A Hierarchical Evaluation Framework for Assessing Climate Simulations Relevant to the Energy-Water-Land Nexus
(DE- SC0016438)

Final Report

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Major goals of the project

The overarching goal was to construct a hierarchy of new and well-tested metrics and analysis tools that support both fundamental and use-inspired research. Motivating this goal was a convergence of needs from climate scientists and stakeholders alike for a systematic, robust framework of model evaluation and diagnosis to

- provide scientific insights, inform model development,
- support best practices for the use of climate model outputs, and
- facilitate communication of climate information in the evolving landscapes of multi-model, multi-resolution, and large ensemble simulations that generate terabytes of data for any single climate run.

Steps toward attaining these goals benefited from expertise and established capability of the project team, which included leadership of the North American Regional Climate Change Assessment Program (NARCCAP) and the Coordinated Regional Downscaling Experiment (CORDEX), development of hierarchical model evaluation approaches, and successful research in the analysis and diagnosis of climate model skill, as well as the understanding and modeling of regional climate processes in North America. As part of the overarching goal, the project worked to disseminate a suite of methodologies, algorithms, and software components that the wider community can employ to advance climate science and applications. With rigorous demonstration, the evaluation framework and the mix of standard and high risk / high reward approaches helped form the basis for future development of a computationally enabled user-friendly system for community use.

Under the overarching goal, specific goals were addressed:

1. Producing an analysis framework consisting of a suite of powerful metrics and analysis tools informed by different use cases that target different uses of climate models and/or climate outputs by climate scientists and stakeholders. This framework included statistical measures of model performance (skill), phenomena-based diagnosis of inter-related model biases and multi-scale processes contributing to the phenomena, and metrics most relevant to the energy-water-land (E-W-L) nexus.

2. Taking advantage of multi-scale, multi-source observational data to evaluate model fidelity and explore the mechanisms and sources of model errors and uncertainty, in order to pinpoint and prioritize areas for future model development.

3. Demonstrating the usefulness of this evaluation framework in a structured manner by selecting representative approaches from a suite of dynamical, empirical, and hybrid downscaling models and design hierarchical experiments. Through differential credibility analysis, the work has been benchmarking simulations across a range of spatial resolutions and modeling approaches, and leveraging results available from the North America - Coordinated Regional Downscaling Experiment (NA-CORDEX, na-cordex.org).

4. Conducting additional numerical experiments to target and analyze human impacts on local-to-regional climate and to evaluate the requirements for coupling human and Earth system models to represent their dynamic interactions. These experiments focused on changes in land use and land cover associated with food and bioenergy crop production and urbanization, and expansion of a

key renewable energy source (wind turbine deployment), which highlight specific challenges for modeling the E-W-L nexus.

Metrics work

Dr. Bukovsky examined the simulations from NA-CORDEX using the climate sensitivity of the driving-GCMs as a metric for the strength of the projected RCM climate changes. This work was written up and published in Climatic Change. Overall, this work showed that climate sensitivity is a very important source of spread in the regional model ensemble, particularly in mean temperature projections from the local-to-regional-to-continental scale. Climate sensitivity also influences the strength of mean precipitation changes, but only in the cold season at a continental scale.

Dr. Bukovsky also examined the usefulness of a suite of metrics designed for regional climate simulations for examining regional model fidelity and ensemble weighting. This work concluded that the metrics are useful for examining individual model fidelity, and that they point to where there may be a need for further analysis, but that they were not useful when combined for determining the differential fidelity of the simulations in the ensemble, as the results of individual metrics balanced each other and did not match credibility as determined by in-depth analysis. This work also determined that weighting using metrics did not and could not (regardless of weighting scheme) significantly change ensemble mean results for historical climate or future climate change.

Metrics were also produced for examining extra-tropical cyclones, and tested in the southeast U.S., where models often have a difficult time producing winter precipitation. Dr. McCrary and Dr. Arritt examined land-atmosphere coupling metrics to look at the control the land surface played on precipitation over North America in summer. Additionally, a number of descriptive metrics were produced to examine model fidelity.

Dr. Bukovsky also led an undergraduate student assistant, T. Rendfrey, in the production of tropical cyclone related metrics and the writing of a manuscript on said topic. R. McCrary contributed to SST related metrics for this work.

R. McCrary and M. Bukovsky also contributed to work that examined extreme precipitation over the Western US in NA-CORDEX. This work focused on examining how differences in projections for Atmospheric-River-type events may contribute to differences in future projections of precipitation over the Western US. This work has been submitted to *Climate Dynamics* (Initial Submission May 2021; Revised and Resubmitted August 2021).

Dr. McGinnis developed a software library in R for working with climate model output that includes a suite of automated analyses and associated metrics for model evaluation. This software is freely available via GitHub. These metrics featured heavily in the Differential Credibility Analysis work and continue to be used in HyperFACETS.

Bukovsky M.S., and L.O. Mearns, 2020: Regional Climate Change Projections from NA-CORDEX and their Relation to Climate Sensitivity. *Climatic Change.* https://doi.org/10.1007/s10584-020-02835-x

Bukovsky, M.S., J. Thompson, and L.O. Mearns, 2019: The effect of weighting on the NARCCAP ensemble mean. Does it make a difference? Can it make a difference? *Climate*

Research., 77, 23-43, https://doi.org/10.3354/cr01541.

Rendfrey, T.S., M.S. Bukovsky, R.R. McCrary, R. Fuentes-Franco, 2021: An assessment of tropical cyclones in North American CORDEX WRF simulations. *Weather & Climate Extremes,* 34, 100382. https://doi.org/10.1016/j.wace.2021.100382

Hughes, M., D. Swales, J.D. Scott, M. Alexander, K. Mahoney, R. McCrary, R. Cifelli, M. Bukovsky, 2021: Changes in extreme integrated water vapor transport on the U.S. west coast in NA-CORDEX, and relationship to mountain and inland precipitation. *Climate Dynamics*. (in review)

Presentations:

- Bukovsky, M.S., T.S. Rendfrey, and L.O. Mearns, 2018: The Sensitivity of Regional Climate Models to Equilibrium Climate Sensitivity. Presentation. *2018 AGU Fall Meeting*, Washington D.C., A31D-02. 12 Dec. 2018.
- Bukovsky, M.S., R.R. McCrary, T.S. Rendfrey, A.S. Schroeder, and L. Mearns, 2017: Causes of Cool-Season Precipitation Bias in the East-South-Central U.S. Poster. *2017 AGU Fall Meeting*, New Orleans, LA. A23D-2396.
- McCrary, R.., R. Arritt, and M. Bukovsky, 2019: Land-Atmosphere Coupling in an Ensemble of Regional Climate Simulations. AMS 2019 Annual Meeting, Phoenix, AZ. J2.1
- McCrary, R.., R. Arritt, and M. Bukovsky, 2018: Land-Atmosphere Coupling in an Ensemble of Regional Climate Simulations. DOE RGCM Meeting.
- McGinnis, S., M. Bukovsky, and L. Mearns, 2017: From Descriptive to Explanatory: Using Metrics to Identify Candidate Phenomena for Process Evaluation in NA-CORDEX and NARCCAP. AGU Fall Meeting.

Software:

- McGinnis, Seth, 2019. "sethmcg/climod", version 1.0.0, Zenodo. [http://doi.org/10.5281/zenodo.3461259]

A suite of simulations has been completed using the Model for Prediction Across Scales (MPAS) atmosphere model coupled with the Community Atmosphere Model (CAM5) physics package. MPAS has been configured using regional refinement for high resolution modeling over the contiguous U.S. at 4-32 km, 12-46 km, 25-100 km, and 50-200 km resolution. For the 25-100 km and 50-200 km configurations, simulations have been performed for 1990-2010 driven by observed sea surface temperature (SST) and sea ice and for 2080-2100 in which SST and sea ice changes simulated by MPI-ESM-LR for the historical and future periods under RCP8.5 are added to the observed SST and sea ice conditions. These simulations are being analyzed using a set of metrics for comparison with regional downscaling using WRF and RegCM and observations, with a regional focus over the Southern Great Plains. The 25-100 km and 50-200 km configurations have been evaluated on their ability to simulate mesoscale convective systems (MCSs) in the U.S. east of the Rocky Mountains (Feng et al. 2020).

Feng, Z., F. Song, K. Sakaguchi, and L.R. Leung, 2021: Evaluation of Mesoscale Convective Systems in Climate Simulations: Methodological Development and Results from MPAS-CAM over the U.S. *Journal of Climate*, 34(7), 2611-2633, doi:10.1175/JCLI-D-20-0136.1.

PNNL researchers developed a method to dynamically classify observational stations into urban and rural based on Defense Meteorological Satellite Program's Operational Linescan System (DMSP/OLS) nighttime lights (NTL) data for use to develop metrics of human systems.

> Yang, X., L.R. Leung, N. Zhao, C. Zhao, Y. Qian, K. Hu, X. Liu, and B. Chen, 2017: Contribution of Urbanization to the Increase of Extreme Heat Events in an Urban Agglomeration in East China. *Geophysical Research Letters,* 122, DOI: 10.1002/2017GL074084.

PNNL researchers also participated in the Atmospheric River Tracking Method Intercomparison (ARTMIP) project using methods they had previously developed.

> Shields, C.A., J.J. Rutz, L.R. Leung, F.M. Ralph, M. Wehner, B. Kawzenuk, J. Lora, E. McClenny, T. Osborne, A. Payne, Y. Qian, C. Sarangi, P. Ullrich, A. Gershunov, N. Goldenson, B. Guan, A. Ramos, S. Sellars, I. Gorodetskaya, K. Mahoney, R. Pierce, A. Subramanian, D. Waliser, G. Wick, A. Wilson, D. Lavers, Prabhat, A. Collow, F. Dominguez, H. Krishnan, G. Magnusdottir, P. Nguyen, T. O'Brien, R. Silva, and M. Tsukernik, 2018: Atmospheric River Tracking Method Intercomparison Project (ARTMIP): Experimental Design and Project Goals. *Geoscientific Model Development,* 11, 2455–2474. https://doi.org/10.5194/gmd-11-2455-2018

A Ph.D. student at Iowa State, A. Caruthers, has been evaluating simulations of the nocturnal low-level jet (LLJ) that occurs over the Great Plains in the central U.S. Her focus has been on regional-climate simulations produced under FACETS for contemporary and future scenario climates. The regional models RegCM4 and WRF-ARW used output from the GFDL, HadGEM2 and MPI global models for boundary conditions and simulated climate at 12.5-, 25- and 50-km grid spacing. Results show that the LLJ is under-predicted in the historical climate simulations under each combination of global model, regional model and grid resolution. Relationship of the bias to simulated boundary-layer and Bermuda High behavior is being explored, along with possible influence by the models' rendition of regional topography. Results are being finalized as Ms. Caruthers completes her thesis.

> Caruthers, A., R. W Arritt, M. Bukovsky and W. J. Gutowski, Jr., 2019: Understanding Sources of Model Uncertainty Through Diagnostic Characteristics of the Great Plains Low-Level Jet. *Fall Meeting*, American Geophysical Union, San Francisco, CA.

Ms. Caruthers is also using the Soil and Water Assessment Tool (SWAT), an ecohydrological model, to evaluate the performance of dynamically downscaled regional climate simulations. The focus has been on how well the regional simulations produced under FACETS replicate the observed hydrology of the Upper Mississippi Basin. RCM output used by SWAT comes from simulations of contemporary climate run at 12.5-, 25- and 50-km grid spacing by RegCM4 and WRF-ARW, using ERA-Interim boundary conditions. The simulated streamflow produced by SWAT is too high compared to observations. Further diagnosis shows that the excessive streamflow is an outcome of a positive precipitation bias that tends to increase as RCM resolution becomes finer. Results are being finalized as Ms. Caruthers completes her thesis.

Caruthers, A., R. W Arritt, M. Chen, P. W Gassman and W. J. Gutowski, Jr., 2020: Using the Soil and Water Assessment Tool to Evaluate the Performance of Dynamically Downscaled Regional Climate Models. *Fall Meeting*, American Geophysical Union (virtual presentation).

In work partially supported by FACETS, the Iowa State team evaluated a common set of metrics for regional-model performance when downscaling for several CORDEX regions around the world.

Glisan, J. M., R. Jones, C. Lennard, N. I. Castillo Pérez, P. Lucas-Picher, A. Rinke, S. Solman and W. J. Gutowski, Jr., 2019: A Metrics-Based Analysis of Seasonal Daily Precipitation and Near-Surface Temperature within Seven CORDEX Domains. *Atmospheric Science Letters,* Article ASL897 (online) https://doi.org/10.1002/asl.897.

Additional work by W. Gutowski that had partial support from FACETS evaluated the quality of CMIP6 simulations of North American contemporary climate. These global simulations will provide the foundation for future regional-climate downscaling, so understanding their characteristics is important for future regional modeling work.

Almazroui, M., M. N. Islam, F. Saeed, S. Saeed, M. Ismail, M. A. Ehsan, I. Diallo, E. O'Brien, M. Ashfaq, D. Martínez-Castro, T. Cavazos, R. Cerezo-Mota, M. K. Tippett, W. J. Gutowski., E. J. Alfaro, H. G. Hidalgo, A. Vichot-Llano, J. D. Campbell, K. Shahzad, I. Ur Rashid, T. Stephenson, M. Taylor, M. Barlow, 2021: Projected changes in temperature and precipitation over the United States, Central America and the Caribbean in CMIP6 GCMs. *Earth Systems and Environment,* [DOI: 10.1007/s41748-021-00199-5].

Differential Credibility Analysis within and across Downscaling Methods

As a precursor to work for HyperFACETS, a pilot project on differential credibility analysis across downscaling methods is continuing under FACETS, to be completed in by Spring 2022. This work involves application of multiple downscaling methods to a domain covering the southern Great Plains (SGP). Dynamical downscaling simulations used include those of two regional models (WRF and RegCM4, part of the NA-CORDEX dataset) and one variable resolution model (MPAS) at 25 km. In this pilot all are driven by the MPI AOGCM for a current and future period. The statistical downscaling methods include: LOCA, SDSM and two bias-correction methods, KDDM and mBCN. We have also developed a machine-learning (ML) downscaling method using a convolutional neural net (CNN). The results of the models driven by a second GCM will be added (e.g., HadGEM) for comparison purposes.

Results have been produced for 20 points over the region using all methods. Changes (current vs. later 21st century) in monthly mean max, min temperature and precipitation focusing on the summer months (April - September) have been analyzed. Interesting contrasts in results across the methods are seen. RegCM, WRF, and SDSM show largely increases in precipitation April - June, whereas KDDM, mBCN, and LOCA show mainly no change or decreases in April-June. Throughout July-September there is more agreement across methods, showing decreases. Interesting contrasts in changes in maximum and minimum temperatures are also seen. Analyzing causes for these differences is ongoing, including analysis of biases and changes in the predictor

variables for the ESD methods as well as the same variables for the dynamical downscaling methods.

To investigate whether the different downscaling methods are getting "the right answers for the right reasons," we have divided days in the analysis period into three groups based on the amount of precipitation (none, low, or high) at one of the 20 points in the region. We then averaged the upper atmosphere variables used as inputs for downscaling on these days to get average dry-, moist- and wet-day synoptic conditions. We are now working to compare these results to observations and overall climatology and interpret the differences.

> Mearns, L., M.S. Bukovsky, R.R. McCrary, S.A. McGinnis, K. Sakaguchi, R. Leung and S. Pryor, 2019: Differential Credibility of Statistical and Dynamical Downscaled Future Climate Projections in the Southern Great Plains. Fall Meeting AGU 2019, A54F-02

An additional key component of this work that is strongly linked to FACETS DCA work is the development of a robust framework to objectively apply differential credibility to climate projections made with empirical-statistical downscaling (ESD) using output from different GCMs.

> Pryor S.C. and Schoof J.T. (2020): Differential credibility assessment for statistical downscaling. *Journal of Applied Meteorology and Climatology* **59** 1333-1349.

> Schoof J.T., Pryor S.C., and Ford T. (2019): Projected changes in United States regional extreme heat days derived from bivariate quantile mapping of CMIP5 simulations. *Journal of Geophysical Research: Atmospheres* **124** 5214-5232.

> Pryor S.C. and Schoof J.T. (2019): A hierarchical analysis of the impact of methodological decisions on statistical downscaling of daily precipitation and air temperatures. *International Journal of Climatology* **39** 2880-2900.

Multi-Sector Dynamics: Wind Energy

Wind energy is (i) a potential mechanism to reduce climate forcing, (ii) a weather, and thus climate, dependent energy source and (iii) a source of impacts on near-surface climate properties adjacent to operating wind turbines because as they harvest kinetic energy they increase turbulence intensity and mixing in the lower atmospheric boundary layer. Our research is generating new projections of climate change mitigation potential from wind energy, and analyzing the mechanisms and magnitude of potential impacts of climate non-stationarity on wind resources and operating conditions (Pryor et al. 2020c). We have improved understanding of, and numerical descriptions of, 'wakes' (region of disturbed air behind a wind turbine and wind turbine arrays) and their impact on system-wide efficiency and near-surface climates both for contemporary wind turbine deployments (Pryor et al. 2020b; Shepherd et al. 2020) and for wind turbine deployments sufficient to achieve the 20% of US electricity supply by 2030 (Pryor et al. 2020a). To maximize dissemination of the results to relevant stakeholders, Pryor and Barthelmie wrote a short non-technical precis of this research for the trade magazine *Windtech International* for its May/June 2020 issue.

Further scholarly products included:

Pryor S.C., Barthelmie R.J. and Shepherd T.J. (2020a): 20% of US electricity from wind will have limited impacts on system efficiency and regional climate. *Nature: Scientific Reports* **10** 541 *doi:*10.1038/s41598-019-57371-1

Pryor S.C., Shepherd T.J., Volker P., Hahmann A.N. and Barthelmie R.J. (2020b): 'Wind theft' from onshore wind turbine arrays: Sensitivity to wind farm parameterization and resolution. *Journal of Applied Meteorology and Climatology* **59** 153-174.

Pryor S.C., Shepherd T.J., Bukovsky M. and Barthelmie R.J. (2020c): Assessingthe stability of wind resource and operating conditions. *Journal of Physics: Conference Series* **1452** 012084 doi: 10.1088/1742-6596/1452/1/012084.

Pryor S.C., Shepherd T., Volker P., Hahmann A., and Barthelmie R.J. (2020d): Diagnosing systematic differences in predicted wind turbine array-array interactions. *Journal of Physics: Conference Series* **1618** 062023 doi:10.1088/1742-6596/1618/6/062023..

Shepherd T.J., Barthelmie R.J. and Pryor S.C. (2020): Sensitivity of wind turbinearray downstream effects to the parameterization used in WRF. *Journal of Applied Meteorology and Climatology* **59** 333-361.

Barthelmie R.J., Shepherd T.J., Aird J.A. and Pryor S.C. (2020): Power and wind shear implications of large wind turbine scenarios in the U.S. Central Plains. *Energies* ***13***(16) 4269 doi: 10.3390/en13164269. ** *this article also reports a partial validation*.

Aird J.A., Barthelmie R.J., Shepherd T.J. and Pryor S.C. (2021): WRF-simulated Low-Level Jets over Iowa: Characterization and sensitivity studies. *Wind Energy Sciences* **6** 1015-1030, doi: 10.5194/wes-2020-113.

Multi-Sector Dynamics: Land-Atmosphere Interactions

Drs. Jing Gao and Brian O'Neill, under partial FACETS support, improved existing long-term, urban land-change modeling in three key aspects: (1) their model captures changes in urbanization styles over time; (2) local-scale spatial variations in urbanization are accounted for by treating the world as 375 sub-national regions each with their own unique models; and (3) the method is capable of modeling the emergence of new urban centers (calibrated to detailed time-series data), in contrast to expanding existing urban centers for new development.

Dr. Melissa Bukovsky produced multiple WRF simulations that included multiple, different scenarios of urban/built-land change provided by the work of Gao and O'Neill, and that also incorporated other projected anthropogenic land-use changes produced by Gao and O'Neill. She then analyzed the impacts of the land-use changes on the overall regional climate change for all of the contiguous U.S. She published this work and also presented it at multiple venues. The work shows that local-to-regional climate change projections of temperature and precipitation are strongly influenced by urban and agricultural land-use changes, and that the urban land expansion has a much greater influence on the climate change projections than the agricultural land expansion.

Gao, J. and O'Neill, B.C., 2019. Data-driven spatial modeling of global long-term urban land development: The SELECT model. *Environmental Modelling & Software*, *119*, pp.458-471.

Gao, J., and B. C. O'Neill, 2020: Mapping global urban land for the 21st century with data-driven simulations and Shared Socioeconomic Pathways. *Nature Communications,* 11, 2302. https://doi.org/10.1038/s41467-020-15788-7

Bukovsky, M.S., J. Gao, L. Mearns, B. O'Neill, 2021: SSP-based land use change scenarios: a critical uncertainty in future regional climate change projections. *Earth's Future,* 9, e2020EF001782. https://doi.org/10.1029/2020EF001782

Presentations:

- Bukovsky, M.S., 2021: The Influence of Future Land-Use Changes on Regional Climate Change Projections. NCAR/RAL Seminar Series, 2 June 2021.
- Bukovsky, M.S., 2021: The Influence of Future Land-Use Changes on Regional Climate Change Projections. Iowa State University, 26 March 2021
- Bukovsky, M.S., 2021: The Influence of Future Land-Use Changes on Regional Climate Change Projections. University of Michigan, 9 April 2021.
- Bukovsky, M.S., J. Gao, and L.O. Mearns, 2020: Extreme Event Exposure Uncertainty in NA-CORDEX Projections. Poster. AGU Fall Meeting, online-only due to pandemic.
- Bukovsky, M.S., L.O. Mearns, J. Gao, B. O'Neill, 2020: The Sensitivity of Regional Climate Projections to SSP-Based Land Use Changes in the North American CORDEX Domain. Presentation. EGU General Assembly, Vienna, Austria. 4 May 2020. Online presentation due to pandemic.
- Bukovsky, M.S., L.O. Mearns, J. Gao, B. O'Neill, 2020: The Sensitivity of Regional Climate Projections to SSP-Based Land Use Changes in the North American CORDEX Domain. Poster. AAG 2020, Denver, CO. Cancelled due to pandemic.
- Bukovsky, M.S., 2019: Exotic Uncertainties in NA-CORDEX**.** IUGG, Montreal, Canada. 11 July 2019. [invited presentation]
- Bukovsky, M.S., L.O. Mearns, J. Gao, B. O'Neill, 2019: The Sensitivity of Regional Climate Projections to SSP-Based Land Use Changes in the North American CORDEX Domain. Poster. EGU General Assembly, Vienna, Austria. 10 April 2019.
- Gao, J., O'Neill, B., 2019. Spatially-explicit global urban land expansion scenarios consistent with the Shared Socioeconomic Pathways. Scenarios Forum 2019. Denver, Colorado: March 11-13.
- Bukovsky, M.S., L.O. Mearns, J. Gao, B. O'Neill, 2019: The Sensitivity of Regional Climate Projections to SSP-Based Land Use Changes in the North American CORDEX Domain. *Scenarios Forum 2019*, Denver, CO. 12 March 2019. [invited presentation]

Land-atmosphere coupling is a major driver of regional climate variability and climate change feedbacks. Nowhere is this coupling more pronounced than over the Tibetan Plateau. Research by the Cornell team has advanced understanding of the linkages between surface sensible heat fluxes over the Tibetan Plateau and indices of the East Asian winter monsoon and wintertime near-surface air temperatures over China.

Chen L., Zhang R., Pryor S.C., Li X. and Wang H. (2020): Coupling of Wintertime Surface Sensible Heat Flux Variability over the Central and Eastern Tibetan Plateau to the East Asian Winter Monsoon. *Climate Dynamics.* Available in early online release: https://doi.org/10.1007/s00382-020-05246-x

Chen L., Pryor S.C., Wang H. and Zhang R. (2019): Distribution and variation of the surface sensible heat flux over the central and eastern Tibetan Plateau: Comparison of station observations and multi-reanalysis products. *Journal of Geophysical Research: Atmospheres* **124** 6191-6206.

In work at Iowa State, Livneh, NCDC and PRISM climate data were evaluated in uncalibrated and calibrated SWAT models for the Upper Mississippi River Basin (UMRB). The SWAT simulations, performed by Manyu Chen (visiting PhD student to Iowa State) under the guidance of Dr. Phil Gassman, were performed in combination with two PET methods: Hargreaves and Penman-Monteith. The SWAT model performed well based on calibration at three gauge sites and spatial validation at 10 other gauge sites. Overall, the PRISM data exhibited the strongest reliability and the Hargreaves method was found to be the preferred PET option for the UMRB. Further work assessed the impact on runoff simulation accuracy from input data quality and the process of watershed delineation. This work contributed to a review of SWAT applications, performance and future needs for simulation of hydro-climatic extremes

Chen, M., P. W. Gassman, R. Srinivasan, Y. Cui and R. W. Arritt, 2020: Analysis of alternative climate datasets and evapotranspiration methods for the Upper Mississippi River Basin using SWAT within HAWQS. *Science of the Total Environment*, 720, 137562. https://doi.org/10.1016/j.scitotenv.2020.137562

Chen, M., Y. Cui, P. W. Gassman and R. Srinivasan, 2021: Effect of Watershed Delineation and Climate Datasets Density on Runoff Predictions for the Upper Mississippi River Basin Using SWAT within HAWQS. *Water*, 13, 422. https://doi.org/10.3390/w13040422

Tan, M. L., P. W. Gassman, X. Yang and J. Haywood, 2020: A review of SWAT applications, performance and future needs for simulation of hydro-climatic extremes. *Advances in Water Resources*, 143, 103662. https://doi.org/10.1016/j.advwatres.2020.103662

Multi-Sector Interactions: Climate Information for Regions and Stakeholders

Members of the project team, with other collaborators, completed publication in *BAMS* of a paper that promotes future directions for regional climate modeling: The Ongoing Need for High-Resolution Regional Climate Models: Process Understanding and Stakeholder Information. Work on the paper began under both FACETS and the Hyperion project.

Gutowski, W. J., A. Hall, R. Leung, T. O'Brien, C. Patricola, P. Ullrich, R. W. Arritt, M. Bukovsky, K. V. Calvin, Z. Feng, A. D. Jones, G. J. Kooperman, E. Monier, M. S. Pritchard, S. Pryor, Y. Qian, A. M. Rhoades, A. F. Roberts, K. Sakaguchi, N. Urban, C. Zarzycki, 2020: The ongoing need for high-resolution regional climate models: Process

understanding and stakeholder information. *Bulletin of the American Meteorological Society.* (online) https://doi.org/10.1175/BAMS-D-19-0113.1
Supplemental material: https://doi.org/10.1175/BAMS-D-19-0113.2

This work was further disseminated at subsequent conferences:

- Gutowski, W.J., 2020: Future Opportunities for Stakeholder-Relevant Regional Climate Modeling. *Advancing Research for Regional Climate Information,* a virtual workshop hosted by Univ. of Graz, Austria, June 2020. [invited]
- Gutowski, W.J., P. Ullrich, A. Hall, L. R. Leung, T. O'Brien and C. Patricola, 2020: The Ongoing Need for High-Resolution Regional Climate Models: Process Understanding and Stakeholder Information. *Fall Meeting – American Geophysical Union*, virtual meeting, December 2020. [invited]

With partial support from FACETS, the Iowa State team in collaboration with others at Iowa State have explored the co-production of actionable climate information with community groups. The transdisciplinary research involved collaboration between the humanities, climate science and various communities. The working hypothesis was that such collaboration could be stimulated, even deepened, by approaching social-environmental simulation models as narrative-makers that produce stories with gaps that become spaces where communities can insert their experiences, needs, and values. The project group developed a storytelling- and gaps-based methodology for using computer simulation that allows communities and researchers to enter into, and transform, each other's stories. The research developed over three years of partnership with community groups, women farmland owners, and university students.

Shenk, L., K. Franz and W. J. Gutowski, 2021: Minding the Gaps to S(t)imulate Collaborative Storytelling: How Humanists, Climate Scientists, and Communities Can Co-Produce Narratives for Action. *Environmental Humanities* (submitted).

Weather and climate extremes

Because of internal variability in both the real-world and global climate models, it is unclear whether disagreement between models and observations reflects true systematic differences, or different phasing of internal variability in the short observational period. A study undertaken by UCLA scientists addressed this issue through an examination of moderate-to-heavy precipitation in large ensembles of global climate models. They found that model inconsistency with a global observational product is lowest for extratropical precipitation in northern hemisphere winter. The inconsistency is systematically greater for the southern hemisphere winter, but the difference between hemispheres could be due to observational quality. Moderate-to-heavy extratropical winter precipitation is less inconsistent than moderate-to-heavy tropical precipitation in most models. Within the tropics, moderate-to-heavy precipitation is particularly inconsistent with the reference in regions including the Caribbean (especially during JJA), the northern and southern flanks of the Pacific and Atlantic ITCZ, and the Indian Ocean.

Goldenson, Naomi, C Thackery, A Hall, DL Swain, and N Berg. 2021. "Using Large Ensembles to Identify Regions of Systematic Biases in Moderate-to-Heavy Daily Precipitation." *Geophysical Research Letters* 48 (9): e2020GL092026. DOI:10.1029/2020GL092026

UCLA scientists performed a study focusing on quantifying future anthropogenic changes in surface runoff associated with extreme precipitation in California's Sierra Nevada. The method involves driving a land surface model with output from a high resolution regional atmospheric simulation of the most extreme atmospheric rivers (ARs). AR events were selected from an ensemble of global climate model simulations of historical and late 21st century climate under the "high-emission" RCP8.5 scenario. They found that average precipitation during the future ARs increases by ~25% but a much lower proportion falls as snow. The resulting future runoff increase is dramatic—nearly 50%, reflecting both the precipitation increase and simultaneous conversion of snow to rain. The "double whammy" impact on runoff is largest in the 2,000–2,500 m elevation band, where the snowfall loss and precipitation increase are both especially large. These findings are very significant because this huge increase in runoff during the most extreme AR events could present major flood control challenges for the region.

Huang X, S Stevenson, and A Hall, 2020: Future warming and intensification of precipitation extremes: a "double whammy" leading to increasing flood risk in California. *Geophysical Research Letters,* 47, e2020GL088679. DOI: 10.1029/2020GL088679

UCLA scientists undertook a study to quantify the uncertainty surrounding future intensification of high-magnitude atmospheric river (AR) events, which are often inadequately resolved by global climate models. They developed a framework involving targeted dynamical downscaling of historical and future extreme precipitation events produced by a large ensemble of a global climate model (CESM LENS). This framework is applied to extreme AR storms in California. They found a substantial (10 to 40%) increase in total accumulated precipitation, with the largest relative increases in valleys and mountain lee-side areas. They also report even higher and more spatially uniform increases in hourly maximum precipitation intensity, which exceed Clausius-Clapeyron expectations. Up to 85% of this increase arises from thermodynamically driven increases in water vapor, with a smaller contribution by increased zonal wind strength. These findings imply substantial challenges for water and flood management in California, given future increases in intense atmospheric river-induced precipitation extremes.

Huang, X, DL Swain, and A Hall. 2020. Large ensemble downscaling of atmospheric rivers. *Science Advances* 6 (29): e2020GL088679. DOI: 10.1126/sciadv.aba1323

To investigate the impacts of urbanization on heat extremes and storms, simulations have been performed at km grid spacing over the U.S. using the WRF model with an urban canopy model. To isolate the urban heat island effect and anthropogenic heat, simulations have been performed to include both urban land cover and anthropogenic heat, urban land cover only, and neither urban land cover nor anthropogenic heat. Comparison of these simulations shows a mean summer urban heat island (UHI) effect ranging between 2-5oC and urban-induced dryness (UQI) of 0.01-2 g/kg. While UHI peaks during nighttime, UQI is maximum during daytime. Urban heat stress island (UHSI) is very sensitive to the background temperature, with urban-induced human discomfort increasing by ~5 hours per day for each degree rise in the background temperature. Largest sensitivity is found in southeastern U.S. during nighttime (Sarangi et al., in review).

Sarangi, C. Y. Qian, J. Li, L.R. Leung, T. Chakraborty, and Y. Liu, 2021: Urbanization Amplifies Nighttime Heat Stress on Warmer Days over the US. *Geophysical Research Letters,* in review.

To investigate the impacts of local SST warming on the hydroclimate and extremes in western U.S., Chen et al. (2020, 2021) performed simulations using WRF at 6 km grid spacing over western U.S. and eastern Pacific with and without SST warming in the northeastern Pacific near the U.S. west coast. Chen et al. (2020) found that local SST warming increases atmospheric river (AR) frequency across the U.S. west coast by expanding AR spatial coverage and increasing AR occurrences. Although AR moisture increases only by 0.4% per degree of local SST warming, extreme precipitation increases by 3% per degree of local SST warming in the west coast as local SST warming not only increase AR moisture but also intensify storms by destabilizing the lower atmosphere. The simulations with and without local SST warming were also used to investigate of the impact of local SST warming on U.S. west coast mountain snowpack (Chen et al. 2021). Local SST warming leads to warmer winter with more precipitation over the mountains. As a result, winter snow accumulation decreases by ~200 mm per season in the Cascade Mountains in the north but increases by ~100 mm per season in the Sierra Nevada in the south. The dipole response results from the competing effects of precipitation and temperature change at different elevations and are amplified by the enhanced atmospheric river moisture transport.

Chen, X., and L.R. Leung, 2020: Response of Landfalling Atmospheric Rivers on the U.S. West Coast to Local Sea Surface Temperature Perturbations. *Geophysical Research Letters,* 47, e2020GL089254, doi:10.1029/2020GL089254.

Chen, X., L.R. Leung, Y. Gao, and Y. Liu, 2021: Response of U.S. West Coast Mountain Snowpack to Local SST Perturbations: Insights from Numerical Modeling and Machine Learning Models. *Journal of Hydrometeorology*, 22, 1045-1062, doi:10.1175/JHM-D-20-0127.1.

The PNNL team used circular statistics to define a seasonality index that reflects the variability of flood occurrence date. The seasonality of annual maximum floods (AMF) has been examined for over 250 natural catchments across the contiguous US.

Ye, S., H.-Y. Li, L.R. Leung, J. Guo, Q. Ren, Y. Demissie, and S. Murugesu, 2017: Understanding Flood Seasonality and its Temporal Shifts within the Contiguous United States. *Journal of Hydrometeorology,* 18, 1997-2009, doi:10.1175/JHM-D-16-0207.1.

The Cornell team applied and evaluated a range of Generalized Extreme Value methods to derive extreme wind speed and wave conditions at the global scale:

Pryor S.C. and Barthelmie R.J. (2021): A global assessment of extreme wind speeds for wind energy applications. *Nature Energy* **6** 268-276 doi: 10.1038/s41560-020-00773-7.

The Cornell team also extended the machine learning for statistical downscaling research to include applications to extreme wind gusts:

Coburn J.J. and Pryor S.C.: Do machine learning approaches offer skill improvement for short-term forecasting of wind gust occurrence and magnitude? *Weather and Forecasting (in review)*.

Mr. Jacob Spender completed a Master’s degree at Iowa State entitled, “Sensitivity of Sub-Daily

Extreme Winter Precipitation to Model Resolution". Analyzing FACETS RCM simulations of contemporary climate by WRF and RegCM, he showed that simulation of six-hourly extreme precipitation was relatively insensitive to resolution in RegCM, but improved markedly with resolution to agree well with observations for 12-km grid spacing.

> Spender, J., 2019: Sensitivity of sub-daily extreme winter precipitation to model resolution, M.S. thesis, Iowa State University, 35 pp.
>
> Spender, J. R., and W. J. Gutowski, 2020: Sensitivity of sub-daily extreme winter precipitation to model resolution. *Fall Meeting – American Geophysical Union*, virtual meeting, December 2020.

Work by Drs. Brandon Fisel and William Gutowski at Iowa State identified drought events over the contiguous U.S.A. using the Method for Object-Based Diagnostic Evaluation (MODE) Time Domain (MTD) software. Using daily precipitation from the Community Earth System Large Ensemble (CESM-LE) for four time periods: contemporary (1981 - 2010) and scenario (2011 - 2040, 2041- 2070, and 2071 - 2099) under RCP 8.5, 36-month running-average Standardized Precipitation Index (SPI) provided input to MTD to identify persistent events. CRU and PRISM data providedobservational comparisons. They used SPI thresholds to evaluate moderate (-1.0 > SPI > -2.0) and extreme (SPI < -2.0) drought events for six analysis regions covering the continental U.S. based on Seneviratne et al. (2012, IPCC SREX). Persistent drought events increase in the southwestern U.S., but generally decrease in other regions of the country, including the northeastern U.S. that is the subject of storyline study in HyperFACETS.

> Fisel, B. J., E. E. Linde and W. J. Gutowski, 2020: Evaluating Multi-Year Drought Events for the Contiguous U.S. in Contemporary and Scenario Climates using Object-Oriented Analysis. *Fall Meeting – American Geophysical Union*, virtual meeting, December 2020.
>
> Fisel, B., and W. J. Gutowski, 2020: Projections of persistent drought events for the continental U.S. in the NCAR CESM Large Ensemble. (in preparation)

Dr. Gutowski also contributed to additional work, partially supported by FACETS, analyzing drought simulations using MODE software. The analysis demonstrated the capability of MODE as a tool to evaluate and monitor drought events in both observations and simulations.

> Abatan, A. A., W. J. Gutowski, Jr., C. M. Ammann, L. Kaatz, B. G. Brown, L. Buja, R. Bullock, T. Fowler, E. Gilleland and J. H. Gotway, 2018: Statistics of multi-year droughts from the method for object-based diagnostic evaluation. *International Journal of Climatology,* **38,** 3405-3420 [DOI: 10.1002/joc.5512].

Further work by Drs. Fisel and Gutowski with various undergraduates at Iowa State has used the Tempest Extremes object-oriented analysis (Ullrich and Zarzycki, 2017, *Geosci. Model Dev.*) to diagnose and analyze the climatology various extreme events (e.g., heavy precipitation, "flash" droughts) using output from regional climate simulations produced under FACETS. These events provide a foundation for storyline approaches to communicating climate-change information.

> Fisel, B. J., A. L. Ellingworth, L. S. Shenk and W. J. Gutowski, 2020: Evaluating Five-Day Precipitation Events for the Contiguous U.S. in Contemporary and Scenario Climates using

Object-Oriented Analysis. *Fall Meeting – American Geophysical Union*, virtual meeting, December 2020.

Gutowski, W., B. Fisel, A. Ellingworth, N. Erickson, E. Linde, C. Todesco and L. Shenk, 2021: Object-oriented analyses of precipitation and drought for stakeholder storylines. *HyperFACETS Project Spotlight Session*, virtual presentation, July 2021.

Fisel, B. J., N. Erickson and W. J. Gutowski, 2021: Heavy Precipitation Events Influencing Missouri River Flooding in Contemporary and Scenario Climates. *Fall Meeting – American Geophysical Union*, December 2021.

Gutowski, W., B. Fisel and C. Todesco, 2021: Flash Droughts Impacting Agriculture in Contemporary and Future Scenario Climates. *Fall Meeting – American Geophysical Union*, December 2021.

Snow Work

As a predecessor to the ephemeral snow work proposed in HyperFACETs, R. McCrary examined snow (means and extremes) in the NA-COREX simulations and CMIP5 models. This work resulted in multiple presentations and two papers. The first paper was submitted (initial submission October 2020; revised and resubmitted August 2021) to *Climatic Change.* The paper had two main goals: 1) to evaluate the historical climatology of snow water equivalent (SWE) over North America in the NA-CORDEX 0.5º and 0.25º simulations and their driving GCMs. 2) to examine future changes in SWE over North America in the same simulations and identify any added information and reliability that the higher resolution simulations provide. In the second paper, R. McCrary collaborated with people outside the project to look at future changes in snowmelt extremes over North America. This work was accepted into *Geophysical Research Letters* in October 2021.

McCrary, R.R., L.O. Mearns, M. Hughes, S. Biner, M.S. Bukovsky, 2021: Projections of North American Snow from NA-CORDEX and their Uncertainties, with a Focus on Model Resolution. *Climatic Change*. (In Review)

Cho, E., R.R. McCrary, J.M. Jacobs, 2021: Future Changes in Snowpack, Snowmelt, and Runoff Potential Extremes over North America. *Geophysical Research Letters*. (Accepted)

Presentations:

- McCrary, R. and L.O. Mearns, 2020: Comparison of gridded snow water equivalent (SWE) products over the Eastern US. 2020 Annual Eastern Snow Conference (Cancelled due to COVID-19)
- McCrary, R. and L.O. Mearns, 2020: What can moderate resolution climate model simulations tell us about future changes in snowpack and snow melt? 2020 Annual Western Snow Conference (Cancelled due to COVID-19).
- McCrary, R., E. Cho, J.M. Jacobs, L.O Mearns, 2020: Evaluation of Snow Water Equivalent and Snowmelt Processes in the NA-CORDEX Regional Climate Simulations, 100th American Meteorological Society Annual Meeting. January 2020. (Poster)
- McCrary, R., M. Bukovsky, L. Mearns, 2018: Uncertainty in Future Changes in Snowpack and Rain-on-Snow events in the US Northern Great Plains using High-Resolution Climate

models. *75th Eastern snow conference*. June 2018. (Talk)
- McCrary, R and L. O. Mearns, 2018: Uncertainty in the Future of Seasonal Snowpack over North America. *86th Western Snow Conference*. April 2018. (Talk)

Data Archive

Dr. McGinnis archived data generated for this project by simulations of WRF and RegCM4. He augmented the dataset with derived data products (regridding the data to a common grid and aggregating averages and climatologies at longer frequencies) and made these datasets available to the community. He will continue work to publish this dataset via the NCAR Climate Data Gateway as adjunct datasets to the NA-CORDEX Data Archive as part of HyperFACETS. FACETS also provided support for the ongoing operation of the NA-CORDEX Data Archive and the publication of derived data products including bias-correction and visualizations, assisting users with data access and provisioning, and work to correct an error in bias-corrected data that was recently discovered. He published a paper with Dr. Mearns in the journal *Climate Services* describing the data archive, and made several presentations on work related to bias-correction and the NA-CORDEX data archive at conferences.

McGinnis, S., and L.O. Mearns, 2021: Building a climate service for North America based on the NA-CORDEX data archive. *Climate Services*, **22,** 100233.

Galmarini, S., A. J. Cannon, A. Ceglar, O. B. Christensen, N. de Noblet-Ducoudré, F. Dentener, F. J. Doblas-Reyes, A. Dosio, J.M. Gutierrez, M. Iturbide, M. Jury, S. Lange, H. Loukos, A. Maiorano, D. Maraun, S. McGinnis, G. Nikulin, A. Riccio, E. Sanchez, E. Solazzo, A. Toreti, M. Vrac, and M. Zampieri, 2019: Adjusting Climate Model Bias for Agricultural Impact Assessment: how to cut the mustard. *Climate Services*, **13,** 65-69.

Datasets:
- Rendfrey, T., M. Bukovsky, and S. McGinnis, 2018. "NA-CORDEX Visualization Collection" UCAR/NCAR, Boulder CO. [https://doi.org/10.5065/90ZF-H771]
- Mearns, L.O., et al., 2017: *The NA-CORDEX dataset*, version 1.0. NCAR Climate Data Gateway, Boulder CO. [https://doi.org/10.5065/D6SJ1JCH]

Presentations:
- McGinnis, Seth. “Bursts and Cascades: Scaling Up Scientific Data Analysis.” SEA Software Engineering Conference and Tutorials, Boulder CO, 11 April 2018.
- McGinnis, Seth, Harry Podschwit, Alison Kessenich, Linda Mearns, and Alison Cullen. “Projected Effects of Climate Change on Simultaneous North American Megafires Based on NA-CORDEX Regional Climate Simulations.” GC081-07, presented at 2020 Fall Meeting, American Geophysical Union, 14 Dec 2020.
- McGinnis, Seth, Melissa Bukovsky, Rachel McCrary, and Linda Mearns. “Comparison of Univariate and Multivariate Bias-Correction of Daily NA-CORDEX Data.” Fall Meeting, American Geophysical Union, Washington DC, 11 Dec 2018.

Modeling Work and Methods Development

Much of the research described above used simulations produced under FACETS. To facilitate the examination of results across a hierarchy of model types and resolutions, Drs. Bukovsky and Arritt produced 12.5-km, 25-km and 50-km simulations with WRF-ARW and RegCM4 using ERA-Interim and 3 different GCMs (GFDL, HadGEM2 and MPI) as boundary conditions. These simulations continue to be used in HyperFACETS.

FACETS incorporated diverse climate regionalization approaches including multiple Empirical Statistical Downscaling (ESD) methods. We have developed new multivariate bias correction methods to improve heatwave projections (Schoof et al. 2019, referenced above) and a new hierarchical framework to quantify value-added by different ESD methodological decisions (Pryor and Schoof, 2019, referenced above).