Proposed Project Title: Toward Resolving the Holocene Climate Conundrum: A Global Data-Model Evaluation and Synthesis

Scientific Motivation: The last 11,700 years, the Holocene epoch, spans the entire length of human civilization and is generally considered an interval of relative climate stability **(Fig. 1)**. An initial global surface temperature reconstruction of the Holocene suggests that the historically documented 1.0°C global-average warming over the past century spans the full range of Holocene global-average temperature variability and reversed a long-term cooling trend that began nearly 5,000 years ago (Marcott et al., 2013). This work agrees well with other surface temperature studies for the past 2,000 years (Mann et al., 2008; Ahmed et al., 2013). Model projections indicate that 21st century global-average warming will substantially exceed even the warmest Holocene conditions (Collins et al., 2013), producing a climate state not previously experienced by human societies, with long-term climatic implications lasting tens of thousands of years (Clark et al., 2016). However, despite knowing the overall trend of future climate change (Collins et al., 2013), there remains considerable uncertainty in the rates and magnitudes of the model projections with model scenarios exhibiting a relatively wide spread (Knutti and Hegerl, 2008; Rohling et al., 2012).

To reduce the uncertainty of future climate projections, it is essential to develop a longer-term perspective on climate change beyond the instrumental record. This can be accomplished only through paleoclimate studies that integrate both data and modeling research. Major efforts to synthesize and analyze global paleoclimate records and model simulations of the last few million years have mostly focused on the past two millennia (PAGES-2k Network: (Ahmed et al., 2013)), the last deglaciation (SynTraCE-21: Liu et al., 2009; Clark et al, 2012; Shakun et al., 2012; He et al., 2013), and past interglacials (PIGS: (Tzedakis et al., 2012)), with little attention paid to the transient evolution of the Holocene (Marcott et al., 2013; Marcott and Shakun, 2015). Given that the Holocene is the closest analog for today's climate state, contains abundant climate proxies across the globe, and the primary climatic forcings (e.g. insolation, greenhouse gases, etc.) are exquisitely known – coordinated scrutiny of the Earth System over this timeframe using both improved data composites and climate models will provide crucial information regarding future climate change. In particular, the Holocene provides a unique natural benchmark against which to validate state-of-the-art climate models. However, current data-model comparisons point to a potentially *serious inconsistency*. Most Holocene model simulations to-date tend to exhibit a smaller range of regional temperature variability **(Fig. 1c)** than the proxy data on decadal and longer time scales (Laepple and Huybers, 2014), and, furthermore, display a long-term global warming rather than the cooling **(Fig.**

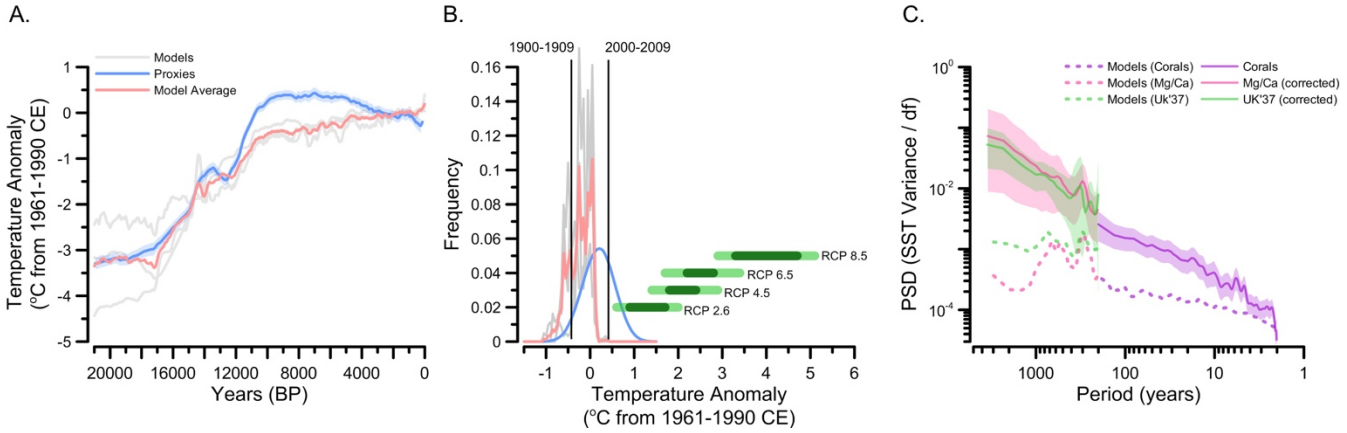

Figure 1. Holocene temperature trends and variability (Marcott and Shakun, 2015). (A) Global mean temperature from proxies (Marcott et al., 2013; Shakun et al., 2012) and models (Liu et al., 2014). **(B)** Histograms of the Holocene time series in (A) showing how the distribution of Holocene temperatures compare to the 20th century instrumental range and IPCC projections for 2100 (Collins et al., 2014). **(C)** Power Spectral Density (PSD) of sea surface temperature variance for Holocene time series (Laepple and Huybers, 2014). RCP = Representative Concentration Pathway. In (A), data (blue) and model (red) exhibit opposite trends over the last 11,000 years, i.e. the Holocene Climate Conundrum.

1a) recorded in the records (Marcott et al., 2013; Liu et al., 2014), creating a discrepancy that has been termed the "**Holocene Climate Conundrum**" (Liu et al., 2014). These problems raise *fundamental questions* in the field of climate reconstructions and climate modeling, with relevance to projecting the future as model simulations are calibrated using both present and past climate scenarios.

- Are we misinterpreting what the proxy record tells us about past climate change, even things as basic as the amount of natural variability and trends in global temperature?
- Or, are models missing key physics in their internal variability and response to major climate forcings?

Both are possibilities and as yet, have not been fully explored by the climate community.

Answering these questions is not trivial, as it requires an entire reevaluation of both the data reconstructions and model simulations. However, determining the cause of the Conundrum is absolutely necessary because the data-model mismatch *challenges the entire field* and some of our principal ideas about paleoclimate proxies and simulations, which feed directly into our understanding of future climate projections from models.

Project Objectives: Taking advantage of the unique opportunity that exists at CCR where both data generators and modelers cohabitate, I propose an interdisciplinary collaboration to fully address the so-called Holocene Climate Conundrum using a comprehensive data-model evaluation and global synthesis. The first phase of developing a global Holocene climate dataset is already underway and will be complete by the end of year 2019 (Marsicek and Marcott, in preparation; PAGES-12k Working Group, in progress). The second phase of improving our simulations of Holocene climate and the potential model disparities that could explain the Holocene Conundrum have not been fully explored. Here I propose to work with Feng He to develop series of modeling experiments to test potential causes of the model-data disparity. To bridge our two research groups, I propose to use the funds from the Reid Bryson Professorship to enlist a postdoctoral researcher who will work with Feng and I on developing modeling simulations with both fully coupled (e.g. CCSM4) and intermediate complexity models (e.g. FOAM, OSU-UVic) to test potential model-based biases (e.g. unaccounted internal feedbacks – aerosols, vegetation, sea-ice parameterization, etc.) that could explain the data-model disagreement. I will leverage the funds from the professorship with potential external (NSF/NOAA postdoc funding) and internal (Dept. Geosciences) funds where possible. Some of the funds from the award will also be used for salary of Feng He to allow him to participate in the collaboration and to begin the initial model simulations during the first year of the project while we recruit a high level postdoctoral candidate.

This proposed work is timely because the Conundrum idea has only recently entered the climate community discourse; the work is of broad interest to the climate community as it will attempt to understand why data reconstructions and model simulation provide divergent results over a relatively well constrained interval (a fundamental problem that can be extended to many other time intervals as well); and the work will be of great interest beyond academia based on the national attention previous work received, both in the popular media (e.g. NYT, WSJ) and in the political spheres (e.g., UN Climate Chief, Congressman Peter DeFazio (OR-D) House floor statement), as it places modern climate change into a historical perspective that can be easily distilled and well understood by nearly everyone.

Broader Impacts: To facilitate an effective interdisciplinary study, I propose to hold a 3 credit course (AOS-Geos 960) on paleo-proxy data methods and climate modeling systematics. Prior version of this course have been quite successful (Geos 875 – Fall 2014, Spring 2016) where I explored climate changes over the late Pleistocene and Feng He attended all of the lectures when first taught and provided critical input on the modeling papers explored during the course. Additionally, I will work with the postdoctoral scholar to develop climate outreach to underrepresented groups (e.g. participation in a recently funded grant to develop a partnership between the College of Menominee and UW-Madison) as well as explore creative outreach activities that the postdoctoral scholar is interested in perusing while at UW-Madison (e.g. possibly a Climate Bowl event modeled off of Oregon State's Salmon Bowl).