Evaluating Land Carbon Cycle Processes in Earth System Models: Have Models Improved Over Time?

RUBISCO

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Introduction to the ILAMB Package

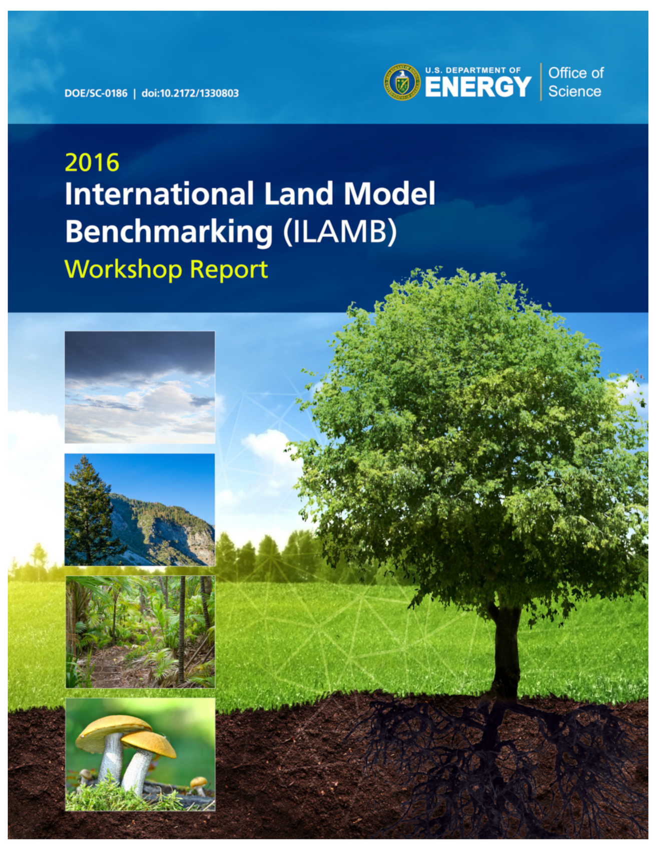
The International Land Model Benchmarking (ILAMB) Project is a community coordination activity to

- Develop internationally accepted benchmarks for scoring land model performance
- Promote the use of these benchmarks in the scientific community
- Strengthen linkages between experimental, remote sensing, and climate modeling communities in developing and applying observational datasets
- Support the design and development of Open Source benchmarking tools

The ILAMB Package (doi:10.18139/ILAMB.v002.00/1251621)

- Is an Open Source toolkit for evaluating land biogeochemistry models through comparisons with observations
- Assesses model fidelity for 29 variables with over 60 observational datasets for biogeochemistry, hydrology, radiation, and climate forcing
- Scores models based on statistical comparisons (period mean, bias, RMSE, phase, amplitude, spatial distribution, Taylor scores) and functional response metrics

Collier, N., F. M. Hoffman, D. M. Lawrence, G. Keppel-Aleks, C. D. Koven, W. J. Riley, M. Mu, J. T. Randerson (2018), The International Land Model Benchmarking (ILAMB) System: Design, Theory, and Implementation, *J. Adv. Model. Earth Sy.*, 10(11):2731–2754, doi:10.1029/2018MS001354.



Model Evaluation and Scoring Methodology

- One or more observational datasets are used to assess model performance for each variable of interest
- For every dataset, ILAMB generates graphical diagnostics (spatial contour maps, time series line plots, and Taylor diagrams)
- Scores are computed for the normalized bias ($S_{\rm bias}$), normalized central RMSE ($S_{\rm rmse}$), timing of the maximum of the annual cycle ($S_{\rm phase}$), interannual variability ($S_{\rm iav}$), and spatial distribution of the period mean ($S_{\rm dist}$)
- Overall scores for each dataset are calculated from individual scores as follows

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

- Scores for each dataset are averaged to produce an absolute score for each variable.
- Absolute scores are reported in ILAMB and are used to compute relative (Z-values) for each variable across all models included in the analysis.

Relative Performance of CMIP6 Land Models

For CMIP6 land models, the multi-model mean (last column) outperforms any single model for most variables.

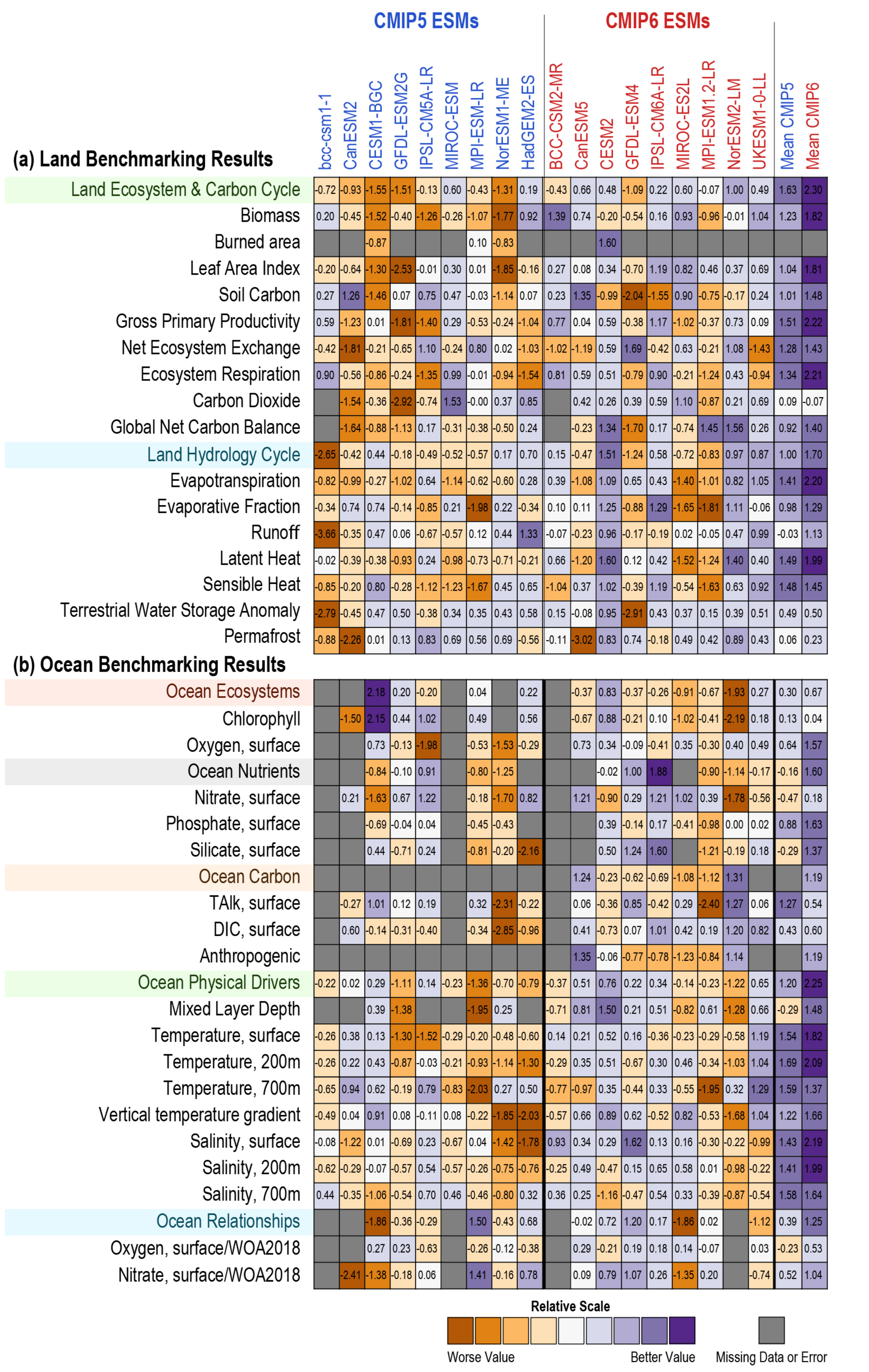


Figure 1: *This portrait plot provides an overview of relative scores for CMIP5 (left-hand side of table) and CMIP6 (right-hand side of table) Earth system models (ESMs), for multiple benchmarks against different datasets. (a) Benchmarking of ESM land models from ILAMB; (b) benchmarking of ocean models from the International Ocean Model Benchmarking (IOMB) package. Scores are relative to other models within each benchmark row, with positive scores indicating a better agreement with observations. Models included are only those from institutions that participated in both CMIP5 and CMIP6 carbon cycle experiments, in order to trace changes from one ensemble to the next. CMIP5 models are labels in blue and CMIP6 in red. This is Figure 5.22 in the IPCC Sixth Assessment Report (AR6), Climate Change 2021: The Physical Science Basis.*

Reasons for Land Model Improvements

ILAMB Analysis and Diagnostics available at https://www.ilamb.org/CMIP5v6/historical/

Climate Forcing Improvements

ESM improvements in climate forcings (temperature, precipitation, radiation) likely partially drove improvements exhibited by land carbon cycle models.

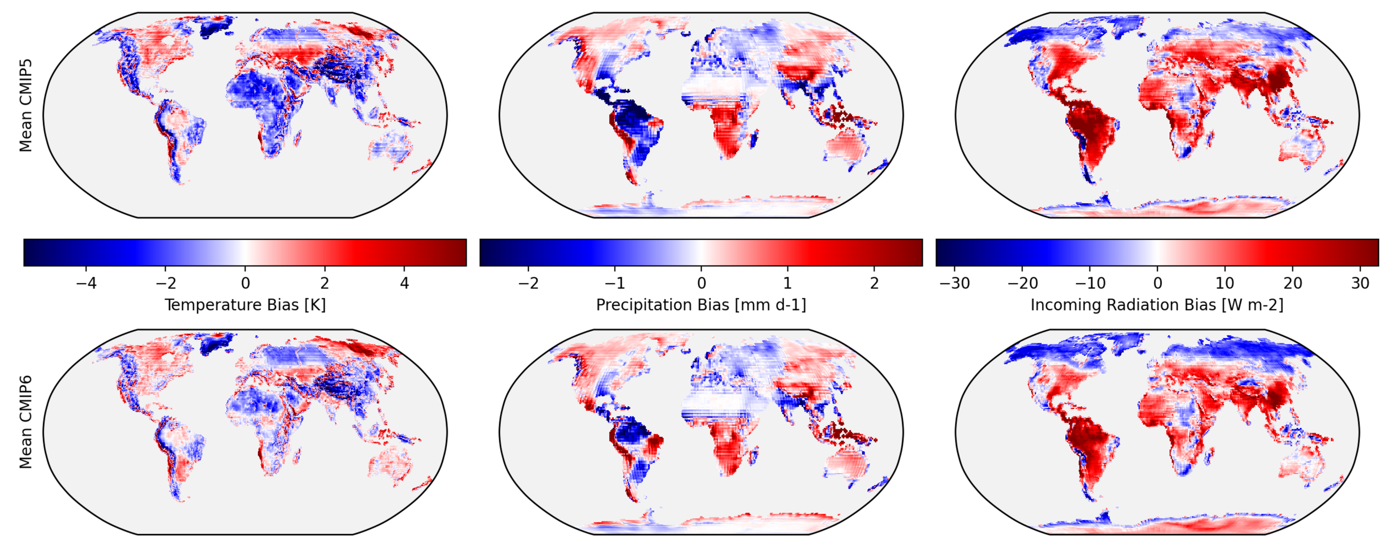


Figure 2: *A comparison of average biases in temperature (first column), precipitation (second column), and incoming radiation (third column) between the mean of the CMIP5 models (top row) and the mean of the CMIP6 models (bottom row) shows a slight reduction in the strengths of those biases in the CMIP6 generation of models.*

Differences in bias scores for temperature, precipitation, and incoming radiation were primarily positive, further indicating more realistic climate representation.

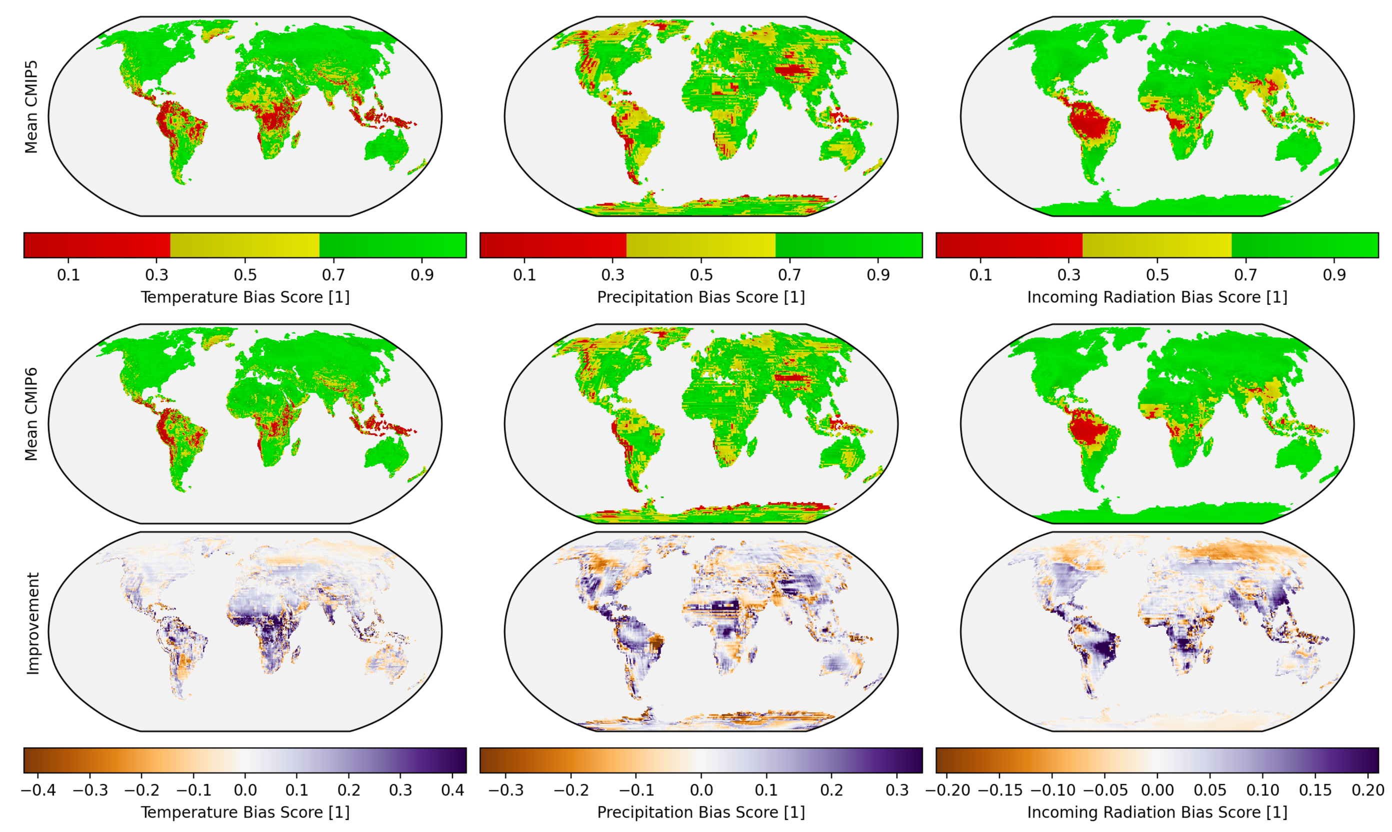


Figure 3: *A comparison of the ILAMB scores of average biases in temperature (first column), precipitation (second column), and incoming radiation (third column) between the mean of the CMIP5 models (top row) and the mean of the CMIP6 models (middle row) shows an increase in bias scores for the CMIP6 generation of models. The bottom row of maps shows the difference between the CMIP6 and CMIP5 bias scores, and the predominance of positive (blue) color indicates an overall improvement in CMIP6 models.*

Land Model Improvements

While atmospheric forcings got better, the largest land model improvements were in **variable-to-variable relationships**, suggesting that increased land model complexity was also partially responsible for higher CMIP6 model scores.

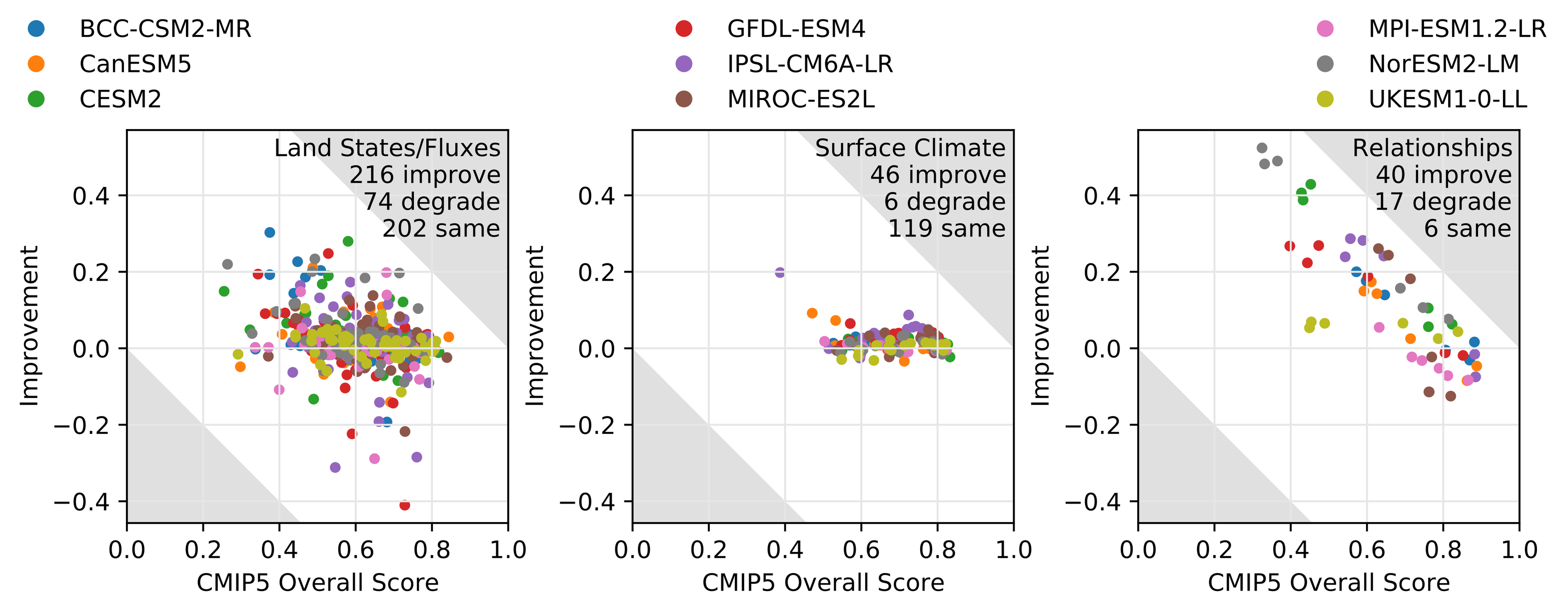


Figure 4: *Improvement in overall ILAMB scores for CMIP6 models (y-axis) versus ILAMB scores for CMIP5 models (x-axis) for nine land models by state and flux variables (first column), surface climate variables (second column), and land variable-to-variable relationships (third column) shows that model results improved in comparison with observations for some land state/flux variables and were degraded for other, but fewer, such variables. The largest improvements were for some of the variable-to-variable relationships.*

Discussion and Conclusions

- **Model benchmarking** is increasingly important as model complexity increases.
- The **ILAMB and IOMB Packages** employ a suite of in situ, remote sensing, and reanalysis datasets to comprehensively evaluation and score land and ocean model performance, irrespective of any model structure or set of process representations.
- Relative scores from the ILAMB Package suggest that **the CMIP6 suite of land models has improved over the CMIP5 suite of land models**.
- Improved land model performance was due to (1) improvements in climate forcings and (2) improvements in land models, **especially in variable-to-variable relationships**.
- **Benchmarking challenges remain** because (1) not all land models represent the same set of processes (e.g., prognostic burned area and vertically resolved soil carbon) and (2) few observational data sets provide quantitative uncertainties.

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