Towards actionable science: assessment of water availability under climate change and climate intervention scenarios

Lead PIs: Jadwiga (Yaga) Richter (CGD), Ethan Gutmann (RAL), Mari Tye (CGD)
Co-PIs: Cindy Bruyere (MMM/UCAR Pres Office), Sue Ellen Haupt (RAL), Andrew Newman (RAL), Andy Wood (CGD/RAL)
University Collaborator: Flavio Lehner, Cornell University

Overview:
The 2020 - 2024 NCAR Strategic Plan is focused on "science with and for society" and calls for advancing scientific understanding of the Earth system inspired by urgent scientific and societal needs. One of the specific goals of this new strategic plan is research on the topic of water availability and food security, which is driven by societal drivers such as the enhancement of human health and well-being. In addition, the new strategic plan calls for policy-relevant research related to climate change, and climate intervention strategies. The realization of the goals of this strategic plan requires a shift towards more actionable Earth system science, new methodologies, new collaborations, and partnerships both internally and externally. With this proposal we are seeking support for the growth of interdisciplinary capabilities aligned with the new NCAR strategic plan with a focus on the ***assessment of water availability under climate change and climate intervention scenarios***. This effort would be a seed effort towards a greater organizational shift focused on actionable Earth system science, promoting collaborative, cross-NCAR initiatives in service to and for society.

The proposed effort will be divided into three tasks: A) investigation of the most pertinent diagnostics for water availability, B) application of newly developed diagnostics to CESM simulations under climate change and climate intervention scenarios, C) exploration of new techniques to be added to CESM to facilitate societally relevant outputs/diagnostics. An approximate breakdown of the budget by task is provided in case funding for the entire effort is not available. This work will also open the door for rigorous benchmarking of our diagnostics for water applications and we'll look for future funding using this proposal's outcomes.

Explanation of the scientific merit of the proposal:
Water availability and water quality for human consumption, ecosystems, and agriculture are fundamental to the well-being of societies across the world. Assessment of water availability under climate change and climate intervention scenarios is crucial to decision makers and resilience of communities, especially those in developing countries. Ongoing and projected changes in the hydrologic cycle arising from climate change are expected to affect substantial portions of the world population, most directly through changes in water availability at or near the surface, as reflected in runoff, snow water equivalent, soil moisture, or groundwater (Sedlacek et al., 2014; Mankin et al., 2017). Yet the decision-making **relevant** information required by water resource managers is not available in a format or at the spatial or temporal scales within global climate models to support their decisions (e.g. Ekström et al., 2018).

Climate intervention using stratospheric aerosol injection (SAI) is currently the most promising

proposed method of deliberately lowering global temperatures, with the goal of reducing the worst consequences associated with climate change. NCAR is one of the world's leading organizations on global modeling of SAI and together with several partnering organizations has created the first Geoengineering Large Ensemble (GLENS; Tilmes et al. 2018). GLENS is being used by the broader community to evaluate the benefits and side-effects of SAI; However, the focus of analysis has been primarily on physical quantities (precipitation, temperature, soil moisture), but tailored diagnostics that highlight or elucidate their implications for societally relevant changes to water availability in these simulations (or any other global simulations of SAI) have not yet been explored.

In this proposal, we aim to expand policy-relevant assessments of water availability in future climates done at NCAR via cross-lab partnership between CGD, RAL and MMM. CGD brings decades of experience running simulations of historical and future climate (including with climate intervention). MMM and RAL have a proven track record of engaging with decision makers in addressing convergent science questions. RAL and MMM personnel actively work on hydroclimate analyses, predictions (from days to decades), climate-scale projections, and associated methods and models in collaboration with major water agencies and stakeholders. Typically, this work uses global Earth system models (ESMs), such as the NCAR Community Earth System Model (CESM) alone or as part of a larger collection of information derived from dynamical and statistical downscaling or offline models, all of which introduce additional layers of uncertainty. While the climate scale work provides input to policy and planning, little work has been done to use the output from our climate models to derive diagnostics that can directly inform policy and decision makers with regard to water availability. The proposed work will bring together the relationships and experience of the existing actionable science with CESM climate change and climate intervention research to facilitate valuable stakeholder-oriented insights and knowledge sharing and transfer toward external planning and policy partners. A circular benefit of science in service to society is that in addition to prioritizing pressing science questions, stakeholder input often stimulates broader research questions that would otherwise not become apparent.

Approach:

a) Identification of relevant water availability and change diagnostics for interpreting ESM output

Critical water availability pattern features include the seasonality, spatial distribution, and frequency of high impact precipitation and temperature across many time scales (sub-daily to inter-annual). Potential changes in the resultant local to regional hydrologic responses (e.g., runoff, snow water equivalent (SWE), evaporative demand) are a concern for water stakeholders, and currently inaccessible or difficult to interpret directly from ESMs. However, local and regional scale patterns and variability are often evident at the larger scales at which ESMs operate. This prompts us to ask: ***Can we develop a suite of ESM-scale indicators and diagnostics that collectively provide useful information on local to regional scales to inform climate and water risk decisions?***

Many years of effort by agencies, stakeholders and boundary organizations have led to a wealth of knowledge and publications on water stakeholder needs for climate, weather, and water information (e.g., Raff et al, 2013; Lukas et al, 2020; USGCRP, 2018; Brekke et al, 2007). Members of the proposal team have contributed to this work and are engaged in ongoing stakeholder-focused

research applications for managing climate and water risk utilizing regional and local models. We will leverage these resources and extensive prior knowledge within NCAR to identify a suite of diagnostics that can be evaluated for usability from ESM outputs. Based on previous work (e.g. Morss et al. 2018, Towler et al., 2018) we anticipate these will include the probability of exceeding temperature and precipitation thresholds, changes in the intensity or duration of extreme events, or "whiplash" changes between wet and dry extremes (Swain et al., 2018). Meaningful combinations of variables will also be considered, such as SWE/precipitation (an index of the storage role of snowpack), runoff/precipitation, or the difference between precipitation and evaporative demand (an indicator of sufficiency of rainfall for agriculture). We will explore different ways of presenting these diagnostics such that they convey the relevant information for water resource planning. For instance, the seasonality of wet and dry spells, frequency of the associated weather types (Prein et al., 2016) or changes in intensity-duration-frequency (IDF) statistics of precipitation.

In the course of the work, team members will reach out to water sector collaborators (e.g. Bureau of Reclamation, state Departments of Water Resources, US Army Corps of Engineers) and other stakeholders to iterate, refine and develop the suite of diagnostics. Case study examples will be developed, for instance over different watersheds, to assess and communicate the relevance of the diagnostics for water availability and climate-water risk assessment. The case study examples will then be used to initiate conversations with external water collaborators to further refine the diagnostic suite during a half-day virtual workshop.

b) Application of new diagnostics to CESM

The suite of diagnostics developed in Part (a) will be scripted and applied at regional scales to CESM simulations. Because water availability questions often center on a basin perspective, some key diagnostics will be calculated both on the native grid of CESM (~ 1^{o}) and for intermediate-scale global basins (the HydroBasins dataset of Lehner and Grill, 2013, offers 12 spatial aggregation levels). The intention is to assess the utility of these diagnostics in decision making particularly for activities that rely on water availability, such as agriculture or energy production. The diagnostics will be applied to the following simulations with CESM: a) historical simulations (1979 to present day) with CESM1 & CESM2, b) future climate simulations under the RCP8.5[1] scenario from 2015 to 2100 with CESM1 c) future climate simulations under RCP8.5 with SAI (GLENS), d) future climate simulation using the SSP2-4.5 & SSP5-8.5[2] scenarios with CESM2, e) additional simulations with CESM2 with SAI that will be carried out as part of a CGD effort on climate intervention funded by SilverLining (exact details TBD).

c) Exploration of new techniques

There are many ways in which the CESM model usage can be updated, including online and in post-processing in order to provide more usable information for some stakeholder relevant diagnostics such as Mountain Snowpack or sub-daily IDF curves that are used in hydrologic design. In particular, we will investigate the application of techniques to provide physically based modifications to

[1] RCP8.5: Representative Concentration Pathways 8.5 scenario (high emissions)

[2] SSP2-4.5 & SSP5-8.5: Shared Socioeconomic Pathways scenarios

precipitation and temperature on a sub-grid scale, so that in the future, CESM can explicitly simulate a mountain snowpack that is necessary for water resources in many parts of the world. Once our feasibility investigation is complete, we will implement an explicit subgrid scale precipitation and temperature representation within the land component of CESM, the Community Terrestrial Systems Model (CTSM), leveraging the recently developed representative hillslopes feature. This will permit a simplified offline example based on our feasibility study, and the results will be compared with state-of-the-art post-processing performed for the water management community.

Anticipated Outcomes & Approximate Timeline:

a) Identification of most relevant water availability diagnostics for addressing needs of water resource planners and managers, regulators and other key decision-makers. (Months 0-3)
b) Application of water availability diagnostics to CESM simulations of climate change and climate intervention (Months 4-12)
c) A feasibility assessment and initial uncoupled testing of incorporating an appropriate explicit subgrid scale precipitation and temperature representation within CTSM (Months 6-12)

Budget & Personnel Roles:
Summary of requested budget:
Task A: $21,684; **Task B**: $100,000, **Task C**: $40,000; **Total:** $161,684.

Detailed budget can be found at the end of the proposal. Salary support is requested for Associate Scientist II, MMM (0.25 FTE), Associate Scientist II, RAL (0.25 FTE), Project Scientist II: Mari Tye, CGD (0.25 FTE), Project Scientist III: Andy Wood, CGD (80 hrs), Project Scientist III: Ethan Gutmann, RAL (80 hrs), and Project Scientist II: Andrew Newman, RAL (80 hrs). In addition, travel funds are requested for University collaborator Flavio Lehner so he can more effectively interact with the team (if COVID19 status permits).

Personnel roles are as follows:
J. Richter will oversee the overall success of the project and provide access to CESM simulations. **Mari Tye** will coordinate input from internal and external stakeholders to identify the suite of water availability diagnostics and will oversee development of any novel statistical analysis. **Andy Newman, Andy Wood, Ethan Gutmann** will provide input on water availability diagnostics and external stakeholder groups, and guidance for RAL ASII in applying water availability diagnostics and exploring subgrid representation of precipitation and temperature. **Ethan Gutmann** will also lead the effort of exploring new techniques. **RAL and MMM AS II's TBD** will run water availability diagnostics on CESM simulations and help implement and evaluate new online and offline techniques within CESM under guidance of Ethan Gutmann, Andy Wood, and Andy Newman. **Sue Haupt** and **Cindy Bruyere** will provide general guidance and advice on the project.

Cosponsorship will be provided from CGD, RAL, and MMM in the form of time for the following scientists (Richter: 0.1 FTE, Haupt: 0.05 FTE, Bruyere: 0.05 FTE). Mari Tye will utilize ~ 20% of her CGD time (via SilverLining NGO funds for climate intervention research) to work on this project. CGD will also provide administrative support for meetings with stakeholders.

Response to questions/criteria:

How does this project support the organization's strategic plans and why should funding be allocated now?

This proposed project directly responds to the vision for NCAR science being actionable and societally relevant, outlined in the 2020-2024 NCAR Strategic Plan. To realize this vision, specifically with respect to water availability and food security, a shift needs to begin as soon as possible to develop the necessary long-term stakeholder engagement needed for the success of this research. The effort proposed here is envisioned as a seed effort towards growing actionable science at NCAR that can subsequently be expanded to other science foci.

Why is this transformational and what long-term impacts can be expected?

The effort is transformational as it will foster relationships between CGD, RAL, and MMM to integrate decades of experience in climate modeling and climate intervention research (CGD) with that of addressing the needs of stakeholders and decision makers in addressing convergent science questions (RAL, MMM). This seed funding will lead to long-term collaborations and future joint proposals between CGD, RAL, and MMM.

How is this project interdisciplinary?

At its most fundamental level, this project brings together experts from weather, climate, and hydrology to bridge a significant gap that has long existed at NCAR. This project will also connect weather and climate research with engineering and industry.

How will this project promote collaboration across the greater NCAR, UCP, university and/or private sector community?

This project will build a stronger collaboration with Flavio Lehner from Cornell University, who will provide expertise on diagnostics development, model evaluation and modeling choices. It also presents the opportunity to engage university students and postdoctoral researchers and leverage complementary projects at Cornell focused on GCM-based studies of projected hydroclimate variability and its evaluation at different scales.

This project will also expand ongoing RAL and MMM collaborations with key US federal water agencies such as the US Army Corps of Engineers (USACE) and US Bureau of Reclamation by providing new avenues to increase the information available to for water security applications, as well as increase stakeholder confidence in the ESMs themselves. Further, MMM and RAL have ongoing collaborations with engineering consultancies and other private sector entities who will contribute substantially to the selection of water diagnostics and communication of NCAR science more broadly to the wider community.

Have all potential partners (internal & external) and funding sources been explored and leveraged?

This project actively includes partners from three major labs at NCAR (CGD, MMM, and RAL), will seek input from UCP, and in addition leverages climate change and climate intervention simulations that were carried out with CESM-WACCM. CESM-WACCM is a high-top version of the NCAR global climate model developed in collaboration between CGD, ACOM and HAO; simulations carried out

with CESM-WACCM have had contributions from all those labs and from several University collaborators. In addition, the project leverages funds that have recently been granted to NCAR by SilverLining NGO for climate intervention research, and a new NCAR-USACE collaboration that will explore a range of ESM performance metrics and deliberate ensemble design for water security applications sensitive to climate change. This project will also seek to establish collaborations with the 2021-2022 NCAR Early Career Faculty Innovator cohort focused on actionable Earth system science.

Be explicit as to why a strategic investment in this activity can be realistically expected to lead to future funding.

Within NCAR, CGD, MMM, and RAL have been doing research on related topics 'side-by-side' for decades, while collaboration on funding efforts between those labs has been minimal. This seed effort will allow time for conversations and relationship building that is necessary to create lasting collaborations and ideas for pursuing future funding opportunities. We expect funding for climate intervention research focusing on policy relevant impacts to significantly increase over the next years. Furthermore, efforts to utilize ESM outputs are underway among the user community, and as a science leader NCAR/UCAR should promote the best and most readily accessible science. The diagnostics developed here will be directly applicable to Earth system prediction on timescales from seasons to decades which is a high priority among several federal agencies and other more localized decision makers.

What are your metrics and success criteria to demonstrate achievement?

Success will be demonstrated by meeting project deliverables (listed above) - several of which are very specific. In particular, by the end of the project we will have applied new/unique diagnostics of water availability to CESM simulations of climate change and climate intervention and have formed new collaboration/relationships within NCAR and with stakeholders.

What are your milestones for when these metrics will be achieved?

Please see "Anticipated Outcomes & Approximate Timeline" section above.

Proposals that leverage monetary co-sponsorship of at least two Lab/Program Directors will be given priority. Proposals with substantial involvement of a UCAR member university will be given priority.

This proposal leverages co-sponsorship from three NCAR labs and substantially involves an Assistant Professor from Cornell University. We will also seek student involvement at Cornell University as well as a connection to the NCAR Early Career Faculty Innovator Program.

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