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Federal Agency and Organization Element to Which Report is Submitted:	4900
Federal Grant or Other Identifying Number Assigned by Agency:	1419445
Project Title:	EaSM-3: Land Use Change and Land Atmosphere Feedback Processes as Regulators of Regional Climate Change
PD/PI Name:	Paul A Dirmeyer, Principal Investigator
Recipient Organization:	George Mason University
Project/Grant Period:	08/01/2014 - 07/31/2020
Reporting Period:	08/01/2019 - 07/31/2020
Submitting Official (if other than PD\PI):	N/A
Submission Date:	N/A
Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	N/A

Accomplishments

*** What are the major goals of the project?**

Goals for the project are:

1. Examine the coupled feedback processes between land and atmosphere in CESM. This includes the relationships

between soil moisture and surface fluxes, and the connection between surface fluxes and the development of the atmospheric boundary layer, clouds and precipitation, and the role of the biogeophysical elements of CLM in these processes.
2. Develop and refine metrics for (a) quantifying land-atmosphere coupling in models and observations for purposes of model validation and the quantification of important climate processes over land; (b) land use changes in the context of their effects on, and response to, climate variations and change.
3. Investigate the evolution of coupled land-atmosphere climate processes in CESM under the dual axes of a changing climate and regional land use change.

These have been executed in the following tasks:

- Task 1: Develop analysis tools for offline and coupled models
- a: Land-atmosphere interaction diagnostics
- b: Metrics for assessment of modeled terrestrial response to land use
- Task 2: Assess land-atmosphere coupling under varying land uses in CAM-CLM
- a: Land-atmosphere coupling assessment across CAM-CLM configurations
- b: Analysis of offline CLM simulation across a variety of land covers and land uses
- c: Analysis of land-atmosphere coupling across range of land cover / land use
- Task 3: Decadal-timescale evolution of land-atmosphere feedbacks due to dual axes of climate and land use change
- a: Assess changes in land-atmosphere feedback due to climate change and land use change separately
- b: Land-atmosphere feedbacks and impact on extremes under scenarios with both climate change and land use change

*** What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?**

Major Activities: As detailed below, this project has thoroughly explored the relative roles of various kinds of land use change and land management on climate via the physical processes of land-atmosphere interactions in various configurations and versions of CESM (including land-only CLM experiments, coupled CLM-CAM simultaions, and fully-coupled models) in different regions of the world. We have also analyzed observational evidence for land use change effects on climate from both in situ flux tower measurements and satellite data, and compared them to model results. In the process of this work, we have also addressed vagaries in the definition and interpretation of "warming", clarifying the differing drivers and effects of near-surface air temperature warming (what most people instinctively think of) versus surface or skin temperature warming (what satellites can measure) over land. Climate models like CESM report both, but historically researchers have not been careful in distinguishing among these signals. Furthermore, the setup of many modeling studies further conflate warming effects, e.g., in the interpretation of warming over different land cover types as a proxy for future climate change when feedbacks in the climate system can muddle signals.

Specific Objectives: Task 1a: we have compiled and made public a Land–Atmosphere Coupling Metrics "Cheat Sheet" and Coupling Metrics Toolkit (COMET; details under "Products") based on the ongoing evaluation of land-atmosphere coupling metrics from observations, and the confrontation of models with these multivariate validation statistics. Also, to pioneer follow-on work from this project, we have begun development and application of non-parameteric forms of land-atmosphere coupling metrics based on Information Theory. Hsu and Dirmeyer (2020) present a methodology that goes beyond bi-variate linear (correlation-based) metrics to multivariate methods based on mutual information that can separate linear from nonlinear contributions as well as the unique, redundant and synergistic contributions from multiple drivers to a single climate response.

Task 1b: we have applied two biogeophysical feedback metrics to observations from FLUXNET sites and land cover / land use change experiments in NCAR CESM. The metrics can be used to quantify the contributions of different aspects (such as albedo, surface roughness and surface heat fluxes) of land surface change to changing climate (Chen and Dirmeyer 2017).

Task 2a: A set of land cover / land use change (LULCC) experiments have been conducted to investigate impacts of LULCC on afternoon precipitation and land-atmosphere coupling strength over North America (Chen and Dirmeyer 2017). We also implemented the Heated Condensation Framework of Tawfik and Dirmeyer (2014) as an additional convective trigger in CESM. The sensitivity of land cover precipitation feedback to convective triggering has been investigated (Chen et al. 2017).

Task 2b: We have conducted single-point offline runs in CLM4.5 and CLM5 (an upcoming release of CLM) at FLUXNET sites with different land cover conditions, so that the simulated climatic response to land cover / land use change can be evaluated by observations.

Task 2b & 2c: We have conducted paired site (open versus forest) offline simulations in CLM and NoahMP land surface models. The simulated surface flux changes are compared with the measurements from paired flux tower sites. The representation of deforestation-induced changes in surface fluxes in the land surface models is evaluated based on the measurements at the paired flux tower sites from FLUXNET2015 (Chen et al. 2018).

Task 2c: We evaluated four sets of uncoupled land surface models (including CLM4.5), coupled weather/climate models (including CESM1.2), and reanalyses with FLUXNET 2015 observations at over 160 sites in terms of their ability to reproduce key metrics of land atmosphere coupling, in addition to the models' basic ability to simulate surface fluxes and their variability (Dirmeyer et al. 2018).

Task 3a: We have provided a protocol for “fair” comparisons between the observations and model simulations in terms of the impacts of deforestation on hot extremes that disambiguates the effect of replacing “space for time”, i.e., substituting current land use changes between two locations in current climate as a proxy for large-scale land use change and its effects in the future (Chen and Dirmeyer 2020a).

Task 3b: We have evaluated the relative importance of land use forcing to temperature extremes compared with other anthropogenic forcings using CESM Last Millennium Ensemble (LME) and CMIP5 output (Chen and Dirmeyer 2019a). We have estimated the local impacts of global irrigation on temperature extremes based on satellite observations and CESM simulations (Chen and Dirmeyer 2019b), and compared the effects of irrigation (land management) versus land use (spreading agriculture) in CESM (Chen and Dirmeyer 2020b). We also have noted and carefully evaluated in observations and climate models, including but not limited to CESM, the differing impacts of land use change on surface versus near-surface air temperature (Chen and Dirmeyer 2019c).

Significant Results: To assess the biogeophysical impacts of land cover/land use change (LCLUC) on surface temperature, two observationbased metrics were extended by L. Chen to CESM simulations to test their applicability to climate models and enhance their

diagnostic capabilities. Both metrics had been developed based on the surface energy balance, and provided insight into the contribution of different aspects of land surface change (such as albedo, surface roughness, net radiation and surface heat fluxes) to changing climate. A revision of the first metric, the intrinsic biophysical mechanism, can be used to distinguish the direct and indirect effects of LCLUC on surface temperature. The other, a decomposed temperature metric, gives a straightforward depiction of separate contributions of all components of the surface energy balance. These two metrics well capture observed and model simulated surface temperature changes in response to LCLUC. Results from paired FLUXNET sites and land surface model sensitivity experiments indicate that surface roughness effects usually dominate the direct biogeophysical feedback of LCLUC, while other effects play a secondary role. However, coupled climate model experiments show that these direct effects can be attenuated by large scale atmospheric changes (indirect feedbacks). When applied to realtime transient LCLUC experiments, the metrics also demonstrate usefulness for assessing the performance of climate models and quantifying land– atmosphere interactions in response to LCLUC. (Chen and Dirmeyer 2017)

With the default convective triggering configuration, we found a strong positive soil moistureprecipitation relationship over the Great Plains, where the agricultural expansion since preindustrial times leads to a significant widespread increase in afternoon precipitation. Impacts of land cover change on precipitation manifest through changes in rainfall frequency that are largely controlled by the distribution of CAPE as the trigger of convective precipitation. With the Heated Condensation Framework as an additional process-based convective triggering criterion in CESM, the coupling strength is weakened over the Great Plains. LULCC-induced precipitation changes are only found over the northern Plains. The discrepancies suggest caveats when investigating the impacts of land cover change on precipitation, because the magnitude and spatial patterns of precipitation change can be greatly modified by the treatment of convection in climate models. (Chen et al. 2017)

Paired-site simulations with flux tower data for validation suggest that both CLM and Noah land models have difficulties representing the energy partitioning between latent and sensible heat flux. Under a mid-latitude deforestation scenario, CLM does not capture the observed decreased daytime latent heat flux and overestimates the increased sensible heat flux during summer. The biases are mainly associated with deficiencies over forest landcover types, radiation biases and the parameterization of soil evaporation. Our results suggest that attention needs to be devoted to improving the representation of surface heat flux processes in land models to increase confidence in land cover change simulations. (Chen et al. 2018)

The comparison among the single-forcing and full-forcing model experiments suggests that land use forcing plays a comparable (even more important geographically) role in temperature extremes than other anthropogenic forcings, especially for the hot extremes and the diurnal temperature range. The CESM LME simulations show that historical LULCC leads to a significant cooling of the annual warmest day and decreased diurnal temperature range over Europe, eastern China, and the central and eastern US. Even though there is not a good agreement concerning the temperature response to the land use forcing among the CMIP5 models, the relative contribution of land use to temperature extremes in fullforcing experiments is very robust. Our results demonstrate the importance of land cover change in affecting temperature extremes among the anthropogenic forcings, implying that land management in the future might

be an approach to mitigate regional hot extremes under the context of global warming. (Chen and Dirmeyer 2019a)

We find that both satellite observations and CESM suggest strong evaporative cooling by irrigation on daytime surface temperature over arid and semiarid regions, even though CESM greatly underestimates the surface cooling, which can be regulated (or amplified) by the interactions between land surface and atmosphere. Results demonstrate the importance of both land use and land management in affecting temperature extremes among the anthropogenic forcings, implying that land use and land management in the future could be an approach to mitigate regional hot extremes under the context of global warming. (Chen and Dirmeyer 2019b)

To reconcile the disagreement between the observed and simulated temperature response to deforestation, we separate the local and nonlocal impacts from the CESM deforestation simulations. CESM can well capture the observed local warming (on summer daily maximum temperature) of deforestation. However, the signal can be overwhelmed by the simulated nonlocal effects mainly due to the changes in atmospheric background state. Our work provides a protocol for “fair” comparisons between the observations and model simulations, which is particularly useful for the model evaluation and comparison in the Land Use Model Intercomparison Project (LUMIP). (Chen and Dirmeyer 2019c, 2020a)

One driver in model surface temperature errors over land and ocean is the bias in downward surface radiation caused by persistent cloud errors. These biases can confound other global change studies such as land use change responses by shifting climate response tipping points. One way of reducing these biases in CESM is by correcting the net shortwave flux at the surface towards values derived from CERES satellite climatological estimates. This approach reduces global mean SST bias in both low and high resolution configurations. SST biases persist over southern oceans, suggesting other processes controlling the net surface heat flux, such as the representation of surface mixed-layer processes in the ocean component. The shortwave flux correction also amplifies the pattern of precipitation biases over ocean, due to complex interactions with atmospheric circulation and moisture flux convergence, global warming trend representation and latent heat flux biases. However, an ITCZ shift and reduced precipitation biases over central to southern Africa do result, but the Pacific double ITCZ bias persists. (Erfani and Burls 2020)

Recognition of the limitations of many of the conventional statitical approaches to assessing land-atmosphere coupling has led to our pursuit of ideas from Information Theory (IT) to address these shortcomings. Conventional statistics for determining relationships between climate variables are largely based on assumptions of linearity and normal distributions of variables. IT allows for nonparametric approaches that ensble multivariate coupling assessment and includes non-linear relationships. Early work by others has focused on very small data sets and limited areas. We have refined methods and expanded scope well beyound previous work to diagnose unique, redundant and synergistic contributions from multiple drivers to a single climate variable by season globally, including assessment of the nonlinear contribution to total coupling. (Hsu and Dirmeyer 2020)

Key outcomes or Other achievements: See publications below.

*** What opportunities for training and professional development has the project provided?**

This project supported postdoctroal fellow Dr. Liang Chen (Texas A&M, Ph.D., May 2015) from August 2015 through December 2018.

This project supported postdoctroal fellow Dr. Ehsan Erfani (U. Nevada Reno, Ph.D., August 2016) from September 2019 to February 2020.

This project supported PhD student Ako Heidari from Spring term 2015 through Fall term 2016, a graduate student in the Department of Geography and GeoInformation Science at George Mason University.

This project supported PhD student Hsin Hsu (National Taiwan U. M.S. June 2016) from Spring term 2019 to Spring term 2020.

Supported on collaborative grant to co-I D. Lawrence (NCAR) funded by USDA, Ahmed Tawfik was hired as a Scientist I at NCAR for this project in January 2015 through February 2018.

*** How have the results been disseminated to communities of interest?**

Results have been presented at the following venues (details below under "Products"):

- 2014 AGU Fall meeting in San Francisco
- 2015 AMS Annual Meeting in Phoenix
- 2015 NCAR Land Model Working Group (LMWG) meeting in Boulder
- 2015 Association of American Geographers Annual Meeting in San Francisco, California
- 2015 Alpine Summer School on Land-Atmosphere Interactions in Valsavaranche, Valle d'Aosta, Italy
- 2015 ECMWF Annual Seminar in Reading, UK
- 2015 AGU Fall meeting in San Francisco
- 2016 NCAR Land Model Working Group (LMWG) meeting in Boulder
- 2016 AGU Fall meeting in San Francisco
- 2017 AMS Annual meeting in Seattle
- 2017 CESM Annual meeting in Breckenridge
- 2017 AGU Fall meeting in New Orleans
- 2018 GEWEX Open Science Conference in Canmore, Alberta, Canada
- 2018 CESM Annual meeting in Boulder
- 2018 AGU Fall meeting in Washington, D.C.
- 2019 AMS Annual Meeting in Phoenix

Results have been published in the following journals [impact factors in brackets]:

- Nature Communications [12.121]
- Journal of Climate (2) [5.922]
- Hydrology and Earth System Sciences [5.153]
- Climate Dynamics [4.875]
- Journal of Hydrometeorology (2) [4.671]
- International Journal of Climatology [3.928]
- Frontiers in Earth Science [2.629]

Products

Books

Book Chapters

Inventions

Journals or Juried Conference Papers

Chen, Liang and Dirmeyer, Paul A (2016). Adapting observationally based metrics of biogeophysical feedbacks from land cover/land use change to climate modeling. *Environmental Research Letters*. 11 (3), 034002. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1088/1748-9326/11/3/034002

Chen, Liang and Dirmeyer, Paul A. (2017). Impacts of {Land}-{Use}/{Land}-{Cover} {Change} on {Afternoon} {Precipitation} over {North} {America}. *Journal of Climate*. 30 (6), 2121--2140. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1175/JCLI-D-16-0589.1

Chen, Liang and Dirmeyer, Paul A. (2019). Differing {Responses} of the {Diurnal} {Cycle} of {Land} {Surface} and {Air} {Temperatures} to {Deforestation}. *Journal of Climate*. 32 (20), 7067--7079. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1175/JCLI-D-19-0002.1

Chen, Liang and Dirmeyer, Paul A. (2019). Global observed and modelled impacts of irrigation on surface temperature. *International Journal of Climatology*. 39 (5), 2587--2600. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1002/joc.5973

Chen, Liang and Dirmeyer, Paul A. (2019). The relative importance among anthropogenic forcings of land use/land cover change in affecting temperature extremes. *Climate Dynamics*. 52 (3-4), 2269--2285. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1007/s00382-018-4250-z

Chen, Liang and Dirmeyer, Paul A. (2020). Distinct {Impacts} of {Land} {Use} and {Land} {Management} on {Summer} {Temperatures}. *Frontiers in Earth Science*. 8 . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.3389/feart.2020.00245

Chen, Liang and Dirmeyer, Paul A. (2020). Reconciling the disagreement between observed and simulated temperature responses to deforestation. *Nature Communications*. 11 (1), . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1038/s41467-019-14017-0

Chen, Liang and Dirmeyer, Paul A. and Guo, Zhichang and Schultz, Natalie M. (2018). Pairing {FLUXNET} sites to validate model representations of land-use/land-cover change. *Hydrology and Earth System Sciences*. 22 (1), 111--125. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.5194/hess-22-111-2018

Chen, Liang and Dirmeyer, Paul A. and Tawfik, Ahmed and Lawrence, David M. (2017). Sensitivities of {Land} {Cover}–{Precipitation} {Feedback} to {Convective} {Triggering}. *Journal of Hydrometeorology*. 18 (8), 2265--2283. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1175/JHM-D-17-0011.1

Dirmeyer, Paul A. and Chen, Liang and Wu, Jiexia and Shin, Chul-Su and Huang, Bohua and Cash, Benjamin A. and Bosilovich, Michael G. and Mahanama, Sarith and Koster, Randal D. and Santanello, Joseph A. and Ek, Michael B. and Balsamo, Gianpaolo and Dutra, Emanuel and Lawrence, David M. (2018). Verification of {Land}–{Atmosphere} {Coupling} in {Forecast} {Models}, {Reanalyses}, and {Land} {Surface} {Models} {Using} {Flux} {Site} {Observations}. *Journal of Hydrometeorology*. 19 (2), 375--392. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1175/JHM-D-17-0152.1

Erfani, E., and Burls, N. J. (2020). The role of shortwave flux correction in reducing climatological temperature biases. *Climate Dynamics*. . Status = UNDER_REVIEW; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Hsu, H., and P. A. Dirmeyer (2020). Nonlinearity and multivariate dependencies in land-atmosphere coupling. *Water Resources Research*. . Status = UNDER_REVIEW; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ;

DOI: 10.1002/essoar.10503533.1

Tawfik, A. B., D. M. Lawrence, and P. A. Dirmeyer (2017). Representing sub-grid convective initiation in the Community Earth System Model. *Journal of Advances in Modeling Earth Systems*. 9 (3), 1740. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1002/2016MS000866

Licenses

Other Conference Presentations / Papers

Tawfik, A. B., and P. A. Dirmeyer (2015). *A New Explicit and Computationally Efficient Subgrid Convective Initiation Scheme [12A.2]*. American Meteorological Society, 27th Conference on Climate Variability and Change. phoenix, AZ, USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Chen, L., O. W. Frauenfeld, and P. A. Dirmeyer (2016). *Biogeophysical Impacts of Land Cover / Land Use Change on Climate (invited)*. Annual Meeting of the Association of American Geographers. San Francisco, CA, USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Dirmeyer, P. A., A. Tawfik (2015). *Confronting CLM with land surface observations*. NCAR Land Model Working Group (LMWG) Meeting. Boulder, CO, USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Dirmeyer, P. A., A. Tawfik, S. Halder, H. Norton, J. Wu, M. G. Bosilovich, J. A. Santanello Jr., and M. B. Ek (2015). *Confronting global land-atmosphere models with coupled process metrics*. American Meteorological Society, 29th Conference on Hydrology [J1.2]. Phoenix, AZ, USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Tawfik, A. B., D. M. Lawrence and P. A. Dirmeyer (2017). *Dynamic scale awareness: Switching parameterized convection on at the right time [4A.4]*. American Meteorological Society 29th Conference on Climate Variability and Change. Seattle, WA, USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Tawfik, A. B., and P. A. Dirmeyer (2014). *Evolution of Soil MoistureConvection Interactions against the Backdrop of Global Oscillations [H11J-05]*. American Geophysical Union Fall Meeting. San Francisco, CA, USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Dirmeyer, P. A., L. Chen and J. Wu (2016). *Extending the confrontation of weather and climate models from soil moisture to surface flux data [NG13A-1692]*. American Geophysical Union Fall Meeting. San Francisco, CA, USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Chen, L. and P. A. Dirmeyer (2016). *Impacts of land use / land cover change on afternoon precipitation*. NCAR 21st Annual CESM Workshop. Breckenridge, CO, USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Chen, L. and P. A. Dirmeyer (2016). *Impacts of land use/land cover change on afternoon precipitation over North America [GC21B-1081]*. American Geophysical Union Fall Meeting. San Francisco, CA, USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Dirmeyer, P. A., A. Tawfik, H. Norton, and J. Wu (2014). *Landatmosphere feedbacks over North America: How well do weather and climate models represent reality?*. World Weather Open Science Conference (WWOSC). Montréal, QB, Canada. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Dirmeyer, P. A. (2015). *Metrics as Tools for Assessing LandClimate Feedback in Observations and Models (Invited). [GC24B-01]*. American Geophysical Union Fall Meeting. San Francisco, CA, USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Chen, L. and P. A. Dirmeyer (2017). *Observed Local Impacts of Global Irrigation on Surface Temperature [A51C-2073]*. American Geophysical Union (AGU) Fall Meeting. New Orleans, LA, USA. Status = PUBLISHED; Acknowledgement of

Federal Support = Yes

Tawfik, A., P. Dirmeyer, and D. Lawrence (2015). *Observed Local Soil MoistureAtmosphere Feedbacks within the Context of Remote SST Anomalies: Lessons From Recent Droughts. [H33J-06]*. American Geophysical Union Fall Meeting. san Francisco, CA, USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Chen, L. and P. A. Dirmeyer (2018). *Observed and Simulated Local Impacts of Global Irrigation on Surface Temperature*. The 8th GEWEX Science Conference. Canmore, AB, Canada. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Chen, L. and P. A. Dirmeyer (2018). *Reconciling the Disagreement between Observed and Simulated Temperature Responses to Deforestation*. NCAR 23rd Annual CESM Workshop. Boulder, CO, USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Chen, L., and P. A. Dirmeyer (2018). *Reconciling the disagreement between observed and simulated temperature responses to deforestation [GC14B-06]*. American Geophysical Union Fall Meeting. Washington, DC, USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Chen, L., and P. A. Dirmeyer (2019). *Response in diurnal cycle of land surface and air temperature to deforestation (invited) [14C.1]*. American Meteorological Society 32nd Conference on Climate Variability and Change. Phoenix, AZ, USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Other Products

Other Publications

Patents

Technologies or Techniques

Thesis/Dissertations

Websites
Coupling Metrics Toolkit (CoMeT)
http://www.coupling-metrics.com/

The Coupling Metrics Toolkit (CoMeT) brings together many commonly used land-atmosphere coupling metrics into a single, standardized set of Fortran 90 modules. Calculate everything from soil moisture retention over time, to the link between convective initiation and surface properties are available.

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Dirmeyer, Paul	PD/PI	1
Chen, Liang	Postdoctoral (scholar, fellow or other postdoctoral position)	10
Erfani, Ehsan	Postdoctoral (scholar, fellow or other postdoctoral position)	1

Heidari, Ako	Graduate Student (research assistant)	3
Hsu, Hsin	Graduate Student (research assistant)	3

Full details of individuals who have worked on the project:

Paul A Dirmeyer
Email: pdirmeye@gmu.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked: 1

Contribution to the Project: PI, leadership and management of project, mentoring of student and postdoc, analysis of model output, authoring and coauthoring of publications, giving conference and workshop presentations on results of project research. Supported for 1 summer month during the project.

Funding Support: N/A

International Collaboration: No
International Travel: No

Liang Chen
Email: lchen12@gmu.edu
Most Senior Project Role: Postdoctoral (scholar, fellow or other postdoctoral position)
Nearest Person Month Worked: 10

Contribution to the Project: Primary modeler and data analyst for this project, lead author on multiple papers, coauthor, presenter of results at conferences and workshops. Worked full time for 40 months of 4 project years for average of 10 months/year.

Funding Support: N/A

International Collaboration: No
International Travel: No

Ehsan Erfani
Email: eerfani@gmu.edu
Most Senior Project Role: Postdoctoral (scholar, fellow or other postdoctoral position)
Nearest Person Month Worked: 1

Contribution to the Project: Post-doc supported for 5 months full time within 4 project years for average of 1 months/year.

Funding Support: N/A

International Collaboration: No
International Travel: No

Ako Heidari

Email: aheidari@masonlive.gmu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 3

Contribution to the Project: Graduate student supported for 4 semesters and 2 summers (1/2015-12/2016) at 20 hours/week (6 mo/year for 2 of 4 project years) for average of 3 months/year.

Funding Support: N/A

International Collaboration: No
International Travel: No

Hsin Hsu
Email: hhsu@gmu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 3

Contribution to the Project: Developing information theoretical approach to assess the interrelation between multiple factors driving land surface fluxes and other climate responses, which can be applied to CESM or observational data (reanalyses; for validation). Graduate student supported for 3 semesters and 1 summer (Fall 2018-Spring 2020) at 20 hours/week (5.25 mo/year for 2 of 4 project years) for average of 3 months/year.

Funding Support: N/A

International Collaboration: No
International Travel: No

What other organizations have been involved as partners?

Name	Type of Partner Organization	Location
NCAR	Academic Institution	Boulder, CO

Full details of organizations that have been involved as partners:

NCAR

Organization Type: Academic Institution
Organization Location: Boulder, CO

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution: Part of this Collaborative Research project - grant support provided by USDA; David Lawrence is NCAR PI, Rich Neale is NCAR co-PI.

What other collaborators or contacts have been involved?
Nothing to report

Impacts

What is the impact on the development of the principal discipline(s) of the project?

Basic land-atmosphere metrics development is being shared with the broader scientific community through the World Climate Research Programme (WCRP) Global Energy and Water Exchanges (GEWEX) Global Land-Atmosphere System Study (GLASS), of which the PI was a cofounder, and which is concerned with modeling and understanding the coupled land climate system. The primary means of distribution has been via the web site: http://tiny.cc/l-a-metrics

Our testing of CLM and CAM in various configurations is also contributing the NCAR CESM model development and has been informing the production of CLM5, released as part of CESM2.

The Land Surface, Snow and Soil Moisture Model Intercomparison Project (LS3MIP); a CMIP6-endorsed project is also be a beneficiary of this work.

Land use change-climate metrics development and results have been shared with the broader scientific community through the Land Use Model Intercomparison Project (LUMIP); a CMIP6-endorsed project of which co-PI Lawrence of NCAR is co-chair, and is helping to inform experiment development and analysis in LUMIP.

What is the impact on other disciplines?
Nothing to report.

What is the impact on the development of human resources?

The PI is a Professor in the department of Atmospheric, Oceanic and Earth Sciences (AOES) which is home of the Ph.D. program in Climate Dynamics. In Fall 2018 a new Ph.D. student is being supported on this project (Hsu); this project is helping him develop skills necessary for independent research.

The postdoc on this project (Chen) has developed independent research skills and expand professional contacts and experience. This has led to his recent hire to a prestigeous joint position with the University of Illinois and the Illinois State Water Survey wherein he will apply his research and organizational skills, as well as have opportunity to participate in teaching and mentoring.

What is the impact on physical resources that form infrastructure?
Nothing to report.

What is the impact on institutional resources that form infrastructure?
Nothing to report.

What is the impact on information resources that form infrastructure?

A university computing proposal was submitted to NCAR/CISL in March 2015 for 4.2M core supercomputing hours to conduct the necessary CESM simulations and analysis of the model output under this project. 3.5M core hours were granted, along with 50TB of project space and 200TB of HPSS storage. Additionally, 200K CPU hours have been granted on Cheyenne to aid transition of the modeling work to the new platform before the end of 2017. With the transition of work to Cheyenne, unused resources were converted to 2M core hours on the new platform. This resource has been used for the CESM model simulations, including some of the earliest analysis of CESM2.

A significant portion of this project involves new simulations with the CESM-CLM model framework. Due to the exploratory and investigative nature of the proposed model work, we do not anticipate that there will be a large demand from the broader

scientific community for model data generated during the course of this project. Consequently, we have not budgeted any costs into this proposal for data dissemination. Naturally, if there are specific requests for data that arise through interactions with current or future collaborators who are external to this project, we will be happy to share the data with them. The data volume is not expected to be large by today's standards so we will be able to transfer this data via normal data transfer methods (e.g., through anonymous ftp site or the Earth System Grid). Results from the model integrations will be reported through conferences and in the peer reviewed literature. Storage costs for any data that needs to be archived for the lifetime of this project have been folded into the Yellowstone request for computing allocations to support the work outlined in this proposal.

What is the impact on technology transfer?
Nothing to report.

What is the impact on society beyond science and technology?
Nothing to report.

Changes/Problems

Changes in approach and reason for change
Nothing to report.

Actual or Anticipated problems or delays and actions or plans to resolve them

The following factors contributed to delays and requests for no-cost extensions during the project:

Delays in release of CESM2 and the timelines for LUMIP and LS3MIP set back execution of some model simulations.

Two personnel issues also contributed to delays. Originally supported PhD student A. Heidari had to suspend graduate studies for personal reasons at the end of 2016. PhD student Hsin Hsu began in Fall 2018 term and has contributed productively to the work supported by the grant, including a publication (in review).

The departure of post-doc Dr. Liang Chen, who has been wonderfully productive, publishing 8 papers as lead author with another after departure, also warranted our request for no-cost extensions. Dr. Erfani Ehsan, who works with Dr. Natalie Burls was supported on a different NSF grant wherein support ended (NSF #1756658), has received partial support from this grant in the last year for work relevant to the role of surface radiative flux errors in the hydrologic cycle and surface energy baance.

None of these changes substantially affected ultimate completion of project goals, as reported above.

Changes that have a significant impact on expenditures
Nothing to report.

Significant changes in use or care of human subjects
Nothing to report.

Significant changes in use or care of vertebrate animals
Nothing to report.

Significant changes in use or care of biohazards
Nothing to report.

Special Requirements

Responses to any special reporting requirements specified in the award terms and conditions, as well as any award specific reporting requirements.
Nothing to report.