Utilizing the International Land Model Benchmarking (ILAMB) package to assess structural advances and forcing uncertainty in the Community Land Model (CLM)

David Lawrence

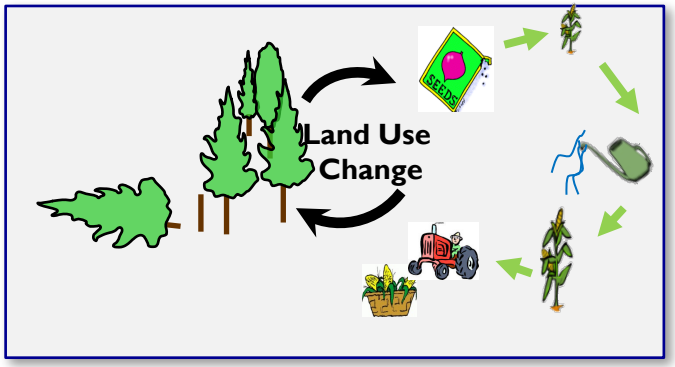
Keith Oleson, Forrest Hoffman, Jim Randerson, Bill Riley, Nathan Collier, Mingquan Mu, Charlie Koven, Rosie Fisher, Sean Swenson, Will Wieder and many others in the CLM development team

What's New for CLM5

Hydrology:	dry surface layer, variable soil depth with deeper (8.5m) max depth, revised GW and canopy interception, adaptive time-stepping, increased soil layer resolution
Snow:	canopy snow, wind and T effects on snow dens., firn model (12 layers), glacier MEC
Rivers:	MOSART (hillslope → tributary → main channel)
Nitrogen:	New C-N coupling (flexible leaf C:N ratio, leaf N optimization, C cost for N)
Vegetation:	plant hydraulics and hydraulic redist, deep roots tropical trees, Medlyn stomatal cond, Ecosystem Demography (FATES), prognostic roots, ozone damage
Fire:	updates, trace gas and aerosol emissions
Crops:	global crop model with transient irrigation and fertilization (9 crop types), grain product pool, revised irrigation scheme
Carbon:	revisions to carbon allocation and soil carbon decomposition
Land cover/use:	dynamic landunits, updated PFT-distribution, wood harvest by mass
Isotopes:	carbon and water isotope enabled

CLM5 default configuration

CLM5 optional feature



What's New for CLM5

Rosie Fisher
Keith Oleson
Sean Swenson
Will Wieder
Charlie Koven
Danica Lombardozzi
Ben Sanderson
Erik Kluzek
Bill Sacks
Peter Lawrence
Yaqiong Lu
Fang Li
Daniel Kennedy

More than 50 scientists and software engineers from 16 different institutions involved in development of CLM5

+ CLM4 → CLM4.5 changes

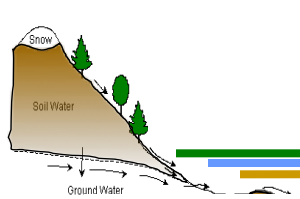
CLM4.5 June 2013 (CESM1.2)

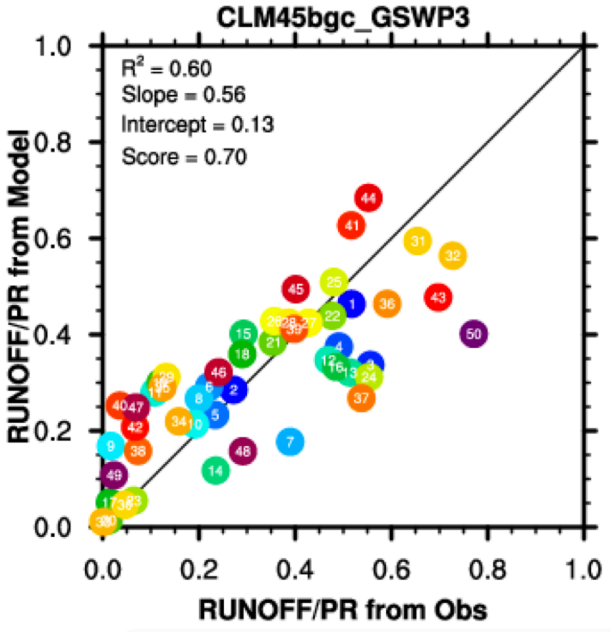
- vertically-resolved soil BGC and revised nitrification-denitrification, N-fixation
- cold region hydrology updates, incl perched water table
- new snow cover fraction parameterization
- revised canopy radiation scheme
- co-limitation and temperature acclimation on photosynthesis
- updated lake model
- multiple urban density classes
- updated fire model with natural and anthropogenic triggers and suppression
- BVOC updated to MEGAN2.1
- CH_4 emissions
- prognostic wetlands and flooding (optional)

International Land Model Benchmarking (ILAMB) package

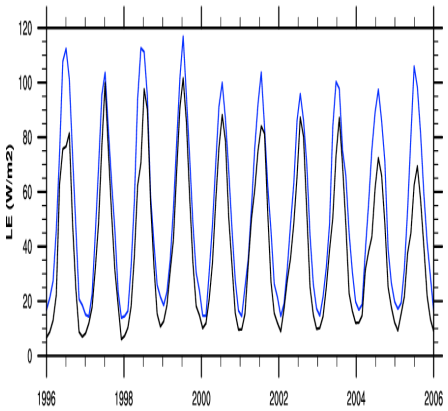
- Currently integrates analysis of 25 variables in 4 categories from ~60 datasets
  - Above ground live biomass, burned area, carbon dioxide, gross primary production, leaf area index, global net ecosystem carbon balance, net ecosystem exchange, ecosystem respiration, soil carbon
  - evapotranspiration, latent heat, sensible heat, runoff, evaporative fraction, terrestrial water storage anomaly
  - albedo, surface upward SW radiation, surface net SW radiation, surface upward LW radiation, surface net LW radiation, surface net radiation
  - surface air temperature, precipitation, surface relative humidity, surface downward SW radiation, surface downward LW radiation
- Graphics and scoring system
  - annual mean, bias, relative bias, RMSE, seasonal cycle phase, spatial distribution, interannual variability, variable-to-variable
  - Global maps, time series plots averaged over specific regions, individual measurement sites, functional relationships
- **Open Source (https://www.ilamb.org/)**

Examples of ILAMB metrics / plots

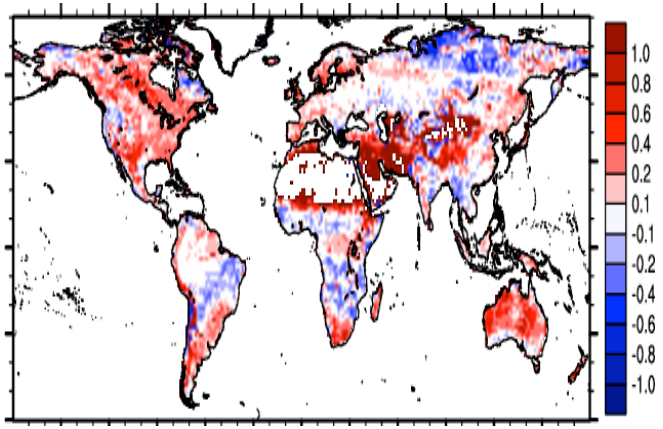




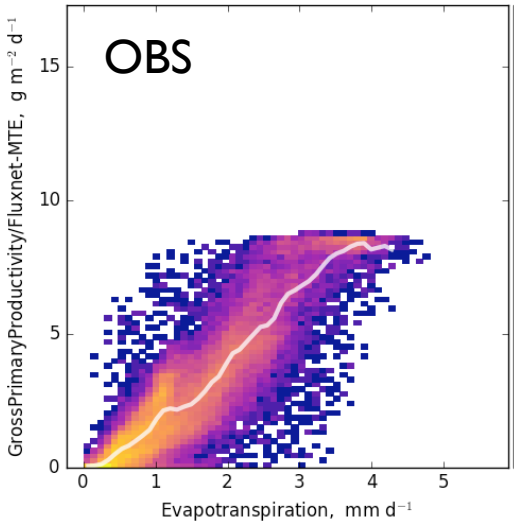
Tower Site

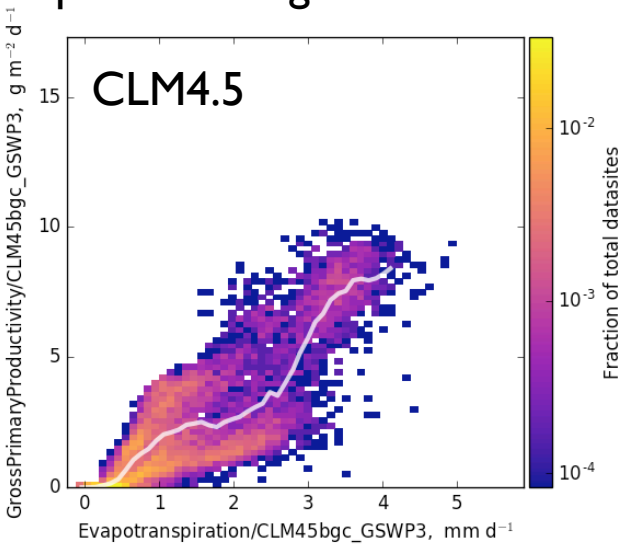


Global bias, relative bias, RMSE

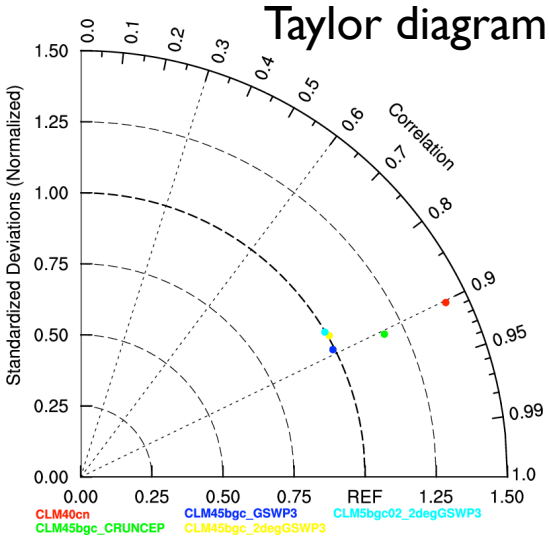


Functional relationships: 2-d histograms





Taylor diagram



Land-only historical simulations for CLM5 release, documentation papers, and CMIP6

	CLM4				CLM4.5				CLM5			
Forcing	SP	BGC	+N, +CO$_2$	no LUC	SP	BGC	+N, +CO$_2$	no LUC	SP	BGC crop	+N, +CO$_2$	no LUC
GSWP3v1	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓
CRUNCEPv7		✓				✓			✓	✓		
WFDEI									✓			

ILAMB Benchmark Results

Mean State | Relationship | **Results Table**

Mean State Scores

Columns...

	CLM40r243GSWP3	CLM45r243GSWP3	CLM50r243GSWP3
Biomass	0.63	0.66	0.68
Burned Area	0.35	0.49	0.56
Gross Primary Productivity	0.71	0.75	0.74
Leaf Area Index	0.58	0.62	0.70
Global Net Ecosystem Carbon Balance	0.71	0.64	0.86
Net Ecosystem Exchange	0.56	0.57	0.60
Ecosystem Respiration	0.68	0.74	0.74
Soil Carbon	0.42	0.69	0.40
Evapotranspiration	0.78	0.81	0.80
Evaporative Fraction	0.85	0.87	0.86
Latent Heat	0.79	0.82	0.84
Runoff	0.81	0.81	0.78
Sensible Heat	0.78	0.80	0.79
Terrestrial Water Storage Anomaly	0.48	0.48	0.47
Albedo	0.77	0.77	0.78
Surface Upward SW Radiation	0.78	0.77	0.77

ILAMB Benchmark Results

Mean State | Relationship | Results Table

Mean State Scores

Columns...

	CLM40r243GSWP3	CLM45r243GSWP3	CLM50r243GSWP3
Biomass	0.63	0.66	0.68
Burned Area	0.35	0.49	0.56
Gross Primary Productivity	0.71	0.75	0.74
Fluxnet (37.5%)	0.70	0.73	0.71
GBAF (62.5%)	0.73	0.76	0.76
Leaf Area Index	0.58	0.62	0.70
Global Net Ecosystem Carbon Balance	0.71	0.64	0.86
Net Ecosystem Exchange	0.56	0.57	0.60
Ecosystem Respiration	0.68	0.74	0.74
Soil Carbon	0.42	0.69	0.40
Evapotranspiration	0.78	0.81	0.80
Evaporative Fraction	0.85	0.87	0.86
Latent Heat	0.79	0.82	0.84
Runoff	0.81	0.81	0.78
Sensible Heat	0.78	0.80	0.79
Terrestrial Water Storage Anomaly	0.48	0.48	0.47

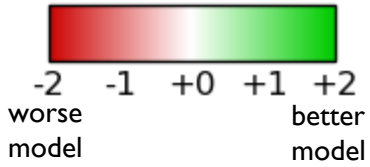
Surface Upward SW Radiation	0.78	0.77	0.77
Surface Net SW Radiation	0.89	0.89	0.89
Surface Upward LW Radiation	0.95	0.95	0.95
Surface Net LW Radiation	0.85	0.85	0.83
Surface Air Temperature	0.97	0.97	0.98
Precipitation	0.82	0.82	0.82
Surface Relative Humidity	0.83	0.83	0.84
Surface Downward SW Radiation	0.92	0.92	0.92
Surface Downward LW Radiation	0.96	0.96	0.96

Relationship Scores

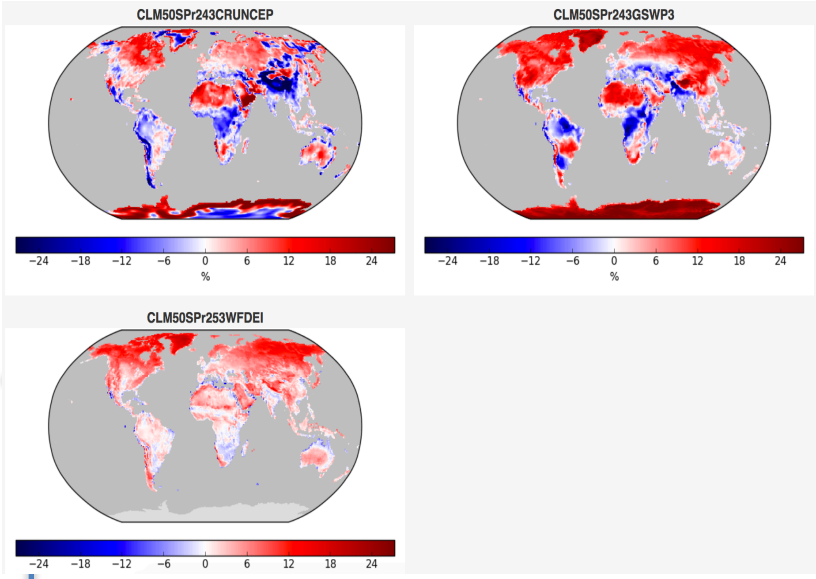
Columns...

	CLM40r243GSWP3	CLM45r243GSWP3	CLM50r243GSWP3
BurnedArea/GFED3	0.45	0.70	0.71
BurnedArea/GFED4	0.46	0.71	0.71
BurnedArea/GFED4	0.46	0.71	0.71
BurnedArea/GFED4S	0.43	0.63	0.66
GrossPrimaryProductivity/GBAF	0.75	0.83	0.85
LeafAreaIndex/AVHRR	0.46	0.61	0.83
LeafAreaIndex/MODIS	0.47	0.66	0.87
Evapotranspiration/GLEAM	0.77	0.89	0.92
Evapotranspiration/MODIS	0.81	0.89	0.86

Forcing Uncertainty: CLM5SP (prescribed vegetation)

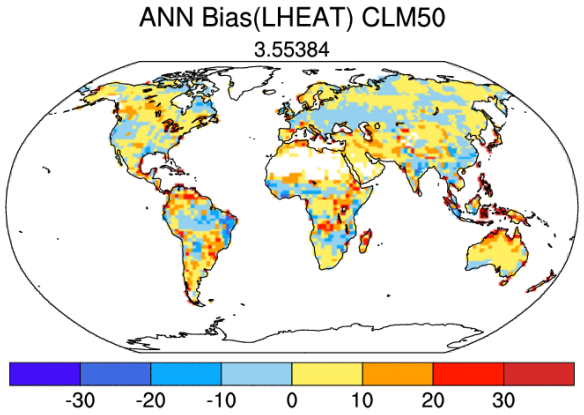


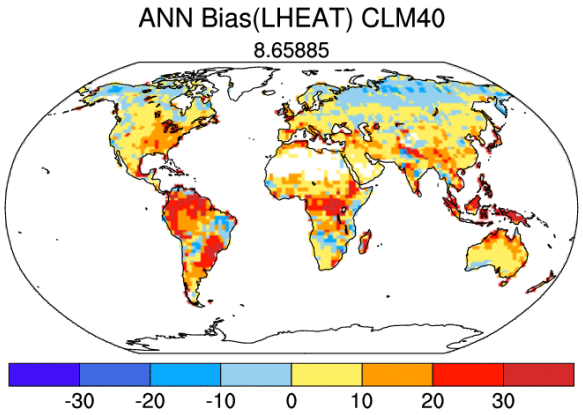
- "Better" forcing corresponds with "Better" model output

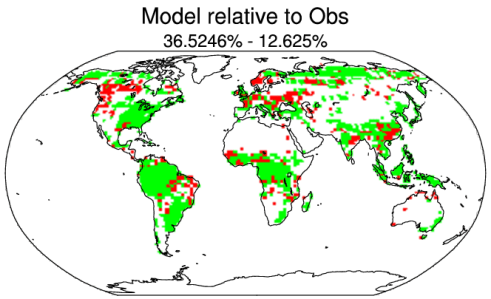


Metrics for selected variables

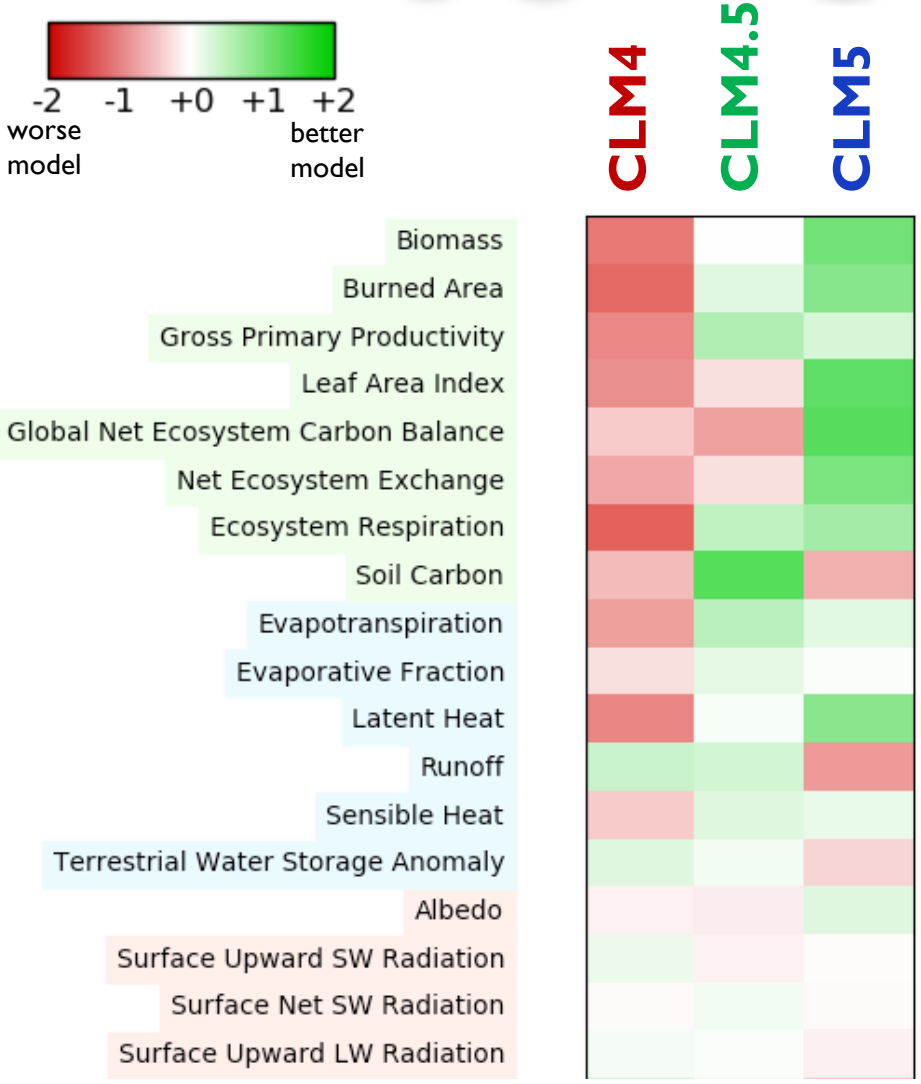
Configuration	LH		GPP		LAI		Live biomass	Burned area
	RMSE	r	RMSE	r	RMSE	r	r	r
CLM4.0 CN	18.7	0.91	1.47	0.87	1.5	0.72	0.61	0.12
CLM4.5 BGC	16.7	0.95	1.	0.94	1.4	0.68	0.74	0.55
CLM5.0 BGC-crop	15.1	0.95	1.27	0.91	1.1	0.86	0.81	0.76





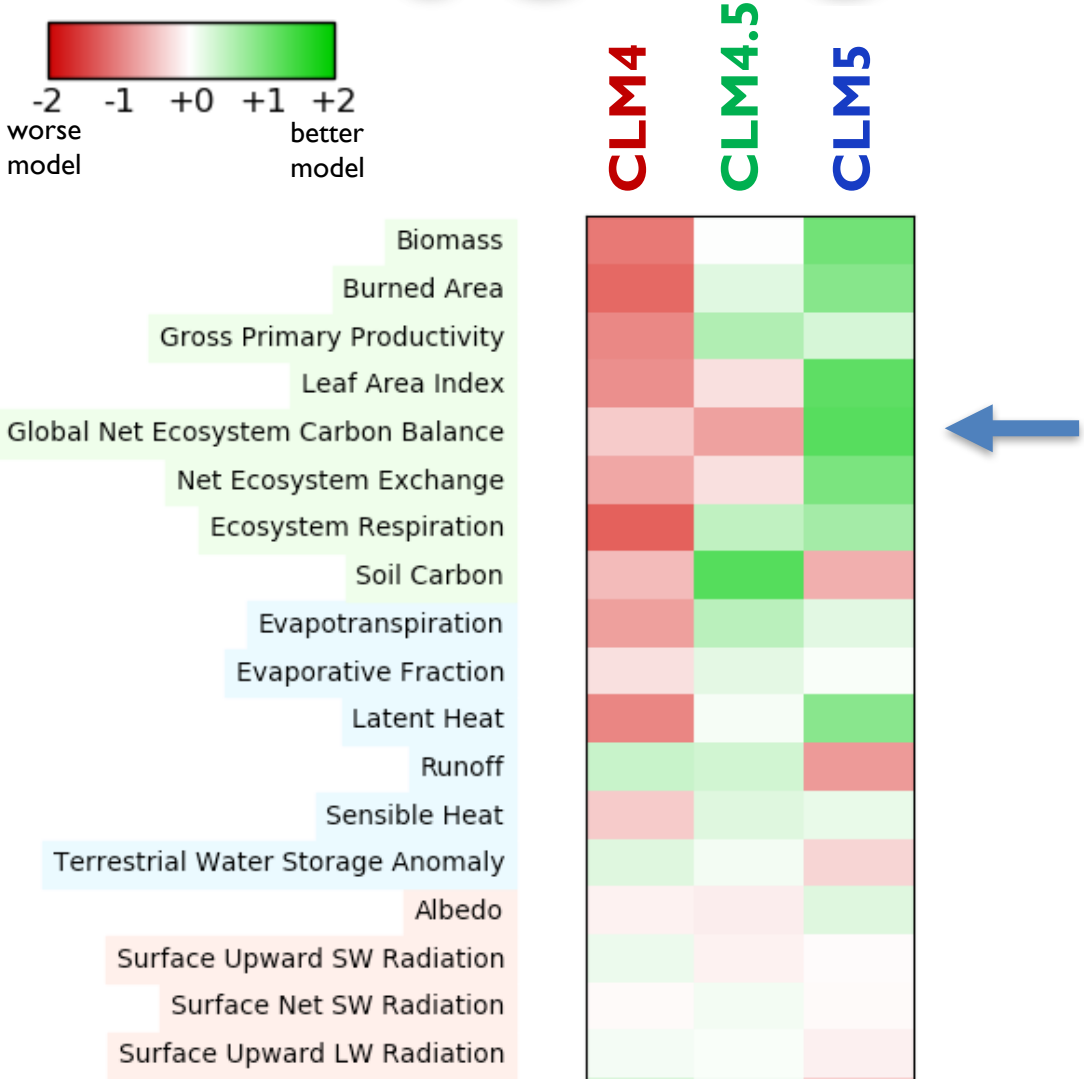


CLM land-only versions forced with GSWP3 prognostic vegetation and carbon configuration

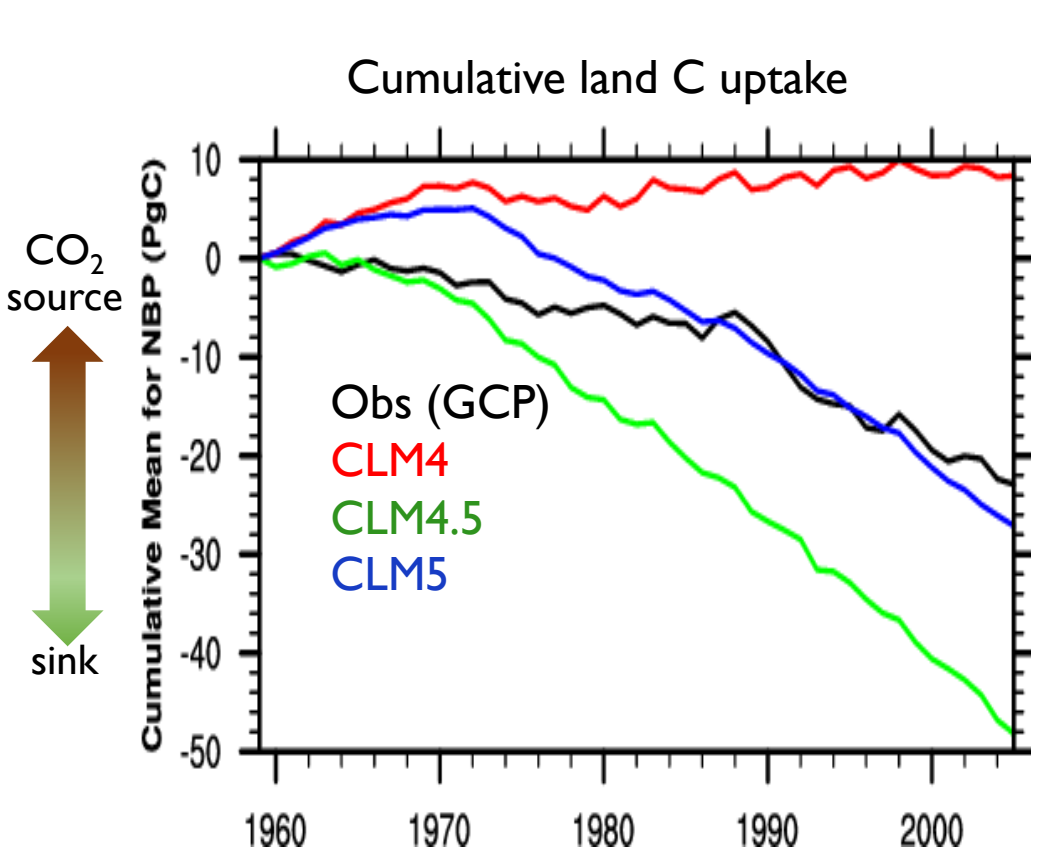


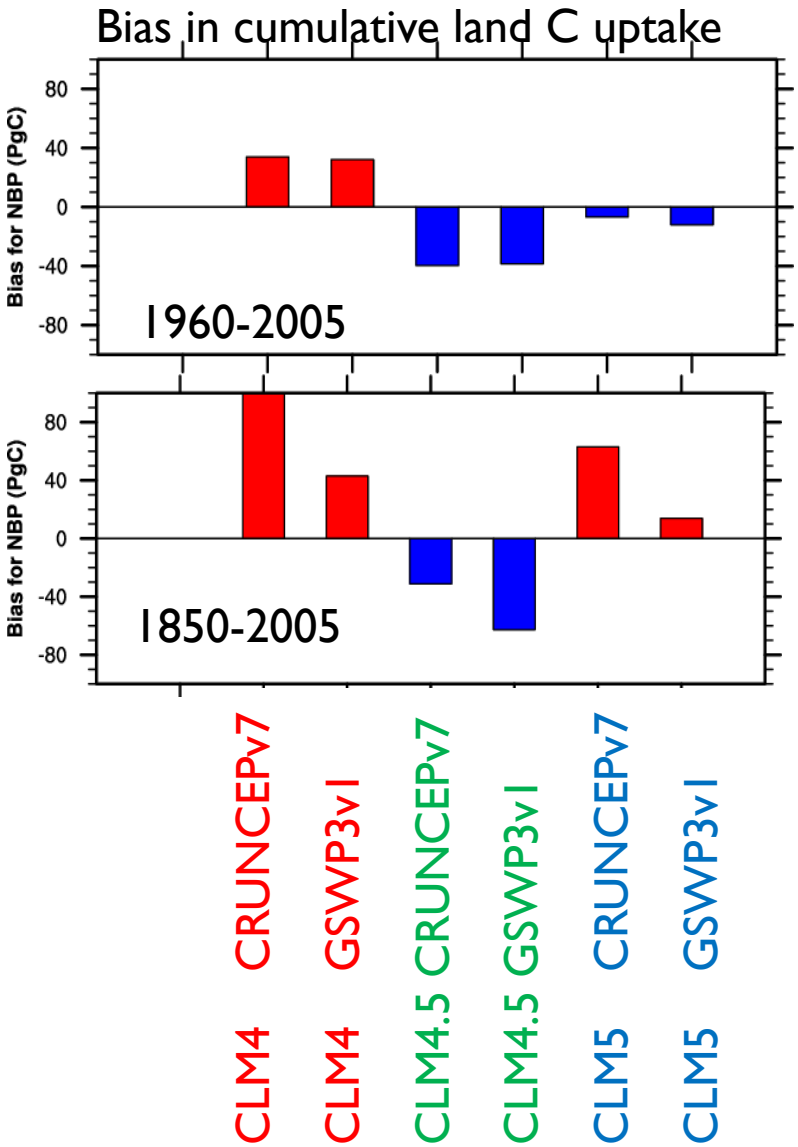
- Improvements in mechanistic treatment of hydrology, ecology, and land use with many more moving parts
- Simulation improved even with enhanced complexity

CLM land-only forced with GSWP3 prognostic vegetation and carbon configuration

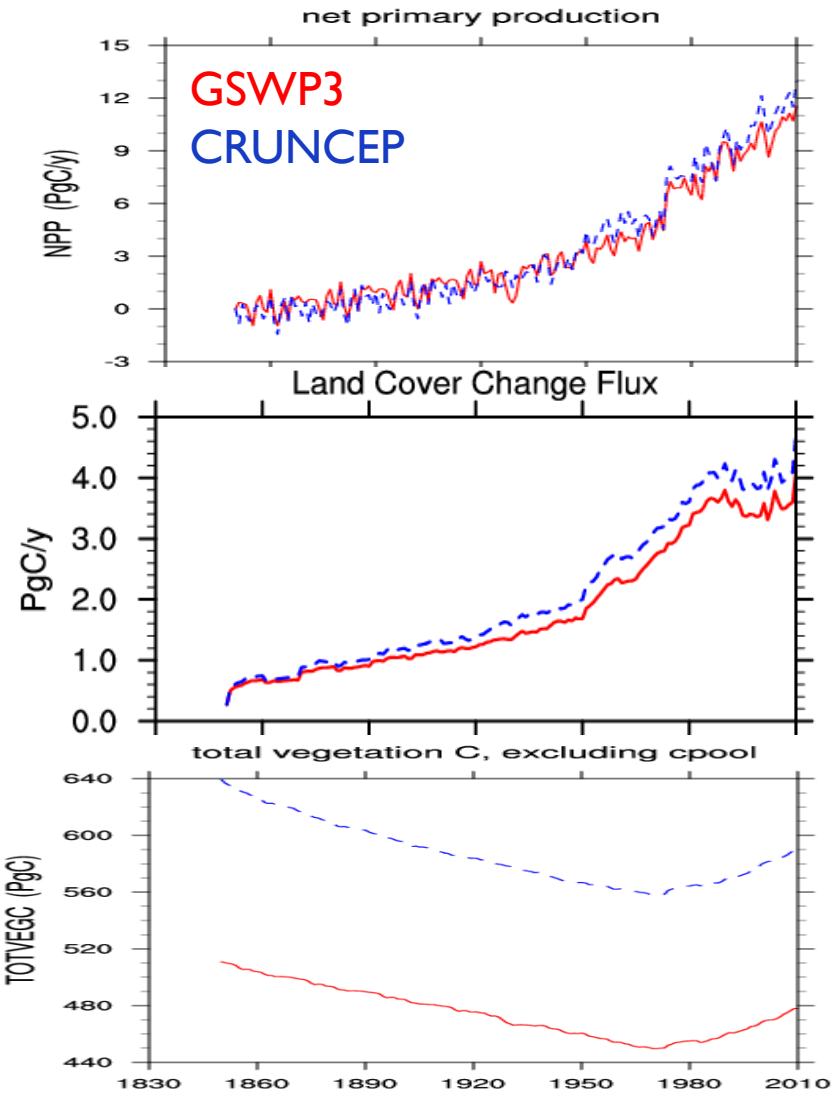


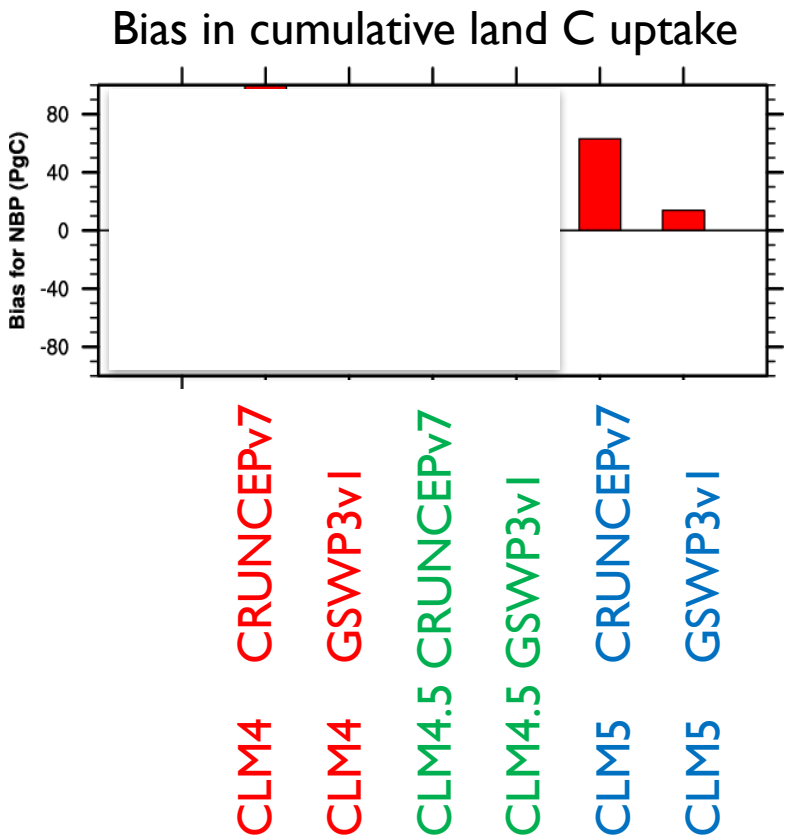
Accumulated land carbon uptake



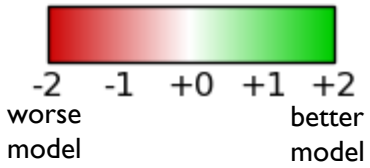


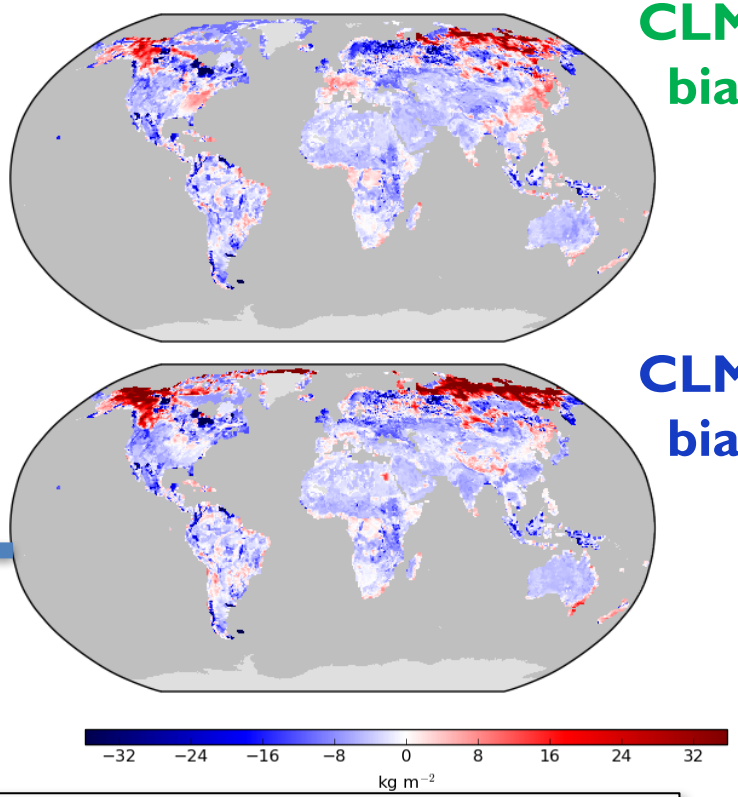
Accumulated land carbon uptake





CLM land-only forced with GSWP3 prognostic vegetation and carbon configuration

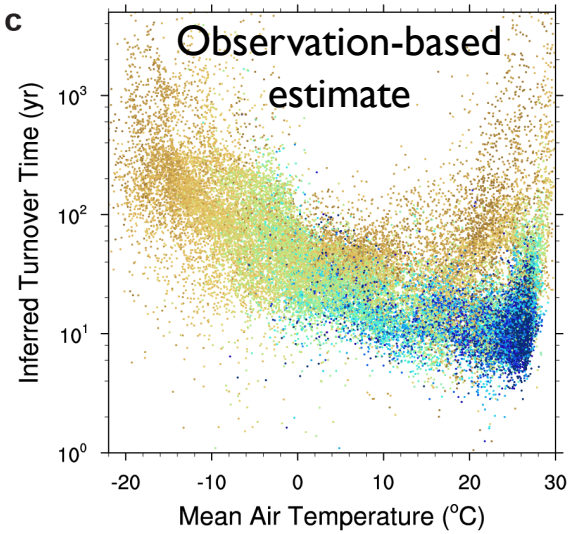




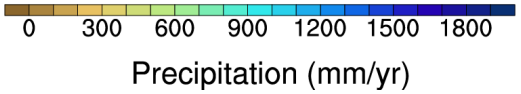
Model	Data	Period Mean [Pg]	Bias [Pg]	Bias Score [1]	Spatial Distribution Score [1]	Overall Score [1]
Benchmark	[-]	1,295.165				
CLM40r243GSWP3	[-]	498.855	-755.294	0.559	0.465	0.512
CLM45r243GSWP3	[-]	857.208	-359.958	0.617	0.777	0.697
CLM50r243GSWP3	[-]	1,029.019	-186.057	0.6	0.178	0.389

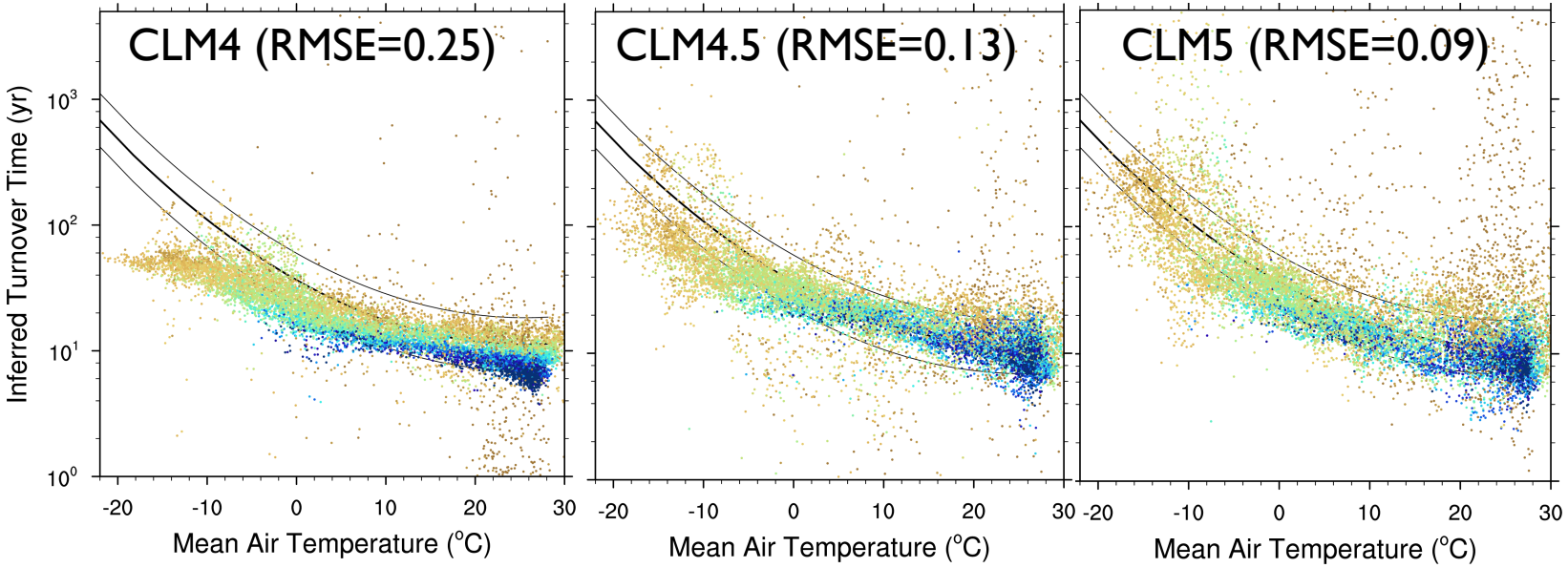
New metric: Soil carbon turnover time

$$\tau = \frac{carbon\ stocks\ (SOM)}{carbon\ inputs\ (NPP)}$$



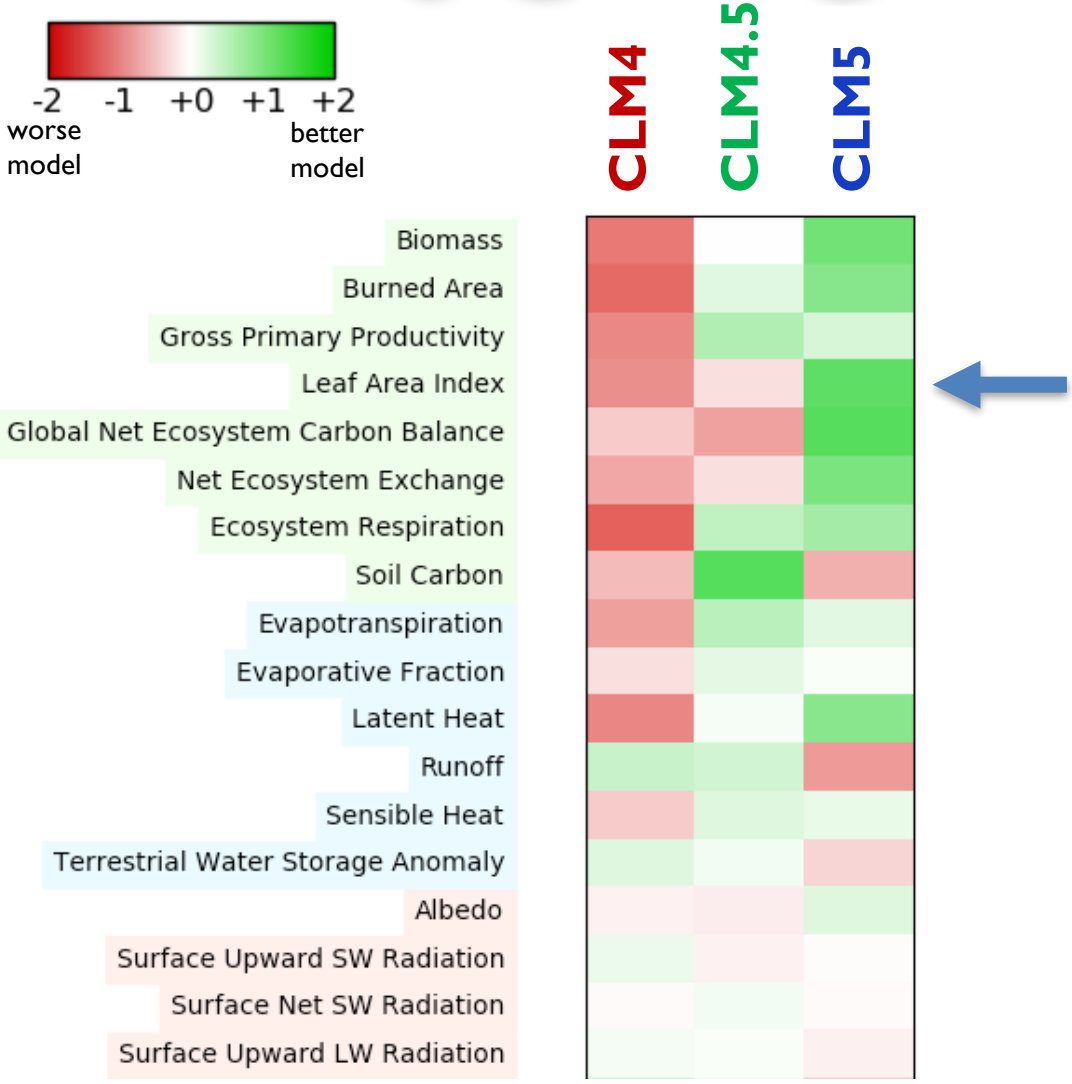
HWSD merged with NCSCD
MODIS NPP





Koven et al., NCC, 2017

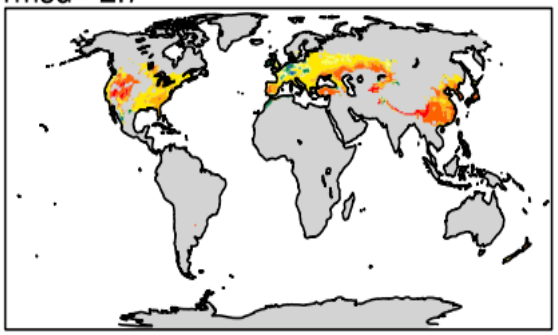
CLM land-only forced with GSWP3 prognostic vegetation and carbon configuration



Future ILAMB diagnostics: LAI bias by Plant Functional Type

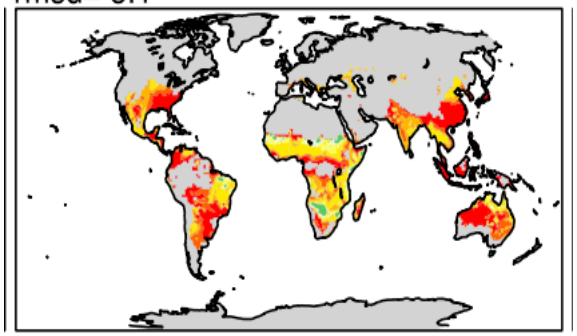
CLM4

rmsd= 2.7



NL Evergreen Temperate Tree

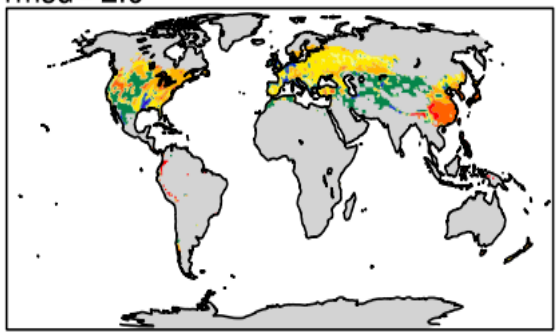
rmsd= 5.1



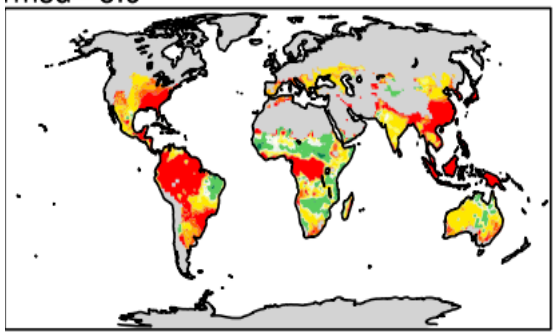
C4 grass

CLM4.5

rmsd= 2.6

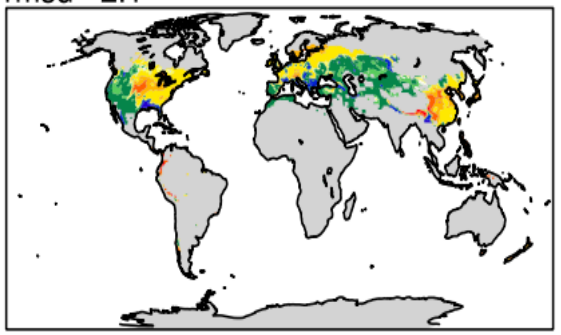


rmsd= 5.9

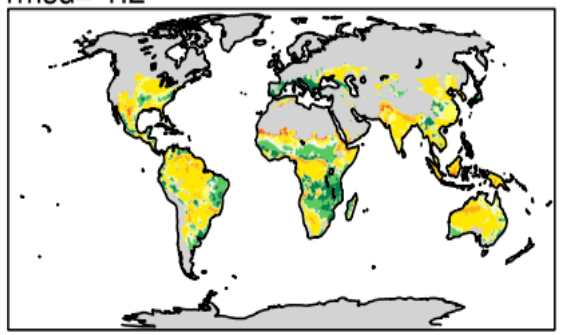


CLM5

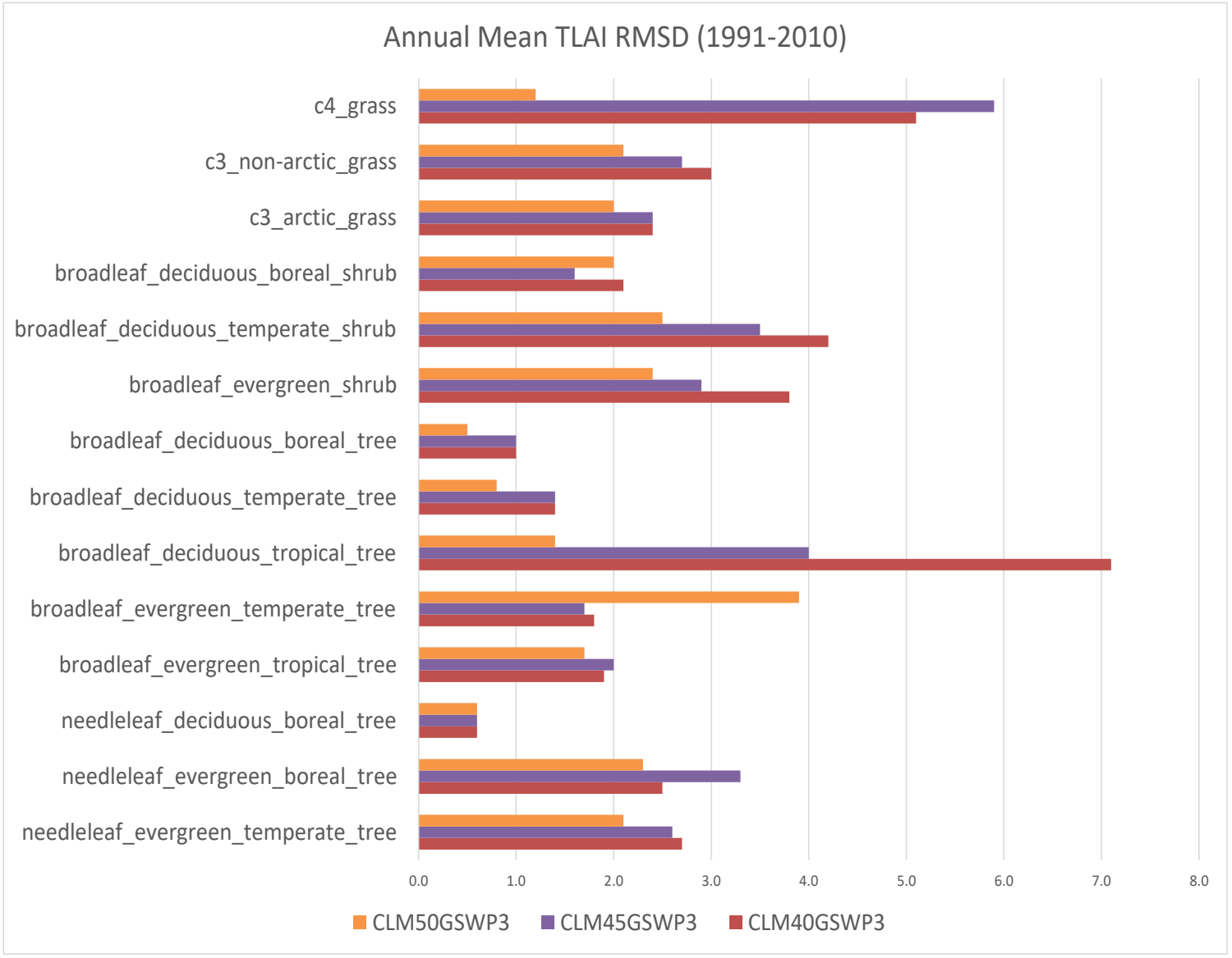
rmsd= 2.1



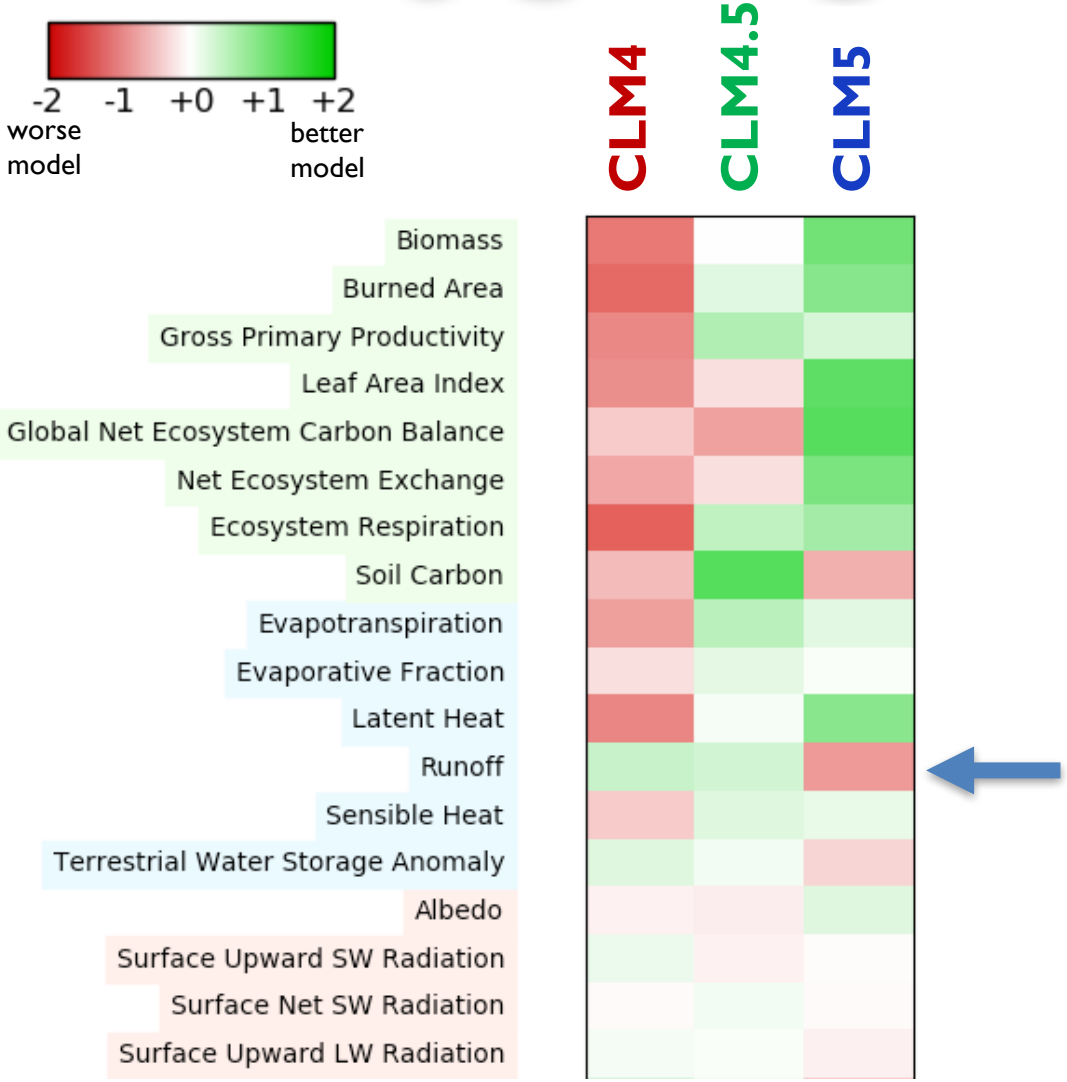
rmsd= 1.2



LAI bias by Plant Functional Type



CLM land-only forced with GSWP3 prognostic vegetation and carbon configuration

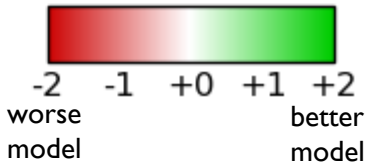


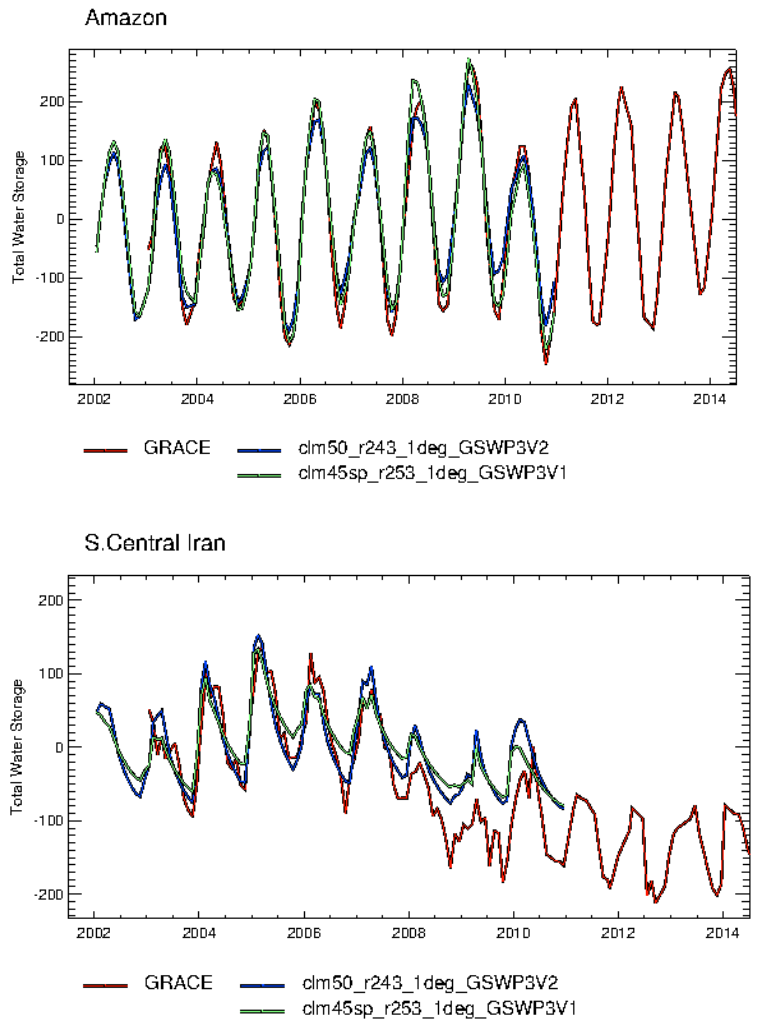
LH improved
ET unchanged
Runoff degraded

Runoff degradation due primarily to degraded interannual variability score

No interannual variability metric for ET or LH

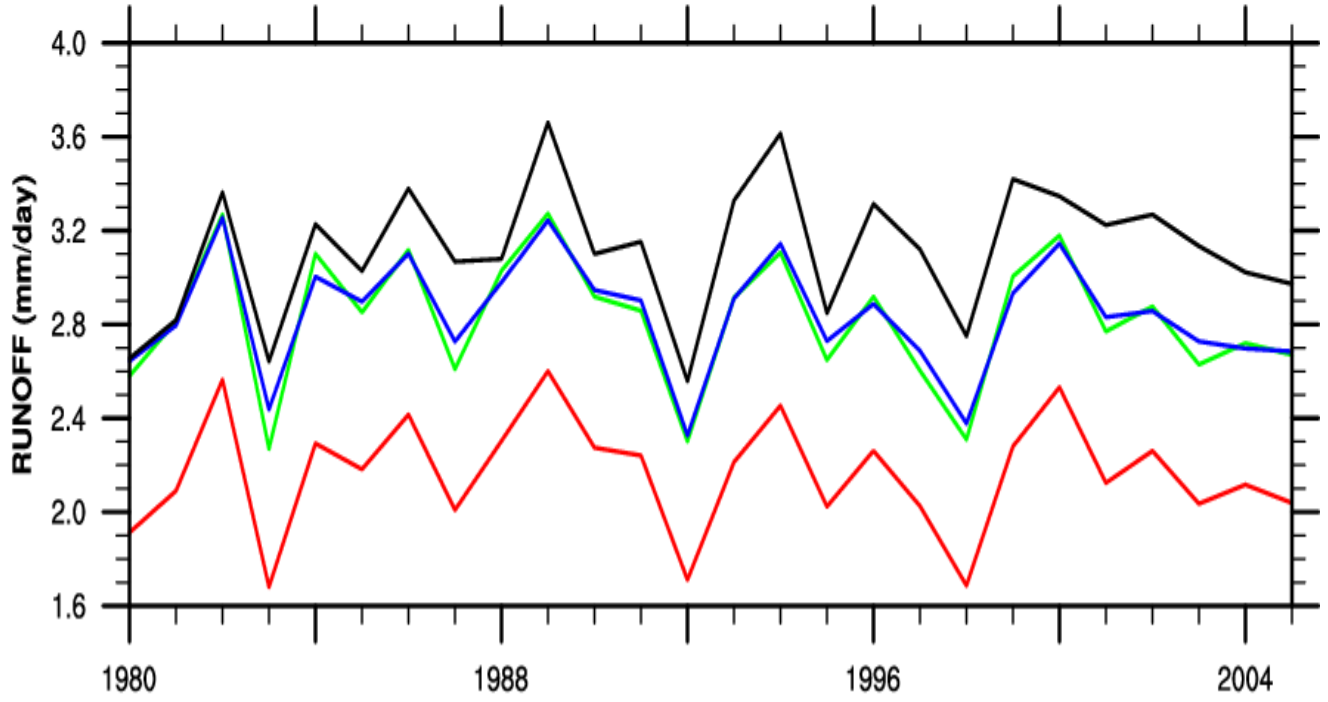
CLM land-only forced with GSWP3 prognostic vegetation and carbon configuration



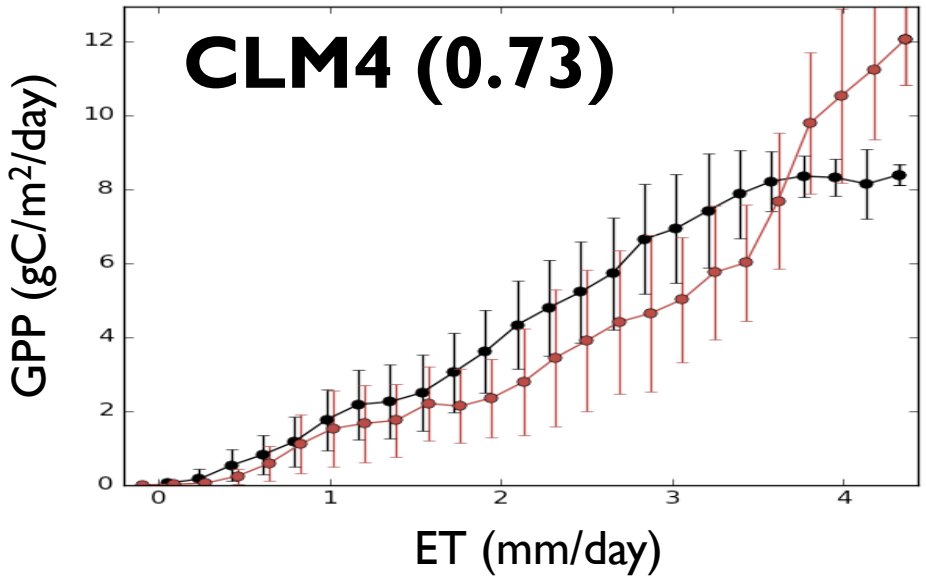


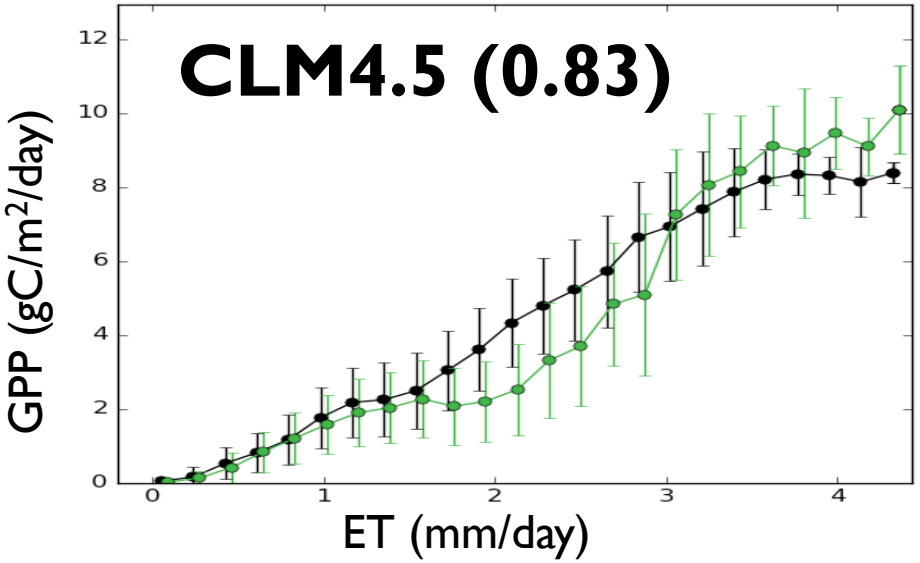
Amazon river discharge

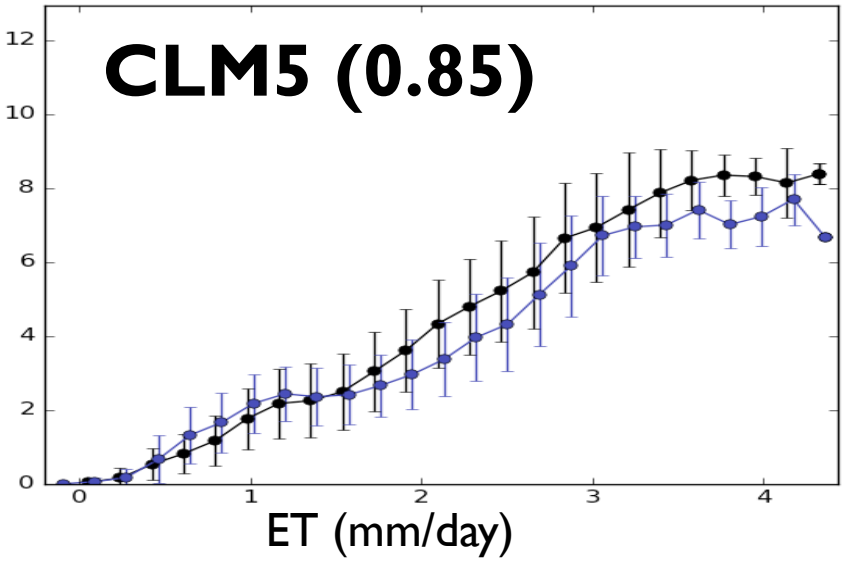
Obs
CLM4
CLM4.5
CLM5



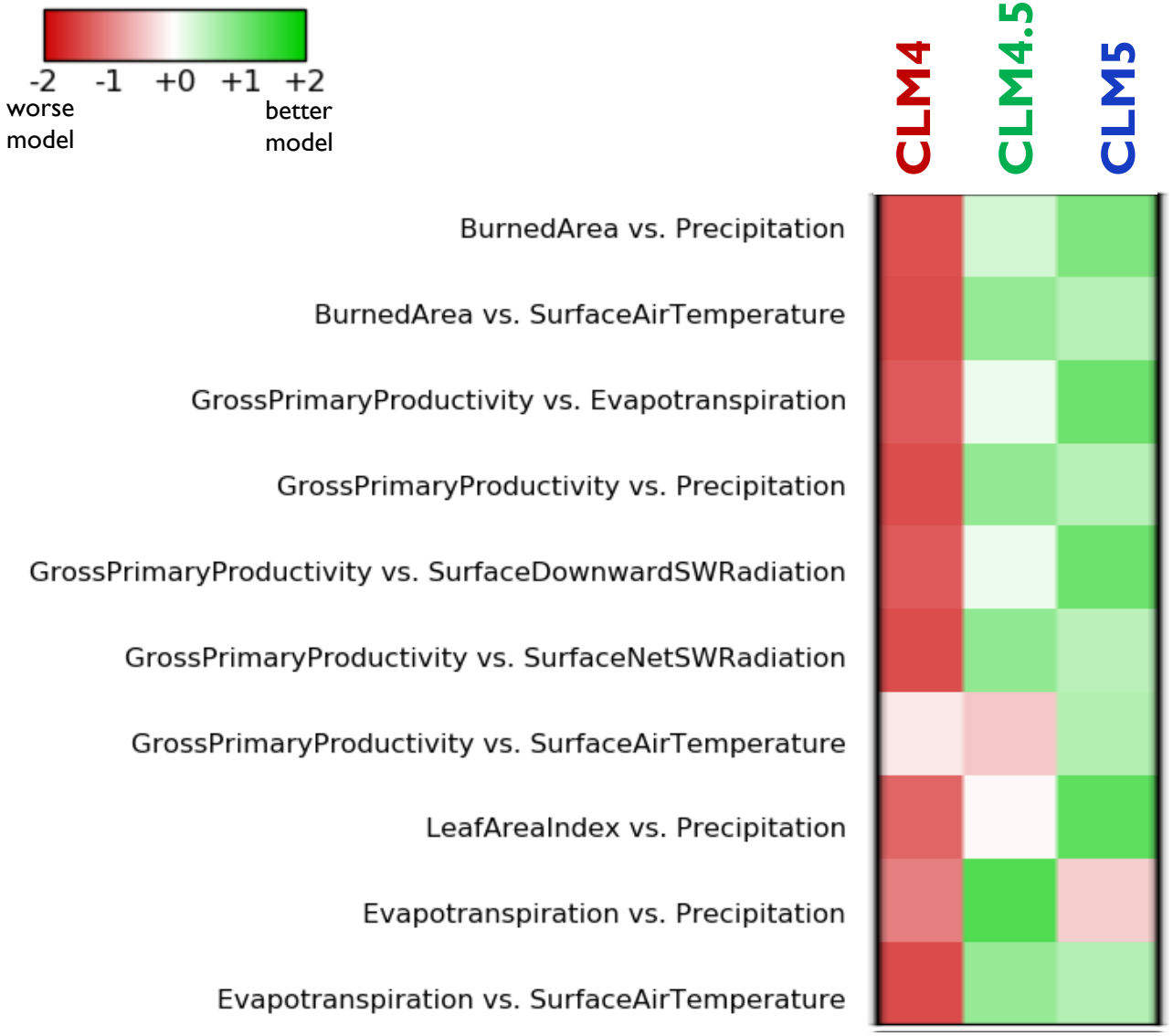
Functional Relationships:
Gross primary production vs Evapotranspiration



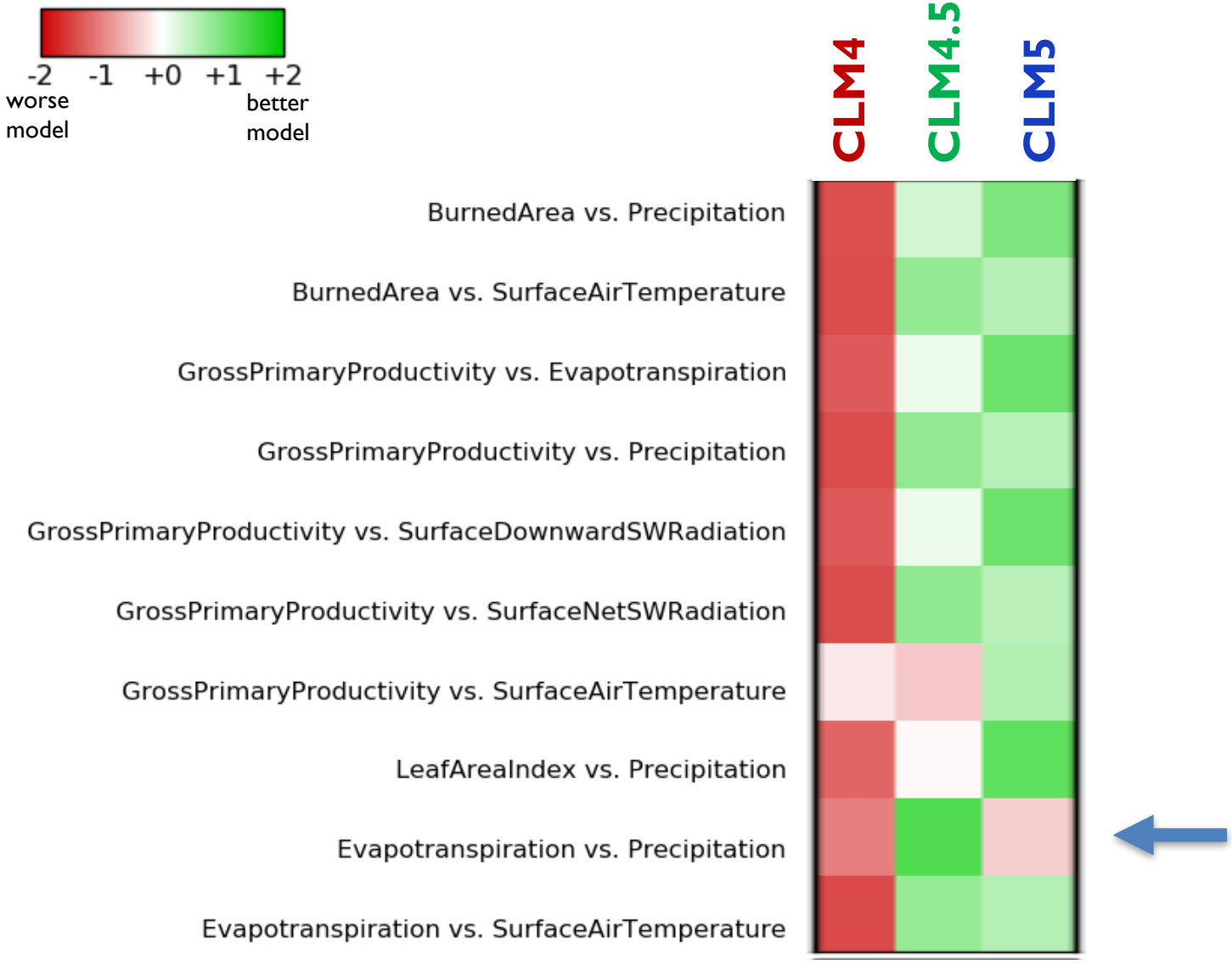




Functional Relationships: Summary diagram



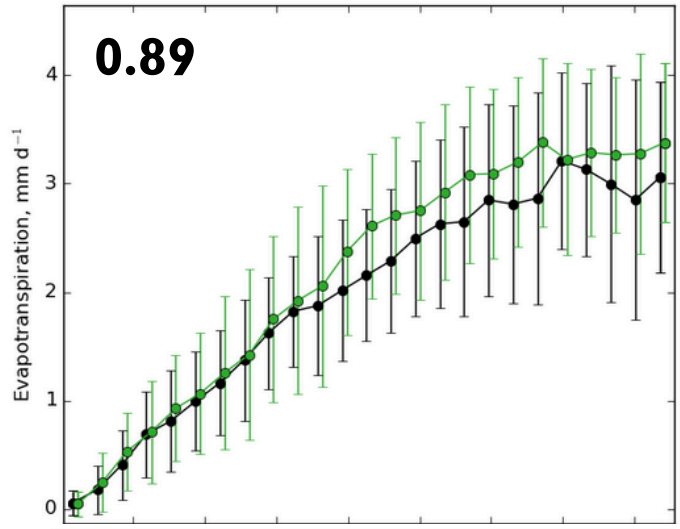
Functional Relationships: Summary diagram

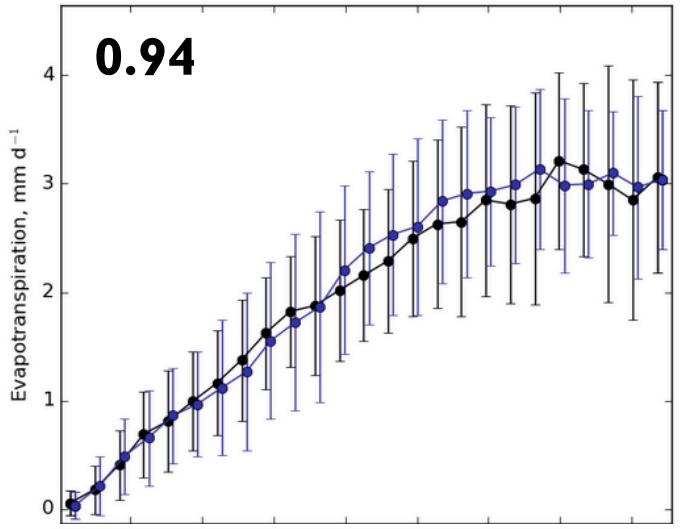


Functional Relationships: Precipitation vs Evapotranspiration

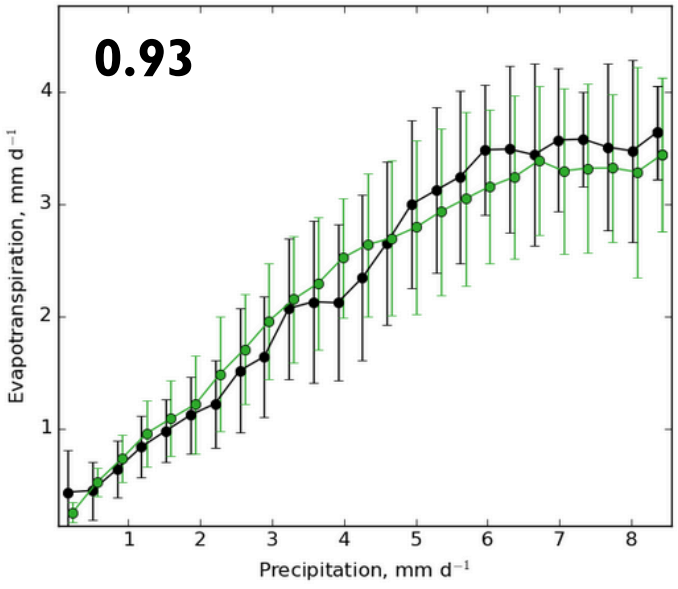
CLM4.5 | **CLM5**

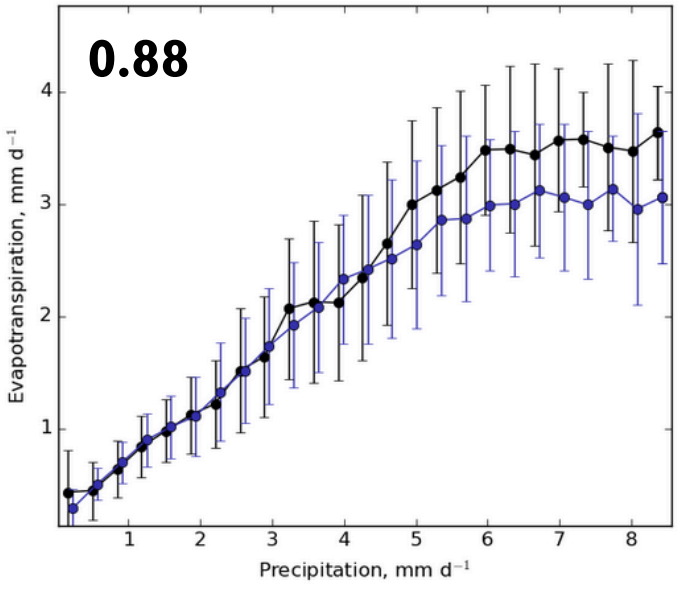
GLEAM ET





MODIS ET

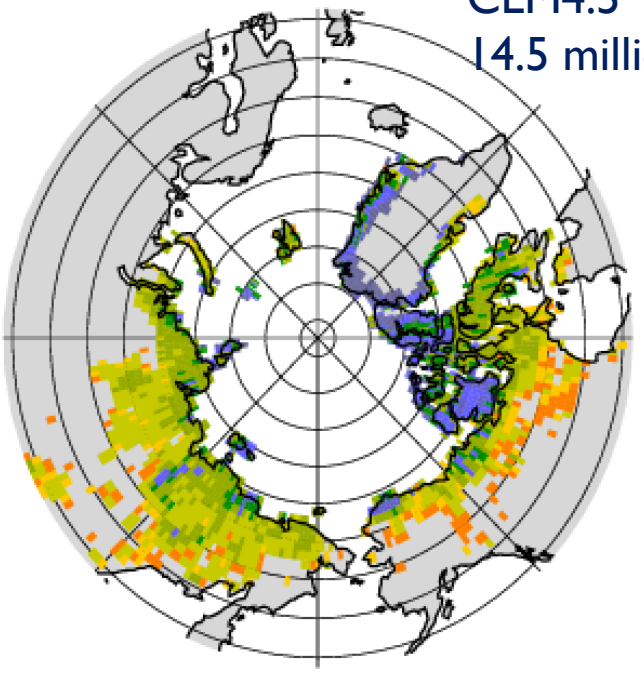




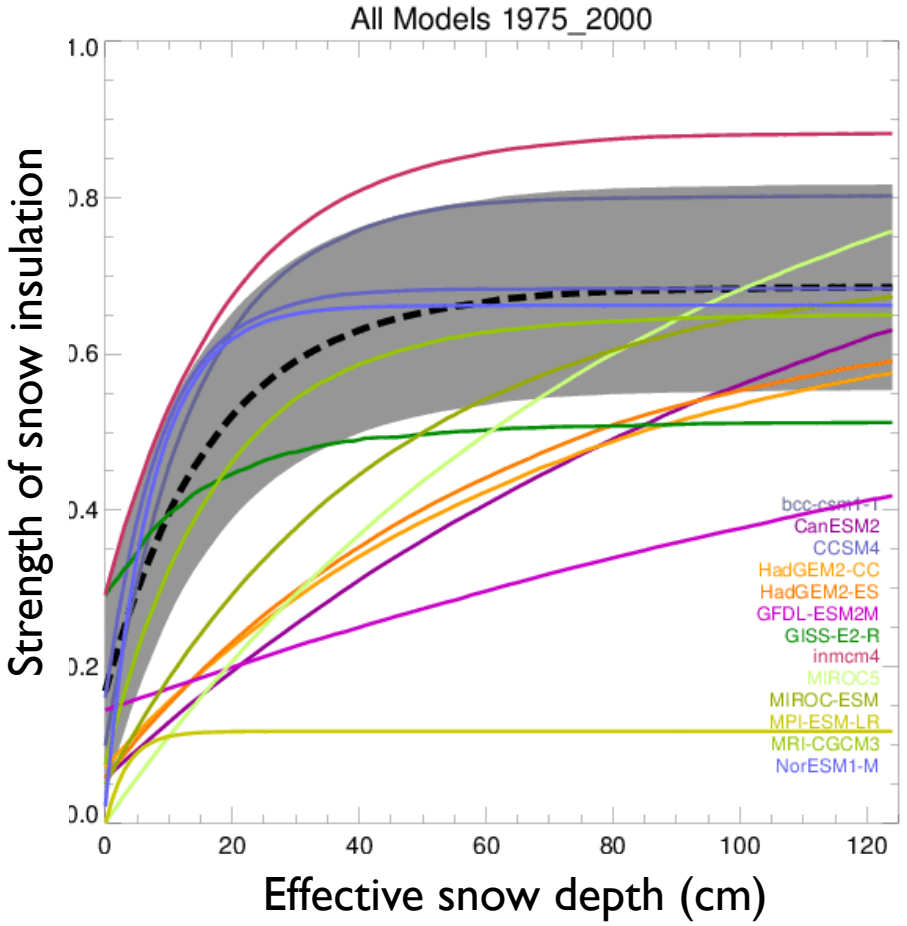
Some possible new metrics

Permafrost distribution and snow insulation

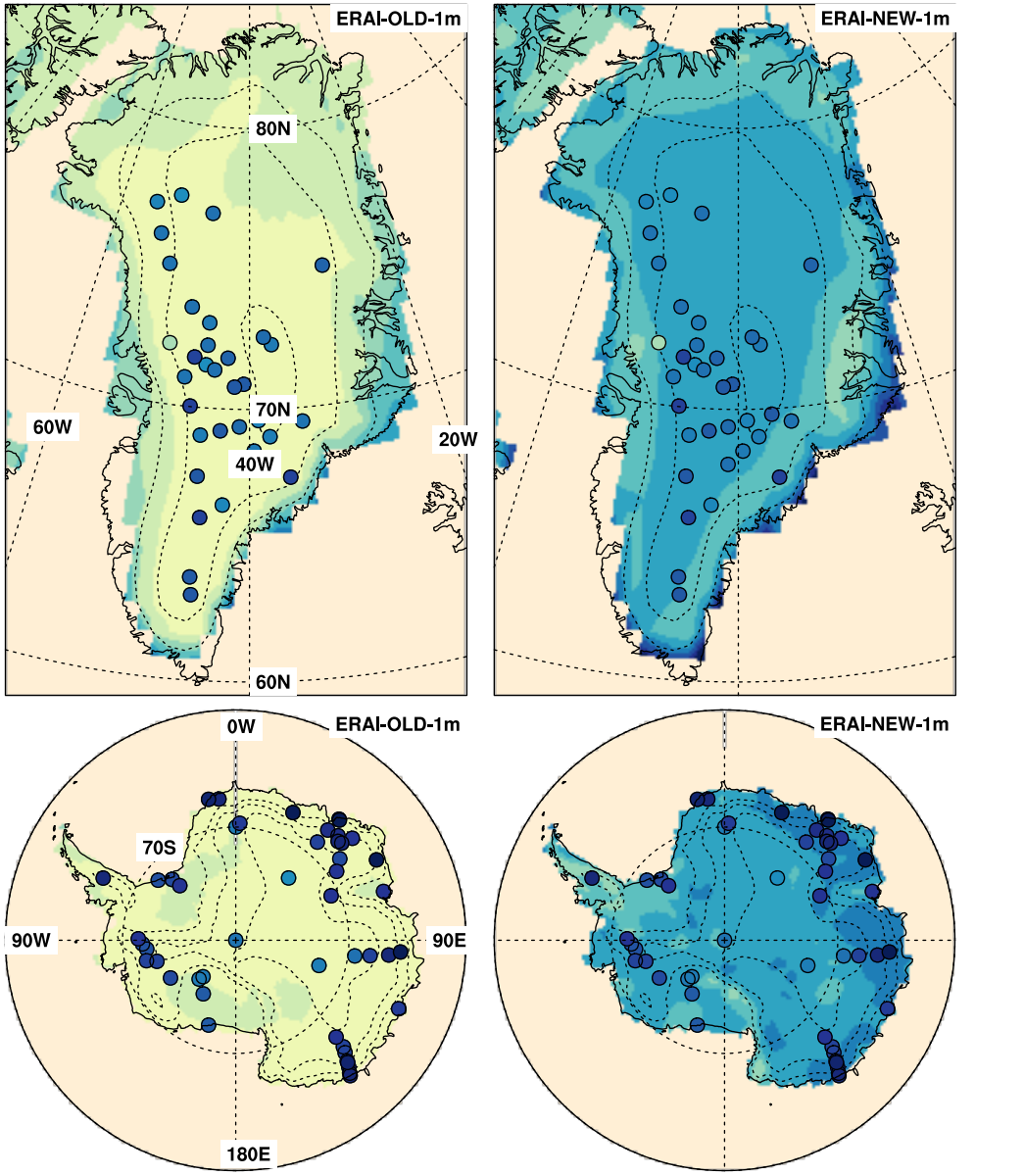
CLM4.5
14.5 million km^2



~15-16 million km^2 (IPA obs)



Slater et al. 2017



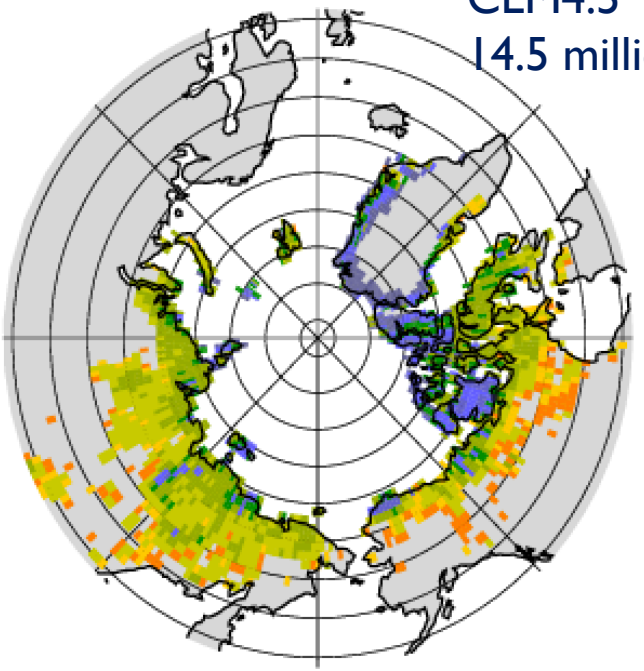
CLM5 snow density

Revised fresh snow density with improved temperature and wind effects
Lead to increased and more realistic snow density and less thermal insulation

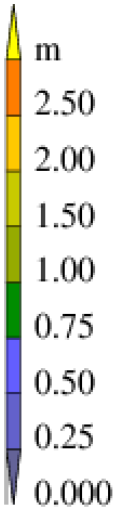
Figure courtesy L. Van Kampenhout

Permafrost distribution and snow insulation

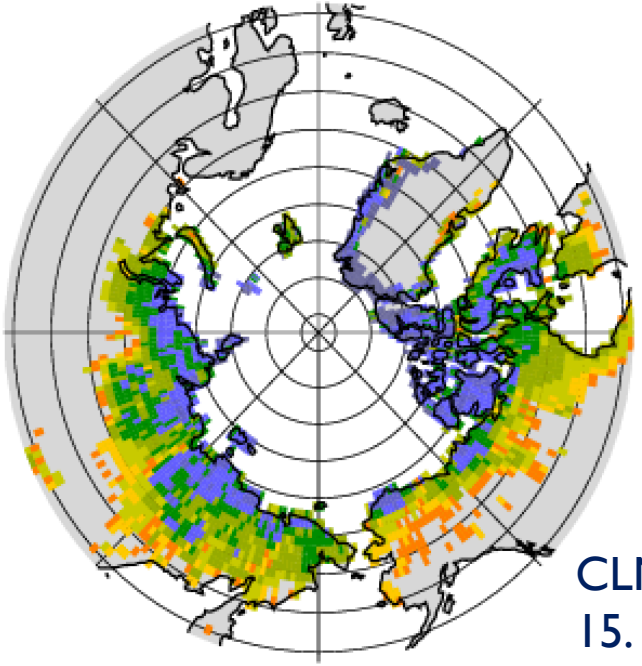
CLM4.5
14.5 million km^2



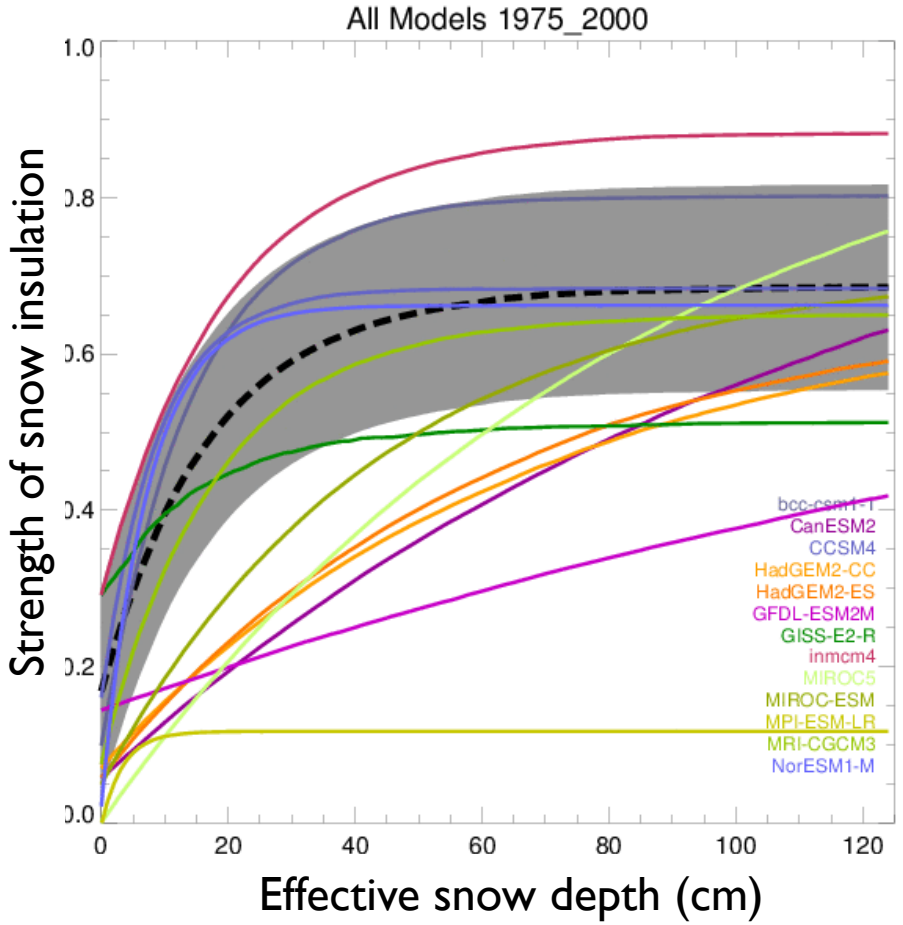
ALT



~15-16 million km^2 (obs)

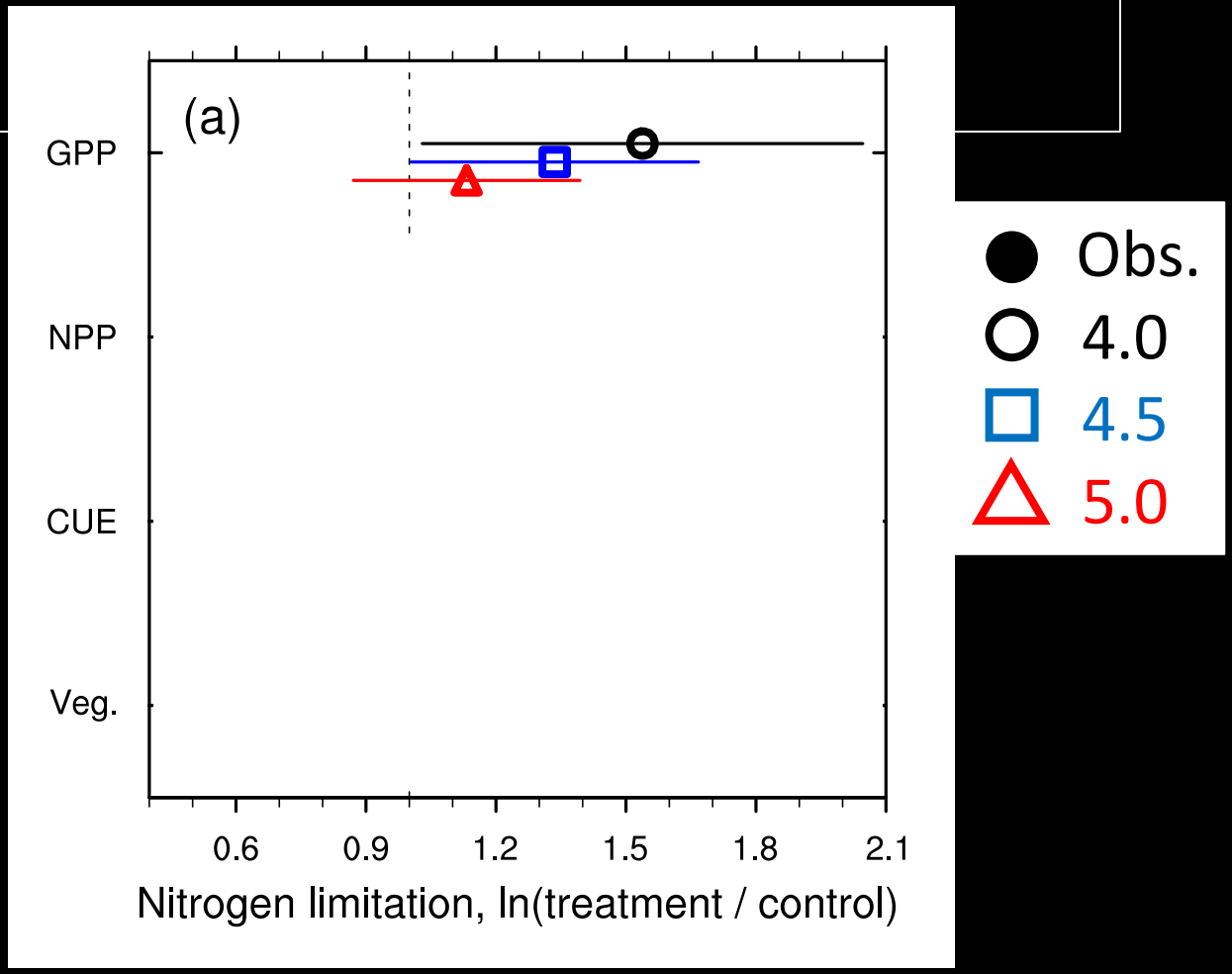


CLM5
15.1 million km^2



Slater et al. 2017

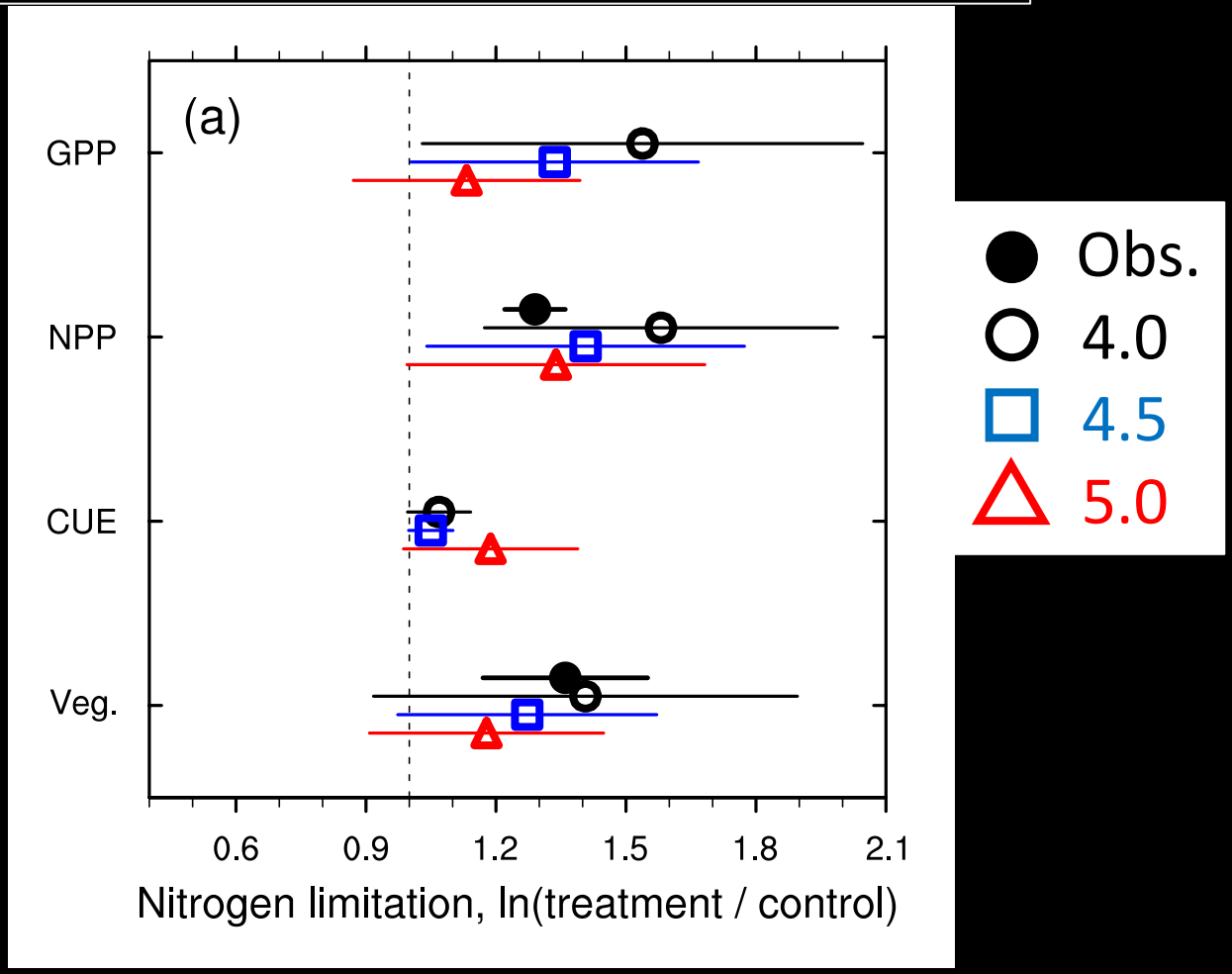
Future ILAMB diagnostics: Response to +N (Bouskill et al. 2014)



ANPP, LeBauer & Treseder 2008
HR, Jannsens et al 2010

Lu et al. 2011
Also Liu & Greaver 2010

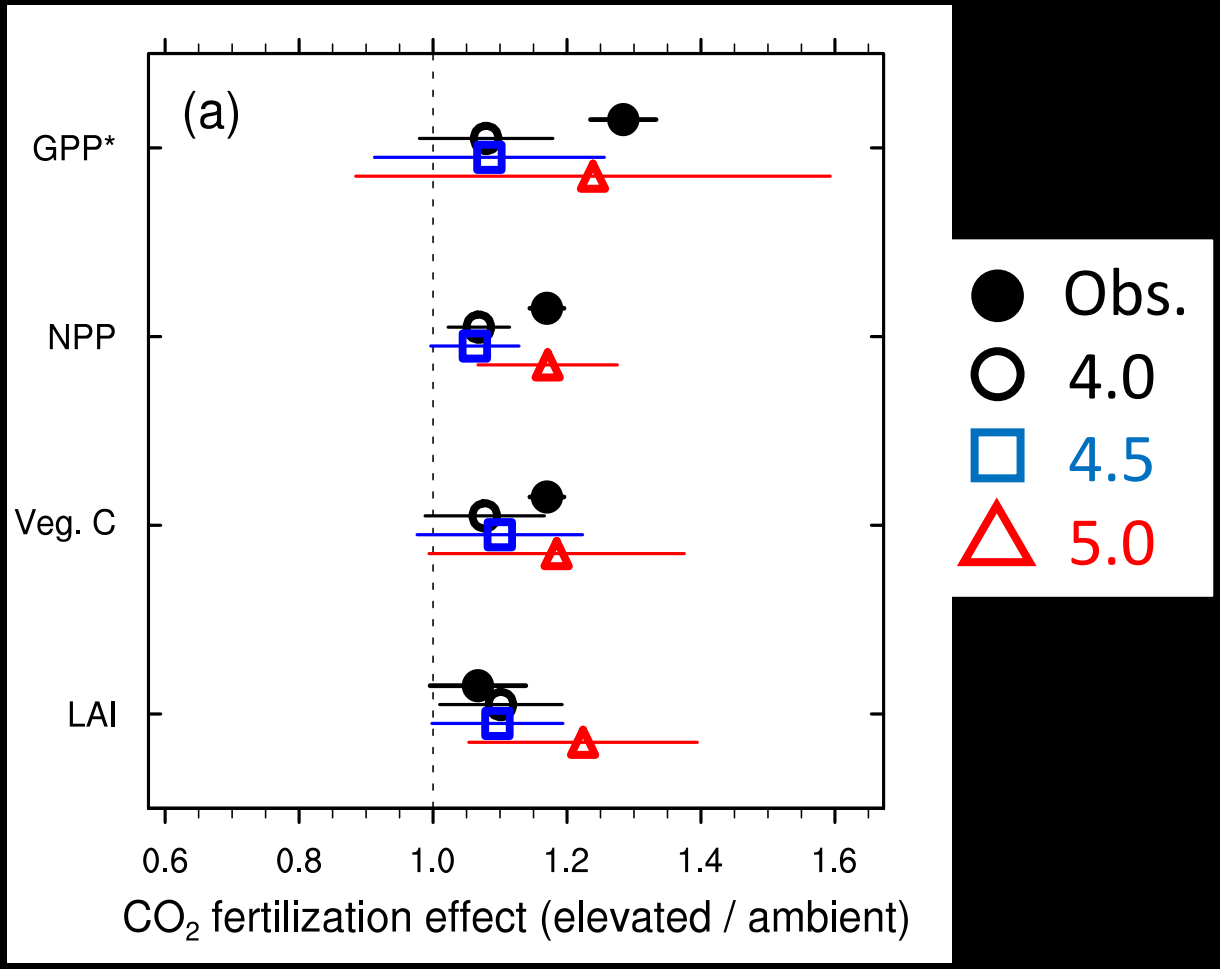
Future ILAMB diagnostics: Response to +N (Bouskill et al. 2014)



ANPP, LeBauer & Treseder 2008
HR, Jannsens et al 2010

Lu et al. 2011
Also Liu & Greaver 2010

FACE (+CO_2) effects



* Monthly mean of maximum daily values

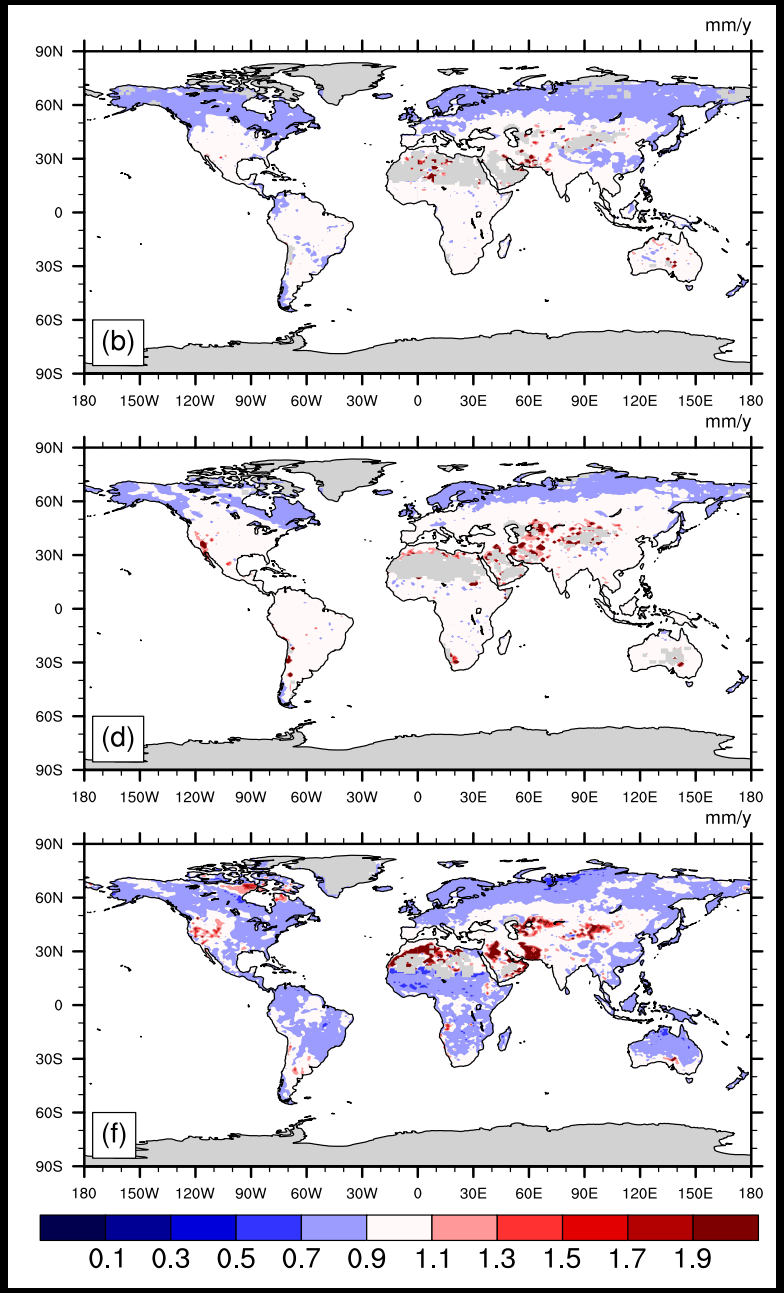
Obs from Ainsworth & Long 2005

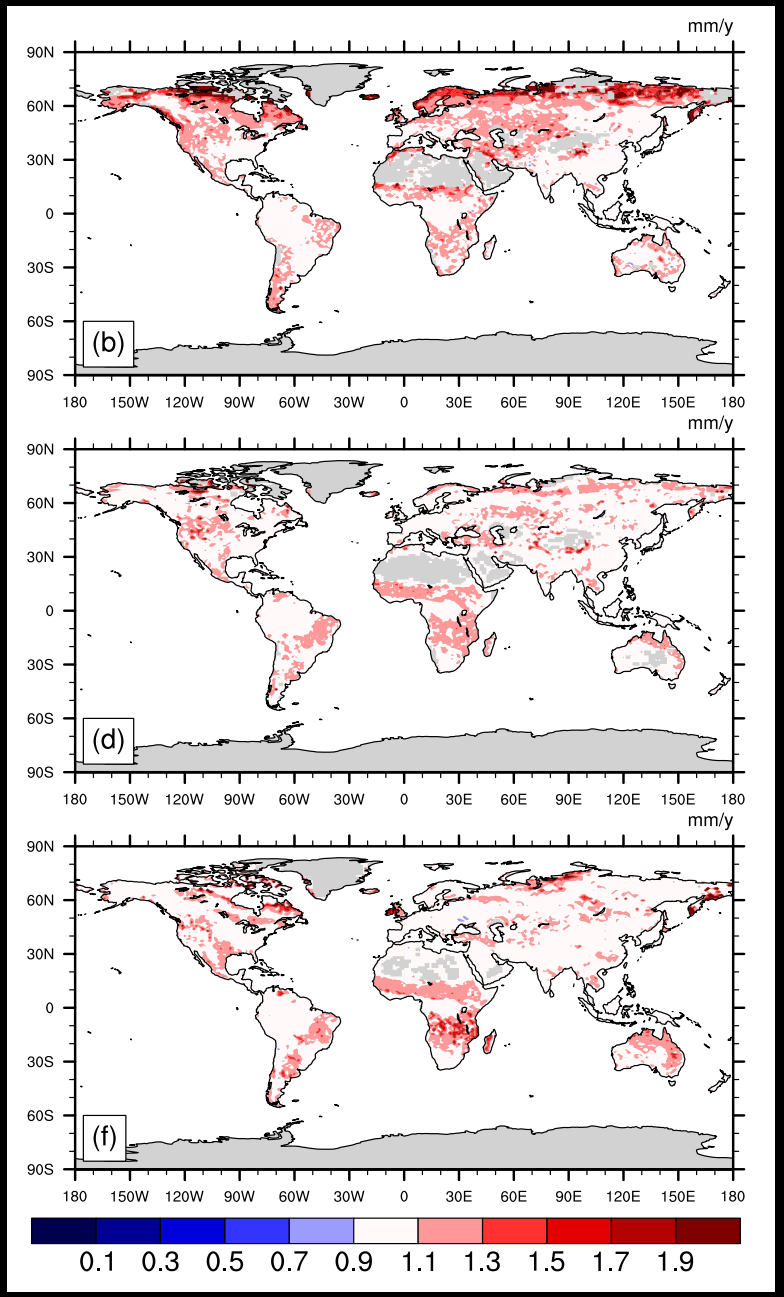
Summary

- ILAMB increasingly useful for multi-variate assessment/tracking of model performance across model generations
- Forcing uncertainty is considerable and can confound assessment of multi-variate impacts of model development
- Despite increasing complexity of CLM, maintain steady improvement in quality of overall simulation … how much longer?
- Room for improvement and enhancements to ILAMB
  - Metrics in the pipeline: diurnal cycle metrics, permafrost distribution and ALT, soil carbon turnover time, snow thermal insulation, FACE, +N, …
  - ILAMB produces a lot of information, could use additional development to aid user in scientific discovery

Thanks. Questions or comments?

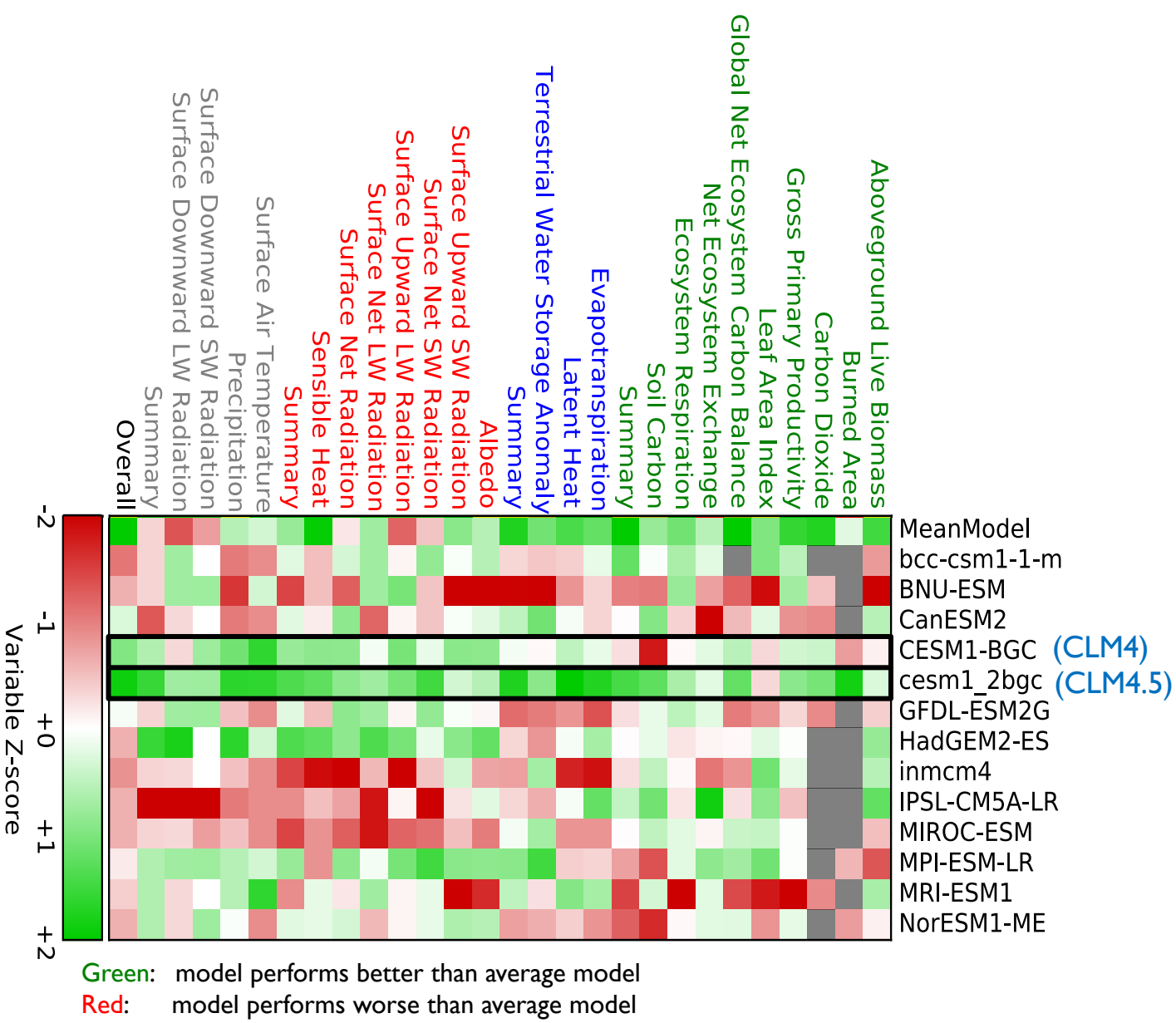
+CO_2 Transpiration +N





International LAnd Model Benchmarking (ILAMB) project

scores for RMSE, interannual variability, pattern correlation, variable-to-variable comparisons, +



Green: model performs better than average model

Red: model performs worse than average model