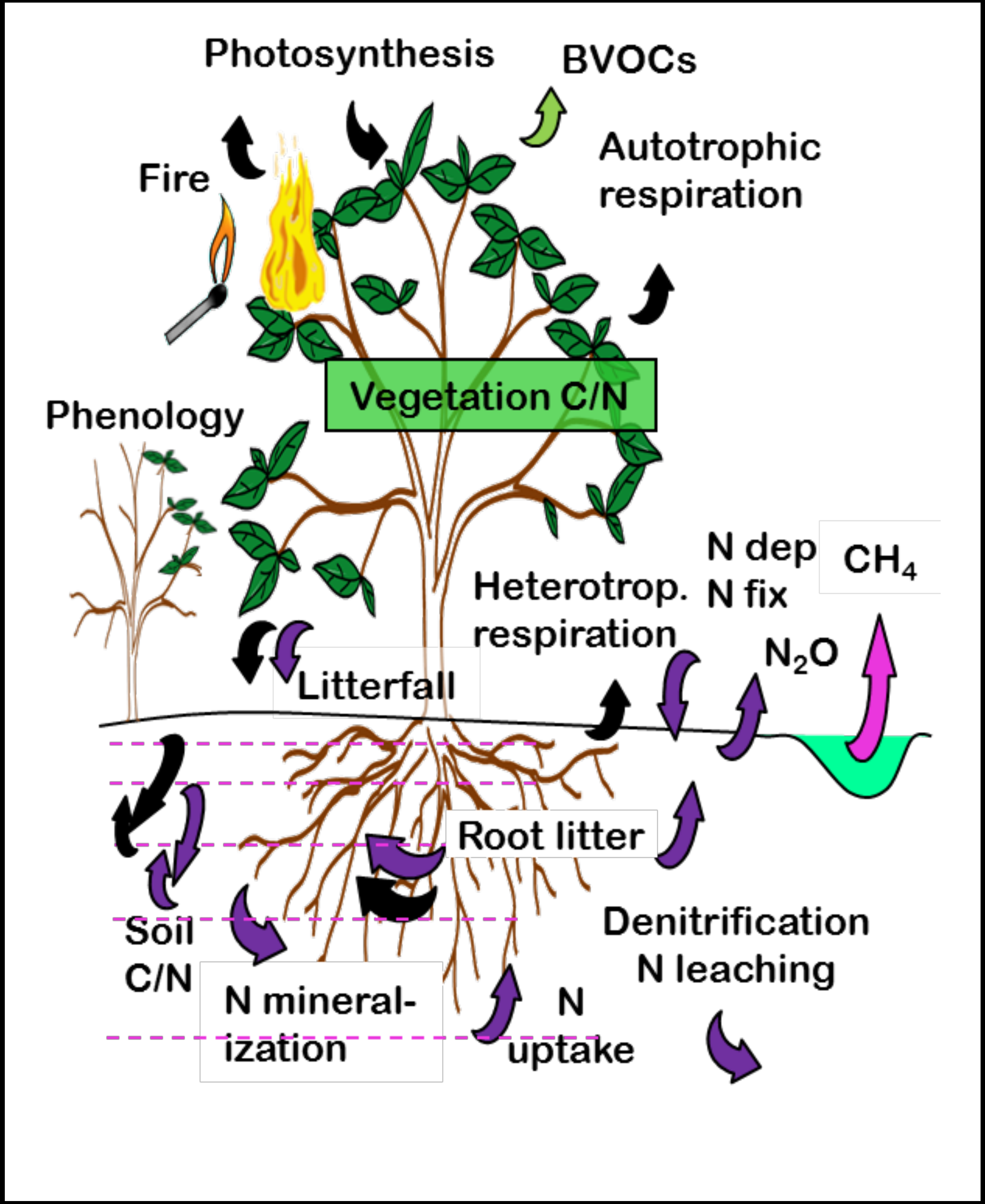
Community Land Model

Carbon Balance



Note: biogeochemistry is not always included in land models

Carbon Balance

(and plant and soil carbon pools)

$$NEE = GPP - R_a - R_h - Fire - LUC$$

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NEE = net ecosystem exchange

GPP = gross primary productivity (photosynthesis)

Carbon Balance

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$$NEE = GPP - R_a - R_h - Fire - LUC$$

Total respiration

NEE = net ecosystem exchange

GPP = gross primary productivity (photosynthesis)

R_a = autotrophic respiration

R_h = heterotrophic respiration

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NEE = net ecosystem exchange

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Fire = carbon flux due to fire

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NEE = net ecosystem exchange

GPP = gross primary productivity (photosynthesis)

R_a = autotrophic respiration

R_h = heterotrophic respiration

Fire = carbon flux due to fire

LUC = C flux due to land use change

How does land use change affect ecosystem carbon?

Assume land use change primarily converts forests to pasture and croplands

a. Increase
b. Decrease
c. Neither
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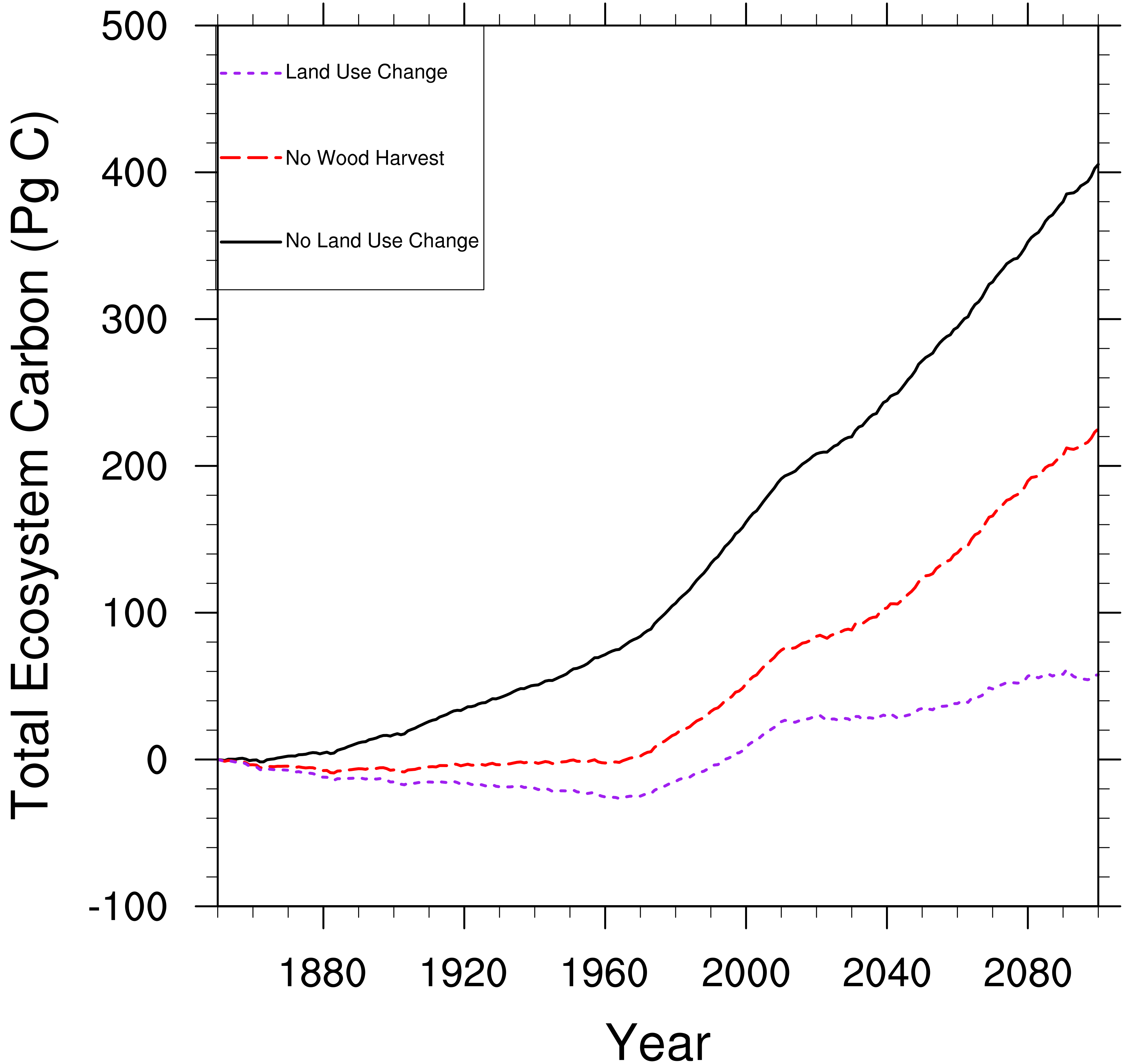

Land use change decreases total C storage

Lombardozzi, unpublished data

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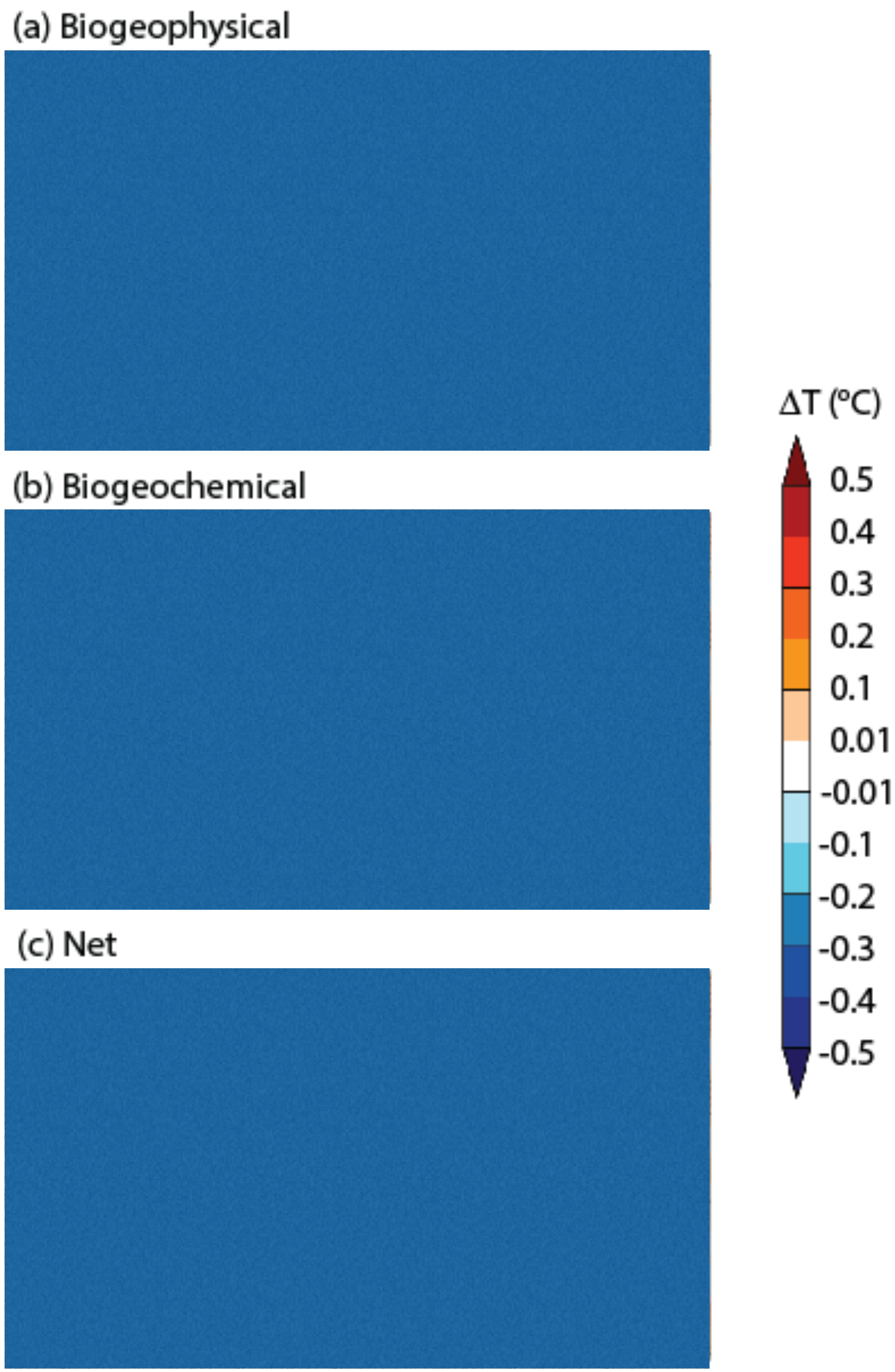
What wins? Biogeophysics vs Biogeochemistry

An example using land use change

Biogeophysics and biogeochemistry

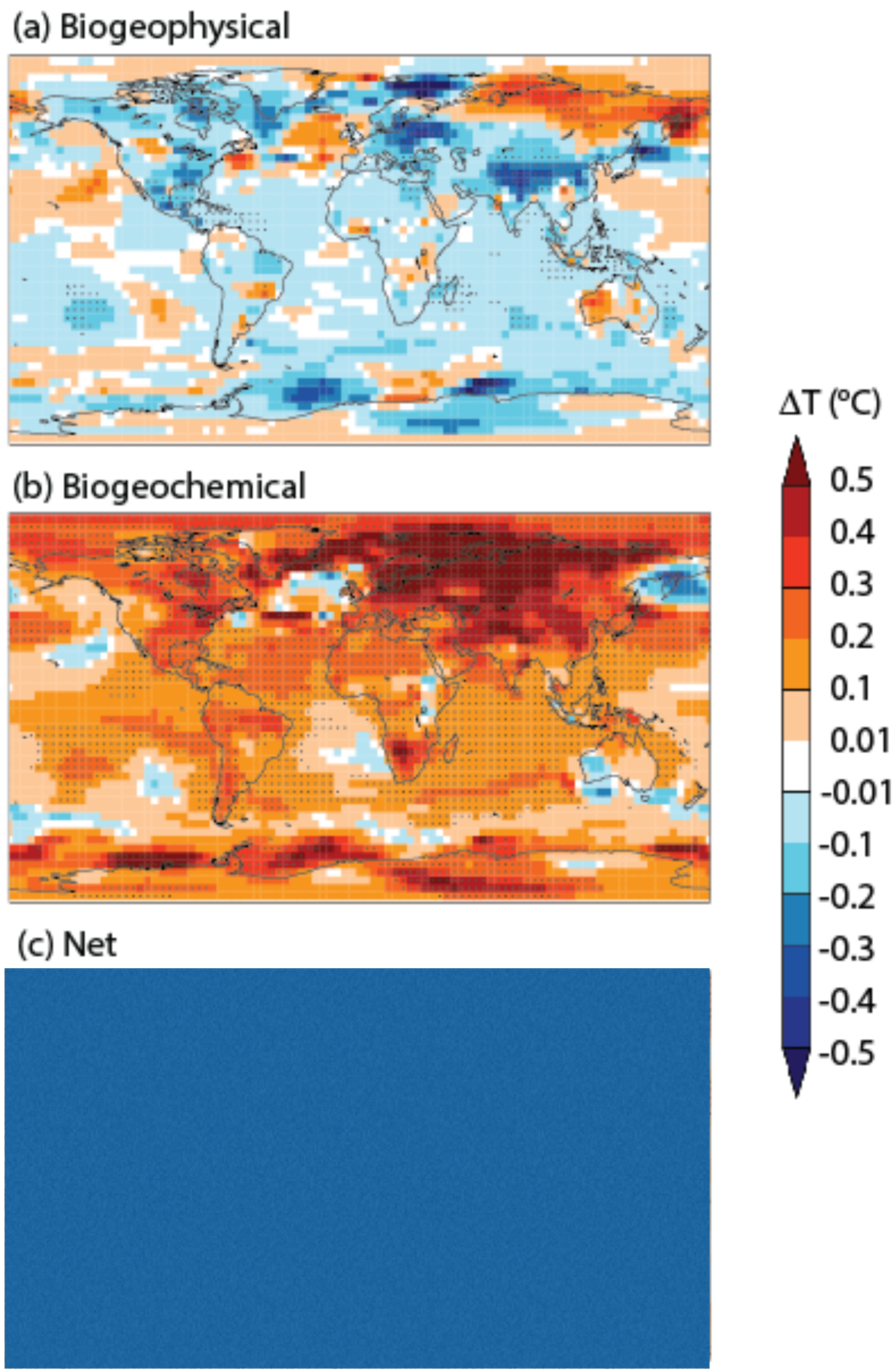


<u>Historical land use & land-cover change</u>

- ❑ Biogeophysical processes decrease annual mean temperature (albedo)
- ❑ Deforestation releases carbon (warms temperature)

Pongratz et al. (2010) GRL, 37, doi:10.1029/2010GL043010

Biogeophysics and biogeochemistry



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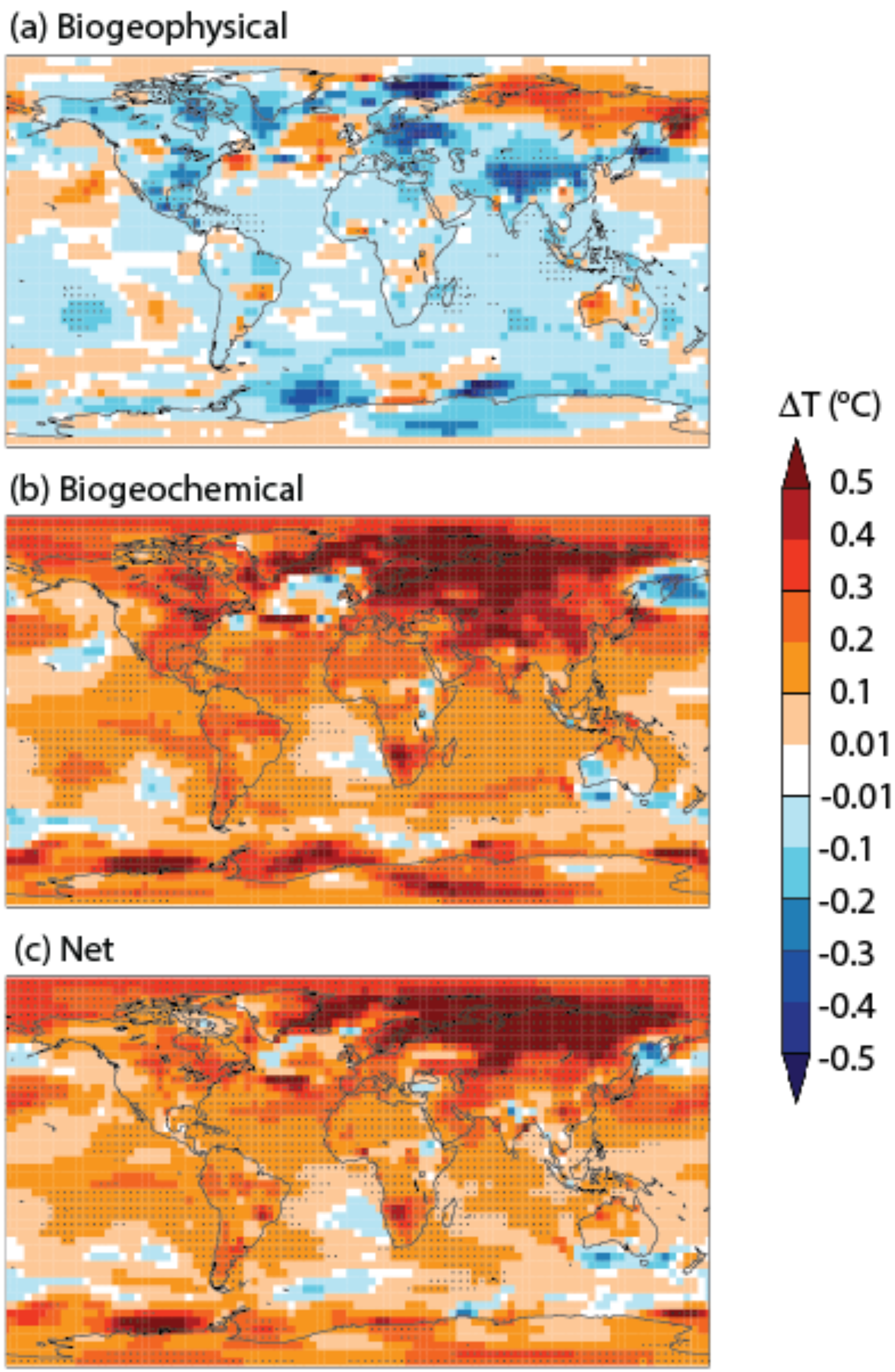

Historical land use & land-cover change

- Biogeophysical processes decrease annual mean temperature (albedo)
- Deforestation releases carbon (warms temperature)
- Biogeochemical warming exceeds biogeophysical cooling

Prevailing paradigm

The dominant competing signals from historical deforestation are an increase in surface albedo countered by carbon emission to the atmosphere

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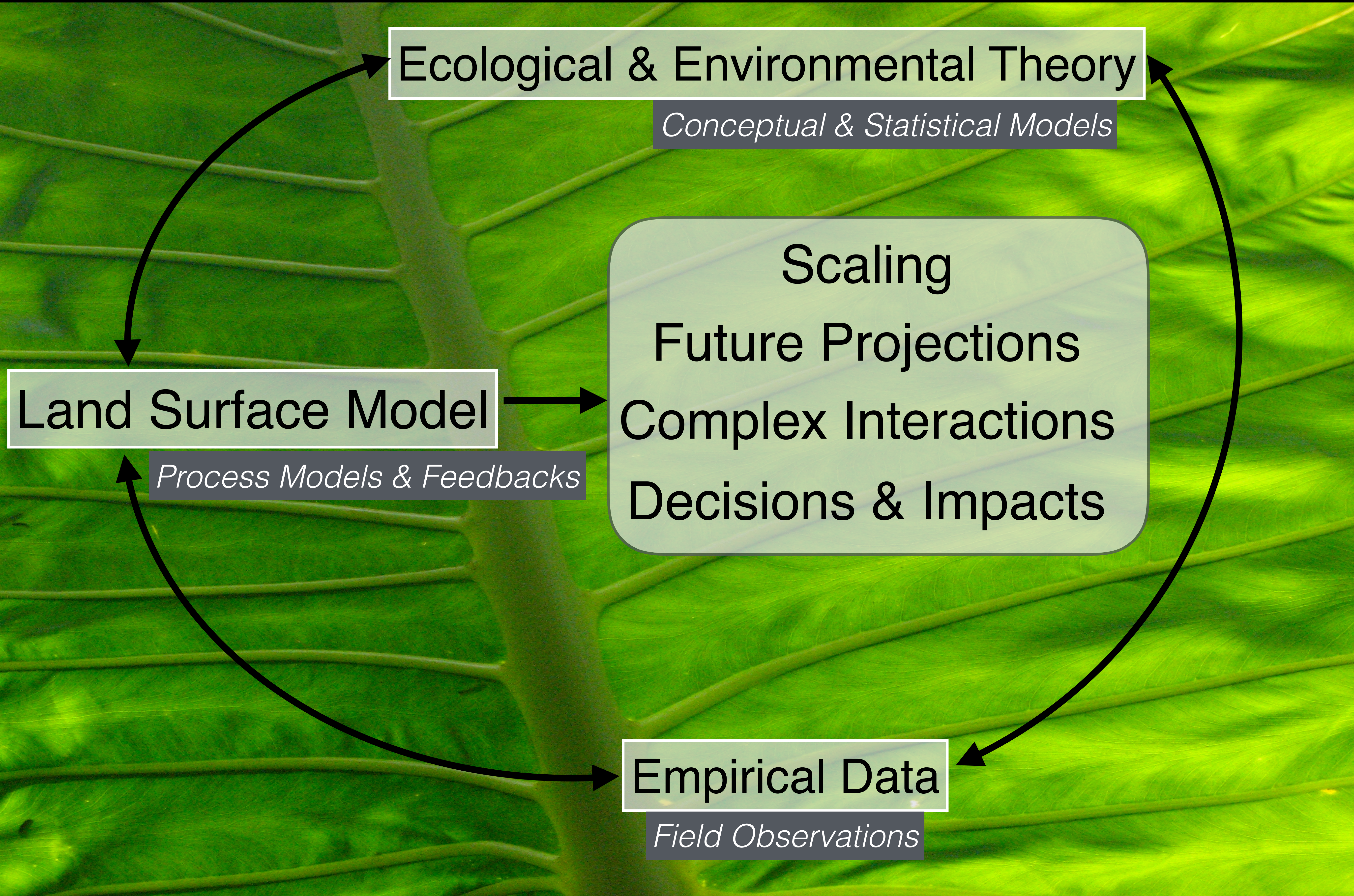
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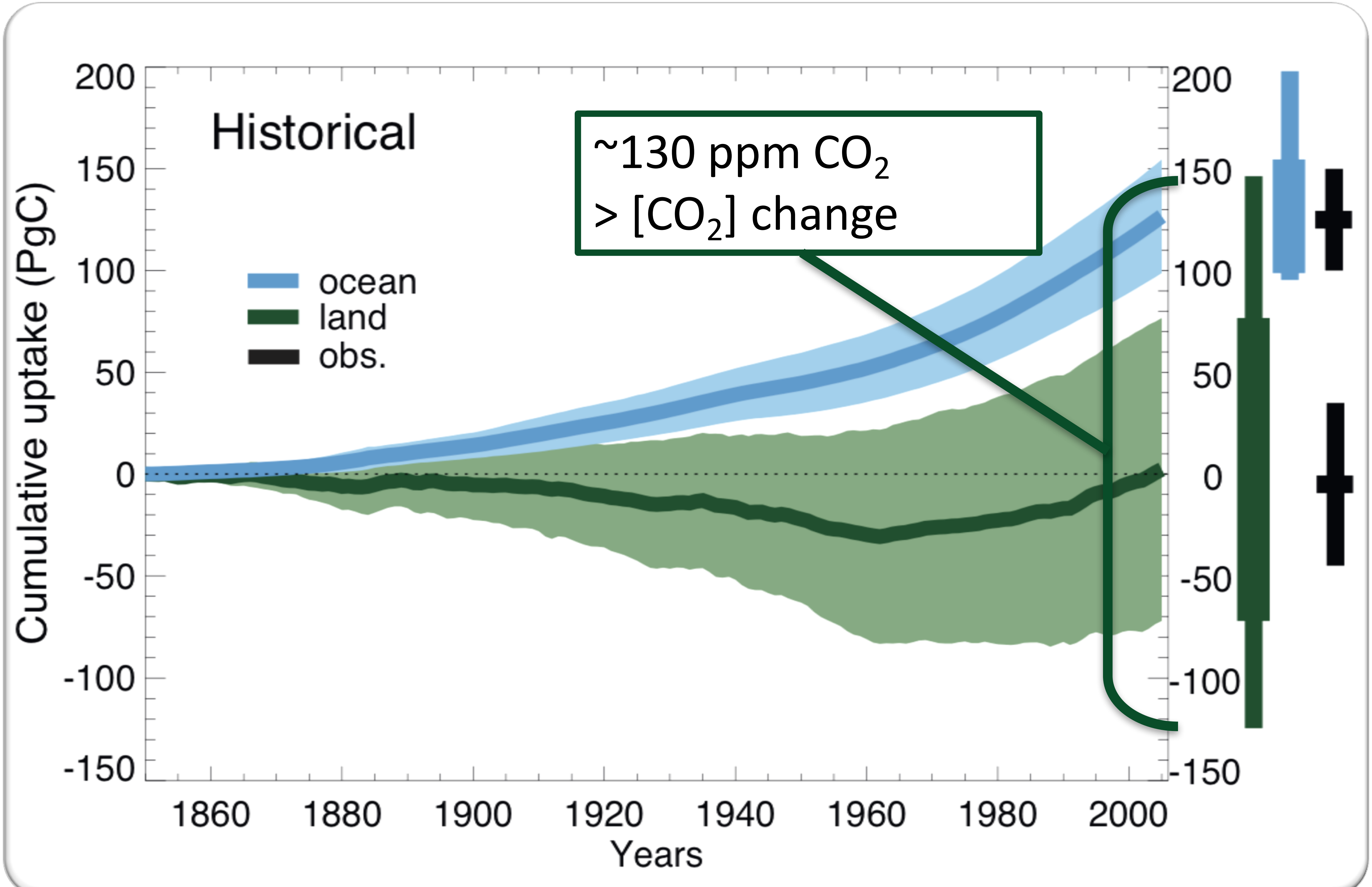
Multi-model carbon cycle uncertainty



IPCC WG1 Ch. 6 (Ciais et al 2013)

Sources of Uncertainty in Carbon Cycle Modeling

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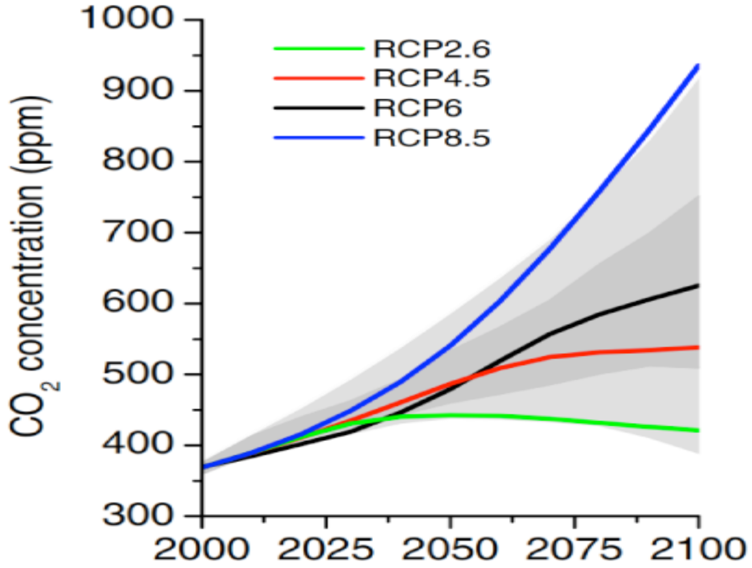
1. Forcing (scenario) uncertainty
   GHG emission scenarios, land use, etc.

   Scientific community: multiple scenarios



Van Vuuren et al. 2011

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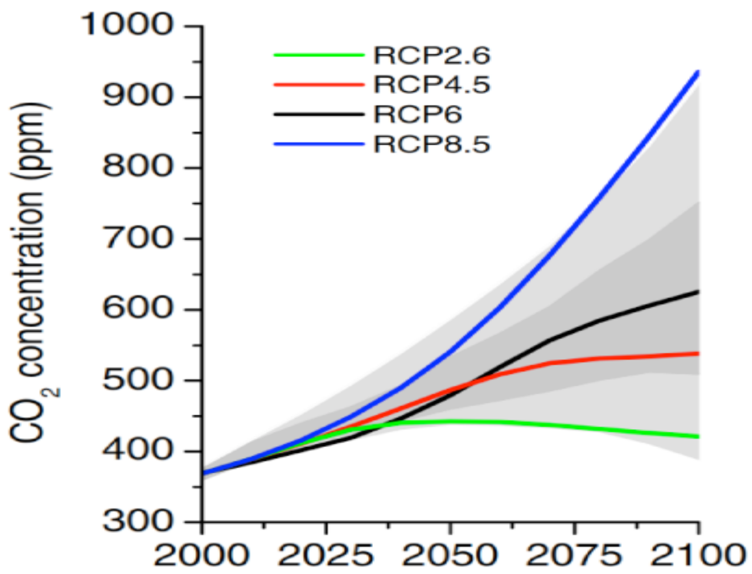
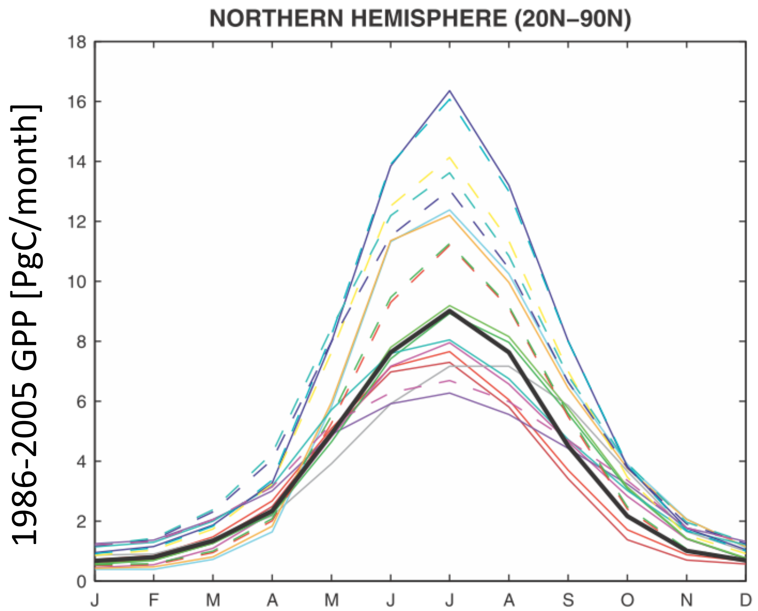


Van Vuuren et al. 2011

2. Response (model) uncertainty
   Parameterizations, resolution, etc.

   Scientific community: multiple models



Anav et al. 2013

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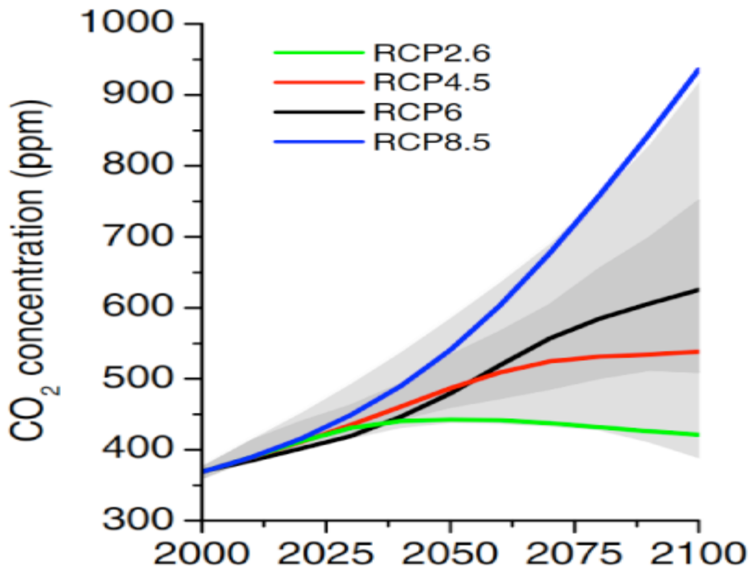
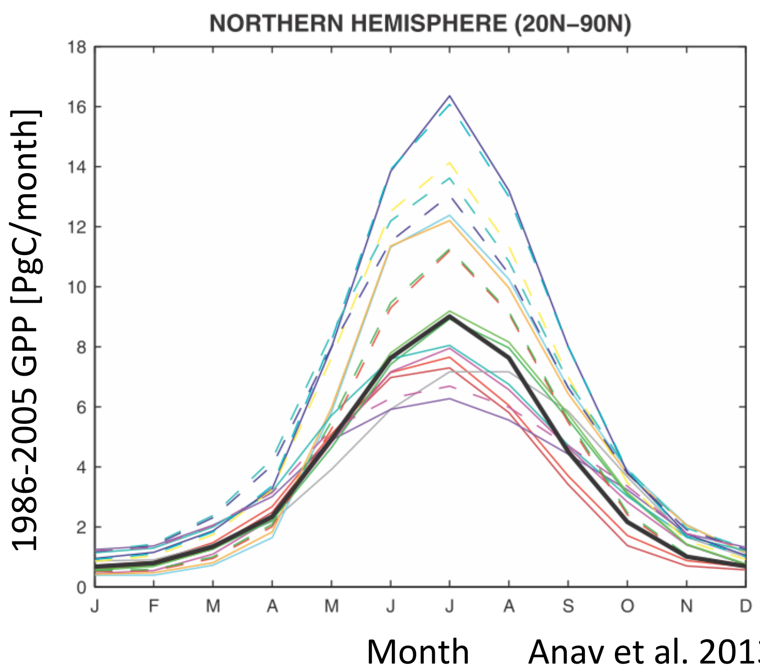


Van Vuuren et al. 2011

2. Response (model) uncertainty
   Parameterizations, resolution, etc.

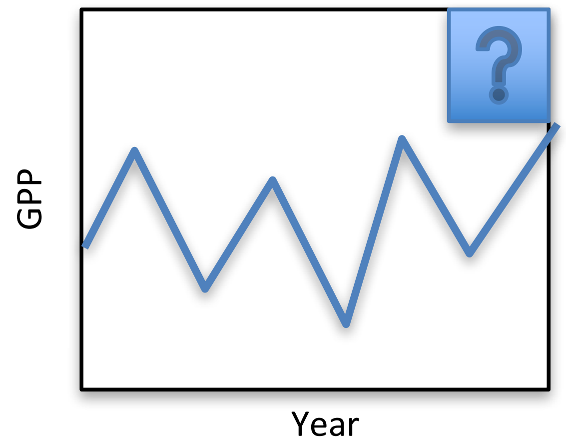
   Scientific community: multiple models



Anav et al. 2013

3. Internal (natural, or unforced) variability
   Initial value problems (e.g., air temperature)

   Scientific community: largely not represented



Many paths to reduce model uncertainty

Model intercomparisons (MIPs)

CMIP6: carbon cycle, land use, land -atmosphere interactions
Range of plausible outcomes, but more models ≠ better results

Model intracomparison

Focus on structural uncertainty within a model to identify processes contributing to uncertainty

Model benchmarking

Comprehensive model evaluation against observations

Model data-fusion

Data assimilation, parameter estimation

Comparison to real-world manipulative experiments

FACE, N addition

"Discover" critical missing processes

Processes that are ecologically important but poorly understood at the global scale
Requires tuning key parameters to get a good simulation

Model hierarchy

Use models with similar process representation but different levels of complexity

Modeling Caveats

Land surface models are just a starting point for the science, not the science itself

It's easy to run the model & get an answer

It's much harder to understand why you got that answer

Land surface models like CLM are very complex and multidisciplinary. Be cognizant of how you use and interpret model simulations.