Geophysical Research Abstracts
Vol. 16, EGU2014-9636-1, 2014
EGU General Assembly 2014

Comparing Apples to Apples: Paleoclimate Model-Data comparison via Proxy System Modeling

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The wealth of paleodata spanning the last millennium (hereinafter LM) provides an invaluable testbed for CMIP5-class GCMs. However, comparing GCM output to paleodata is non-trivial. High-resolution paleoclimate proxies generally contain a multivariate and non-linear response to regional climate forcing. Disentangling the multivariate environmental influences on proxies like corals, speleothems, and trees can be complex due to spatiotemporal climate variability, non-stationarity, and threshold dependence. Given these and other complications, many paleodata-GCM comparisons take a leap of faith, relating climate fields (e.g. precipitation, temperature) to geochemical signals in proxy data (e.g. δ^{18}O in coral aragonite or ice cores) (e.g. Braconnot et al., 2012). Isotope-enabled GCMs are a step in the right direction, with water isotopes providing a connector point between GCMs and paleodata. However, such studies are still rare, and isotope fields are not archived as part of LM PMIP3 simulations. More importantly, much of the complexity in how proxy systems record and transduce environmental signals remains unaccounted for.

In this study we use proxy system models (PSMs, Evans et al., 2013) to bridge this conceptual gap. A PSM mathematically encodes the mechanistic understanding of the physical, geochemical and, sometimes biological influences on each proxy. To translate GCM output to proxy space, we have synthesized a comprehensive, consistently formatted package of published PSMs, including δ^{18}O in corals, tree ring cellulose, speleothems, and ice cores. Each PSM is comprised of three sub-models: sensor, archive, and observation. For the first time, these different components are coupled together for four major proxy types, allowing uncertainties due to both dating and signal interpretation to be treated within a self-consistent framework. The output of this process is an ensemble of many (say N = 1,000) realizations of the proxy network, all equally plausible under assumed dating uncertainties.

We demonstrate the utility of the PSM framework with an integrative multi-PSM simulation. An intermediate-complexity AGCM with isotope physics (SPEEDY-IER, (Molteni, 2003, Dee et al., in prep)) is used to simulate the isotope hydrology and atmospheric response to SSTs derived from the LM PMIP3 integration of the CCSM4 model (Landrum et al., 2012). Relevant dynamical and isotope variables are then used to drive PSMs, emulating a realistic multiproxy network (Emile-Geay et al., 2013). We then ask the following question: given our best knowledge of proxy systems, what aspects of GCM behavior may be validated, and with what uncertainties?

We approach this question via a three-tiered “perfect model” study. A random realization of the simulated proxy data (hereafter “PaleoObs”) is used as a benchmark in the following comparisons: (1) AGCM output (without isotopes) vs. PaleoObs; (2) AGCM output (with isotopes) vs. PaleoObs; (3) coupled AGCM-PSM-simulated proxy ensemble vs. PaleoObs. Enhancing model-data comparison using PSMs highlights uncertainties that may arise from ignoring non-linearities in proxy-climate relationships, or the presence of age uncertainties (as is most typically done is paleoclimate model-data intercomparison). Companion experiments leveraging the 3 sub-model compartmentalization of PSMs allows us to quantify the contribution of each sub-system to the observed model-data discrepancies. We discuss potential repercussions for model-data comparison and implications for validating predictive climate models using paleodata.

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