Quantifying Uncertainty in Teleconnections Simulated by Climate Models

Samantha Stevenson

National Center for Atmospheric Research, University of California at Santa Barbara
“Teleconnections” come in many varieties

SST/air temp/SLP composite:
DJF of El Nino peak

ERSST v3b / GISTEMP / HadSLP2r
1979-2015 7/6
“Teleconnections” come in many varieties

SST/air temp/SLP composite: DJF of El Nino peak

Spatial pattern of SST associated with the PDO
“Teleconnections” come in many varieties

SST/air temp/SLP composite:
DJF of El Nino peak

Spatial pattern of SST associated with the PDO

Spatial pattern of SST associated with the AMO

NCAR Climate Variability Diagnostics Package
Models simulate broad features of ENSO teleconnections

Correlations of precipitation, 850 hPa wind with NINO3.4 SSTA

Fasullo, Otto-Bliesner & Stevenson (2017), Nature Climate Change, in revision
Models capture broad features of PDO teleconnections as well.

Sheffield et al. (2013) - DJF regressions on PDO index
Obs: CRU TS3.1

Sheffield et al. (2013)
AMO teleconnections not well represented

SON regressions on AMO index, 1900-1999
Obs: HadISST1.1, CRU TS3.1
Sheffield et al. (2013)
Evaluation of Climate Models

Chapter 9

Atlantic Niño

CMIP3 models have considerable difficulty simulating Atlantic Niño in their 20th century climate simulations. For many models the so-called 'Atl-3' SST index (20°W to 0°W, 3°S to 3°N) displays the wrong seasonality, with the maximum value in either DJF or SON instead of JJA as is observed (Breugem et al., 2006). Despite large biases in the simulated climatology (Section 9.4.2.5.2), about one third of CMIP5 models capture some aspects of Atlantic Niño variability, including amplitude, spatial pattern and seasonality (Richter et al., 2013). This represents an improvement over CMIP3.

9.5.3.4 Indo-Pacific Modes

9.5.3.4.1 El Niño-Southern Oscillation

The ENSO phenomenon is the dominant mode of climate variability on seasonal to interannual time scales (see Wang and Picaut (2004) and Chapter 14). The representation of ENSO in climate models has steadily improved and now bears considerable similarity to observed ENSO properties (AchutaRao and Sperber, 2002; Randall et al., 2007; Guildewart et al., 2009b). However, as was the case in the AR4, simulations...
Amplitude of climate modes not always well simulated

Maximum time lag when the autocorrelation first crosses the significance line at the 80% level (Figure 3). A close inspection finds that the model persistence varies from 5 and up to 22 years, implying the potential for predicting future SSTs. However, for most of the models, the persistence is shorter than that of observation (the persistence of ERSST is about 12 years). Meanwhile, the AMO persistence in CMIP5 is much longer than that in CMIP3 which shows an averaged persistence about 5 years [Medhaug and Furevik, 2011]. Figure 4 shows the power spectrum of the detrended annual mean AMO index. ERSST primarily has three peaks of energy spectrum around 40 years, 25 years, and 15 years.
Amplitude of climate modes not always well simulated

PDO Taylor diagram, CMIP3/CMIP5 historical simulations and CESM Large Ensemble

Newman et al. (2016)
a), b): PDO spatial structure in CMIP5 models closest to, farthest from observations

Model A

Model B
Major feedbacks relevant to the ENSO cycle

(a) Atm. Bjerknes feedback

(b) Surf. Fluxes feedback

(c) Shortwave feedback

Bjerknes: sensitivity of SST to wind stress
Surf. fluxes: damping of SST by latent heat flux
Shortwave feedback: damping of SST by shortwave fluxes

Bellenger et al. (2014)
Understanding internal variability: large model ensembles

**CESM Last Millennium Ensemble (CESM LME): Otto-Bliesner et al. (2016)**
Multiple ensembles, varying sizes: different combinations of climate forcings 850-2005 (Orbital, solar, volcanic, GHG, ozone/aerosol, land use/land cover, all of the above)

**CESM Large Ensemble: Kay et al. (2016)**

**CESM Medium Ensemble: Sanderson et al. (2016)**

**GFDL ESM2M: Rodgers et al. (2015)**
Internal variability affects ENSO teleconnections

Composite SST/surface air temperature (colors), SLP (contours) during DJF of El Nino peak
Internal variability affects AMO teleconnections

SST anomaly pattern associated with AMO: observations, CESM Large Ensemble

ERSST v3b

1979-2015

CESM1-CAM5-BGC-LE #8

1979-2015

CESM1-CAM5-BGC-LE #105

1979-2015

CESM1-CAM5-BGC-LE #19

1979-2015
Newman et al. (2016)

PDO in the CMIP5 historical runs, we fit each PDO time series with the extended AR1 model:

\[ \text{PDO}(n) = r \times \text{PDO}(n-1) + \exp(\sigma^2) \eta(n) \]

where PDO is the PDO time series, ENSO1 and ENSO2 are the time coefficients of the leading two EOFs of tropical Pacific (20°S–20°N) SSTAs, \( \eta \) is white noise, and \( n \) is the time step. This model, estimated for detrended and normalized annual mean time series averaged from Fig. 8. The PDO over the historical record as simulated by coupled CGCMs. (a),(b) As in Fig. 1a,b, showing two selected members of the historical CMIP5 ensemble that are (a) closest and (b) farthest from the reference pattern in Fig. 2. (c),(d) As in (a),(b), but showing two selected members of the CESM-LE that are (c) closest and (d) farthest from the reference pattern in Fig. 2. (e) PDO times series from all ensemble members; all time series are smoothed with the Zhang et al. (1997) filter (used in Fig. 1c). Thin gray lines represent each ensemble member, the thin black solid (dashed) line in the CMIP5 panel represents model A (B), and the thick black line is the ensemble mean for each set of models.

Internal variability affects PDO teleconnections

PDO spatial structure in members of the CESM Large Ensemble closest to, farthest from observations

Newman et al. (2016)
What portion of long-term variability in teleconnected regions is driven by changes to major climate modes?
Large ensemble application: multidecadal “megadrought”

200-year moving window

Palmer Drought Severity Index (PDSI), North American Southwest: LME

Climate variability: ENSO amplitude

Megadrought persistence, risk

Risk = % years in megadrought
ENSO: strong influence on drought persistence

15-year drought (0.5σ threshold)

Stratified by mode (above 60th/below 40th percentile)

Brown = higher drought risk
Green = lower drought risk

Stevenson et al. (2017), in review

Stronger ENSO:
- **Shorter** drought in Australia, Africa, Southeast Asia, SW US
- **Longer** drought in Amazon basin, Mexico
21st century: drying projected for western N. America, Amazon

Difference in 0-30cm soil moisture: (2006-2100) - (1920-2005), CESM Large Ensemble

Stevenson et al. (2017), in prep for Nature Climate Change
Drought risk changes: function of both mean and variance shifts

Stevenson et al. (2017), in prep for Nature Climate Change

15-year drought (0.5σ threshold)
Brown = higher drought risk;
Green = lower drought risk

Stevenson et al. (2017), in prep for Nature Climate Change
Conclusions

Teleconnections are influenced by internal atmospheric variability, coupled atmosphere/ocean/land processes, and impacts from external forcings.

- Models capture ENSO teleconnections more reliably than AMO.

- Strong inter-model differences in teleconnection performance: both structural differences among models and internal variability are important.

- Large model ensembles can clear up differences, diagnose externally driven teleconnection responses.

Large 20th/21st c. model ensembles, multi-centennial model simulations, and targeted observational improvements needed to constrain uncertainties in teleconnection estimates.
Advancing Teleconnection Simulations

Samantha Stevenson

National Center for Atmospheric Research, University of California at Santa Barbara
Newman et al. (2016)

PDO in the CMIP5 historical runs, we fit each PDO time series with the extended AR1 model:

\[ \text{PDO}(n) = r \cdot \text{PDO}(n-1) + a \cdot \text{ENSO}_1(n) + b \cdot \text{ENSO}_2(n) + \epsilon(n), \] (4)

where PDO is the PDO time series, ENSO1 and ENSO2 are the time coefficients of the leading two EOFs of tropical Pacific (20\textdegree S–20\textdegree N) SSTAs, \( \epsilon \) is white noise, and \( n \) is the time step. This model, estimated for detrended and normalized annual mean time series averaged from Fig. 8. The PDO over the historical record as simulated by coupled CGCMs. (a), (b) As in Fig. 1a, b, showing two selected members of the historical CMIP5 ensemble that are (a) closest and (b) farthest from the reference pattern in Fig. 2. (c), (d) As in (a), (b), but showing two selected members of the CESM Large Ensemble. (e) PDO times series from all ensemble members; all time series are smoothed with the Zhang et al. (1997) filter (used in Fig. 1c). Thin gray lines represent each ensemble member, the thin black solid (dashed) line in the CMIP5 panel represents model A (B), and the thick black line is the ensemble mean for each set of models.

a), b): PDO spatial structure in CMIP5 models closest to, farthest from observations

c), d): Same as a), b) for members of the CESM Large Ensemble

Issue: both structural, internal differences matter to teleconnections

Newman et al. (2016)
First two EOFs of North Pacific SST: CESM Large Ensemble, observations

**Figure 1:**
- **a:** CESM-LE EOF1
- **b:** CESM-LE EOF2
- **c:** OBS EOF1
- **d:** OBS EOF2

**Graphs:**
- **e:** Time series of PC1 and PC2 for OBS and CESM-LE, showing the variance explained by each EOF. The red line represents the observed PC1, while the black line is the CESM-LE ensemble mean. The blue line shows PC2.

Note: The figure illustrates the spatial patterns of the first two empirical orthogonal functions (EOFs) of the North Pacific Sea Surface Temperature Anomaly (SSTa) for both CESM Large Ensemble (CESM-LE) and observations (OBS). The EOFs are extracted from the CESM Large Ensemble (CESM-LE) for 1920–2100 and the observational reanalysis (OBS) for 1950–2015. The figures show the spatial distribution of the SSTa anomalies for EOF1 and EOF2, with the percentage of variance explained by each EOF indicated below the respective panels.

**Supplementary Information:**
- **Methods:** The methods for extracting EOFs and analyzing the variance explained by each EOF are described in the supplementary information (Supplementary Fig. 2).

**References:**
- Di Lorenzo & Mantua (2016)

DOI: 10.1038/NCLIMATE3082
CMIP5 projections: shift in location of ENSO teleconnections

SLP composites during DJF of El Nino peak: CMIP5 historical, RCP4.5 projections
Left: Regression of temperature onto NINO3.4 index in the CESM Large Ensemble (Kay et al. 2015)

Right: change in the regression coefficient between 2040-2100 and 1920-1980

Fasullo, Otto-Bliesner, & Stevenson 2017, Nature Climate Change, in revision
No agreement on future changes in ENSO amplitude

Running 20-year NINO3.4 variance, RCP8.5

Community Earth System Model (NCAR)

Earth System Model 2M (NOAA GFDL)

Fasullo, Otto-Bliesner, & Stevenson 2017, Nature Climate Change, in revision
CESM: differential ENSO response to anthropogenic forcings

2S-2N SST vs. lon, time: 0 = January of peak year
PI = 850-1849
20th c. = 1850-2005

Stevenson et al. (2017), Climate Dynamics
What new simulations and observations are needed to improve understanding of teleconnections in climate models?
Simulations planned for CMIP6 (DECK)

<table>
<thead>
<tr>
<th>Experiment short name</th>
<th>CMIP6 label</th>
<th>Experiment description</th>
<th>Forcing methods</th>
<th>Start year</th>
<th>End year</th>
<th>Minimum no. years per simulation</th>
<th>Major purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DECK experiments</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AMIP</td>
<td>amip</td>
<td>Observed SSTs and SICs prescribed</td>
<td>All; CO₂ concentration prescribed</td>
<td>1979</td>
<td>2014</td>
<td>36</td>
<td>Evaluation, variability</td>
</tr>
<tr>
<td>Pre-industrial control</td>
<td>piControl</td>
<td>Coupled atmosphere–ocean pre-industrial control</td>
<td>CO₂ concentration prescribed or calculated</td>
<td>n/a</td>
<td>n/a</td>
<td>500</td>
<td>Evaluation, unforced variability</td>
</tr>
<tr>
<td>Abrupt quadrupling of CO₂ concentration</td>
<td>abrupt-4×CO₂</td>
<td>CO₂ abruptly quadrupled and then held constant</td>
<td>CO₂ concentration prescribed</td>
<td>n/a</td>
<td>n/a</td>
<td>150</td>
<td>Climate sensitivity, feedback, fast responses</td>
</tr>
<tr>
<td>1 % yr⁻¹ CO₂ concentration increase</td>
<td>1pctCO2</td>
<td>CO₂ prescribed to increase at 1 % yr⁻¹</td>
<td>CO₂ concentration prescribed</td>
<td>n/a</td>
<td>n/a</td>
<td>150</td>
<td>Climate sensitivity, feedback, idealized benchmark</td>
</tr>
<tr>
<td><strong>CMIP6 historical simulation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Past ~ 1.5 centuries</td>
<td>historical</td>
<td>Simulation of the recent past</td>
<td>All; CO₂ concentration prescribed or calculated</td>
<td>1850</td>
<td>2014</td>
<td>165</td>
<td>Evaluation</td>
</tr>
</tbody>
</table>

Eyring et al. (2016)
CMIP6: also supports “sub-MIPs” with specific scientific targets

These GCs will be using the full spectrum of observational, modelling and analytical expertise across the WCRP, and in terms of modelling most GCs will address their specific science questions through a hierarchy of numerical models of different complexities. Global coupled models obviously constitute an essential element of this hierarchy, and CMIP6 experiments will play a prominent role across all GCs by helping to answer the following three CMIP6 science questions:

1. How does the Earth system respond to forcing?
2. What are the origins and consequences of systematic model biases?
3. How can we assess future climate change given internal climate variability, climate predictability, and uncertainties in scenarios?

These three questions will be at the centre of CMIP6. Science topics related specifically to CMIP6 will be addressed through a range of CMIP6-Endorsed MIPs that are organized by the respective communities and overseen by the CMIP Panel (Fig. 2). Through these different MIPs and their connection to the GCs, the goal is to fill some of the main scientific gaps of previous CMIP phases. This includes, in particular, facilitating the identification and interpretation of model systematic errors, improving the estimate of radiative forcings in past and future climate change simulations, facilitating the identification of robust climate responses to aerosol forcing during the historical period, better accounting of the impact of short-term forcing agents and land use on climate, better understanding the mechanisms of decadal climate variability, along with many other issues not addressed satisfactorily in CMIP5 (Stouffer et al., 2015). In endorsing a number of these MIPs, the CMIP Panel acted to minimize overlaps among the MIPs and to reduce the burden on modelling groups, while maximizing the scientific complementarity and synergy among the different MIPs.

4.2 The CMIP6-Endorsed MIPs

Close to 30 suggestions for CMIP6 MIPs have been received so far, of which 21 MIPs were eventually endorsed and invited to participate (Table 3). Of those not selected some were asked to work with other proposed MIPs with overlapping science goals and objectives. Of the 21 CMIP6-Endorsed MIPs, 4 are diagnostic in nature, which means that they define and analyse additional output, but do not require additional experiments. In the remaining 17 MIPs, a total of around 190 experiments have been proposed resulting in 40,000 model simulation years with around half of these in Tier 1. The CMIP6-Endorsed MIPs show broad coverage and distribution across the three CMIP6 science questions, and all are linked to the WCRP Grand Science Challenges (Fig. 3).

Each of the 21 CMIP6-Endorsed MIPs is described in a separate invited contribution to this special issue. These contributions will detail the goal of the MIP and the major scientific gaps the MIP is addressing, and will specify what is new compared to CMIP5 and previous CMIP phases. The contributions will include a description of the experimental design and scientific justification of each of the experiments for Tier 1 (and possibly beyond), and will link the experiments and analysis to the DECK and CMIP6 historical simulations. They will additionally include an analysis plan to fully justify the resources used to produce the various requested variables, and if the analysis plan is to compare model results to observations, the contribution will highlight possible model diagnostics and performance metrics specifying whether the comparison entails any particular requirement for the simulations or outputs (e.g. the use of observational simulators). In addition, possible observations and reanalysis products for model evaluation are discussed and the MIPs are encouraged to help facilitate their use by contributing them to the obs4MIPs/ana4MIPs archives at the ESGF (see Sect. 3.3). In some MIPs, additional forcings beyond those used in the DECK and CMIP6 historical simulations are required, and these are described in the respective contribution as well.
CMIP6: also supports “sub-MIPs” with specific scientific targets

<table>
<thead>
<tr>
<th>MIP</th>
<th>Questions</th>
<th>Grand science challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerosols &amp; Chemistry MIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AerChemMIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C4MIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CFMIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DAMIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DCPP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FAFMIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GeoMIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Global Monsoons MIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GMMIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HighResMIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ISMIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land Surface, Snow and Soil Moisture MIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LS3MIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LUMIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OMIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiative Forcing MIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RFMIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ScenarioMIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VoIMIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dynamics &amp; Variability MIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CORDEX</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DynVarMIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIMIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VIACS AB</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3. Contributions of CMIP6-Endorsed MIPs to the three CMIP6 science questions and the WCRP Grand Science Challenges. A filled circle indicates highest priority and an open circle, second highest priority. Some of the MIPs additionally contribute with lower priority to other CMIP6 science questions or WCRP Grand Science Challenges.
Uncertainty quantification: process-level insights

Major feedbacks relevant to the ENSO cycle

(a) Atm. Bjerknes feedback

(b) Surf. Fluxes feedback

(c) Shortwave feedback

Bjerknes: sensitivity of SST to wind stress
Surf. fluxes: damping of SST by latent heat flux
Shortwave feedback: damping of SST by shortwave fluxes

Bellenger et al. (2014)
Chapter 7: Implementation and Transition

7.4.4.1 Denser near equatorial moorings

We recommend increasing the meridional density of enhanced fixed-point sampling spanning the equator at several (2–4) longitudes along the cold tongue by adding well instrumented moorings, initially at 140°W and 110°W from 2°S to 2°N at 1-degree intervals (see sections 3.1.3, 3.4, 3.3.3 and 5.9.1, Recommendation 15).

Action 5: Moorings at 1°S and 1°N at selected longitudes should be added to enhance the resolution of near-equatorial dynamics. Enhancement of instrumentation on all moorings from 2°S to 2°N at these longitudes should be targeted.

The cold tongue front will pass repeatedly back and forth across eastern sites, giving many samples of its vertical structure and its (two-way) interaction with the southeasterly winds. A similar enhancement should be considered at 165°E and 170°W.

In addition, consideration should be given to adding nearby subsurface ADCP moorings (as presently done only at the four equatorial sites) to make velocity profiles at each of the moorings from 2°S to 2°N as part of this enhancement.

7.4.4.2 Reduce TMA presence in the trade wind regions

In the presence of Argo (and the now-recommended increased resolution; section 7.4.3), and the ability of scatterometers and models to capture the trade winds (sections 3.1.1.2, 5.1), there is now the possibility to reduce the TMA presence. The locations to be targeted are not the focus of any enhancements (see section 7.4.4) and the negative impact of the observation losses is expected to be tolerable. Freed resources can be redeployed to support other aspects of the TMA (section 7.3).
Important observational target: vertical temperature structure

CESM: zonal SST gradient weakens, vertical stratification increases

ESM2M: zonal SST gradient strengthens, vertical stratification doesn’t increase as much as CESM

Stevenson et al. (2017b), in prep
Nonlinear zonal advection: anomalous advection of anomalous gradient

NINO3: Eastern Pacific El Niño

Important observational target: mixed-layer eddies

\[-u' \cdot \nabla T'.\]

Stevenson et al. (2017b), in prep
Also critical: improving long-term 20th c. estimates

3. Results
3.1. Data Coverage

In order to discriminate between secular climate change and naturally occurring multi-decadal variability, it is important to consider as long a period of record as possible. Seeking a balance between adequate data coverage (see Figure S1 in the auxiliary material) and length of record, we have examined SST trends using a variety of start dates (1900, 1910 and 1920) and data sampling thresholds; all of the results discussed below are robust to the different choices.

In the figures that follow, we show trend maps based on the period 1900–2008 using a 3 month per decade threshold; trends based on 1920–2008 using a 24 month per decade threshold are shown in Figure S2 of the auxiliary material. We emphasize that although our sampling criterion is lenient, we rely on additional factors such as regional coherency (note that no additional spatial smoothing has been applied to any of the data sets) and consistency with independently measured marine air temperatures to assess the reality of the SST trends.

3.2. Global SST Trends

The 20th century SST trend distributions from the 5 different data sets are compared in Figure 1 for the period 1900 to 2008 (2002 for Minobe/Maeda, the latest year available), along with air temperature trends based on HadCRUTv3 over land and MOHMAT4 over the oceans for the period 1900 to 2005 (the latest year available). The SST trends from the un-interpolated HadSST2 and Minobe/Maeda archives are similar, exhibiting positive values everywhere except the western portion of the northern North Atlantic. The largest warming trends (approximately 1.2–1.6°C per century) occur directly east of the continents in the northern hemisphere, in the Southern Ocean and the eastern tropical Atlantic. The eastern tropical Pacific warms by approximately 0.8–1.0°C per century, similar in magnitude to the tropical Indian Ocean and the central tropical Atlantic.

Deser et al. (2010)
Also critical: improving long-term 20th c. estimates
Paleoclimate: key piece of the puzzle

Cook et al. (2015)

or modern period, considerably adding to the previous report of an MCA megadrought in southern Finland (29), and it now more completely defines the spatial pattern and extent of dryness during that time.

In contrast, the Romania and Ukraine regions of eastern Europe have more similar patterns of dryness, and northern Fennoscandia and Russia have more similar patterns of wetness, in all three epochs. Notably, the overall timing of MCA dryness in north-central Europe is consistent with that described for large areas of North America (26, 27) (see later discussion).

A summary of the history of drought and wetness since 870 CE in the core region of Old World MCA drought (Fig. 3A, yellow rectangle) is presented in Fig. 3B. The overall mean ± 1 sdPDSI units from the expected mean of zero for the 1928–1978 calibration period, which reflects the general tendency for drier conditions in the preindustrial past. In contrast, the most recent period (1998–2012) has been anomalously wet (+0.97 ± 0.24). It is necessary to go back to 1721–1739 to find a wetter period of comparable duration (+1.55 ± 0.24). As a relative index of drought, scPDSI has a high degree of spatial comparability across a broad range of precipitation climatologies (30). This allows us to compare this drought to another reconstructed megadrought occurring at around the same time in western North America (26). The 1000–1200 CE megadrought over north-central Europe has a reconstructed mean of −0.72 ± 0.10 scPDSI units. By comparison, the worst megadrought in the California and Nevada regions of the NADA (26) last from 832 to 1074 CE (−0.84 ± 0.09, calculated after adjusting the mean of the California/Nevada series to match that of the north-central Europe series over their 870–2005 common interval). Thus, in terms of relative dryness as modeled by the scPDSI, this MCA megadrought in the OWDA is comparable to one of the more exceptional MCA megadroughts in the NADA.

Besides the MCA, Fig. 3B also reveals the occurrence of a mid–15th-century megadrought in north-central Europe. The most intense drought phase lasted for 37 years from 1437 to 1473 CE (−1.84 ± 0.20), with only two isolated years of positive scPDSI. The timing of this megadrought is similar to that of the worst drought reconstructed to have occurred over the past 1000 years in the southeastern United States (27). This suggests the existence of some common hydroclimatic forcing across the North Atlantic, perhaps related to Atlantic Ocean sea surface temperature variations and/or the North Atlantic Oscillation (31, 32). Finally, a third megadrought occurred from 1779 to 1827 (−1.34 ± 0.16). This period has as a subperiod of "major long-duration drought" (33) from 1798 to 1808 (−1.89 ± 0.38) in England and Wales identified from early instrumental records.
The interannual cycles are observed for the instrumental significant ENSO periodicities fall within interannual (2–7 years) (Fig. 1f). The multi-taper method and anomalies (SSTAs) are relative to the mean of observed SSTs during 1971–2000. The green bold line denotes a 31-yr low-pass filter.

**Paleoclimate: key piece of the puzzle**

[Map showing SST anomalies with color codes for correlation and a time series graph of SST anomalies from 1300 to 2000 AD. Site locations are indicated.]
21st c. teleconnected responses governed by changes to modal amplitude, atmospheric responses to SST variability

- Some teleconnection responses are robust across models (El Nino impacts), some may not be

- Anthropogenic forcing is extremely complex, implemented differently across models: e.g. details of land-use changes, aerosol microphysics

- CMIP6-endorsed MIPs may help clarify some issues, as may observational process studies
Discussion Questions

- Should US CLIVAR make recommendations on priorities for new model experiments/
analyses of simulations planned for CMIP6?

- What are best practices for process-based model evaluation using observational data?

- What are the highest priority new observations to target for improvements in simulated
teleconnections?
**15-year drought (0.5σ threshold)**

Stratified by mode
(above 60th/below 40th percentile)

Brown = higher drought risk
Green = lower drought risk

**Stronger AMO:**
- **Shorter** drought in northern Amazon, parts of Australia
- **Longer** drought in SW US, monsoon Asia

Stevenson et al. (2017), in review
Paleoclimate: key piece of the puzzle

Emile-Geay et al. (2013)
Forced changes to teleconnections also matter

Fig. 9. Teleconnections with ENSO in LME simulations for (a) surface air temperature and (b) precipitation. (c) and (d) same as (a) and (b) for LME simulations with and without the effects of volcanism. Stippling indicates regression differences insignificant at the 90% level, as measured using a Wilcoxon rank-sum test.

Stevenson et al. (2017), in review
Megadrought
Volcanic Aerosol Forcing
Precipitation, land temperature changes
Circulation shifts
Megapluvial
Changes in tropical Pacific mean state
AMO excitation
Aerosol-driven circulation changes
Land surface cooling
Weaker ENSO coupling
Volcanic Aerosol Forcing
Regional Hydroclimate Variations

Stevenson et al. (2017), in review