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

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NCAR

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

NSF

U.S. DEPARTMENT OF ENERGY

RUBISCO

CLM4 (June 2010) CLM4.5 (June 2013) CLM5 (Feb 2018)

- Carbon and nitrog
  prognostic vegetat
- Transient land cov
  wood harvest
- 'Permafrost-enable
  deep ground
- Aerosol depositio
- Simple groundwat
- Urban model

- Vertically-
- Co-limitat
  of photos
- Variable r
- Natural C
- Human tr
  suppressi
- Cold regi
- Revised la
- Multiple u
  classes

- Flexible leaf stoichiometry, leaf N optimize for photosynthesis
- Carbon costs for plant N uptake
- Plant hydraulics w/ hydraulic redistribution, *Ecosystem demography (FATES), ozone damage*
- Spatially explicit soil depth (0.4 – 8.5m), dry surface layer, revised GW, canopy interception, *representative hillslopes*
- MOSART river model (hillslope → tributary → main channel)
- Canopy snow, snow dens (T, wind), simple firn model
- Global crop model (8 crop types), transient irrigation and fertilization, *shifting cultivation*
- Dynamic landunits (nat veg ←→ crop, *glacier* ←→ *nat veg*,)
- Urban heating and AC, heat stress indices
- Carbon isotopes
- *Coupled fire trace gas emissions*

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

	CLM4				CLM4.5				CLM5			
Forcing	SP	BGC	+CO_2 +N	no LULCC	SP	BGC	+CO_2 +N	no LULCC	SP	BGC crop	+CO_2 +N	no LULCC, LUMIP LM
GSWP3 v1	✓º	✓º ❄	✓	✓	✓	✓º ❄	✓	✓	✓º	✓º ❄	✓	✓
CRUNCEP v7		✓				✓			✓	✓❄		✓
WATCH/ WFDEI									✓	✓		

✓ **Historical simulation (1850-2014)**

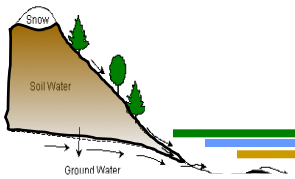
❄ **Projection period simulation (RCP8.5 2015-2300)**

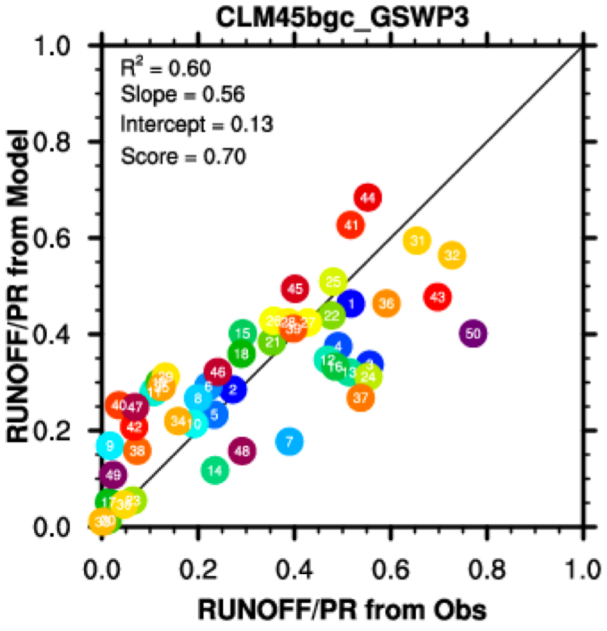
º **Daily and hourly output**

International Land Model Benchmarking (ILAMB) package

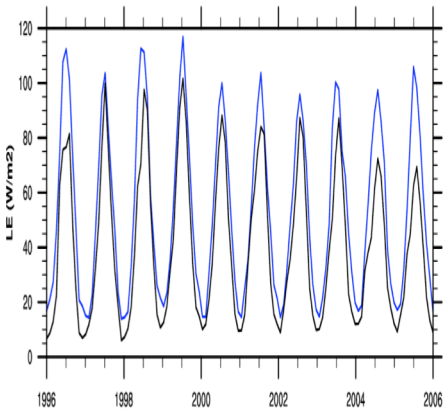
- Currently integrates analysis of 27 variables in 4 categories from >60 datasets
  - above ground live biomass, burned area, carbon dioxide, gross primary production, leaf area index, global net ecosystem carbon balance, net ecosystem exchange, ecosystem respiration, soil carbon
  - evapotranspiration, 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://pypi.org/project/ILAMB/)**

Examples of ILAMB metrics / plots

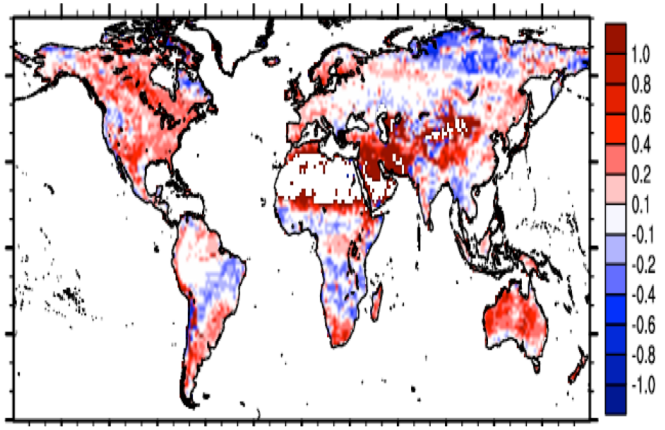




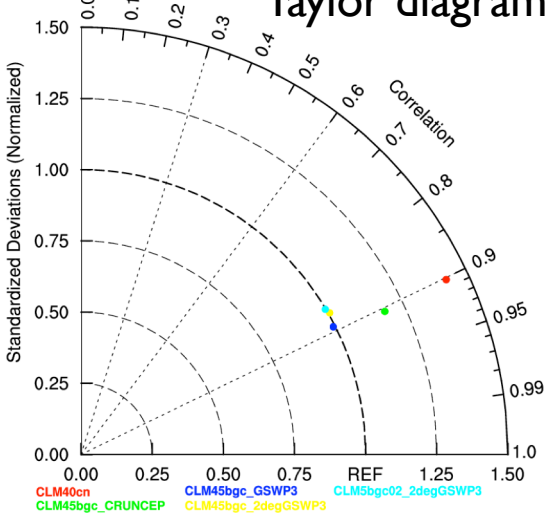
Tower Site



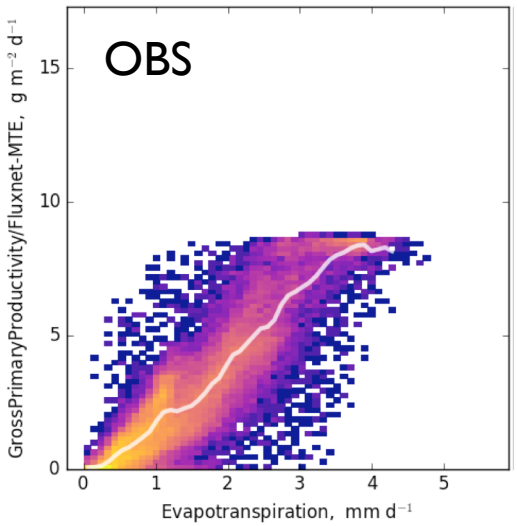
Global bias, relative bias, RMSE

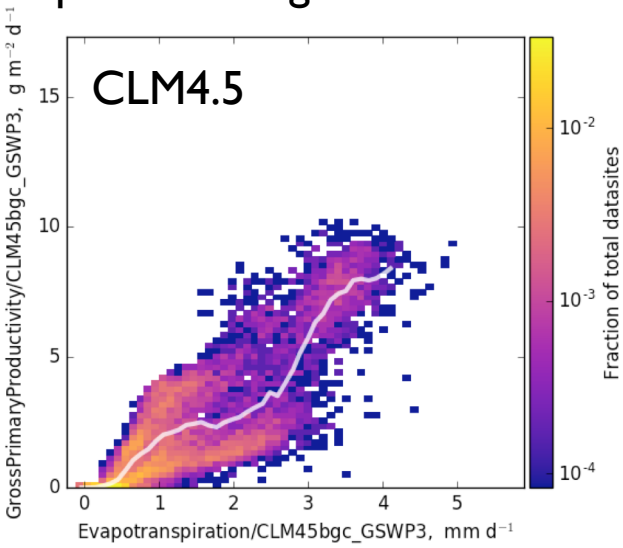


Taylor diagram

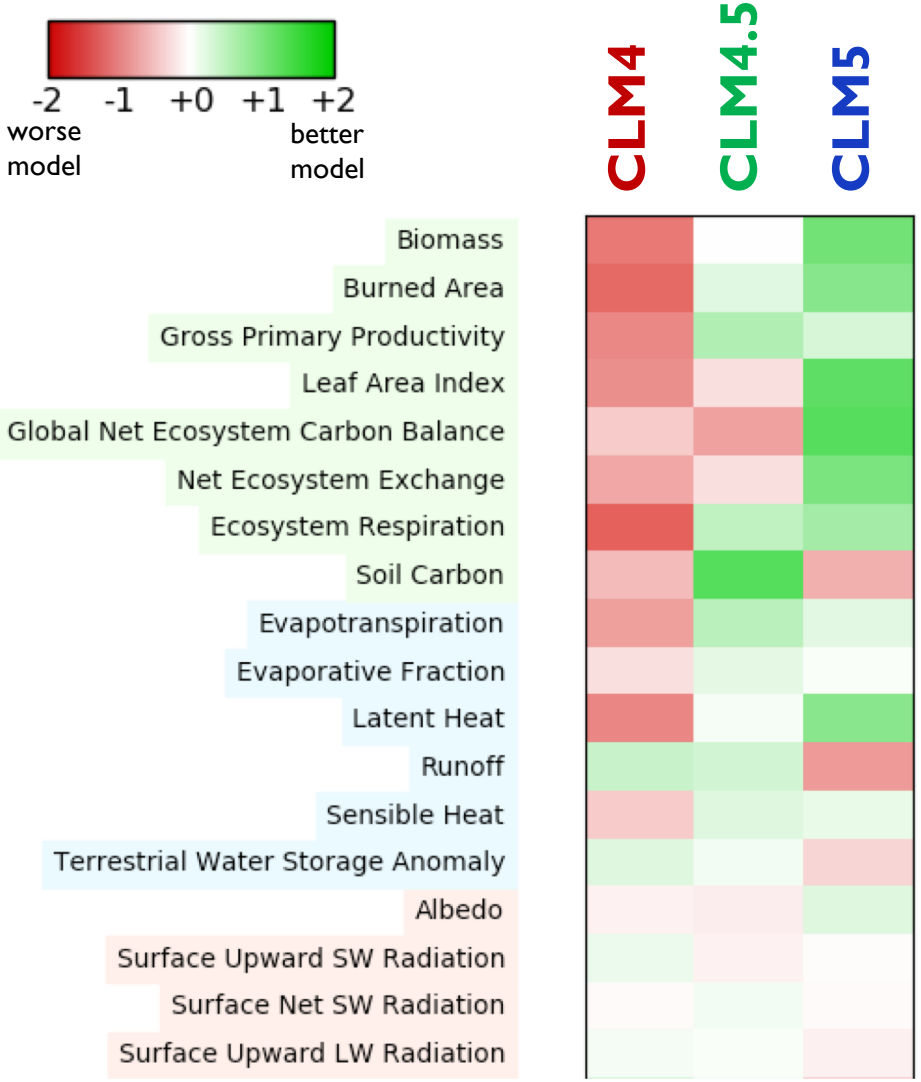


Functional relationships: 2-d histograms





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



- For majority of variables, progression in simulation quality from CLM4 to CLM5
- Why?
  - Improvements in mechanistic treatment of processes (e.g., hydrology, biogeochemistry, land use)
  - But, many more moving parts

http://webext.cgd.ucar.edu/I20TR/_build_set1CO2/index.html

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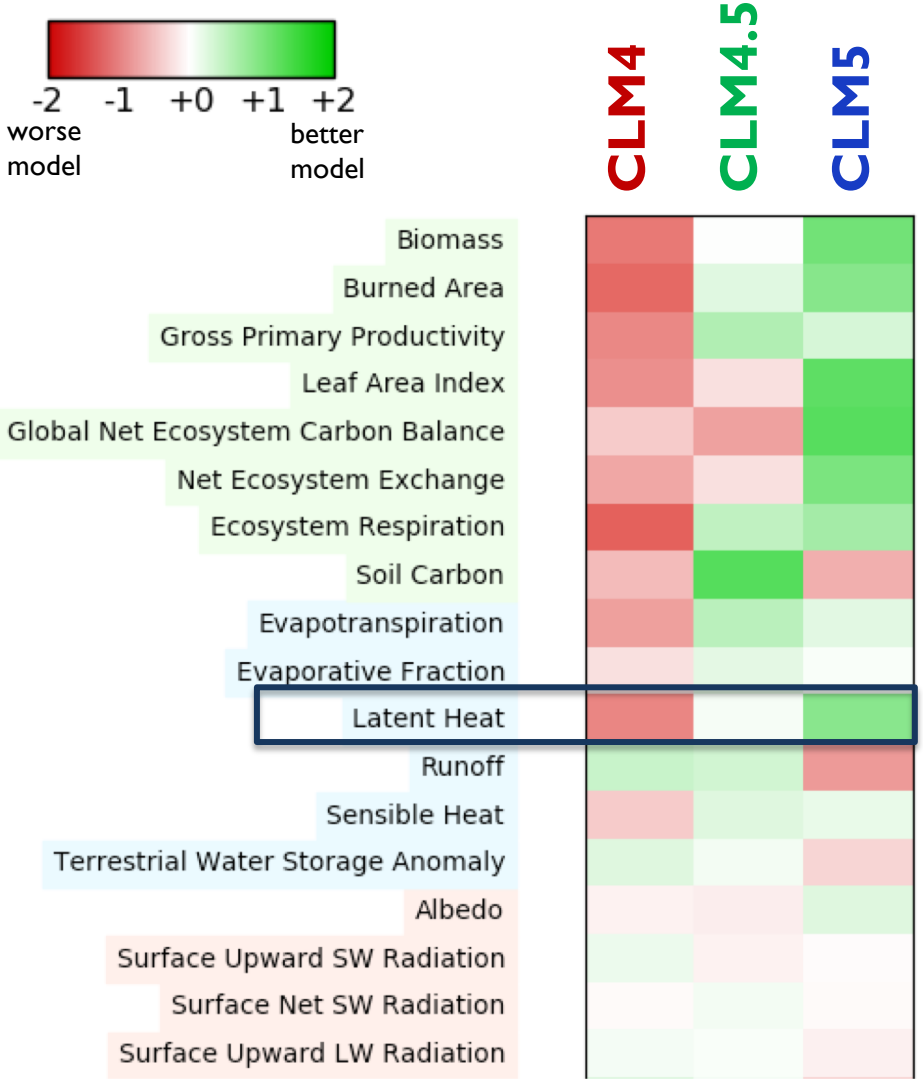
Surface Upward SW Radiation	0.78	0.77	0.77
Surface Net SW Radiation	0.89	0.89	0.89
Surface Upward LW Radiation	0.95	0.95	0.95
Surface Net LW Radiation	0.85	0.85	0.83
Surface Air Temperature	0.97	0.97	0.98
Precipitation	0.82	0.82	0.82
Surface Relative Humidity	0.83	0.83	0.84
Surface Downward SW Radiation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

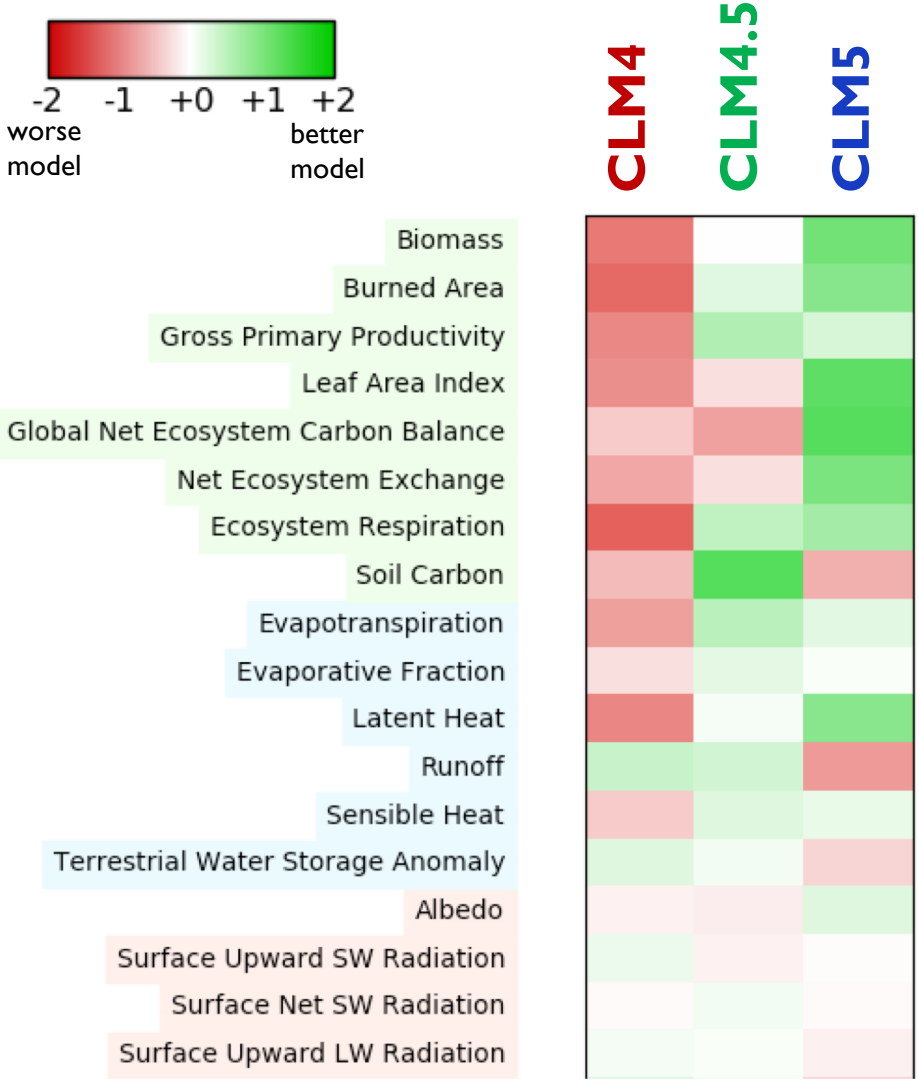
CLM land-only forced with GSWP3 prognostic vegetation and carbon configuration



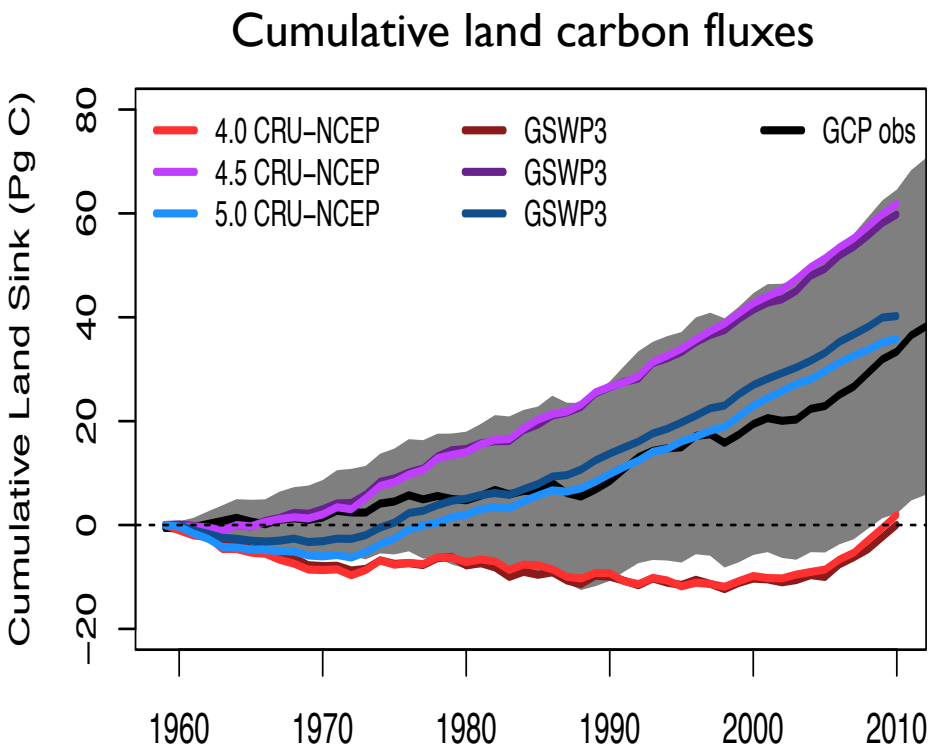
CLM land-only forced with GSWP3 prognostic vegetation and carbon configuration

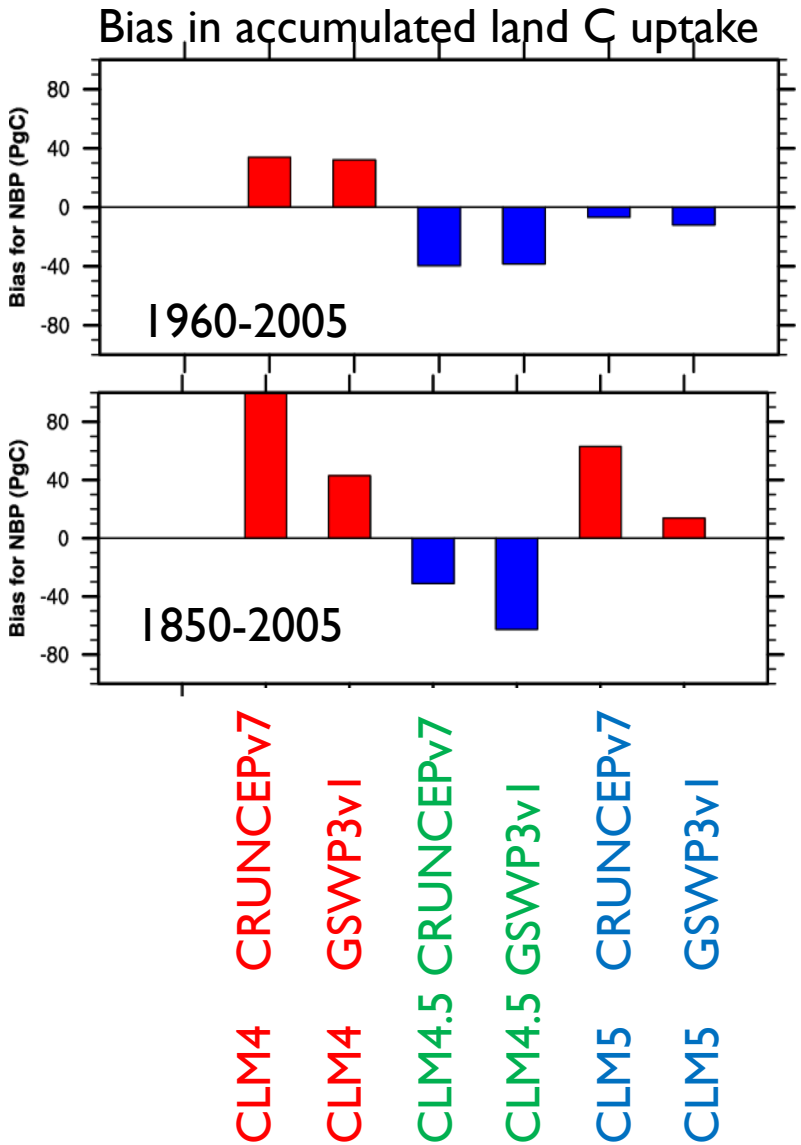
	Download Data	Period Mean (original grids) [W/m2]	Model Period Mean (intersection) [W/m2]	Model Period Mean (complement) [W/m2]	Benchmark Period Mean (intersection) [W/m2]	Benchmark Period Mean (complement) [W/m2]	Bias [W/m2]	RMSE [W/m2]	Phase Shift [months]	Bias Score [1]	RMSE Score [1]	Seasonal Cycle Score [1]	Spatial Distribution Score [1]	Overall Score [1]
Benchmark	[-]	39.1												
CLM40CRUNCEP	[-]	43.1	50.1	21.0	39.4	16.4	10.6	22.7	0.803	0.95	0.64	0.86	0.83	0.79
CLM40GSWP3	[-]	39.1	46.7	8.21	39.4	16.4	7.78	20.1	0.934	0.96	0.68	0.84	0.88	0.81
CLM45CRUNCEP	[-]	38.7	46.0	8.58	39.4	16.4	7.20	19.7	0.815	0.97	0.69	0.86	0.88	0.82
CLM45GSWP3	[-]	36.4	43.3	8.23	39.4	16.4	4.35	18.1	0.926	0.98	0.72	0.85	0.92	0.83
CLM50CRUNCEP	[-]	38.2	45.6	8.18	39.4	16.4	6.75	19.3	0.846	0.97	0.69	0.85	0.88	0.82
CLM50GSWP3	[-]	33.5	39.9	7.26	39.4	16.4	0.890	16.3	0.883	0.98	0.74	0.85	0.93	0.85

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

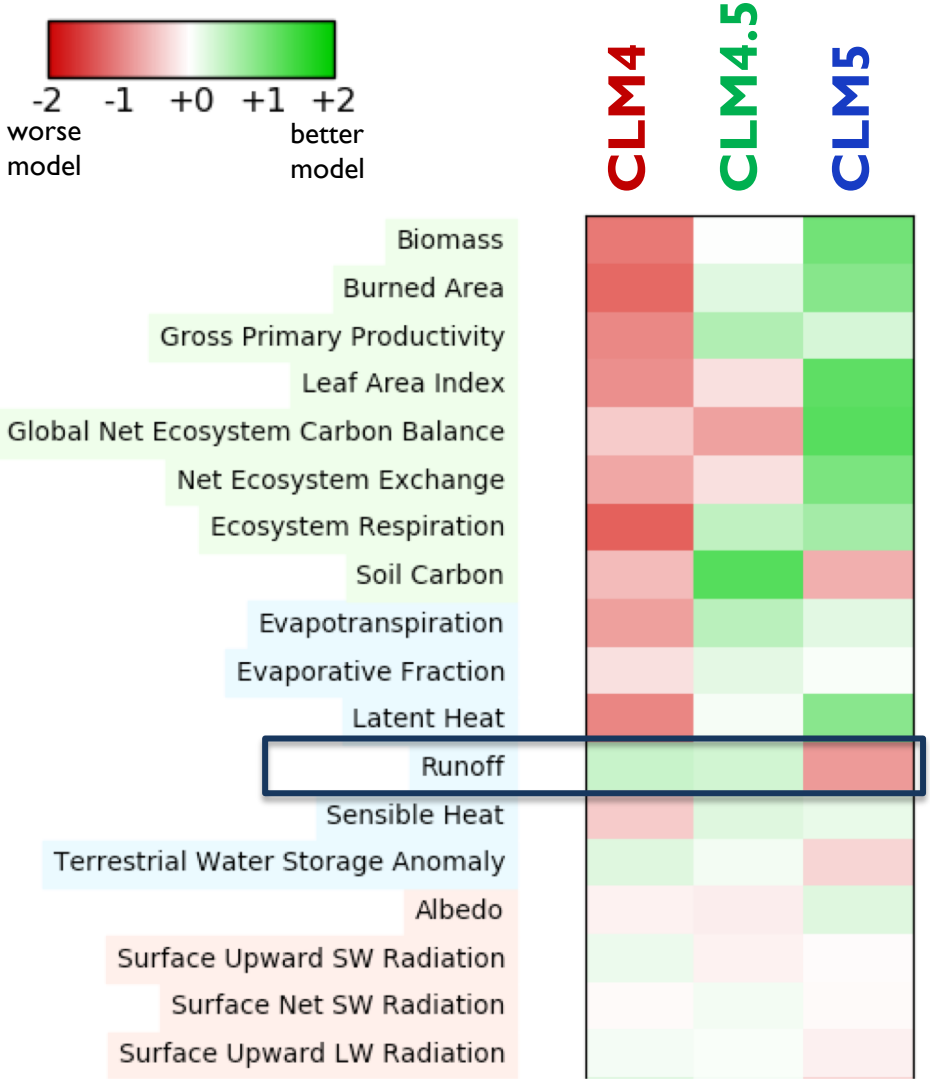


Accumulated historical land carbon fluxes





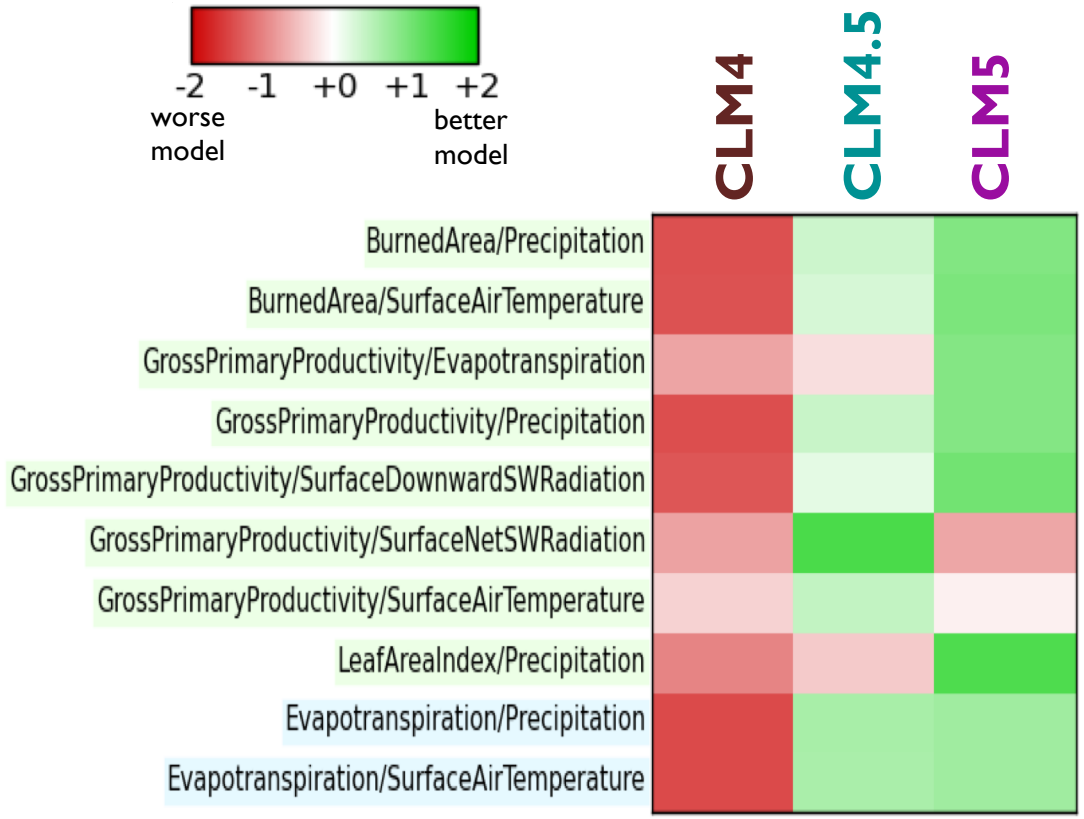
CLM land-only forced with GSWP3 prognostic vegetation and carbon configuration

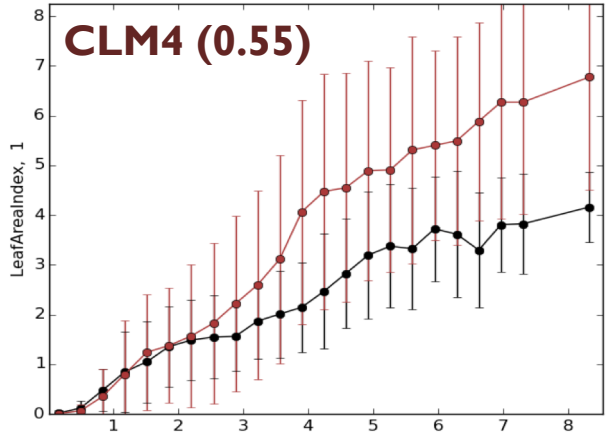


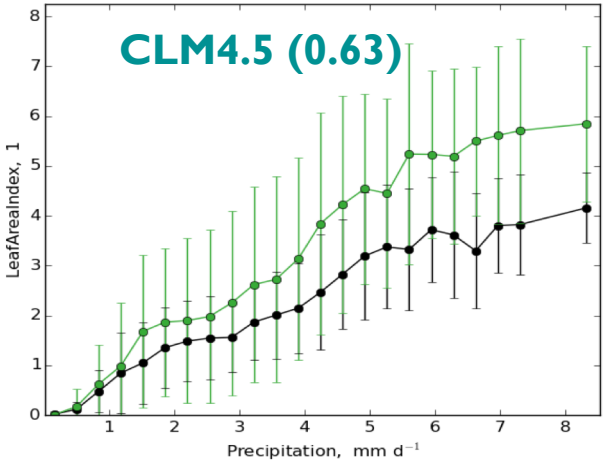
ILAMB Runoff Metrics Table

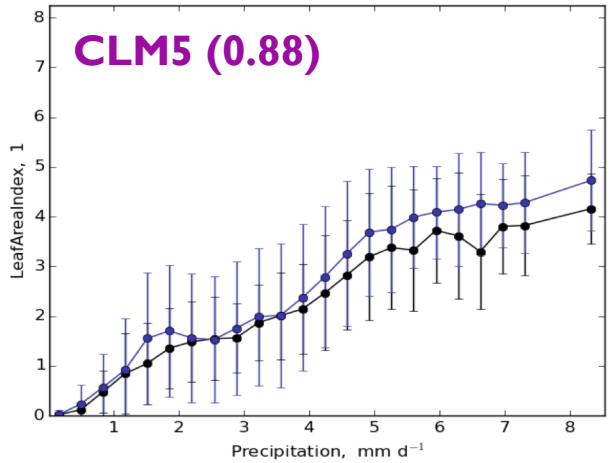
	Download Data	Period Mean [mm d-1]	Bias [mm d-1]	Bias Score [1]	Spatial Distribution Score [1]	Interannual Variability Score [1]	Overall Score [1]
Benchmark	[-]	0.825					
CLM4.0_CRUNCEP	[-]	0.525	-0.300	0.68	0.68	0.69	0.68
CLM4.0_GSWP3	[-]	0.769	-0.0568	0.81	0.93	0.68	0.81
CLM4.0SP_GSWP3	[-]	0.861	0.0353	0.81	0.97	0.64	0.81
CLM4.5_CRUNCEP	[-]	0.581	-0.244	0.72	0.87	0.67	0.75
CLM4.5_GSWP3	[-]	0.812	-0.0137	0.80	0.97	0.66	0.81
CLM4.5SP_GSWP3	[-]	0.836	0.0108	0.82	0.98	0.66	0.82
CLM5.0_CRUNCEP	[-]	0.581	-0.245	0.69	0.80	0.58	0.69
CLM5.0_GSWP3	[-]	0.913	0.0875	0.79	0.97	0.59	0.79
CLM5.0SP_GSWP3	[-]	0.888	0.0627	0.81	0.97	0.61	0.79

Functional Relationships









What is in the overall score?

$$S_{overall} = \frac{S_{bias} + 2S_{rmse} + S_{phase} + S_{iav} + S_{dist}}{1 + 2 + 1 + 1 + 1}$$

Scores are based on the:

- S_{bias} - normalized bias
- S_{rmse} - normalized central RMSE
- S_{phase} - timing of the maximum of the annual cycle
- S_{iav} - interannual variability
- S_{dist} - spatial distribution of the period mean

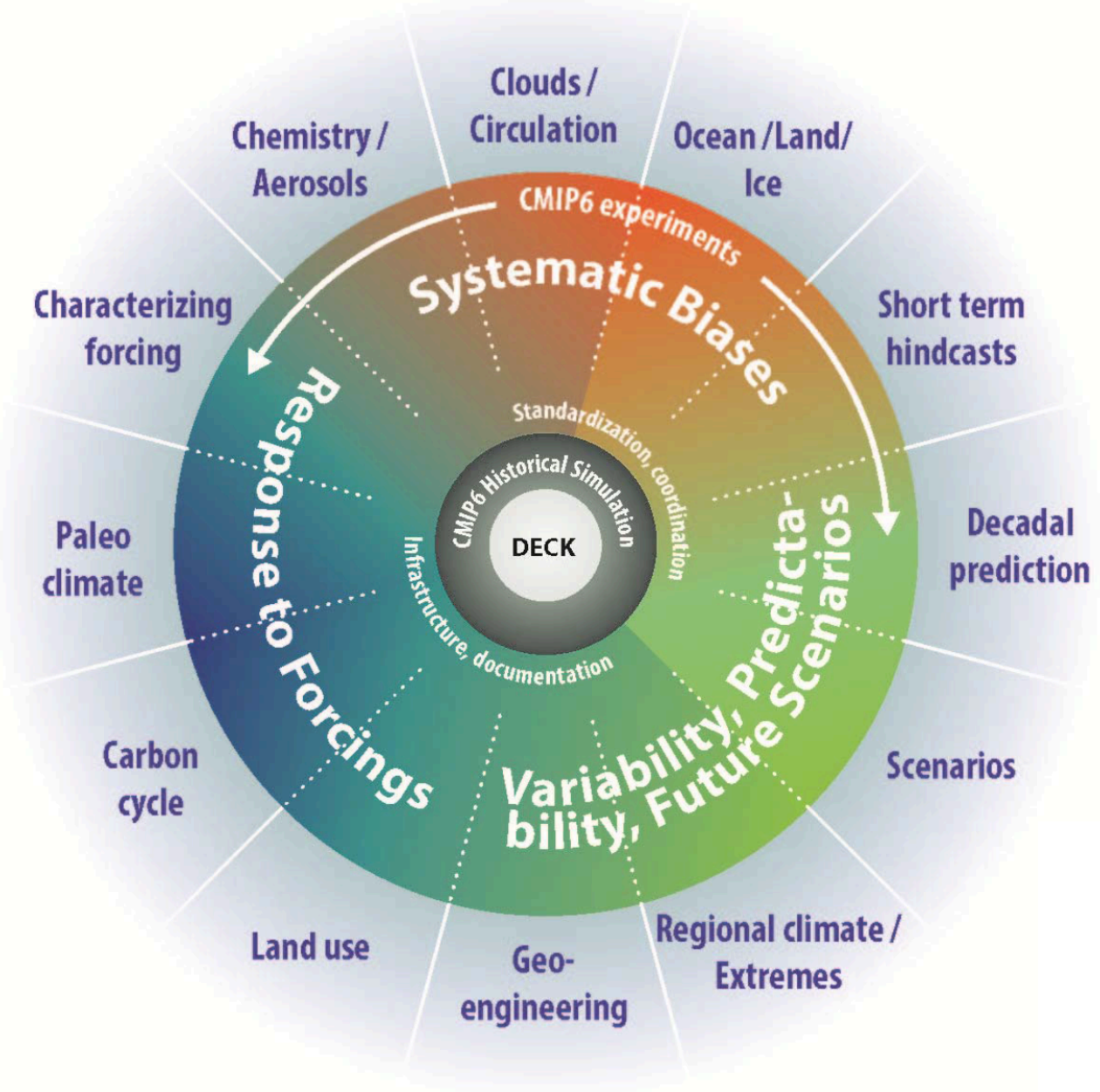
Better to show you:

`http://webext.cgd.ucar.edu/I20TR/_build_figure4a/index.html`

Increased focus on terrestrial processes in CMIP6

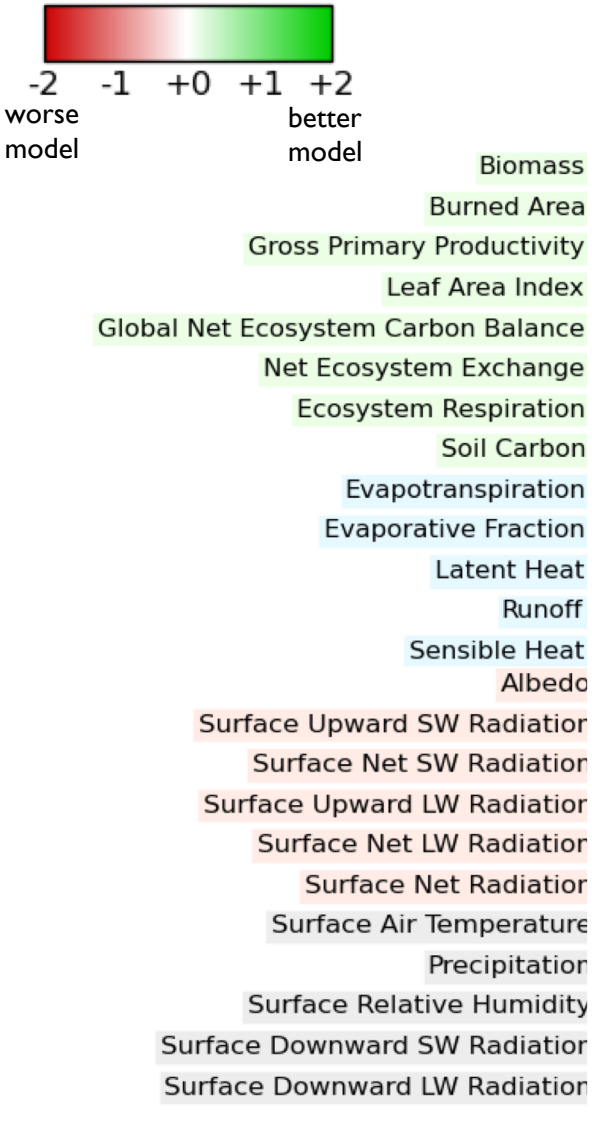
Coordinated activities to assess land role in climate and climate change

- **Land-only** simulations forced with obs historical climate, land-systematic biases
- **Land Use = LUMIP** land use forcing on climate, biogeophysics and biogeochemistry with policy relevance
- **Land = LS3MIP** biogeophys feedbacks including soil moisture and snow feedbacks
- **Carbon Cycle = C4MIP** land biogeochemical feedbacks on climate



Updated from Meehl et al., EOS, 2014

Assessment against CMIP5 Coupled Models



Note that this comparison 'unfair' because other ESMs are from previous generation

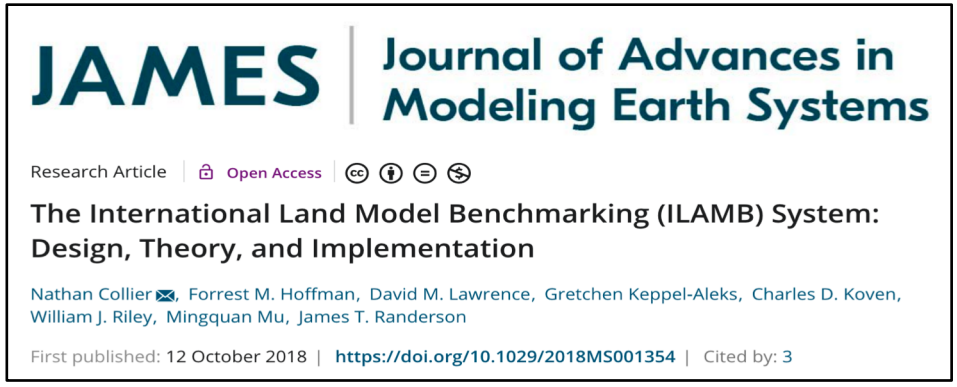
Dataset Weighting Rubric

Score	Certainty of data	Scale appropriateness and coverage	Overall important of constraint or process
1	No uncertainty, significant methodological issues affecting quality	Site level observations with limited space/time coverage	Observations that have limited influence on the targeted Earth system dynamics
2	No uncertainty, some methodological issues affecting quality	Partial regional coverage, up to 1 year	Observations have direct influence on the targeted Earth system dynamics
3	No uncertainty, methodology has some peer review	Regional coverage, at least 1 year	Observations useful to constrain processes that contribute to the targeted Earth system dynamics
4	Qualitative uncertainty, methodology accepted	Important regional coverage, at least 1 year	Observations well-suited to constrain important processes
5	Well-defined and relatively low uncertainty	Global scale spanning multiple years	Observations well-suited for discriminating critical processes among models

ILAMB Summary

https://bitbucket.org/ncollier/ilamb

- Provides consistent and systematic comparison of model output against a community-assembled collection of observational datasets
- The system scores models, but also organizes results to aid the scientist in discovery
- Implementation is open source and general, ready to accept and incorporate new datasets
- Methodology as is can be thought of as an initial suggestion and can be adapted to meet new science goals



JAMES | Journal of Advances in Modeling Earth Systems

Research Article | Open Access

The International Land Model Benchmarking (ILAMB) System: Design, Theory, and Implementation

Nathan Collier, Forrest M. Hoffman, David M. Lawrence, Gretchen Keppel-Aleks, Charles D. Koven, William J. Riley, Mingquan Mu, James T. Randerson

First published: 12 October 2018 | https://doi.org/10.1029/2018MS001354 | Cited by: 3

Summary

- ILAMB useful for multi-variate assessment/tracking of model performance across model generations … in addition to multi-model assessments
- Impact of forcing uncertainty is considerable and can confound assessment of impacts of model development
- Despite increasing complexity of CLM (version 4 to 4.5 to 5), consistent improvement in quality of overall simulation
- Opportunities for improvement and enhancements to ILAMB
  - E.g., metrics in the pipeline: diurnal cycle metrics, permafrost distribution and ALT, soil carbon turnover time, snow thermal insulation, response to CO_2 and N fertilization
  - Additional new metrics welcome

Important Links

- Open source git repository

  https://bitbucket.org/ncollier/ilamb

- CLM (4/4.5/5) over the Arctic

  http://www.ilamb.org/IARPC/

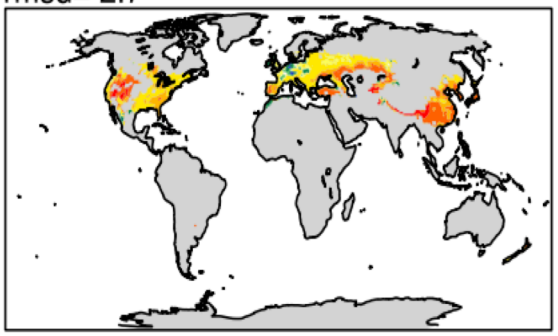
- ILAMB paper preprint

  https://www.ilamb.org/ILAMB_paper.pdf

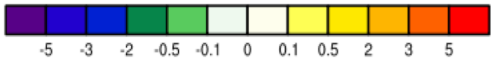
Future ILAMB diagnostics: Leaf Area Index (LAI) bias by Plant Functional Type

CLM4

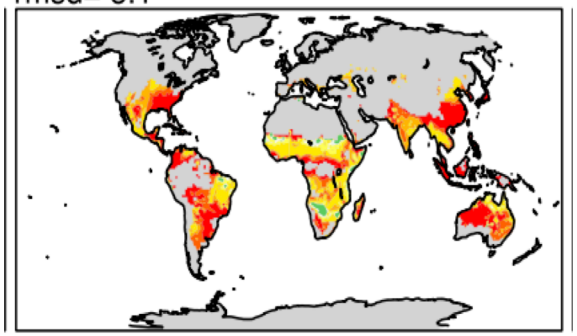
rmsd= 2.7



NL Evergreen Temperate Tree



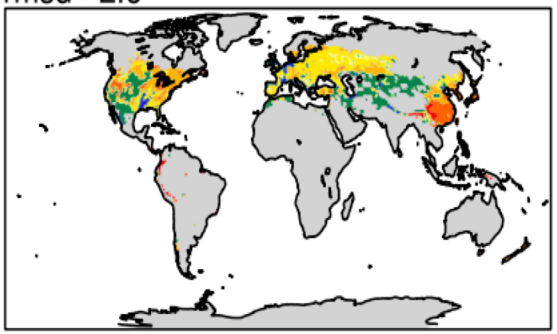
rmsd= 5.1



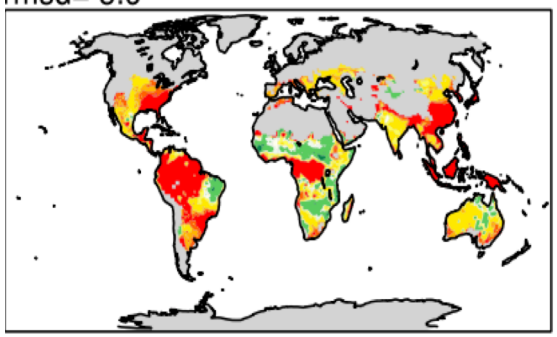
C4 grass

CLM4.5

rmsd= 2.6

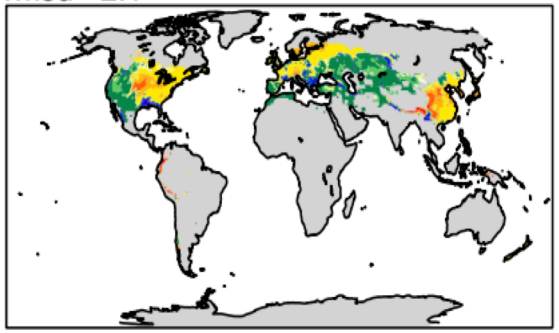


rmsd= 5.9



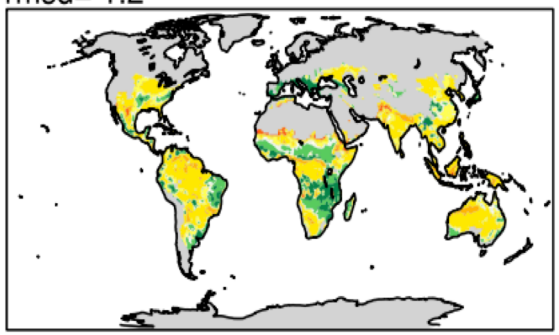
CLM5

rmsd= 2.1



Reduced bias for
12 out of 14 PFTs

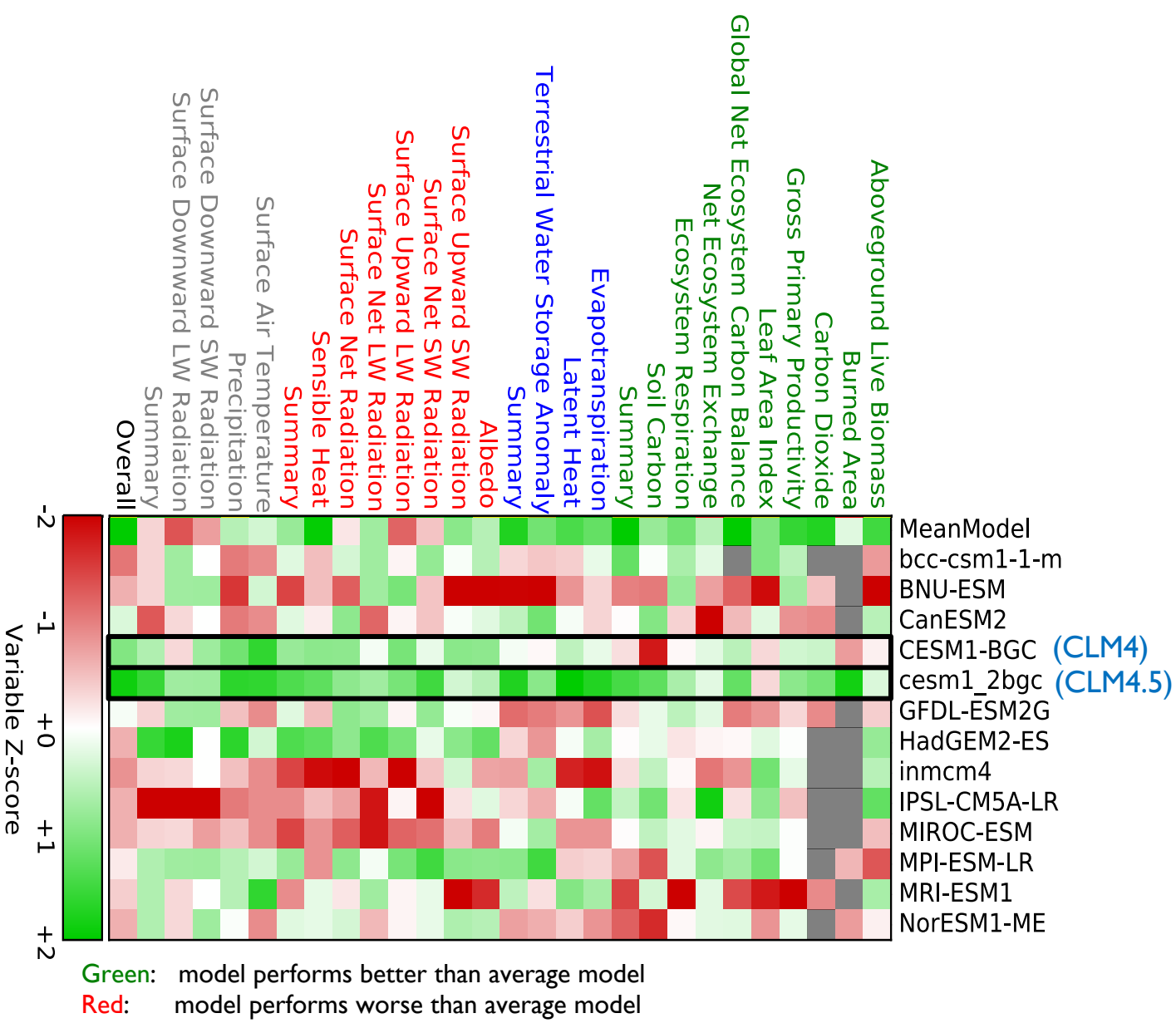
rmsd= 1.2



Thanks. Questions or comments?

International LAnd Model Benchmarking (ILAMB) project

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



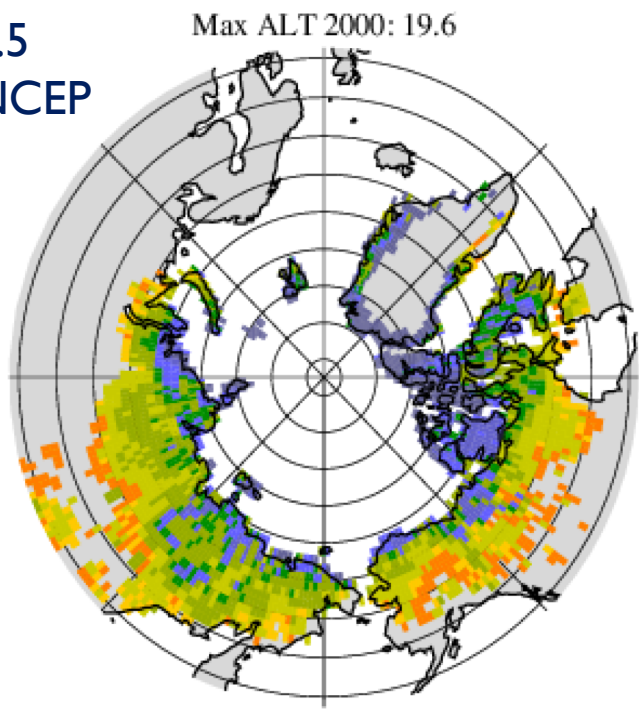
Green: model performs better than average model

Red: model performs worse than average model

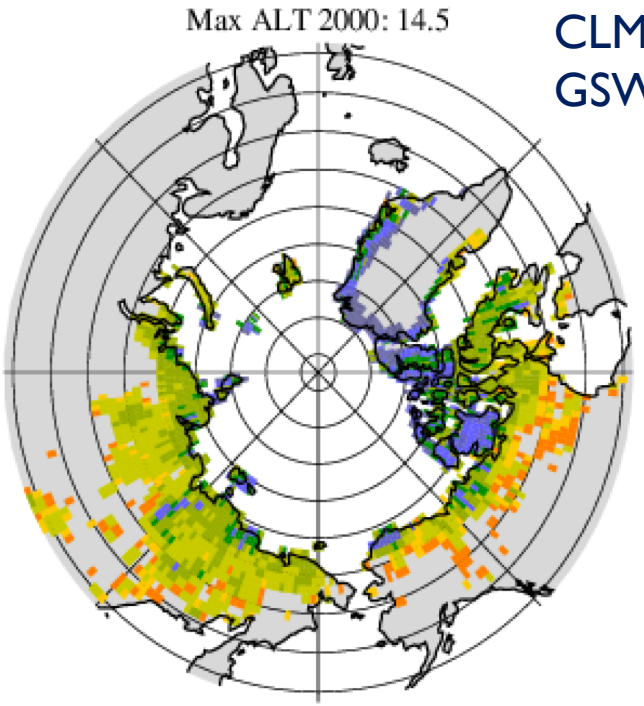
Permafrost Distribution

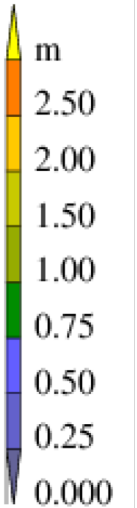
~15-16 million km^2 (obs)

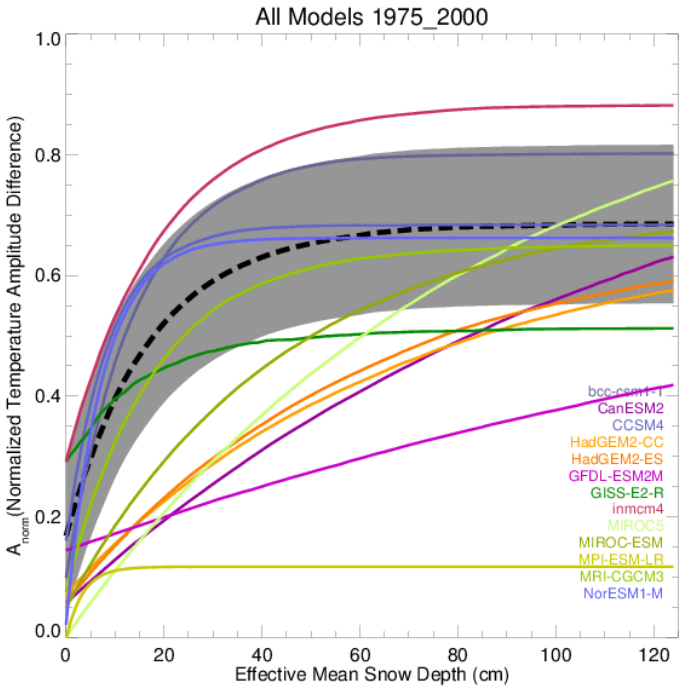
CLM4.5 CRUNCEP



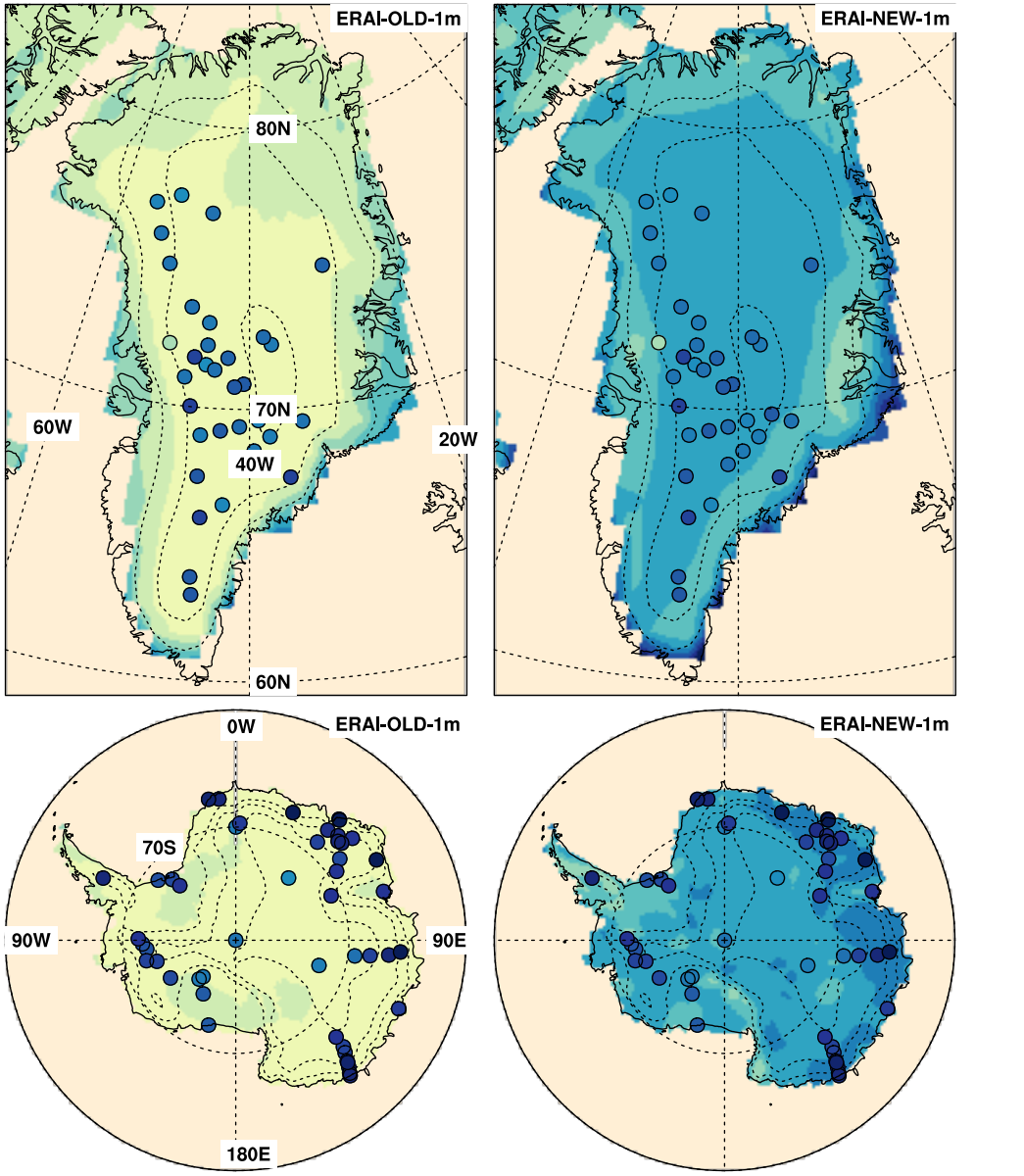
CLM4.5 GSWP3







Slater et al. 2017



CLM5 snow density

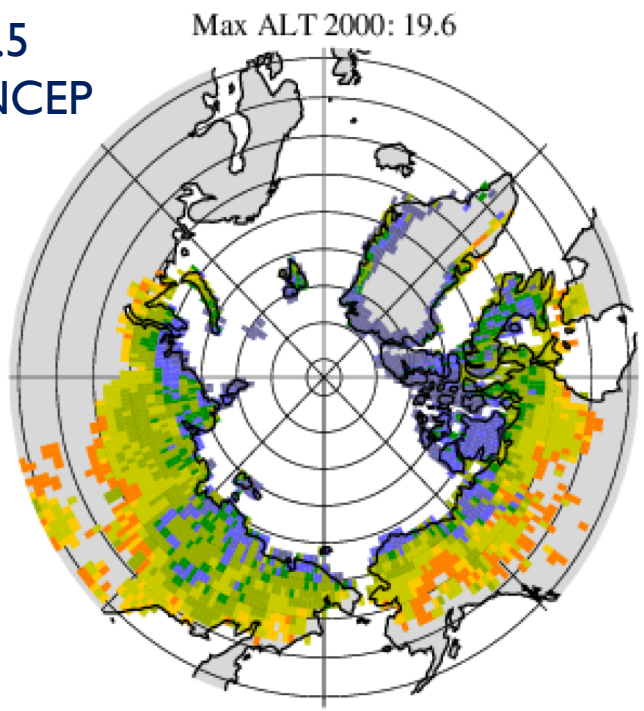
Revised fresh snow density with improved temperature and wind effects
Lead to increased and more realistic snow density and less thermal insulation

Figure courtesy L. Van Kampenhout

Permafrost Distribution

~15-16 million km^2 (obs)

CLM4.5 CRUNCEP



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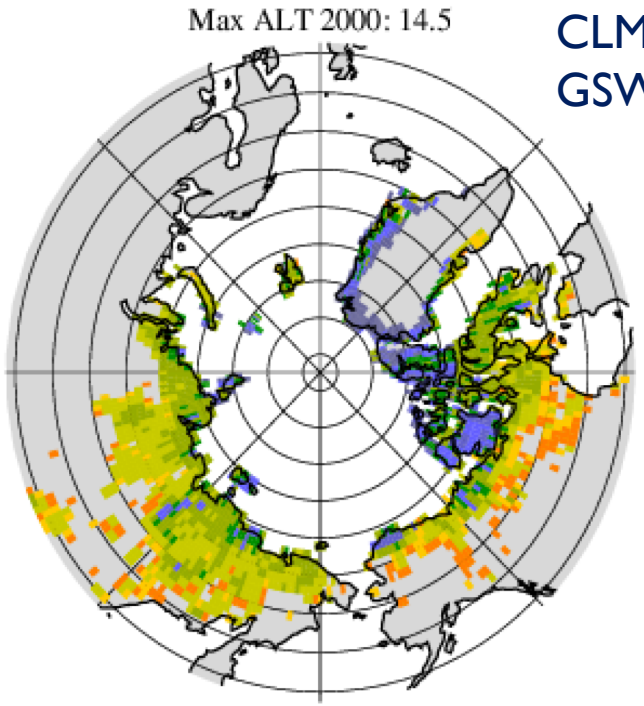

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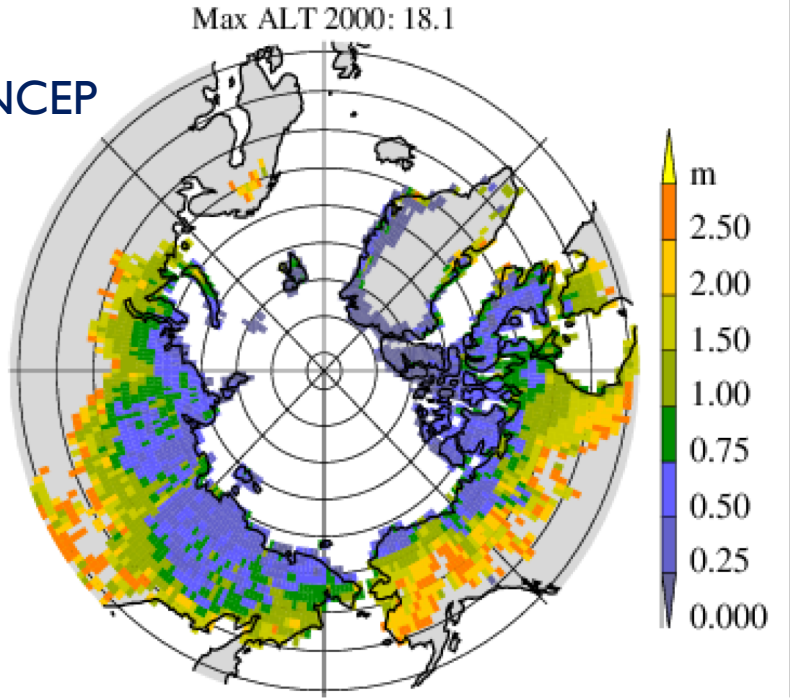

CLM5 GSWP3