Multi-model ensemble analysis of Pacific and Atlantic SST variability in unperturbed climate simulations

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1. MOTIVATION

Important aspects of inter- and multi-decadal climate dynamics and variability remain poorly understood[1]. Moreover, variability modes may not be stationary in time and their representation may be model dependent.

We consider a multi-model ensemble based on multicentennial control climate simulations from the CMIP5/PMIP3 archive:

- to assess whether robust features can be found across state-of-the-art models pointing to a consistent description of the general dynamics behind low-frequency internal climate variability
- to determine whether observed features of low-frequency climate variability appear also as prominent features of unperturbed climate simulations, and can therefore be attributed to internal climate dynamics. Focus is, in this case, on the inter-basin relation between dominant modes of low-frequency sea-surface temperature (SST) variability in the Pacific and Atlantic oceans [2-4]

2. EXPERIMENTAL SETUP

Our assessment focuses on within-ensemble robustness of spatial patterns of regional annual-average SST variability and emerging prevalent features of (cross-)wavelet-based phase-frequency diagrams [5] of corresponding paired indices.

We consider the piControl simulations performed with the following CMIP5 models: ACCESS1-0, ACCESS1-3, CanESM2, CCSM4, CESM1-BGC, CNRM-CM5, CSIRO-Mk3L-1-2, CSIRO-Mk3-6-0, FiO-ESM, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, GISS-E2-H, GISS-E2-R, HadGEM2-ES, IROC5, MPI-ESM-MR, MPI-ESM-P, MRI-CGCM3, and NorESM1-M. Local trends are removed.

Indices of regional SST variability are calculated based on annual-average SST data following [6]:

- PAC1 and PAC2: the first and second principal component of annual-average SSTs over the tropical and North Pacific (120-240E; 20S-50N).
- ATL is the spatially-averaged annual-average SST over the North Atlantic (80W-0; 0-60N).

3. RESULTS – Ensemble SST patterns and variability

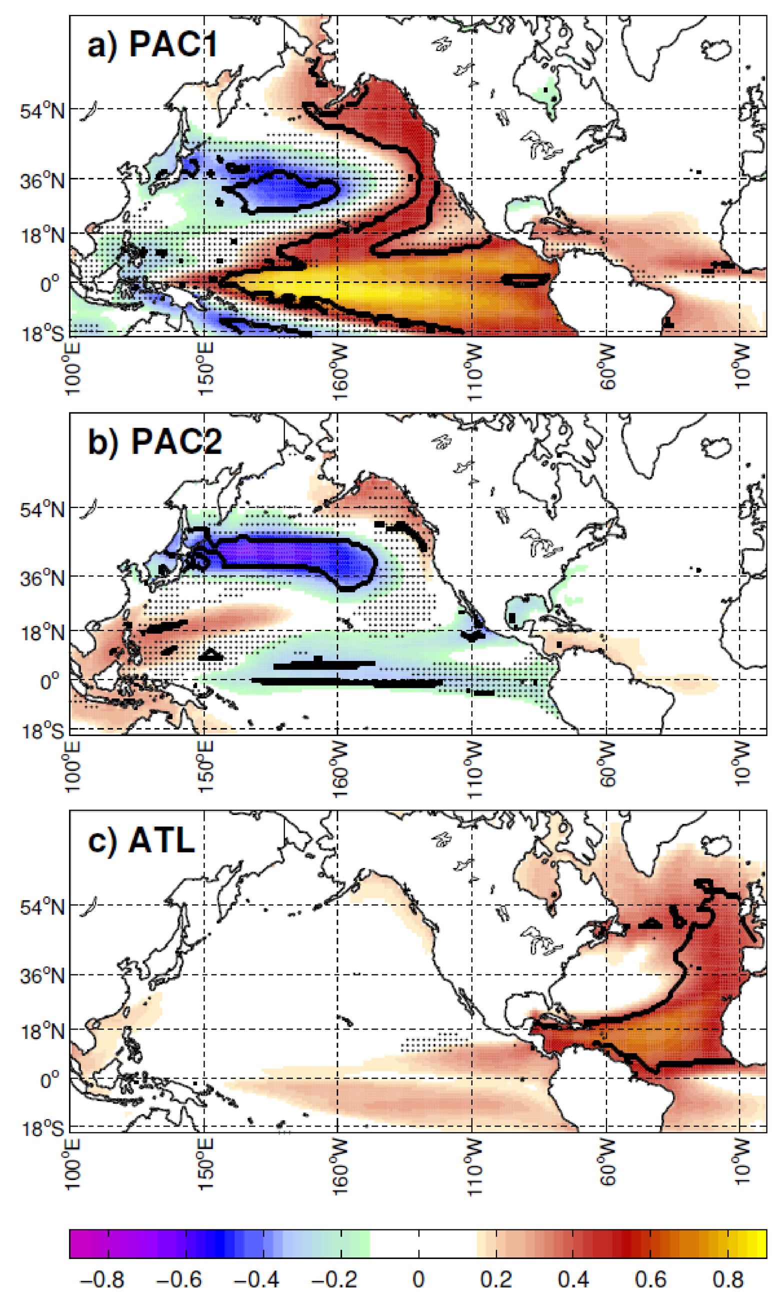

Figure 1 - Ensemble-mean regression patterns of standardized tropical-North Pacific and North Atlantic SSTs on selected indices. Regression statistics (unitless) for individual simulations were regridded to a 1°x1° regular grid. Thick line contours indicate locations where the regression is significant at 95% confidence level in all simulations; dots indicate locations where the ensemble standard deviation of local regression is larger than 0.2. CSIRO-Mk3-6-0/-Mk3L-1-2, FIO-ESM, GISS-E2-H/-R and MIROC5 were excluded in the ensemble analysis for panel b as the associated pattern is poorly correlated with its observational counterpart.

PAC1 explains between 18.8 and 41.8% of tropical and North Pacific SST variability. PAC2 explains between 10.5 and 20.2% of tropical and North Pacific SST variability in individual simulations. ATL explains between 15.5 and 27.6% of total variance of North Atlantic SST variability.

The spatial patterns of PAC1 and ATL are robust in the ensemble over extensive regions. They overall compare well with the corresponding observed patterns, despite a generally weaker signature (not shown). Furthermore, ATL and PAC1 signatures partly superpose in the tropical region, suggesting that common variability may result from (lag-0) inter-basin interactions. Conversely, individual simulations differ in the variability captured by the PAC2 index and its ensemble robustness is more regionally confined.

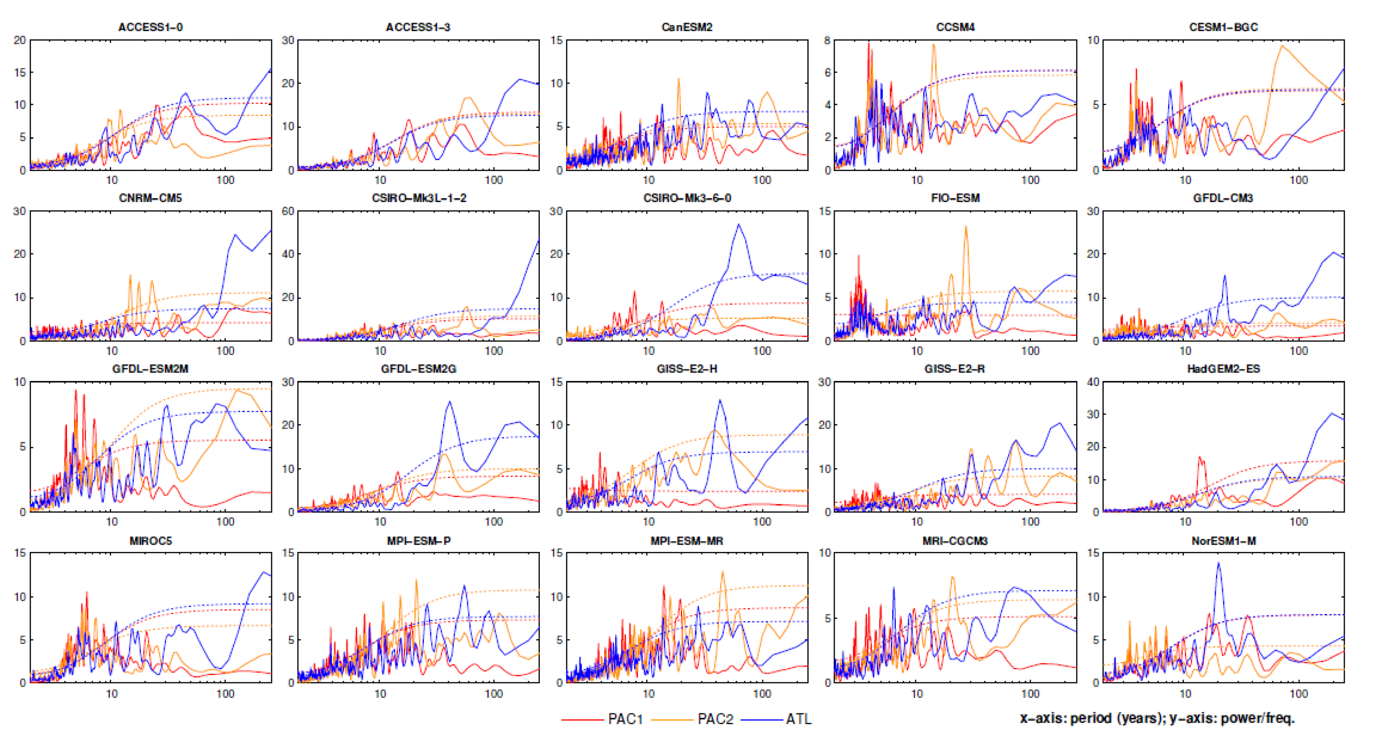

Figure 2 - Spectral density (via smoothing of periodogram with Hamming window) of SST indices for individual simulations. The dashed lines individuate the corresponding 95% confidence levels against red noise, calculated for a lag-1 autoregressive process fitted to the data.

Details of the spectral features of the SST indices can vary strongly between simulations, also between those pertaining to the same family of models as shown, e.g., by CSIRO and GFDL simulations (Figure 2).
There are, however, also features pointing towards general ensemble similarities. PAC1 expresses generally strong interannual variability and generally weak multidecadal and centennial variability. PAC2 generally exhibits more broadband variability, with comparatively stronger and often significant spectral amplitudes at multidecadal and longer timescales. ATL entails significant multidecadal and/or centennial variability in most but not all simulations.

4. RESULTS – Ensemble phase-frequency diagrams

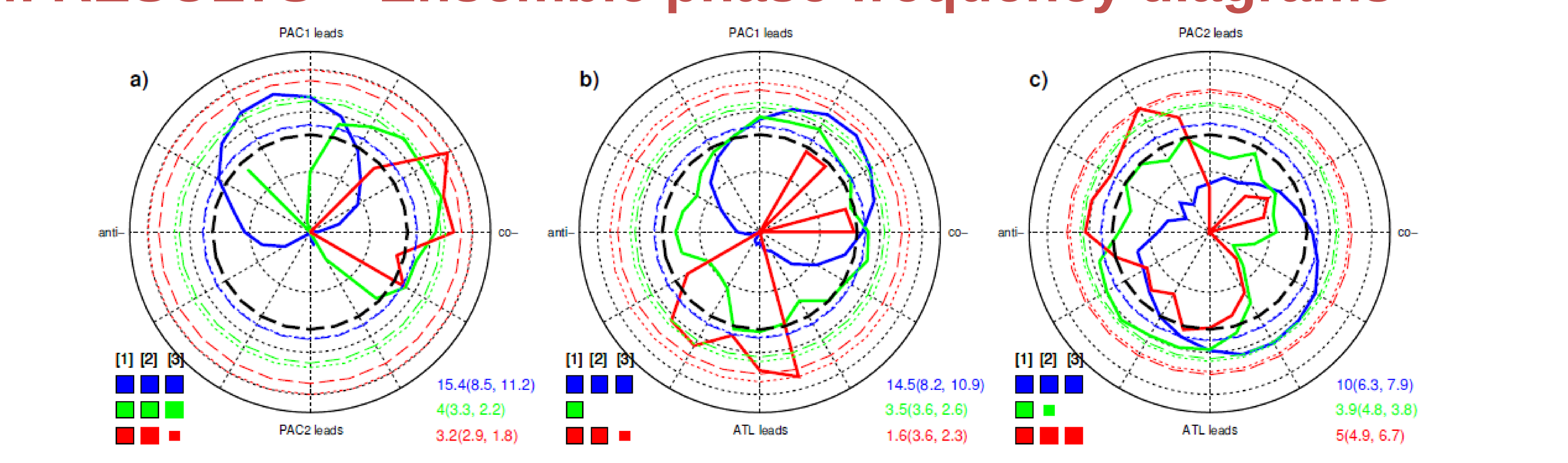

Figure 3 - Ensemble phase-frequency diagrams describing phase relations between pairs of SST indices for different time-scales. Only significant regions of the cross-wavelet spectrum are retained for the calculation of the diagrams. The extent of significant regions for the different time-scales is reported, in percent, by the numbers on the bottom right of each panel. In brackets are the mean values for random realizations obtained using surrogate indices created through two different methods. Dashed and dotted colored lines are 95% confidence levels evaluated based on the two randomization methods. Black thick dashed circle: expected uniform distribution. Small, large and bracketed squares on the bottom left of each panel indicate, respectively, rejection of the null hypothesis with 90%, 95% and 99% confidence according to the three performed tests (1: uniform distribution, 2: lag-1 surrogates, 3: spectral surrogates). Grid is drawn at π/6 and at frequency intervals of 0.01, 0.1 and 0.5 (on a log2 scale in the range [0, 1]). Labels at quadrature phases are according to an expected co-phase. CSIRO-Mk3-6-0/-Mk3L-1-2, FIO-ESM, GISS-E2-H/-R and MIROC5 were excluded in the ensemble analysis for panels a and c.

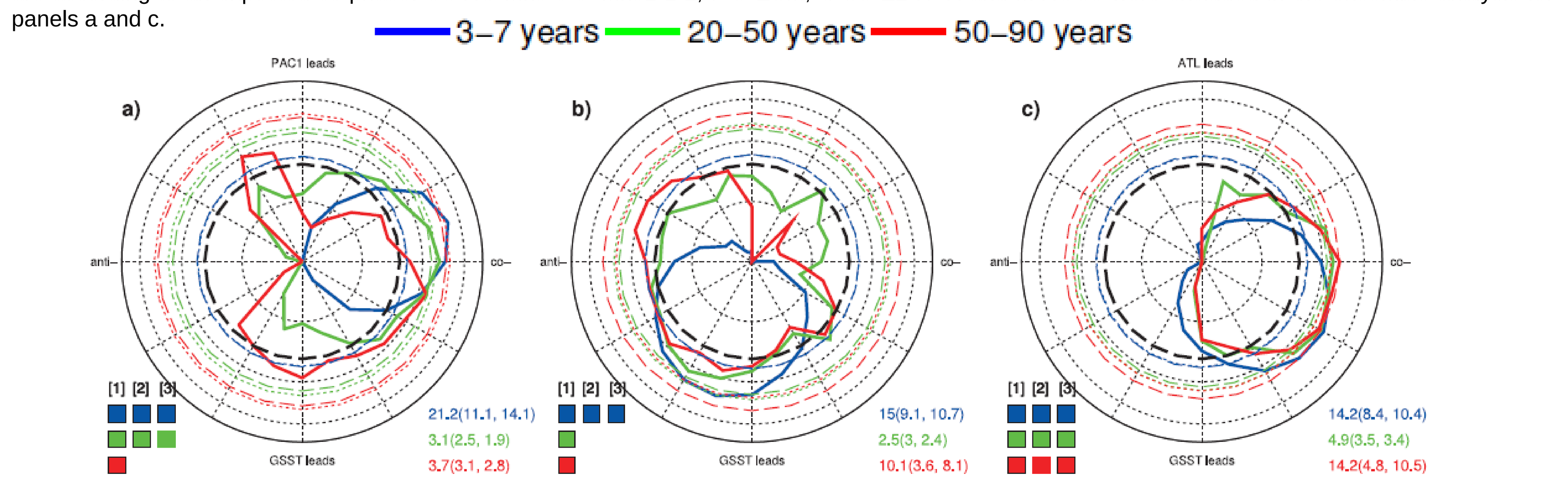

Figure 4 -Same as Figure 3, but for the phase relation between SST indices and global-average SST (GSST). GSST data were detrended before analysis (see Table 1). CSIRO-Mk3-6-0/-Mk3L-1-2, FIO-ESM, GISS-E2-H/-R and MIROC5 were excluded in the ensemble analysis for panel b.

The interannual results (blue lines in Figs. 3 and 4) indicate that Atlantic and global signals lag the Pacific in agreement with indications from observations.
A significant but non-representative (<5%) co-phase characterizes the PAC1-PAC2 inter- and multi-decadal variability (green and red curves in Figure 3a). Decadally-smoothed indices produce a highly representative (>40%) interdecadal phase-frequency curve confirming the significance of the rough co-phase (not shown). Thus PAC1 is a leading variable at these timescales.
No robust prevalent interdecadal phase relations are detected between PAC1/PAC2 and ATL (green curve in Figure 3b,c). By contrast, there are at least hints of a multidecadal connection between PAC indices and ATL that support direction and timing of the observational low-frequency AMO-PDO connection (red curves in Figure 3b,c).. Evidently there are periods in individual simulations when inter-basin SST fluctuations are characterized by a preferred phasing.
A broadband rough co-phase characterizes the ATL connection with GSST on inter- and multi-decadal timescales (Figure 4c).

5. CONCLUSIONS

- **Linearly-independent Pacific indices describing tropical and extra-tropical variability converge toward co-phase at inter- and multi-decadal time scales, indicating that the Pacific Decadal Oscillation is a combination of tropical and extra-tropical processes.**
- **Multidecadal fluctuations in the North Atlantic SSTs generally co-vary with, but also often lag global changes, which renders difficult to discern the Atlantic variability from the global signal.**
- **Whereas individual simulations and/or periods within individual simulations exhibit phase-locked inter- and multi-decadal fluctuations between Pacific and Atlantic modes of SST variability, results are mostly smeared out in the ensemble analysis. We conclude that diversity or non-stationarity of inter- and multi-decadal inter-basin SST relations and of underlying mechanisms are inherent features of unperturbed simulated climates.**

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