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Improved spectral comparisons of paleoclimate models and observations via proxy system modeling: Implications for multi-decadal variability

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ABSTRACT

The spectral characteristics of paleoclimate observations spanning the last millennium suggest the presence of significant low-frequency (multi-decadal to centennial scale) variability in the climate system. Since this low-frequency climate variability is critical for climate predictions on societally-relevant scales, it is essential to establish whether General Circulation models (GCMs) are able to simulate it faithfully. Recent studies find large discrepancies between models and paleoclimate data at low frequencies, prompting concerns surrounding the ability of GCMs to predict long-term, high-magnitude variability under greenhouse forcing (Laepple and Huybers, 2014a, 2014b). However, efforts to ground climate model simulations directly in paleoclimate observations are impeded by fundamental differences between models and the proxy data: proxy systems often record a multivariate and/or nonlinear response to climate, precluding a direct comparison to GCM output. In this paper we bridge this gap via a forward proxy modeling approach, coupled to an isotope-enabled GCM. This allows us to disentangle the various contributions to signals embedded in ice cores, speleothem calcite, coral aragonite, tree-ring width, and tree-ring cellulose. The paper addresses the following questions: (1) do forward-modeled "pseudoproxies" exhibit variability comparable to proxy data? (2) if not, which processes alter the shape of the spectrum of simulated climate variability, and are these processes broadly distinguishable from climate? We apply our method to representative case studies, and broaden these insights with an analysis of the PAGES2k database (PAGES2K Consortium, 2013). We find that current proxy system models (PSMs) can help resolve model-data discrepancies on interannual to decadal timescales, but cannot account for the mismatch in variance on multi-decadal to centennial timescales. We conclude that, specific to this set of PSMs and isotope-enabled model, the paleoclimate record may exhibit larger low-frequency variability than GCMs currently simulate, indicative of incomplete physics and/or forcings.

1. Introduction

Our understanding of the complex dynamics of climate response to anthropogenic forcing rests jointly upon observations over the instrumental period, general circulation models (GCMs), and paleoclimate data. GCMs provide a basis for exploring the mechanisms driving forced and stochastic climate variability; however, improved predictions of decadal- to centennial-scale hydroclimatic variability from GCMs additionally depend on constraints from high-resolution paleoclimate observations (e.g. Mann et al., 2009; PAGES2K Consortium, 2013). Such data provide much-needed statistics for climate variability and augment the relatively short instrumental record. Thus, combining data from both models and high-resolution paleoclimate records yields meaningful advances for understanding future climate.

Constraining climate models with paleoclimate data requires a robust method for comparing the two. Recently, a number of studies have compared GCM simulations and paleoclimate data in the frequency domain, applying spectral analysis to both the simulated and observed climate record. For temperature, precipitation, or any other key indicator in a paleoclimate archive, comparing the power spectral densities (PSDs) across models and data al-

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lows one to assess the dominant modes of variability in both signals (Kutzbach, 1976; Hays et al., 1976; Huybers and Curry, 2006). Recently, Laepple and Huybers (2014a, 2014b) showed that commonly employed proxies for Holocene sea surface temperature (SST) exhibit a spectrum of SST variability inconsistent with GCM simulations on millennial timescales. Similarly, Ault et al. (2013) found that last-millennium terrestrial records from western North American exhibit larger low-frequency variability (and larger spectral slopes) when compared to the suite of CMIP5 Last-Millennium GCM simulations (Taylor et al., 2012; Landrum et al., 2013). While the absolute variability simulated in climate models is different from the shape of the power spectrum (which measures variability as a function of timescale), the two are closely related (we evaluate both via Supplementary Information, SI hereafter); the spectrum observed in these paleoclimate records implies scaling behavior originating from the climate system, and high variability on longer timescales. Scaling behavior can also imply longer climate-system memory of extreme events, such as megadrought (Ault et al., 2013, 2014). Thus, the mismatch in the shape of the spectrum simulated by GCMs vs. that observed in paleoclimate data has been interpreted as a deficiency in the ability of GCMs to simulate climate with a level of realism required for predicting decadal to centennial variability (Laepple and Huybers, 2014a, 2014b). Such findings harbor important implications about risk prediction using climate models (e.g. future drought in the southwest U.S., Ault et al., 2014).

The direct comparison of climate model output with paleoclimate observations involves three main challenges (e.g. Ault et al., 2013): (1) internal variability in models is not directly comparable to paleoclimate data in time; (2) biases in climate models limit their ability to correctly simulate extremes in hydroclimate; (3) proxy archives naturally filter and distort the original climate signal, confounding direct comparisons of paleoclimate data to climate model variables. To address the first two of these issues, comparing PSDs removes model biases while comparing time-scale dependent variances, and ignores phase relationships (which are not expected not match because of natural climate variability, *inter alia*). This allows for a more robust analysis of the partitioning of variance across different timescales in models vs. data (Ault et al., 2013).

In this study, we take additional measures to address the third challenge, which relates to the filtering of the initial climate signal by proxy systems. A conversion step is needed to translate between model output and the proxy signal. Accomplishing a major part of this conversion, recent advances in climate modeling have allowed for the explicit incorporation of stable water isotope tracers in both the atmosphere and the ocean (see Table S7, SI). For water isotope-based proxy systems, stable water isotopes translate between the dynamical climate model variables (e.g. temperature and precipitation) and the geochemical signal that the proxy data encode (e.g. δ^{18}O of precipitation). Adding water isotope physics to GCMs provides crucial insight, helping to determine the drivers of isotopic variations observed in proxy data and associated climate patterns (Sturm et al., 2010). Embedded water-isotope physics bring us closer to a direct comparison between models and data, but do not account for physical processes by which proxy systems alter and subsequently record the original climate signal. In an effort to avoid assumptions inherent to inverse approaches (e.g. inverse-method or calibration-based reconstructions in paleoclimate), we turn to proxy system modeling (for a review, see Evans et al., 2013; Dee et al., 2015a), and employ a new approach using both water isotope physics and proxy system models (PSMs) as tools for simulating biological, physical, or geochemical impacts of the proxy system on the input climate signal. Dynamical and isotope variables are *translated to proxy units* for a direct comparison between GCM output and observations (a forward approach).

Our study builds upon the analysis of Ault et al. (2013) and Laepple and Huybers (2013, 2014a, 2014b) by employing this forward approach for data-model comparison in the frequency domain. In general, there are two methods that allow for a meaningful comparison of proxy and model spectra. One is the inverse-method correction of the proxy spectra accounting for the distortion applied by the recording processes (e.g. Laepple and Huybers, 2013), and one is the forward modeling employed in this manuscript, which in many cases affords increased flexibility. Here, we use forward modeling to disentangle the multivariate influences on proxy data using state-of-the-art PSMs for ice cores, corals, tree-ring cellulose, speleothem calcite (Dee et al., 2015a) and tree-ring width (Tolwinski-Ward et al., 2010). Within this novel framework, we address the following questions: (1) are there proxy system processes that alter the spectrum of simulated (hydro)climatic variability, and are the impacts of these processes distinguishable from climate in spectral space? (2) accounting for these processes, do GCM+PSM-driven pseudoproxies exhibit spectral characteristics comparable to proxy observations?

Section 2 outlines our experimental design, and Section 3 describes results showing case studies for the piece-wise transformation of the climate signal down to proxy units. We extend this analysis to a global scale using the PAGES2k Phase 1 Network in Section 4. Finally, we discuss the limitations and caveats of our approach, and suggestions for future research, in Section 5.

2. Methods

2.1. GCM & PSM-generated pseudoproxies

To provide climate model estimates of hydroclimate variability over the last millennium, as well as climate fields for the PSM-generated network, we use the water isotope-enabled GCM `SPEEDY-IER` (Dee et al., 2015b) (see SI Section S8 for details). We forced a transient simulation of `SPEEDY-IER` with sea surface temperatures from the last millennium simulation (Landrum et al., 2013) of the CCSM4 coupled model (Gent et al., 2011), spanning 850–2005 (1000–2005 considered for this study). We generate synthetic proxy time series using 'proxy system models' (PSMs, Evans et al., 2013; Dee et al., 2015a). PSMs convert the simulated climate (e.g. temperature, precipitation) into a proxy time series. A given PSM includes three sub-models, each of which mimics a separate modification of the original input signal as it would occur in nature: (1) a *sensor* model, which describes any physical, geochemical or biological processes altering the climate signal; (2) an *archive model*, which accounts for any processes that affect the emplacement of the signal in the proxy medium, and (3) an *observation* model, which accounts for dating uncertainties and analytical errors in the final measurement made on the paleoclimate data (Dee et al., 2015a). The sub-model framework of PSMs helps to quantify changes that occur at each stage of the climate signal's evolution through the proxy system.

Each proxy type employs its own unique PSM. We used VS-Lite (Tolwinski-Ward et al., 2010) to generate tree ring width records for all of the tree proxy locations using temperature and precipitation fields from `SPEEDY-IER`. We model ice core, coral, speleothem, and tree cellulose records using fields from CCSM4/`SPEEDY-IER` coupled with a synthesis of previously published models for water isotopes in high-resolution proxy data (`PRYSM v.1.0`, Dee et al., 2015a). We apply these models to the individual case study locations listed below in Section 3 and to the larger PAGES2k Phase 1 network (Section 4, PAGES2K Consortium, 2013). The complicated nature of proxy data (e.g. chronological uncertainties and impacts on phasing) precludes point-to-point comparisons of time series, and thus there is a strong case for comparing simulated proxy to the observations in the frequency domain.