A. Project Information:

- **Project Title:** High resolution simulations of the last deglaciation for understanding abrupt hydroclimate change in Southwest North America
- **Title of NSF Award:** Collaborative Research: P2C2 - Multi-Time-Scale Climate Dynamics in California (CA): An Integrated Multi-Proxy Stalagmite, Monitoring, and Modeling Approach
- **NSF Award Number:** 1804747
- **Project Lead:** Clay Tabor (University of Connecticut)
- **Submission Date:** September 10th, 2019

B. Overview of Project

Our proposal looks to understand hydroclimate changes in Southwest North America (SWNA) during the last deglaciation (21,000 years ago to present-day) using a combination of isotopic measurements from cave records (speleothems), primarily from California, and water isotope enabled Earth system model simulations with iCESM. Here, we request computing time to perform simulations of several intervals within the last deglaciation to compare with the SWNA speleothem records currently being collected and analyzed. Our simulations will help validate the Earth system model and interpret the signals found in the speleothems. To allow for robust model–proxy comparison, we will use the water isotope tracer enabled version of the Community Earth System Model at ~0.25° horizontal resolution. This model configuration will allow us to both directly simulate the isotopic composition of the precipitation that enters the karst systems, and better resolve smaller scale topographic features such as the Sierra Nevada. We will perform a total of four experiments that capture the most probable drivers of abrupt SWNA hydroclimate change during the last deglaciation, including changes in ice sheet configuration and freshwater forcing. Given the horizontal resolution, these simulations will be computationally expensive. However, the experiments will build upon previous model simulations (iTraCE) performed on Cheyenne and Blue Waters. Ultimately, this work will help us understand the mechanisms that led to a very different climate in SWNA during much of the last deglacial.

C. Science Objectives

Speleothem records from SWNA suggest several sources of variability during the last deglaciation (e.g. COHMAP Members, 1988; Thompson et al., 1993; Oster et al., 2015a; Wong et al., 2016; Lora et al., 2017). Primary drivers include configuration of the Northern Hemisphere ice sheets, freshwater fluxes from melting ice sheets, greenhouse gas concentrations, and orbital configuration. Here, we are particularly interested in relatively abrupt changes found in SWNA speleothem records, where the isotope values suggest that the climate transitioned from glacial to interglacial conditions over only a few hundred years. The causes of these abrupt changes remain uncertain. However, the most likely explanations include: 1) changes in the ocean overturning circulation as a result of significant freshwater input into the North Atlantic Ocean from Heinrich events (e.g. Munroe and Laabs, 2013; Ibarra et al., 2014), and 2) a rearrangement of the atmospheric circulation due to the collapse of the saddle connecting the Cordilleran and Laurentide ice sheets (e.g. Ivanovic et al., 2017; Lora et al., 2016; Löfverström and Lora, 2017). Our proposed experiments will explore the relative importance of these forcing agents.

To this end, we will use a version of the Community Earth System Model with water isotopologue tracers to allow for a more direct comparison with the isotopic measurements in the California speleothem records collected by our collaborators. Further, because many of our speleothem records come from topographically heterogenous terrain in and around the Sierra Nevada, the simulations require a high spatial resolution to better resolve these topographic features (**Figure 1**). Finally, synoptic weather systems, including atmospheric river activity (i.e., moisture intrusion from the tropics), are often invoked to explain the SWNA hydrologic changes during the last deglaciation (Lora et al., 2017). Therefore, to fully understand the mechanisms driving the speleothem signals will require several high frequency output fields from the model.

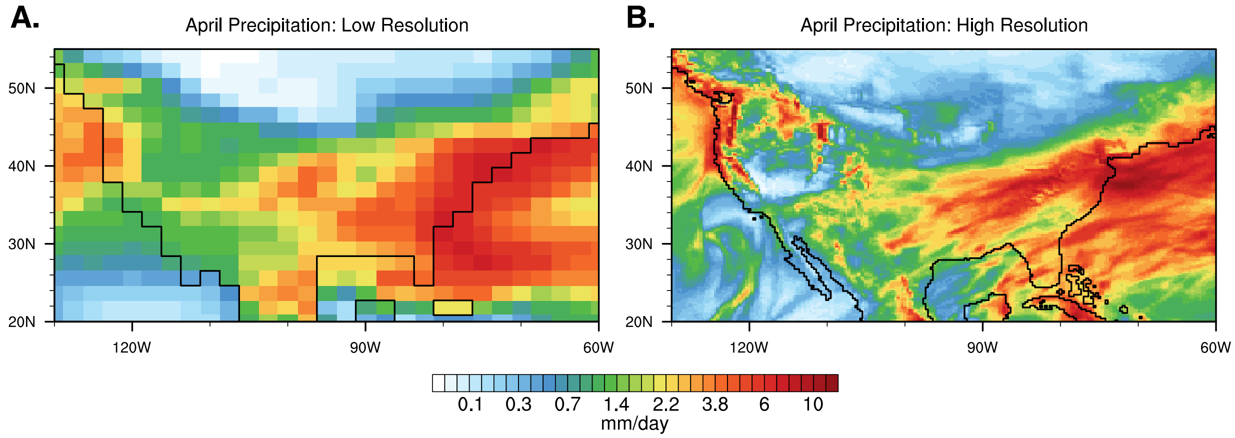

Figure 1: Contrasting simulated North American precipitation from low- and high-resolution configurations. Average April precipitation of a random year during the LGM at **A**) ~2° (standard) resolution and **B**) ~0.25° (high) resolution. This figure exemplifies the importance of high spatial resolution for capturing regional orographic precipitation, especially in the Sierra Nevada.

D. Computational Experiments and Resource Requirements

Numerical Approach.

We will use the Community Earth System Model version 1 (CESM1) with prognostic water isotopologue tracking (Brady et al., 2019). CESM1 is a widely employed, state-of-the-art Earth-system model with the ability to accurately simulate preindustrial and present-day climates (Hurrell et al., 2013). This version of CESM1, known as iCESM, has the ability to track δ^{18}O and δ^{2}H in all model components. Previous studies demonstrate that the δ^{18}O and δ^{2}H distributions within this version of CESM compare favorably with other isotope-enabled models of similar complexity (**Figure 2**; Nusbaumer et al., 2017; Wong et al., 2017). To capture the microclimate variability recorded in the speleothem records, we propose simulations with the finite volume configuration of iCESM at 0.23° x 0.31° horizontal resolution. This resolution is necessary to resolve key topographic features at and around the cave sites. We will maintain the default vertical resolution of 30 levels. We have tested this model configuration on Cheyenne with both preindustrial and Last Glacial Maximum (LGM) boundary conditions, and discussed model configuration with several previous users at NCAR. This model configuration is now stable and our preliminary δ^{18}O of precipitation results compare favorably with present-day Global Network of Isotopes in Precipitation (GNUP) measurements.

Computational Experiments.

We propose a series of four time slice experiments aimed at understanding abrupt changes in SWNA hydroclimate during the last deglaciation. This includes experiments focused on the climate at 16 ka (16,000 years before present) when a large ice sheet calving event, known as

Heinrich Stadial 1, led to an influx of freshwater into the North Atlantic and altered ocean circulation (McManus et al., 2004). Studies suggest that this calving event impacted climate in many areas including SWNA (e.g. Hendy et al., 2004). To test the impact of Heinrich Stadial 1 on SWNA hydroclimate, we will perform two simulation at 16 ka, one with and one without freshwater flux into the North Atlantic. These twin simulations will separate the influences of atmospheric composition, land-ice extent, and orbital configuration from freshwater forcing at 16 ka. To explore the importance of the collapse of the Cordilleran-Laurentide ice saddle, we will perform two additional experiments with ice sheet configurations from 15 ka and 14 ka, which bound the timing of collapse at ~14.5 ka (Gomez et al., 2015).

Due to the high resolution of the proposed simulations, it is not feasible to perform a complete Earth system spin-up for each time period of interest. Instead, we will create climatologies of fixed sea surface temperatures, sea ice, and ocean surface isotopic values from previous transient simulations of the deglaciation. These simulations, known as iTraCE, were run by Dr. Otto-Bliesner and Dr. Liu as part of a separate NSF grant and span the deglaciation from 20 ka to 11 ka. The iTraCE simulations were configured with atmosphere and land on a 1.9° x 2.5° finite-volume grid, and ocean and sea ice on a nominal 1° rotated pole grid (f19_g16 resolution B-compset). Boundary conditions for iTraCE including ice sheet configurations from the ICE-6G reconstructions (Peltier et al., 2015), greenhouse gas concentrations from Dome C ice core measurements (Monnin et al., 2001; 2004), and orbital calculations from Laskar et al. (2004). Several iTraCE experiments were perform with varying orbital, land ice, greenhouse gas, and freshwater flux forcings.

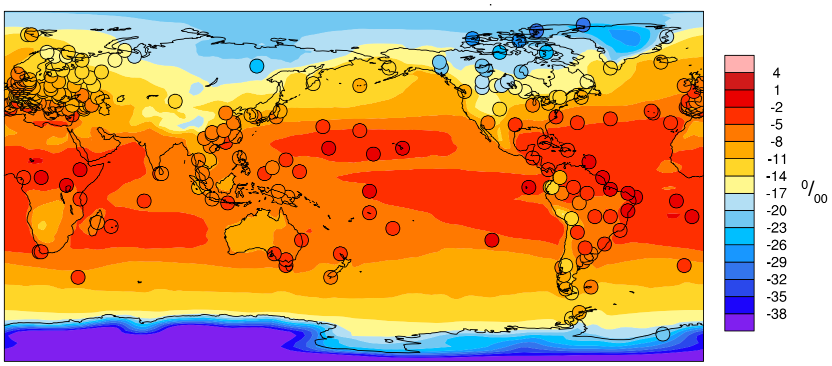

Figure 2: A comparison of precipitation climatology from a fully coupled iCESM simulation with Global Network of Isotopes in Precipitation (GNIP) observations (circles). Note: although the simulation and measurements generally agree, this is not an exact comparison because the model represents 1850 C.E. and the measurements come from present-day.

For our purposes, we will use iTraCE simulations with (orb_ice_ghg_wtr) and without (orb_ice_ghg) freshwater forcing in the North Atlantic. We will create ocean forcing files (50 year averages of sea-surface temperature, sea-ice extent, and isotopic values) from iTraCE data starting at 16 ka (orb_ice_ghg and orb_ice_ghg_wtr), 15 ka (orb_ice_ghg), and 14 ka (orb_ice_ghg). These ocean climatologies will then be used as inputs for our 0.23° x 0.31° configuration (f02_f02 resolution F-compset). To reduce runtime, we will also initialize the prescribed SST simulations with interpolated atmosphere and land outputs from the iTraCE simulations. Still, the interpolation of the land surface from ~2° to ~0.25° produces some blocky patterns, especially across sharp elevation gradients. Therefore, we will need to run these high resolution, prescribed SST simulations for at least an additional 20 years to allow the fluxes between the upper soil levels and the atmosphere to re-equilibrate. This land re-equilibration process has been shown to be important for simulation of the water isotope distribution. Note that we will turn off carbon and nitrogen cycling in these simulations to reduce the adjustment time required by the vegetation. Thirty additional years of simulation (50 years total) with prescribed SSTs should allow for the creation of robust climatologies to compare with speleothem records from SWNA.

Code performance.

We have tested the performance of iCESM at ~0.25° resolution on Cheyenne. We found that a total of 936 cores provides a good compromise between simulation speed and computational efficiency. **With this PE-layout, we get ~0.3 model years per day at a cost of ~79,000 core hours per year.** Note that the finite volume dynamical core is not as scalable as the spectral element dynamical core. However, we chose to continue working with the finite volume dynamical core because it has been extensively tested with water isotope tracers and is significantly easier to configure with paleoclimate boundary conditions. Further, our tests show that the spectral element code does not scale as well with the inclusion of water isotope tracers.

Table 1: Project resource requirements. See text for additional explanation and justification.

Experiment Name	**Spin up**	**Production**	**Core-Hours**	**Campaign Storage**
16 ka (no water)	20 years	30 years	50*79,000	39 GB*20 + 153 GB*30 + 109 MB*4*365*30
16 ka (freshwater)	20 years	30 years	50*79,000	39 GB*20 + 153 GB*30 + 109 MB*4*365*30
15 ka (pre-collapse)	20 years	30 years	50*79,000	39 GB*20 + 153 GB*30 + 109 MB*4*365*30
14 ka (post-collapse)	20 years	30 years	50*79,000	39 GB*20 + 153 GB*30 + 109 MB*4*365*30
Total	**80 years**	**120 years**	**15.8 million**	**40.6 TB**

Output and analysis.

We will output variables necessary to analyze changes in temperature, precipitation, storm track position and strength, and moisture isotopic variability and source from all four simulations. We also plan to explore the isotopic signatures associated with atmospheric rivers in each time slice. See details below.

HPC.

As shown in **Table 1,** to run an iCESM simulation with fixed SSTs at ~0.25° resolution for **50 model years will require approximately 3.95 million core hours**. Therefore, our **total request comes to 15.8 million core-hours** for the proposed simulations. Again, our computational cost estimates are based on previous experiments performed on Cheyenne using the same model configuration and PE-layout. Although these simulations will be slow, they will be independent and can therefore be performed simultaneously. The iTraCE outputs that will provide the ocean data for these simulations have already been completed, so our simulations will be able to start soon after we receive computing time.

Campaign storage archive.

By default, outputs from an iCESM simulation with fixed SSTs at ~0.25° resolution require ~69 GB of data per history write. To reduce storage requirements, we will only save yearly (instead of monthly) data during the 20 years required for land spin-up. We will also turn off some of the default atmosphere and land outputs during this period, and regularly zip the restart files (~50% size reduction), which require the most storage space (~80% of the total storage cost). With our reduced output protocol, we estimate a total storage of **3.1 TB** during land spin-up for the four simulations **(4 simulations x 20 years x 39 GB per year; Table 1).** During the production part of our simulations, we will save the majority of the default monthly atmospheric outputs, as we plan to work with most of the default 3D fields. Also, applications that we have not considered might be of interest to the paleoclimate community. We will continue to only store zipped annual restart files to save space. This will result in a production storage requirement of **18.4 TB** for the remaining 30 years of the four simulations **(4 simulations x 30 years x 153 GB per year; Table 1).**

In addition to the default monthly outputs, we also want to explore the isotopic signature associated with changes in the midlatitude storm tracks, atmospheric rivers, and tropical cyclones in each time slice. To do so, we will need 6-hourly output of vertically integrated moisture transport, total precipitable water, total precipitation, temperature at 500 hPa, sea-level pressure, and U, V, and Z at 250, 500, and 850 hPa and sea-level pressure (personal communications with Colin Zarzycki and Juan Lora). We will also need to output ^{16}O, ^{18}O, and ^{2}H of convective and large-scale snow and rain, and column integrated vapor to understand the isotopic composition of these weather features. Previous tests show that each 6 hourly output of these variables requires ~109 MB of storage (32 variables x 3.4 MB per variable). Scaling these outputs to the final 30 years of our simulations results in a total storage requirement of **19.1 TB (4 simulations x 30 years x 365 days x 4 writes per day x 109 MB per write; Table 1)** of data for tracking midlatitude storm systems, atmospheric rivers, and tropical cyclones. In total, **our simulations will require 40.6 TB (19.1 TB + 18.4 TB + 3.1 TB) of storage.**

Project file space.

We request **15 TB of project space** due to the long integration times associated with these simulations. In the best case scenario, we anticipate needing 170 days to perform these simulations (0.3 years per day x 50 years each). Therefore, it is required to run these simulations in parallel to reduce the overall simulation time. Project space will give us time to post-process the model variables for easier analysis and longer term storage. Further, although we will only save yearly restart files to Campaign, we would like to temporarily output monthly restarts to limit the potential loss of computing time in the case of model or system instability. With temporary monthly restart files and the output variables specified above, we should be able to store almost 4 years of data from each of the four simulations in the proposal. In reality, we will likely be able to store significantly less than 4 years of data due to the data duplication required for post-processing. After we complete all simulations, the project storage will provide a location to implement the atmospheric river and tropical cyclone tracking scripts for the entire 30 years of simulation simultaneously.

Data analysis and visualization plan.

Some of the scripts for analyzing the high resolution model outputs, especially those involving storm tracks, require significant memory. However, we have not yet tested these scripts at high-resolution output. We will therefore begin with the standard 10,000 core-hours on Casper. If necessary, we will ask for additional time during a future allocation request period.

E. Data Management Plan

All simulations will be completed within the duration of the NSF grant. We anticipate that the setup and running of all four simulations will require at least a year to complete. The second year, which is the final year of our NSF grant, will mainly involve analysis of the model outputs.

As we perform our analyses, we will reassess the output variables required for longer term storage, and if possible, eliminate variables that we determine are unlikely to be used by ourselves or the paleoclimate community. Near the conclusion of our NSF grant, we will use Globus to transfer the data to a more permanent storage facility maintained by the University of Connecticut. There it will be available upon request by the broader research community.

F. Accomplishment Report

CISL Project NCGD0026: In June 2016, Clay Tabor along with Bette Otto-Bliesner and Esther Brady were awarded an NSC allocation of 6,900,000 pe-hours to investigate the global isotopic responses to orbital, CO_2, and land ice changes during the Plio-Pleistocene. So far, this work has resulted in multiple conference presentations and three publications. Several other publications are currently in preparation.

Hu, J., Emile-Geay, J., Tabor, C.R., Nusbaumer, J., Partin, J., & Adkins, J (2019). Deciphering Chinese speleothems with an isotope-enabled climate model. *Paleoceanography and Paleoclimatolog*y (in review)

Chang, Q., Hren, M., Lin, A.T., Tabor, C.R., Yu, S., Yvette, E., & Harris, G. (2019). The biomarker stable isotope record for the late Quaternary climate change in Southwestern Taiwan. *Global and Planetary Change*. (in review)

Brady, E., Stevenson, S., Baily, D., Liu, Z., Noone, D., Nusbaumer, J., Otto-Blienser, B., Tabor, C.R., Tomas, R., Wong, T., Zhang, J., & Zhu, J. (2019). The connected isotopic water cycle in the Community Earth System Model. *Journal of Advances in Modeling Earth Systems*.

Tabor, C.R., Otto-Bliesner, B.L., Brady, E., Nusbaumer, J., Zhu, J., Erb, M. Wong, A., Liu, Z., and Noone, D. (2018). The d18O response in the South Asian Monsoon to precession, *Journal of Geophysical Research: Atmospheres*.

CISL Project NCGD0030: In December 2016, Clay Tabor along with Charles Bardeen and Bette Otto-Bliesner were awarded an NSC allocation of 8,000,000 pe-hours to investigate the climate response to the asteroid impact at the end-Cretaceous. These simulations are currently in development. Preliminary results have led to several presentations that garnered media attention and one in review manuscript:

Tabor, C.R., Bardeen, C.G., Otto-Bliesner, B.L., Garcia, R., & Toon, O.B. (2019). Causes and consequences of the end-Cretaceous impact winter. *Nature Communications* (in review)

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