Model Benchmarking: An Informal Tour of the International Land Model Benchmarking (ILAMB) Prototype

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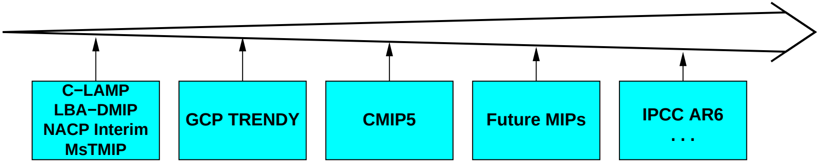
Why Benchmark?

- to demonstrate to the science community and public that the representation of coupled climate and biogeochemical cycles in Earth system models (ESMs) is improving;
- to quantitatively diagnose impacts of model development in related fields on carbon cycle processes;
- to guide synthesis efforts, such as the Intergovernmental Panel on Climate Change (IPCC), in the review of mechanisms of global change in models that are broadly consistent with available contemporary observations;
- to increase scrutiny of key datasets used for model evaluation;
- to identify gaps in existing observations needed for model validation;
- to accelerate incorporation of new measurements for rapid and widespread use in model assessment;
- to provide a quantitative, application-specific set of minimum criteria for participation in model intercomparison projects (MIPs);

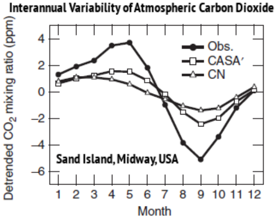
An Open Source Benchmarking Software System



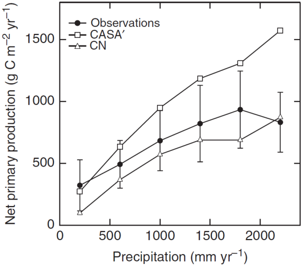
- Human capital costs of making rigorous model-data comparisons is considerable and constrains the scope of individual MIPs.
- Many MIPs spend resources "reinventing the wheel" in terms of variable naming conventions, model simulation protocols, and analysis software.
- **Need for ILAMB:** Each new MIP has access to the model-data comparison modules from past MIPs through ILAMB (*e.g.*, MIPs use one common modular software system). Standardized international naming conventions also increase MIP efficiency.

What is a Benchmark?

- A **Benchmark** is a quantitative test of model function achieved through comparison of model results with observational data.
- Acceptable performance on benchmarks **is a necessary but not sufficient condition** for a fully functioning model.
- **Functional benchmarks** offer tests of model responses to forcings and yield insights into ecosystem processes.
- Effective benchmarks must draw upon a broad set of independent observations to evaluate model performance on **multiple temporal and spatial scales**.

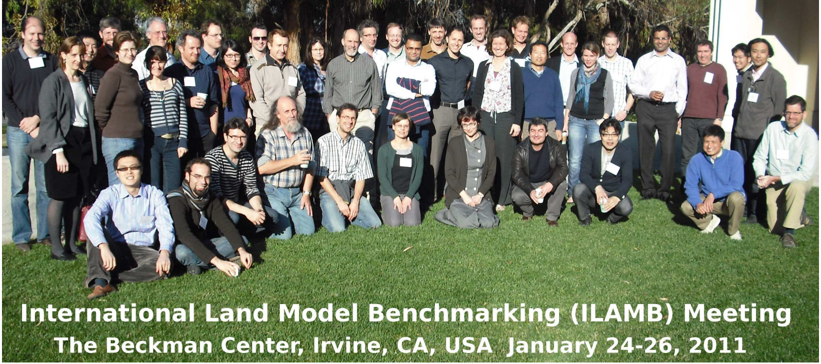


Models often fail to capture the amplitude of the seasonal cycle of atmospheric CO_2.



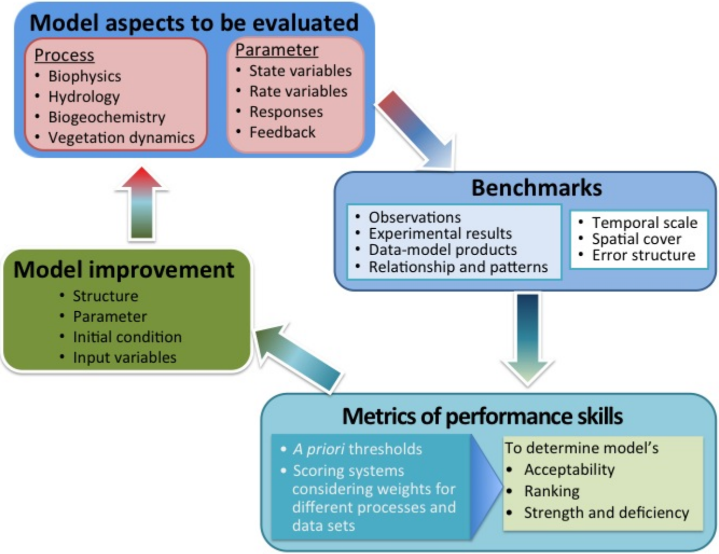
Models may reproduce correct responses over only a limited range of forcing variables.

(Randerson et al., 2009)



- We co-organized inaugural meeting and ∼45 researchers participated from the United States, Canada, the United Kingdom, the Netherlands, France, Germany, Switzerland, China, Japan, and Australia.
- **ILAMB Goals:** Develop internationally accepted benchmarks for model performance, advocate for design of open-source software system, and strengthen linkages between experimental, monitoring, remote sensing, and climate modeling communities. *Initial focus on CMIP5 models.*
- Provides methodology for model–data comparison and baseline standard for performance of land model process representations (Luo et al., 2012).

General Benchmarking Procedure



(Luo et al., 2012)

Example Benchmark Score Sheet from C-LAMP

Models →

BGC Datasets ↓

Metric	Metric components	Uncertainty of obs.	Scaling mismatch	Total score	Sub-score	CASA′		CN	
LAI	Matching MODIS observations			15.0		13.5		12.0	
	• Phase (assessed using the month of maximum LAI)	Low	Low		6.0		5.1		4.2
	• Maximum (derived separately for major biome classes)	Moderate	Low		5.0		4.6		4.3
	• Mean (derived separately for major biome classes)	Moderate	Low		4.0		3.8		3.5
NPP	Comparisons with field observations and satellite products			10.0		8.0		8.2	
	• Matching EMDI Net Primary Production observations	High	High		2.0		1.5		1.6
	• EMDI comparison, normalized by precipitation	Moderate	Moderate		4.0		3.0		3.4
	• Correlation with MODIS (r^2)	High	Low		2.0		1.6		1.4
	• Latitudinal profile comparison with MODIS (r^2)	High	Low		2.0		1.9		1.8
CO_2 annual cycle	Matching phase and amplitude at Globalview flash sites			15.0		10.4		7.7	
	• 60°–90°N	Low	Low		6.0		4.1		2.8
	• 30°–60°N	Low	Low		6.0		4.2		3.2
	• 0°–30°N	Moderate	Low		3.0		2.1		1.7
Energy & CO_2 fluxes	Matching eddy covariance monthly mean observations			30.0		17.2		16.6	
	• Net ecosystem exchange	Low	High		6.0		2.5		2.1
	• Gross primary production	Moderate	Moderate		6.0		3.4		3.5
	• Latent heat	Low	Moderate		9.0		6.4		6.4
	• Sensible heat	Low	Moderate		9.0		4.9		4.6
Transient dynamics	Evaluating model processes that regulate carbon exchange on decadal to century timescales			30.0		16.8		13.8	
	• Aboveground live biomass within the Amazon Basin	Moderate	Moderate		10.0		5.3		5.0
	• Sensitivity of NPP to elevated levels of CO_2: comparison to temperate forest FACE sites	Low	Moderate		10.0		7.9		4.1
	• Interannual variability of global carbon fluxes: comparison with TRANSCOM	High	Low		5.0		3.6		3.0
	• Regional and global fire emissions: comparison to GFEDv2	High	Low		5.0		0.0		1.7
			Total:	**100.0**		**65.9**		**58.3**	

(Randerson et al., 2009)

Benchmarking System Development Goals

As a part of the new Biogeochemistry Feedbacks SFA,

- We will develop an extensible benchmarking system for land and ocean models, building upon the C-LAMP prototype (Randerson et al., 2009).
- Software engineering will be co-led by developers at ORNL and LBNL, in collaboration with Mingquan Mu at UCI and David Lawrence, the CESM Land Model Working Group co-chair.
- The diagnostics will be based entirely on Open Source software and be freely distributed and thoroughly documented.
- All metrics and diagnostics code will be developed in software that operates within UV-CDAT or UV-CDAT-lite.
- This flexibility maximizes the potential for use within the Land Model and Ocean Model Testbeds within ACME and the more general PCMDI Metrics Package being developed to support the WGNE/WGCM Climate Model Metrics Panel.

Community Engagement

- Many of us are part of the ACME Land Model Benchmarking team, ensuring the framework can be used for ACME.
- We are actively working to deploy the benchmarking system for land and ocean models in CESM.
- We are involved in the Obs4MIPs group to help identify data sets useful for comparison with models.
- ILAMB will be used by the C^4MIP group for CMIP6, and we are working with Veronika Eyring and Peter Gleckler to include it in standard diagnostics for CMIP6 models at PCMDI.
- We are communicating with other modeling centers, measurement activities, and MIPs, including GEWEX, iLEAPs, MAREMIP, MsTMIP, TRENDY/RECCAP/GCP, GSWP3, and future FACE-MIP and LBA-DMIP.
- We will convene two community workshops and offer training sessions on using and extending the benchmarking system.

ILAMB Prototype Diagnostics System

An initial ILAMB prototype has been developed by Mingquan Mu at UCI.

- Current variables:

  Aboveground live biomass (North America FIA, tropical Saatchi et al.), Burned area (GFED3), CO_2 (NOAA GMD, Mauna Loa), Global net land flux (GCP), Gross primary production (Fluxnet-MTE), Leaf area index (AVHRR, MODIS), Net ecosystem exchange (Fluxnet), Respiration (Fluxnet), Soil C (HWSD, NCSCDv2), Evapotranspiration (LandFlux, GLEAM, MODIS), Latent heat (Fluxnet-MTE), Soil moisture (ESA), Terrestrial water storage change (GRACE), Precipitation (GPCP2), Albedo (MODIS, CERES), Surface up/down SW/LW radiation (CERES, WRMC.BSRN), Sensible heat (Fluxnet), Surface air temperature (CRU).

- Graphics and scoring systems:
  - Annual mean, Bias, RMSE, seasonal cycle, spatial distribution, interannual coeff. of variation and variability, long-term trend scores
  - Global maps, variable to variable, and time series comparisons

- Software:

  Freely distributed, designed to be user friendly and to enable easy addition of new variables

(Mu, Hoffman, Riley, Koven, Lawrence, Randerson)

Supporting Information: Description of Scoring Metrics and Data Processing

Part One Scoring Metrics

A.1. Root Mean Square Error Metric

$$M = \frac{\sum_{i=1}^{ncells} M_i \times A(i)}{TotalArea}, \ M_i = 1 - \frac{RMSE_i}{\sigma_{obs,i}}, \ TotalArea = \sum_{i=1}^{ncells} A(i) \qquad \text{(A.1)}$$

Where $\sigma_{obs,i}$ is the standard deviation of monthly mean annual cycle of benchmark at each grid cell (for grid data) or site (for site observations). $RMSE_i$ is the root mean square error between model and observation. If the metric M_i was negative, we set the quantity equal to 0 at that grid cell or site. If the benchmark data was grid data, the metric M_i was area-weighted over all the land grid cells to obtain the global-scale metric M, otherwise straight averaging (no-weighting) was applied to all sites to obtain the mean value (*Ref: David Lawrence's personal Communication*). This metric was used to compare magnitude and phase difference of monthly mean annual cycle between model and benchmark.

A.2. Global Bias Metric

This metric is alternative of root mean square error metric (A.1) when A.1 is not available.

$$M = 1 - \frac{|G_m - G_o|}{G_o} \qquad \text{(A.2)}$$

Where G_m and G_o are the global total or global mean of benchmark and model respectively. If the metric M is negative (G_m is two times than G_o), set M equal to 0.

ILAMB Prototype Layout: Global Variables

Global Variables (Info)

	MeanModel	bcc-csm1-1-m	BNU-ESM	CanESM2	CESM1-BGC	GFDL-ESM2G	HadGEM2
Aboveground Live Biomass	0.88	-	0.14	0.81	0.68	0.81	0.86
Burned Area	0.41	-	-	-	0.37	-	-
Carbon Dioxide	0.88	-	0.53	0.94	0.86	0.96	-
Global Net Land Flux	0.25	-	0.25	0.32	0.32	0.49	0.63
Gross Primary Production	0.80	0.74	0.74	0.74	0.77	0.72	0.75
Leaf Area Index	0.59	0.64	0.30	0.78	0.53	0.33	0.53
Net Ecosystem Exchange	0.36	0.29	0.19	0.16	0.28	0.64	0.28
Ecosystem Respiration	0.78	0.71	0.78	0.75	0.74	0.70	0.77
Soil Carbon	0.71	-	0.35	0.73	0.31	0.74	0.63
Summary	0.63	0.59	0.41	0.65	0.54	0.67	0.64
Evapotranspiration	0.75	0.83	0.74	0.82	0.73	0.76	0.77
Latent Heat	0.77	0.79	0.71	0.80	0.71	0.72	0.71
Soil Moisture	0.18	0.17	0.20	0.21	0.19	0.18	0.21
Terrestrial Water Storage Change	0.25	0.29	0.25	0.26	0.25	0.24	0.25
Precipitation	0.82	0.83	0.82	0.82	0.86	0.86	0.90
Summary	0.55	0.58	0.54	0.58	0.55	0.55	0.57
Albedo	0.76	0.74	0.75	0.77	0.80	0.76	0.79
Surface Downward SW Radiation	0.86	0.90	0.89	0.87	0.89	0.89	0.87
Surface Upward SW Radiation	0.77	0.70	0.63	0.74	0.77	0.77	0.78
Surface Net SW Radiation	0.80	0.83	0.82	0.83	0.84	0.85	0.82

ILAMB Prototype Layout: Variable to Variable

Variable to Variable Relationships

	Relationship	Benchmark	MeanModel	bcc-csm1-1-m	BNU-ESM	CanESM2	CESM1-BGC	GFDL-:
Precipitation vs. Burned Area	function_bar	1	0.57	-	-	-	0.57	
Precipitation vs. Gross Primary Production	function_bar	1	0.91	0.92	0.93	0.50	0.93	0.
Surface Air Temperature vs. Burned Area	function_bar	1	0.00	-	-	-	0.08	
Surface Air Temperature vs. Gross Primary Production	function_bar	1	0.62	0.50	0.45	0.92	0.50	0.
Surface Downward SW Radiation vs. Gross Primary Production	function_bar	1	0.85	0.74	0.91	0.64	0.81	0.
Surface Net SW Radiation vs. Gross Primary Production	function_bar	1	0.72	0.72	0.72	0.86	0.79	0.
Overall			0.61	0.72	0.75	0.73	0.61	0.

ILAMB Prototype Layout: Time Series

Time Series Comparisons

	Benchmark
Burned Area	GFED3 [Giglio et al. (2010)]
Carbon Dioxide	NOAA.GMD [Dlugokencky et al. (2013)]
Gross Primary Production	FLUXNET [Lasslop et al. (2010)]
Net Ecosystem Exchange	FLUXNET [Lasslop et al. (2010)]
Ecosystem Respiration	FLUXNET [Lasslop et al. (2010)]
Surface Downward SW Radiation	WRMC.BSRN [Konig-Langl et al. (2013)]
Surface Upward SW Radiation	WRMC.BSRN [Konig-Langl et al. (2013)]
Surface Net SW Radiation	WRMC.BSRN [Konig-Langl et al. (2013)]
Surface Downward LW Radiation	WRMC.BSRN [Konig-Langl et al. (2013)]
Surface Upward LW Radiation	WRMC.BSRN [Konig-Langl et al. (2013)]
Surface Net LW Radiation	WRMC.BSRN [Konig-Langl et al. (2013)]

Touring the ILAMB Prototype

- Presently, the ILAMB prototype has been used to evaluate CMIP5 models and two versions of the Community Land Model (CLM).
- The system currently works for historical comparisons, but may be extended to support single-factor, perturbation, and step-change simulations.

ILAMB Landing Page

http://www.cgd.ucar.edu/tss/clm/diagnostics/ILAMB/

ILAMB Trello Development Page

https://trello.com/b/jd950saq/land-model-benchmarking-development

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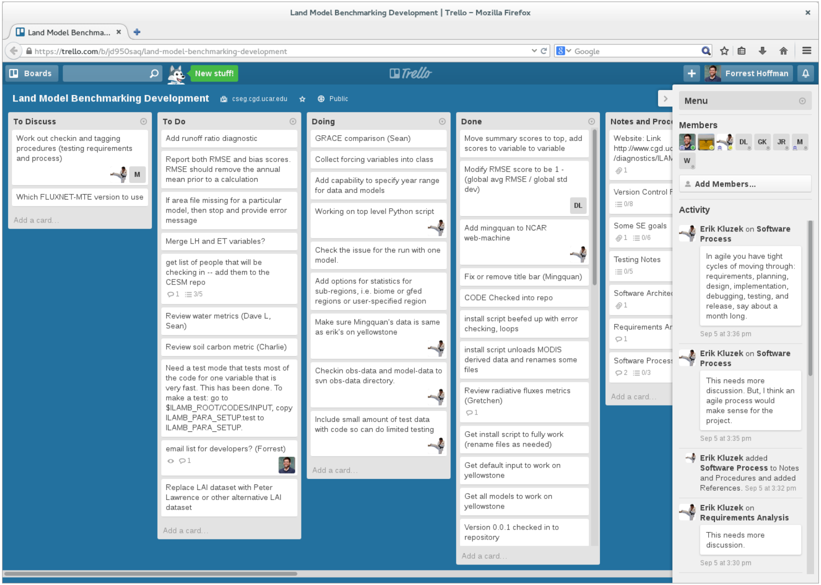
Extra Slides

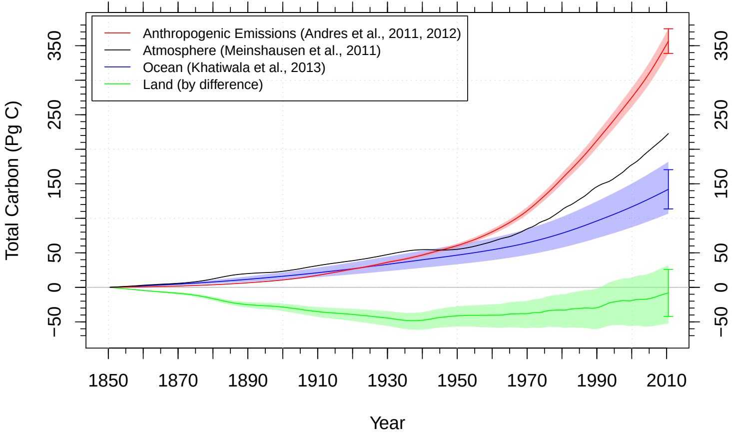
ILAMB Trello Development Page



Atmospheric Observations for Benchmarks

Variable	Data Source	Location/Citation	Questions
Atmospheric CO_2 *in situ* flasks	NOAA-GMD CSIRO SIO	http://www.esrl.noaa.gov/gmd/dv/data/ http://www.csiro.au/greenhouse-gases/ http://cdiac.ornl.gov/trends/co2/sio-keel.html	A, B, E1
Atmospheric CO_2 aircraft vertical profiles	NOAA-GMD	http://www.esrl.noaa.gov/gmd/cegg/aircraft/	A, E1, E4
Atmospheric CH_4 *in situ* flasks and continuous analyzers	NOAA-GMD AGAGE	http://www.esrl.noaa.gov/gmd/ccgg/globalview/ http://agage.eas.gatech.edu/	A
Atmospheric profiles	HIPPO	http://hippo.ornl.gov/ (*Wofsy et al.*, 2011)	A, E1
Total column X_{CO_2}	TCCON GOSAT	https://tccon-wiki.caltech.edu/ (*Wunch et al.*, 2011) http://www.gosat.nies.go.jp/ (*Yokota et al.*, 2009)	A, B

Observed Carbon Accumulation Since 1850



Observational estimates of anthropogenic carbon emissions (excluding land use change) and accumulation in the atmosphere, ocean, and land reservoirs from 1850 to 2010. Land carbon accumulation/loss and its uncertainty were calculated by mass balance from an adjusted ocean carbon accumulation time series with uncertainty from *Khatiwala et al.* (2013). Figure from *Hoffman et al.* (2014).

Terrestrial Hydrology/Energy Observations for Benchmarks

Variable	Data Source	Location/Citation	Questions
Site-level sensible heat, latent heat, and net radiation	Fluxnet	http://fluxnet.ornl.gov/	B, D
	AmeriFlux	http://ameriflux.ornl.gov/	
	MAST-DC	http://nacp.ornl.gov/	
Gridded latent and sensible heat	MPI-BGC	https://www.bgc-jena.mpg.de/bgi/index.php/Services/Overview	B, D
Soil moisture	ESA	http://www.esa-soilmoisture-cci.org	B, D
	SMAP	http://smap.jpl.nasa.gov/	
	de Jeur	http://www.falw.vu/ jeur/lprm/	
Snow cover	AVHRR	http://noaasis.noaa.gov/NOAASIS/ml/avhrr.html	E2
	GlobSnow	http://www.globsnow.info/	
Snow depth	CMC (N. America)	http://nsidc.org/data/nsidc-0447.html	E2
Permafrost soil temperatures	IPY-TSP	https://www.aoncadis.org/dataset/network_of_permafrost_observatories_in_north_america_and_russia.html	E2
Terrestrial water storage	GRACE	http://www.csr.utexas.edu/grace/ http://grace.jpl.nasa.gov/	B
Albedo	MODIS	https://lpdaac.usgs.gov/	E, E2
	CERES	http://ceres.larc.nasa.gov/cmip5_data.php	
Net radiation	CERES	http://ceres.larc.nasa.gov/cmip5_data.php	D
River flow	GRDC	http://www.bafg.de/GRDC/EN/Home/	
	Dai	http://www.cgd.ucar.edu/cas/catalog/surface/dai-runoff/	
	GFDL	http://data1.gfdl.noaa.gov/	
Air temperature and precipitation	CRUP	http://www.cru.uea.ac.uk/data	D
	GPCP	http://www.gewex.org/gpcp.html	
	TRMM	http://trmm.gsfc.nasa.gov/	
Circumpolar climate	Hijmans	(*Hijmans et al.* 2005)	E

Terrestrial Ecosystem/State Observations for Benchmarks

Variable	Data Source	Location/Citation	Questions
Gridded soil C and N	HWSD	http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/	D, E
	NCSCDv2	http://bolin.su.se/data/ncscd/	
Alaska pedon data	Michaelson	*Michaelson et al.* (2013)	D, E
Circumpolar Arctic pedon data	Hugelius	*Hugelius et al.* (2013)	D, E
Litter C and N	LIDET	http://andrewsforest.oregonstate.edu/research/intersite/lidet.htm	E, F
	CIDET	https://cfs.nrcan.gc.ca/publications?id=5030	
GPP, R_e, and NEE	Fluxnet	http://fluxnet.ornl.gov/	D
	MAST-DC	http://nacp.ornl.gov/	
Soil respiration	Bond-Lamberty	http://daac.ornl.gov/SOILS/guides/SRDB.html	D
Gridded GPP	MPI-BGC MTE	https://www.bgc-jena.mpg.de/bgi/index.php/Services/Overview	D
LAI and FPAR	MODIS	https://lpdaac.usgs.gov/	C, E3
	SeaWIFS	http://cybele.bu.edu/modismisr/products/seawifs/	
	LAI3g/FPAR3g	http://cliveg.bu.edu/modismisr/lai3g-fpar3g.html	
	Landsat	http://landsat.usgs.gov/	
	Corona	https://lta.cr.usgs.gov/declass_1	
NDVI	MODIS	http://glcf.umd.edu/data/ndvi/	C
	GIMMS NDVI3g	http://cliveg.bu.edu/modismisr/lai3g-fpar3g.html	
Above ground live biomass	Saatchi – pan tropics	http://carbon.jpl.nasa.gov/data/dataMain.cfm	C, D, E, F
	Blackard – North America	http://webmap.ornl.gov/biomass/biomass.html	
Canopy height	Lefsky	*Lefsky* (2010)	E
	Simard/Fisher	http://josh.yosh.org/datamodels.htm	

Additional Terrestrial Observations for Benchmarks

Meta-analysis and Manipulative Experiments

Variable	Data Source	Location/Citation	Questions
Warming	Lu	*Lu et al.* (2013)	F, G
N fertilization	Janssens, Yahdjian	*Janssens et al.* (2010); *Yahdjian et al.* (2011)	F, G, E4
Drought/precipitation manipulation	Beier	*Beier et al.* (2012)	G
CO_2 enrichment	FACE	http://climatechangescience.ornl.gov/content/free-air-co2-enrichment-face-experiment	G
Land use change	LBA	https://daac.ornl.gov/LBA/lba.shtml	G

Vegetation Dynamics

Variable	Data Source	Location/Citation	Questions
Burned areaa	GFED3	http://www.globalfiredata.org/	E, E3
Wood harvest	Hurtt	http://luh.umd.edu/links.shtml	E, E3
Current land cover	MODIS PFT fraction	https://lpdaac.usgs.gov/	E, E3
	USGS	http://ww.epa.gov/mrlc/nlcd	

Ocean Observations for Benchmarks

Variable	Data Source	Location/Citation	Questions
Nitrate, phosphate, silicate, oxygen	WOA2013	http://www.nodc.noaa.gov/OC5/indprod.html	H, I, E5
DIC, alkalinity, CFC11, CFC12	GLODAP	http://cdiac.ornl.gov/oceans/glodap/	H
Temperature, salinity, density, mixed layer depths	WOA2013	http://www.nodc.noaa.gov/OC5/indprod.html	J
Dissolved iron	GEOTRACES; *Moore and Braucher* (2008)	http://www.bodc.ac.uk/geotraces/data/historical/	I, E5
Surface pCO_2	CDIAC	http://cdiac.ornl.gov/oceans/LDEO_Underway_Database/	J, E7
Anthropogenic CO_2	GLODAP; *Khatiwala et al.* (2013)	http://cdiac.ornl.gov/oceans/glodap/	J, E5
DMS	*Lana et al.* (2011)	http://saga.pmel.noaa.gov/dms/	J
Nitrogen fixation	MAREDAT	http://www.maredat.info/	I, E6
Plankton group-specific biomass	MAREDAT	http://www.maredat.info/	I
N_2O	MEMENTO	https://memento.geomar.de/	I
Chlorophyll	SeaWiFS, MODIS	http://oceancolor.gsfc.nasa.gov/	H, I
NPP	SeaWiFS, MODIS	http://www.science.oregonstate.edu/ocean.productivity/	H, I
Phytoplankton C biomass	SeaWiFS, MODIS	http://www.science.oregonstate.edu/ocean.productivity/	H, I
Phytoplankton growth rate	SeaWiFS, MODIS	http://www.science.oregonstate.edu/ocean.productivity/	H
Phytoplankton C/Chl ratio	SeaWiFS, MODIS	http://www.science.oregonstate.edu/ocean.productivity/	H

Application of the Benchmarking System

- **Year 1:** Package will work with CMIP5 historical (1850–2005) and RCP 8.5 future (2006–2100) model results from ESGF.
- **Year 2:** Package will work with CESM-CLM and ACME-CLM offline simulation results, and operate on experimental step change simulations.
- We will apply the system to quantify improvements in CESM and ACME, and to evaluate CMIP5 and CMIP6 results.
- Specifically, we will evaluate and compare CESM1.0, CESM1.2 (released), and CESM2.0 (late 2015); and compare CESM2.0 vs. CMIP5 models and ACME vs. CMIP5 models.
- **Long Term Goal:** Be prepared to rapidly and comprehensively evaluate CMIP6 results and help lead the community in publishing projection assessments.