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Statistical Link between Solar Activity and Internal Climate Variability in Proxies, Observations, and Climate Model Simulations?

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1st Swiss SCOSTEP (Scientific Committee on Solar-Terrestrial Physics) Workshop 2016

Internal Climate Variability

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- Variability due to natural internal processes within the climate system
- Known examples of internally generated variability include
  - El Niño-Southern Oscillation (ENSO)
  - Atlantic Multi-decadal Oscillation (AMO)
  - Pacific Decadal Oscillation (PDO)

Internal Climate Variability

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Coupling between ENSO, AMO, and PDO

> Previous studies suggest that ENSO, AMO, PDO are correlated (Zhang et al 1996; Barnett et al 1999; Fedorov et al 2000 & 2001; Pierce et al 2000; Vimont et al 2001 and 2003a &b; Dong et al 2002, 2006 & 2007; Yeh et al 2003; Newman et al 2003; Schneider et al 2005; Goswami et al 2006; Newman 2007; Zhang et al 2007; D'Orgeville et al 2007; Wu, et al 2011; Sutton et al 2007; Timmermann et al 2005 & 2007; Kucharski et al 2011; Frauen et al 2012; Kang et al. 2014; Kayano, et al 2014; McGregor et al 2014)

Questions

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1. Is there any link between solar Activity and modes of ocean variability (ENSO, AMO, PDO)?

2. At what timescales these ocean modes are linked to solar activity?

3. Can the interaction between ENSO, AMO, and PDO affect the relationship of each mode with solar activity?

4. Can CO_2, anthropogenic aerosols, and volcanic eruption modulate the relationship between solar activity and these modes of ocean variability?

Methods

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> **De-trended Partial Cross Correlation Analysis (DPCCA)**

> **Why DPCCA?**
  > DPCCA is based on DCCA and PCCA
    - **Climate Variables are often non-stationary**
      - Include local/global trends
      - If variables are non-stationary, traditional cross correlation analysis can give erroneous results
      - DCCA can remove the local/global trends and thus non-stationarities
    - **Climate variables often have background signals**
      - DCCA along with PCCA can remove the effects of background signals or external forcings

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- Suppose we have 3 un-correlated time series and without any trends
  - $X_i^A, X_i^B, \& X_i^C$

$$X_i^{\acute{A}} = X_i^A + X_i^C + Quadratic$$

$$X_i^{\acute{B}} = X_i^B + X_i^C + Quadratic$$

These 2 time series are now correlated and have an external signal X_i^C and quadratic trend

Methods

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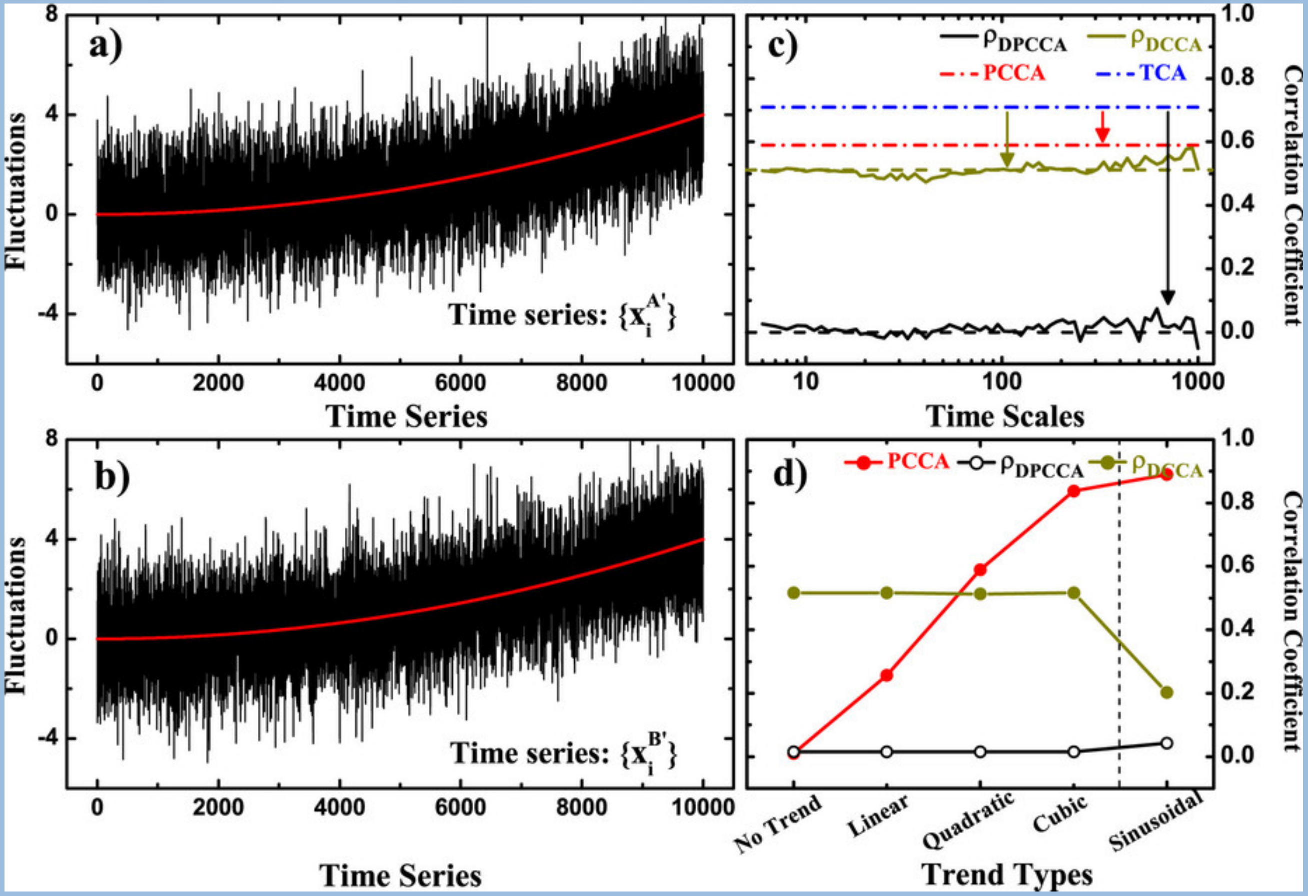

Yuan et al. (2015)

Data: Observations and Proxies

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AMO, PDO, & Nino3

- Extended Reconstructed SSTs v4 (ERSST) v4: (Huang et al. 2014, 2015; Liu et al 2014) AD 1854-1999
- SST reconstruction by Mann et al (2009): AD 1600-1999
- AMO reconstruction by Gray et al (2004): AD 1600-1990
- PDO reconstruction by Shen et al (2006) AD 1600-1990
- Nino3(DJF) reconstruction by (Cook et al. 2008): AD 1600-1990

Data: External Climate Forcings (1600-1999)

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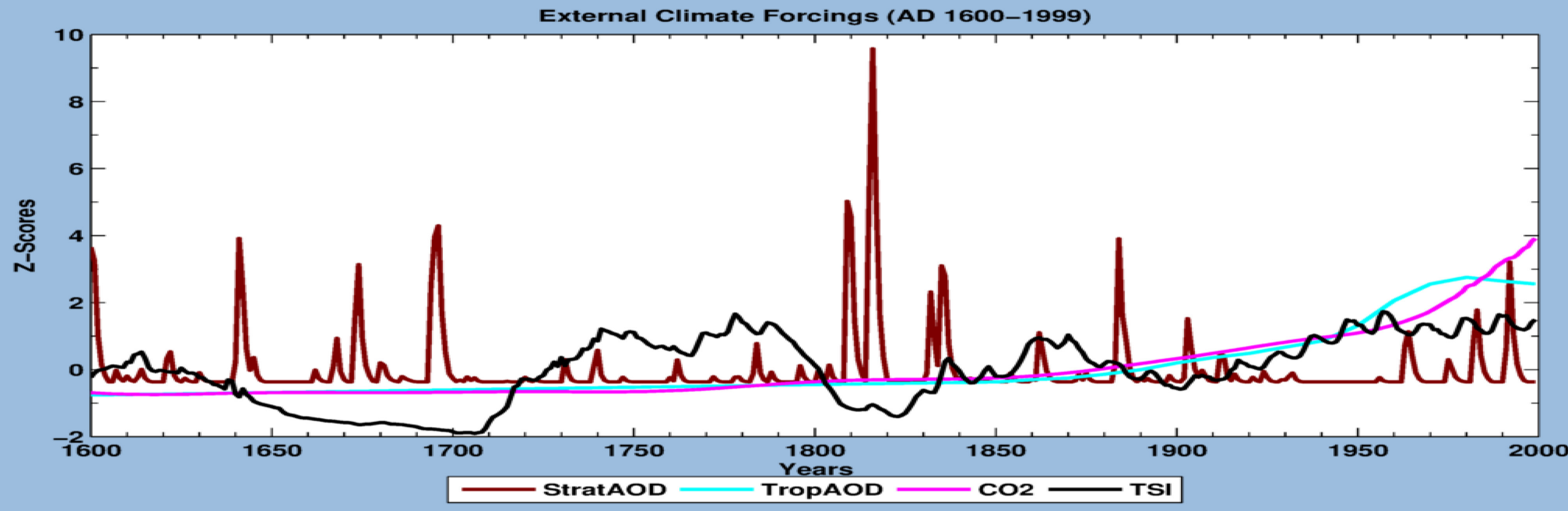
- TSI: (Shapiro et al. 2011)
- CO_2: (Ramaswamy et al., 2001)
- StratAOD: (Arfeuille et al., 2014)
- TropAOD: (Bauer 2011, personal communication)



Data: Climate Model

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- Atmosphere-Ocean-Chemistry-Climate Model (AOCCM) simulations with SOCOL MPIOM over the period AD 1600-1999 (Muthers et al 2014)
- Horizontal resolution of T31 ($\approx 3.75^o \times 3.75^o$)
- 39 irregular vertical pressure levels (L39) from 1000hPa up to 0.01hPa
- Four transient simulations (L1, L2, M1 & M2) including all major forcings (solar, volcanic, GHG, and aerosol)
- **L1 & L2:** Strong solar forcing with different initial ocean conditions for both runs.
- **M1 & M2:** Medium solar forcing with different initial ocean condition for both runs.

Results: Solar Influence on AMO

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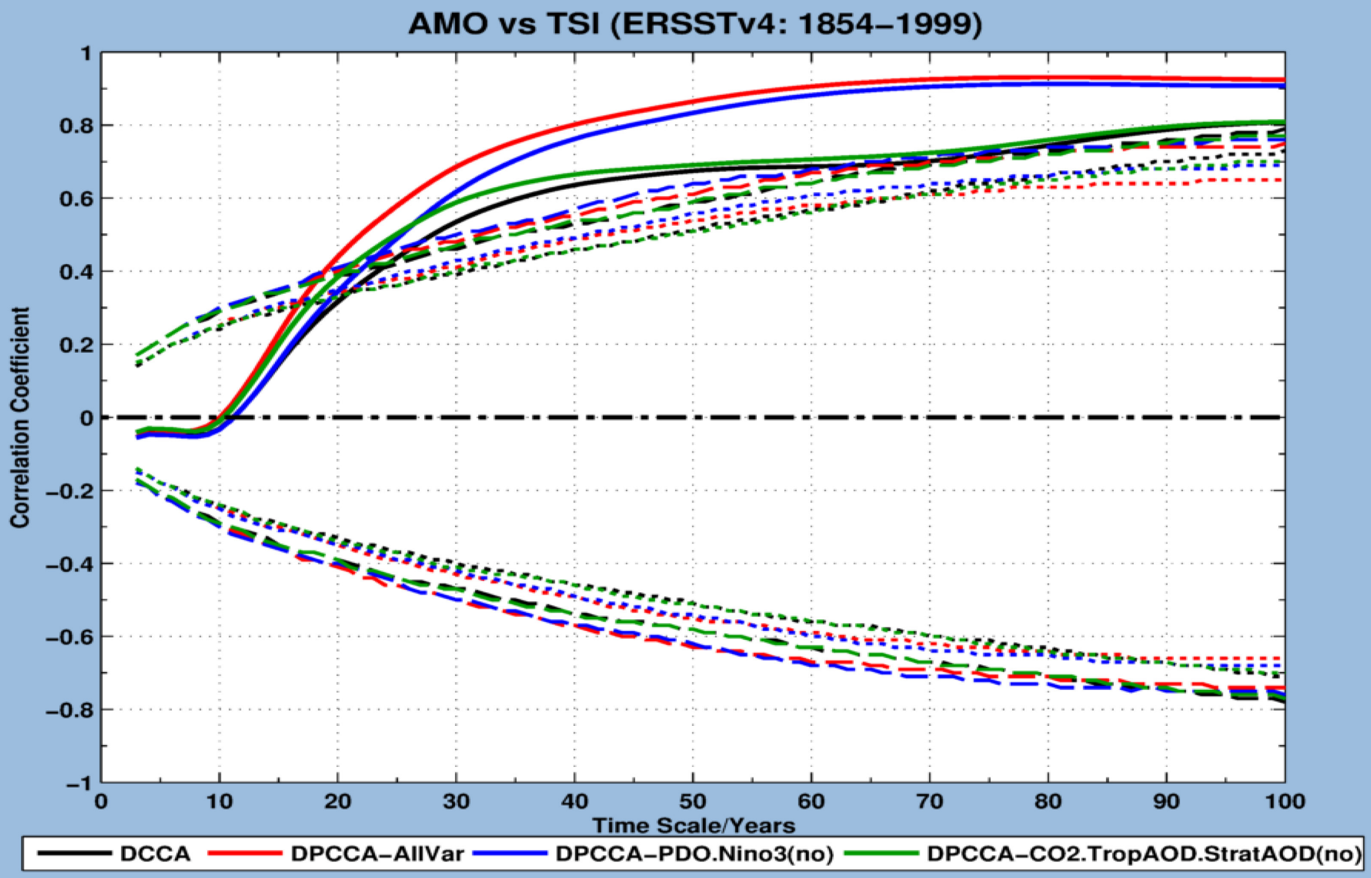
In Observations



Results: Solar Influence on AMO

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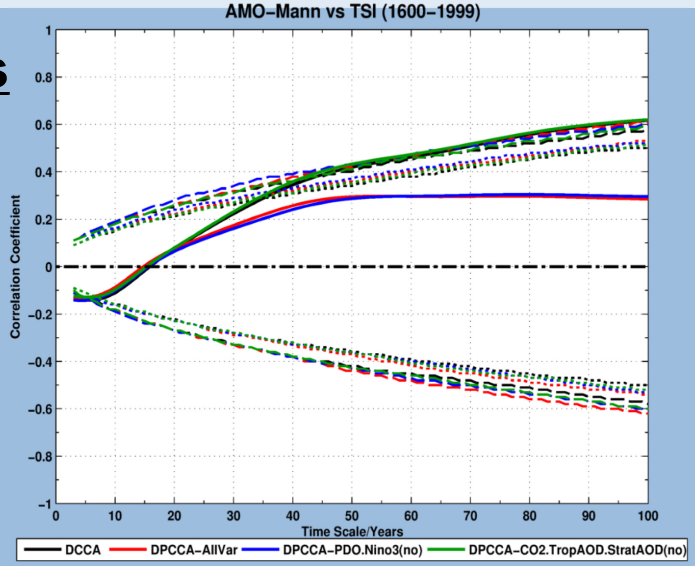
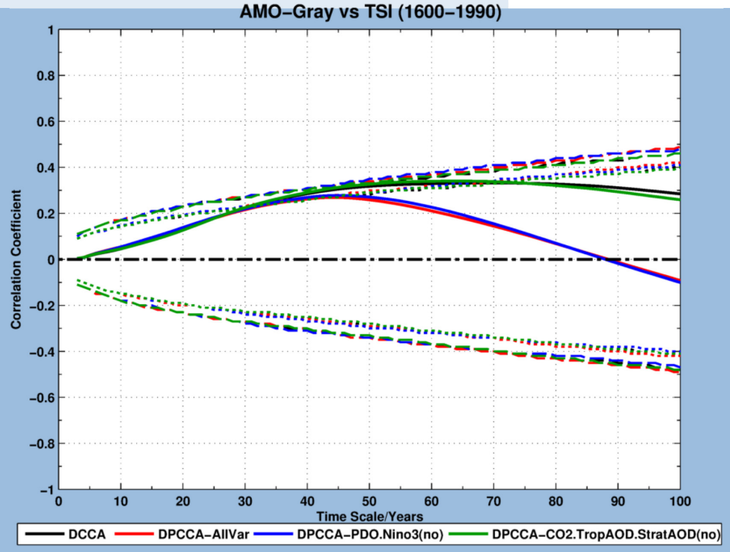
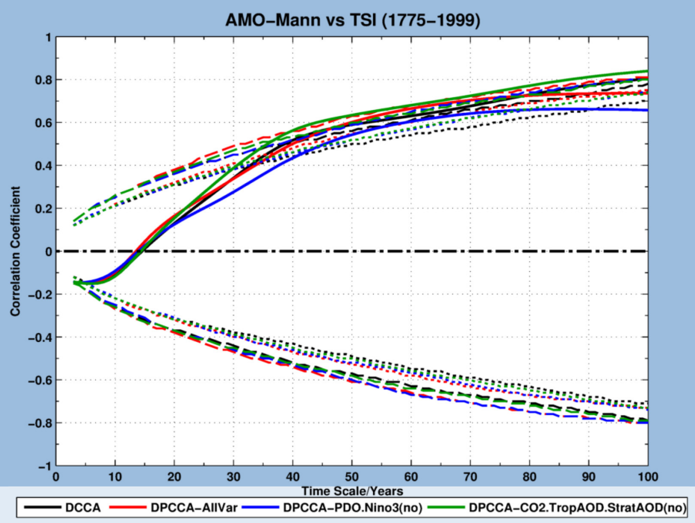
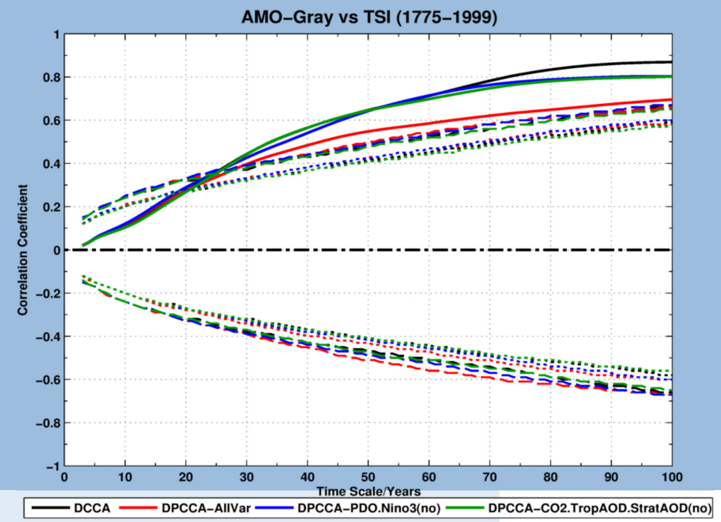
In Proxies









Results: Solar Influence on AMO

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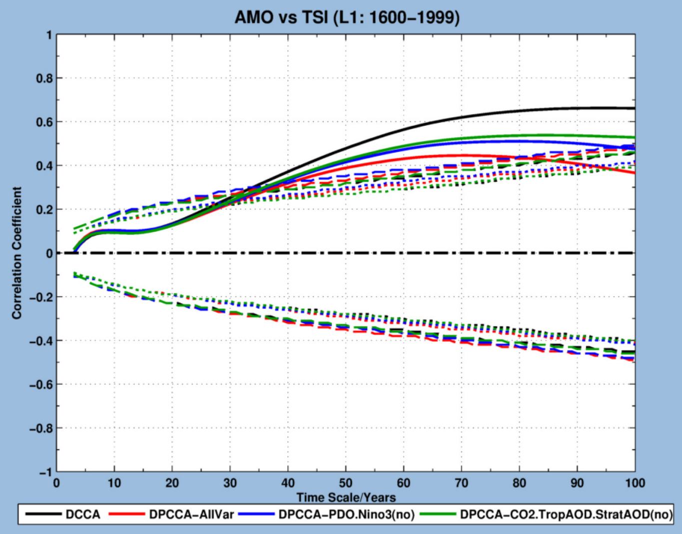
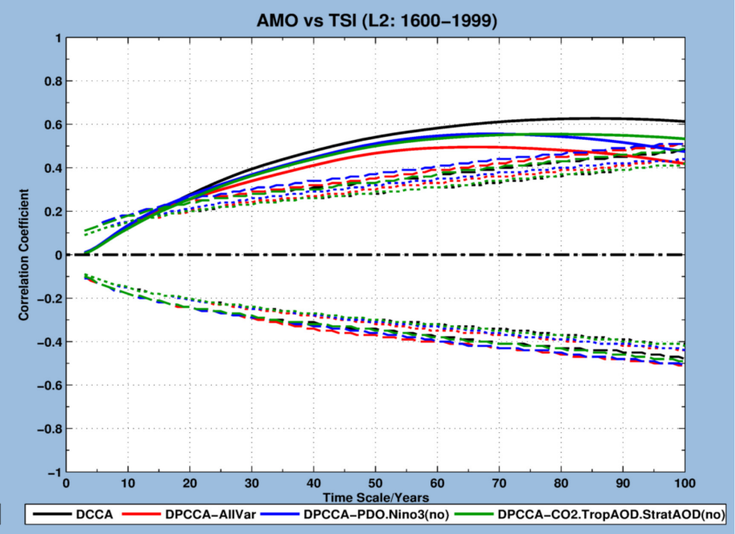
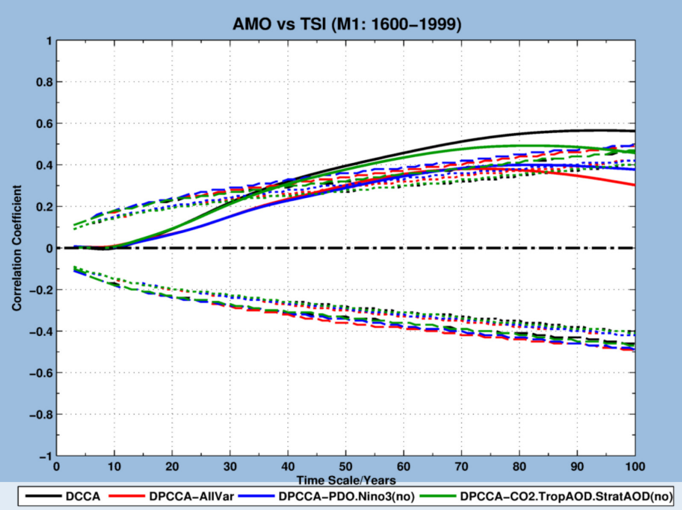
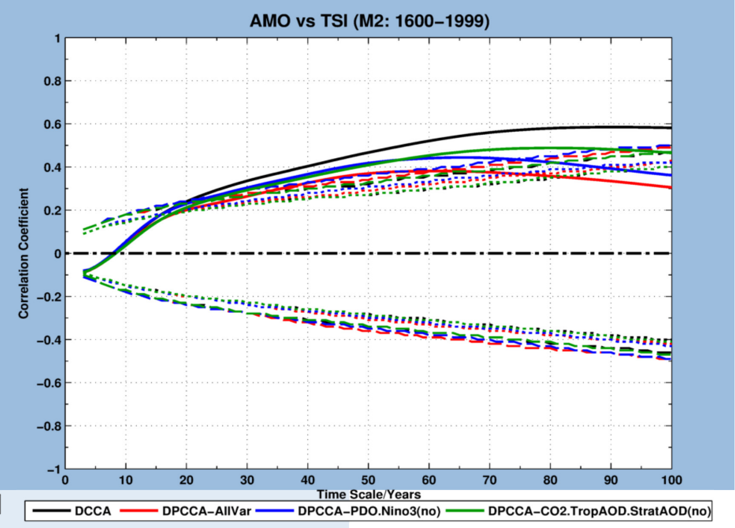
In Climate Model









Results: Solar Influence on Niño3

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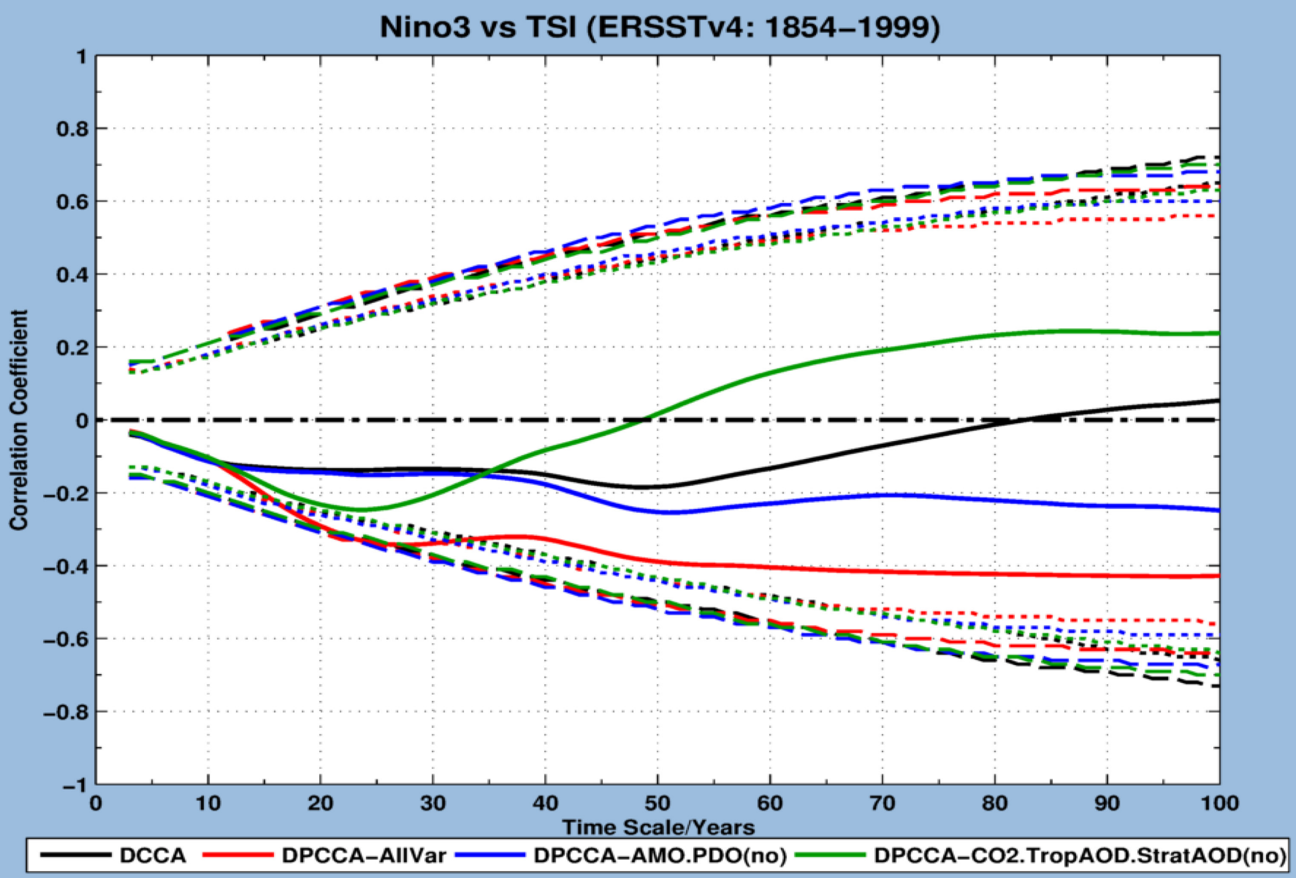
In Observations



Results: Solar Influence on Niño3

In Proxies

No Evidence

Results: Solar Influence on Niño3 (in Climate Model)

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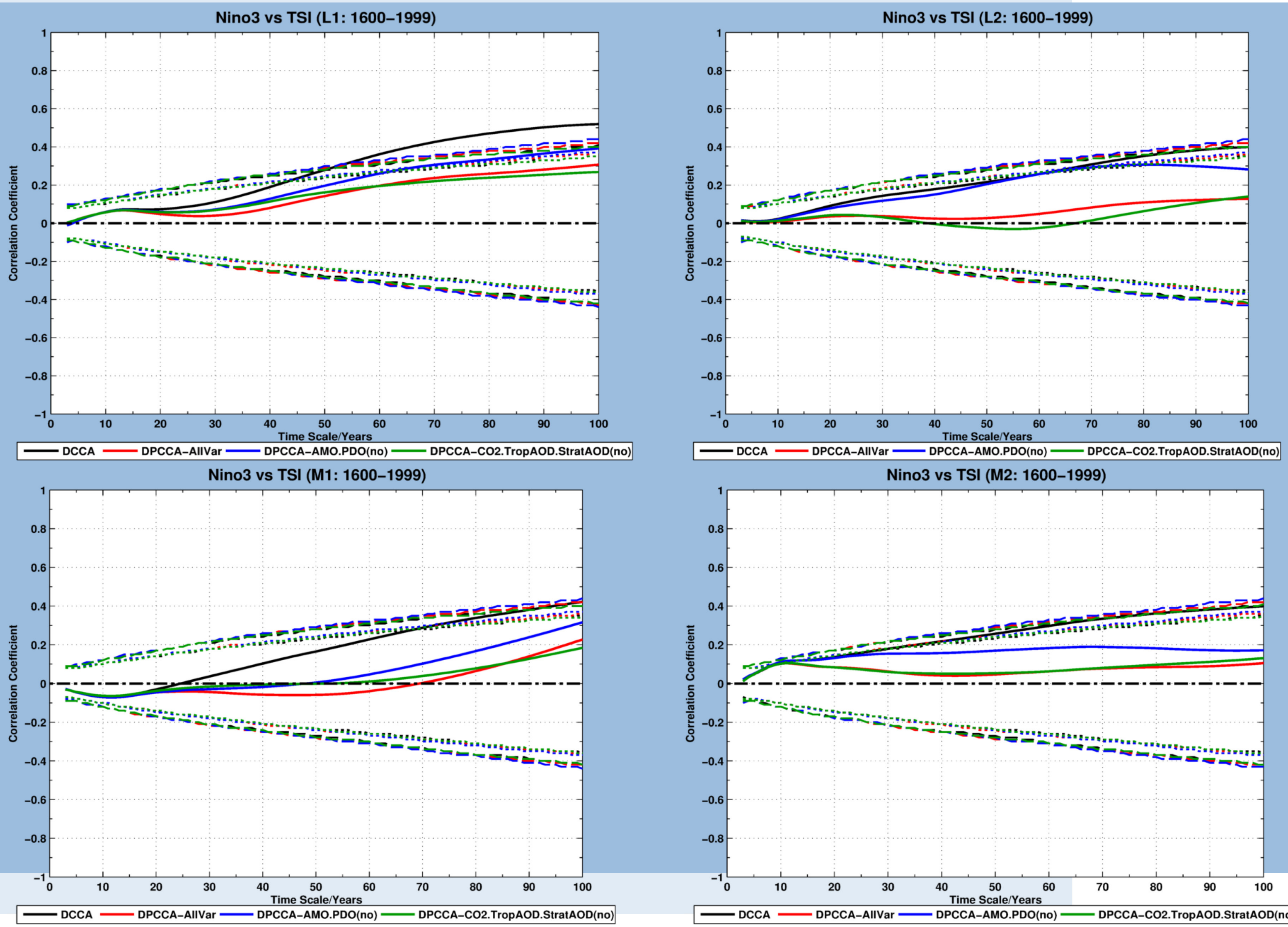

Results: Solar Influence on PDO

No Evidence

Conclusion

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> Robust statistical evidence of the influence of solar activity on AMO on decadal to centennial timescale

> There is an intrinsic relation between solar activity and AMO

> The intrinsic relation between AMO and solar activity is modulated j by PDO and ENSO, and other forcings factors such as tropospheric and stratospheric aerosols, and CO_2

> The influence of solar activity on AMO is consistent among observations, proxies, and climate model simulations

Conclusion

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- There is intrinsic link between solar activity and Nino3 on decadal timescale (17-30-yr) in observations which is modulated by AMO and PDO, and other forcings factors such as tropospheric and stratospheric aerosols, and CO_2
- Climate model simulations show an indirect influence of solar activity on Nino3 with a difference of sign in correlation (+v), consistent with climate model based study of Fan et al (2009)
- No statistically significant evidence of solar influence on PDO

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Thanks for Your Attention
Questions??

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Methods

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Algorithm (Yuan, et al., 2015)

1) Suppose we have **m** time series

$$\{x_i^1\}, \{x_i^2\}, \{x_i^3\}, \cdots, \{x_i^m\}$$

$$i = 1,2,3,\cdots,N.$$

2) We build **profiles** as:

$$P_k^j \equiv \sum_{i=1}^{k} x_i^j,$$

$$j = 1,2,3,\cdots,m,\ k = 1,2,3,\cdots,N.$$

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3) Divide each profile into ***N-s*** overlapping boxes where each box i contains **s+1** values, starts at i and ends at **i+s**

4) In each box **i** determine a trend by a **polynomial fit** and define **de-trended walk** to get residual time series:

$$Y^{j}_{(i-1)(s+1)+k-i+1} = P^{j}_{k} - \widetilde{P^{j}_{k,i}},$$

$$Y^{j}_{l},\ l = 1,2,3,\cdots,(N-s)(s+1),$$

Trend for $\mathbf{k_{th}}$ element of $\mathbf{i_{th}}$ overlapping-box in $\mathbf{j_{th}}$ time series.

Methods

5) Calculate **covariance** between any two residual time series

$$F^2_{j_1,j_2}(s) \equiv \frac{\sum_{l=1}^{(N-s)(s+1)} Y_l^{j_1} Y_l^{j_2}}{(N-s)(s-1)},$$

$$j_1, j_2 = 1, 2, 3, \cdots, m,$$

6) Obtain the **covariance matrix** as:

$$\boldsymbol{F}^2(\mathrm{s}) = \begin{pmatrix} F^2_{1,1}(s) & F^2_{1,2}(s) & \dots & F^2_{1,m}(s) \\ F^2_{2,1}(s) & F^2_{2,2}(s) & \dots & F^2_{2,m}(s) \\ \vdots & \vdots & & \vdots \\ F^2_{m,1}(s) & F^2_{m,2}(s) & \dots & F^2_{m,m}(s) \end{pmatrix}.$$

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7) The cross correlation (**DCCA**) between any two time series can be obtained as:

$$\rho_{j_1,j_2}(s) \equiv \frac{F^2_{j_1,j_2}(s)}{F_{j_1,j_1}(s) \cdot F_{j_2,j_2}(s)},$$

8) Define **DCCA coefficient matrix**:

$$\boldsymbol{\rho}(\mathbf{s}) = \begin{pmatrix} \rho_{1,1}(s) & \rho_{1,2}(s) & \dots & \rho_{1,m}(s) \\ \rho_{2,1}(s) & \rho_{2,2}(s) & \dots & \rho_{2,m}(s) \\ \vdots & \vdots & & \vdots \\ \rho_{m,1}(s) & \rho_{m,2}(s) & \dots & \rho_{m,m}(s) \end{pmatrix}.$$

DCCA ranges between -1 & +1

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9) To calculate partial correlation, define the **inverse of DCCA** coefficient matrix

$$\boldsymbol{C}(s) = \boldsymbol{\rho}^{-1}(s) = \begin{pmatrix} C_{1,1}(s) & C_{1,2}(s) & \dots & C_{1,m}(s) \\ C_{2,1}(s) & C_{2,2}(s) & \dots & C_{2,m}(s) \\ \vdots & \vdots & & \vdots \\ C_{m,1}(s) & C_{m,2}(s) & \dots & C_{m,m}(s) \end{pmatrix},$$

10) Thus the **DPCCA** between any two time series can be obtained as:

$$\rho_{DPCCA}(j_1, j_2; s) = \frac{-C_{j_1,j_2}(s)}{\sqrt{C_{j_1,j_1}(s) \cdot C_{j_2,j_2}(s)}}.$$

Timescale

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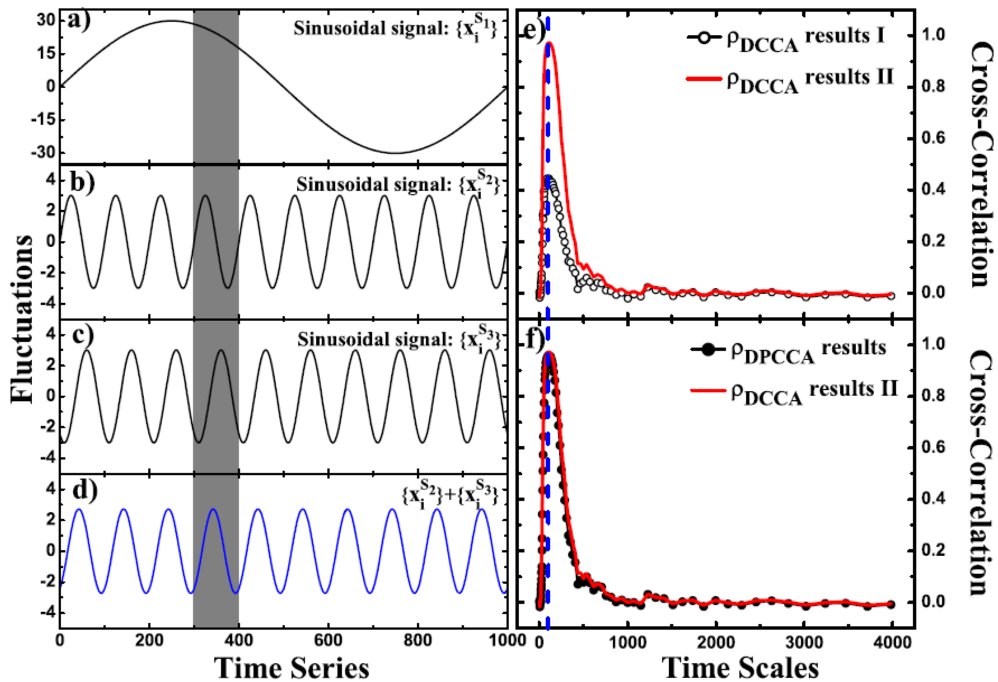
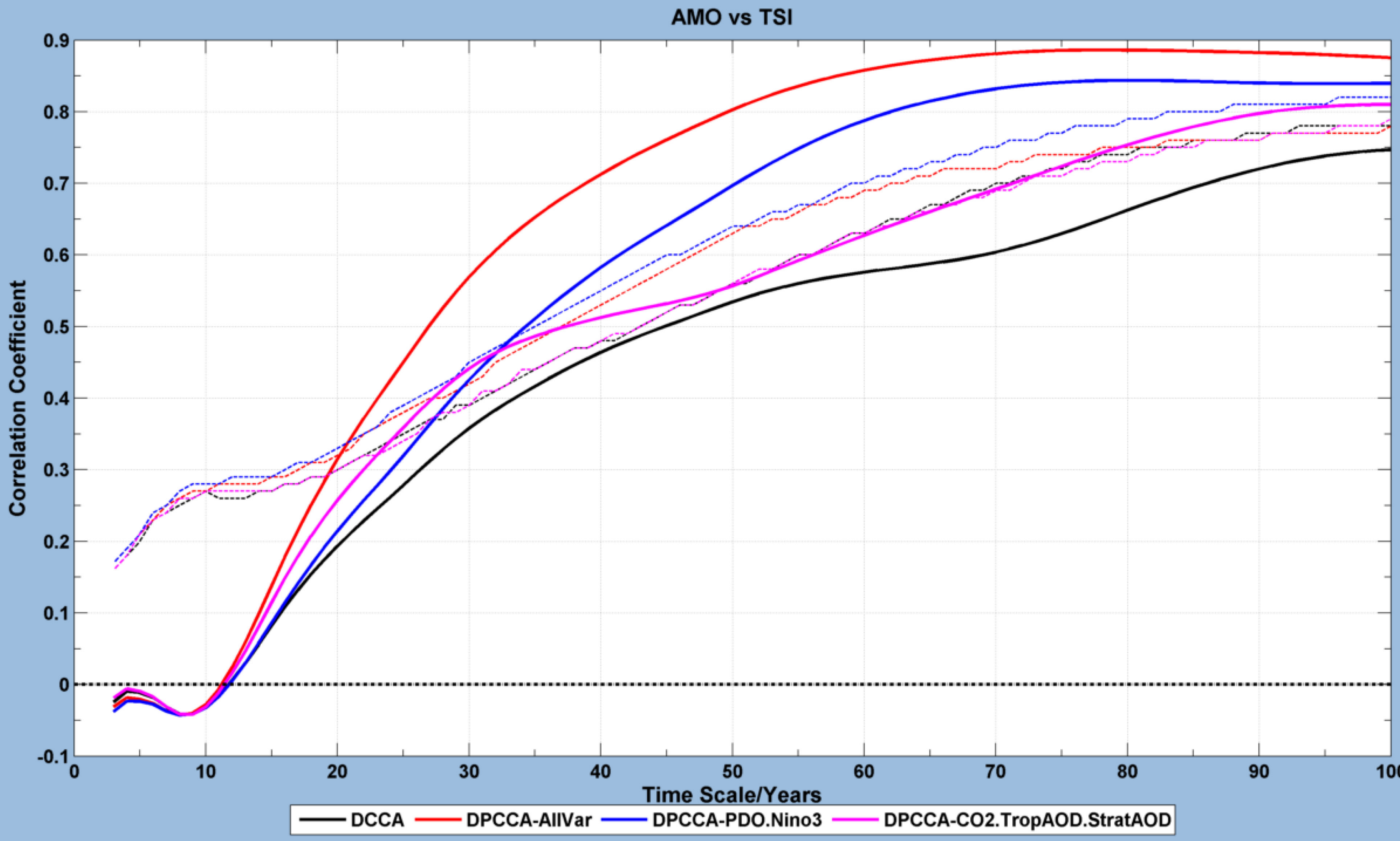


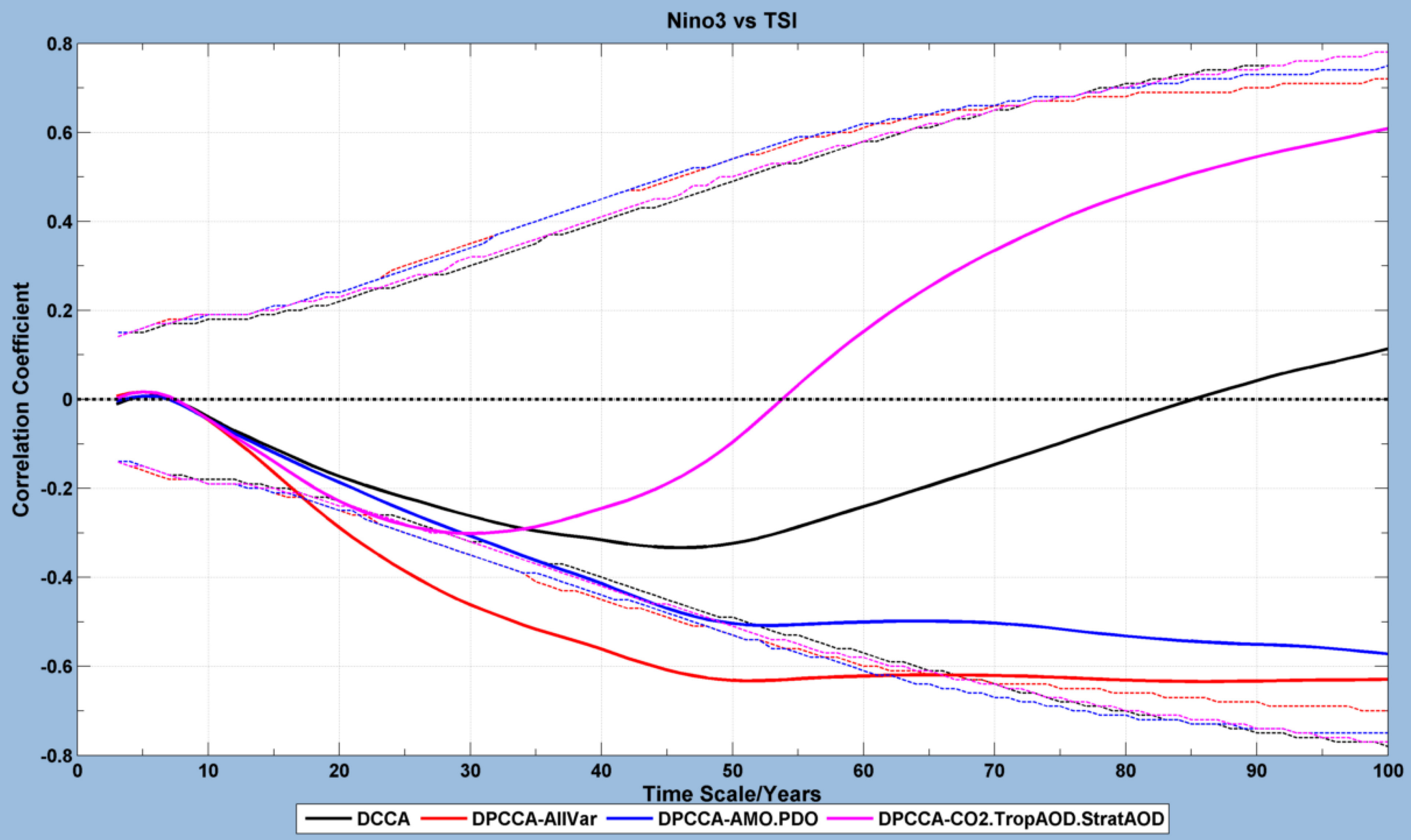
Figure 4 | Time series and related results in Test II. (a–c) show fractions of the three sinusoidal signals in test II: $\{x_i^{S_1}\}$, $\{x_i^{S_2}\}$, and $\{x_i^{S_3}\}$. $\{x_i^{S_1}\}$ acts as a background field, with low-varying frequency and larger amplitude. $\{x_i^{S_2}\}$, and $\{x_i^{S_3}\}$ have different phases (see the gray part), and their combination is shown in (d). The red curve in (e) is the DCCA cross-correlation coefficient ρ_{DCCA} between $\{x_i^{A'}\}=\{x_i^{A}\}+\{x_i^{S_1}\}+\{x_i^{S_2}\}$ and $\{x_i^{B'}\}=\{x_i^{B}\}+\{x_i^{S_2}\}$ (denoted as ρ_{DCCA} results II), and the blue dashed line shows the time scale of 100 (days). If the signal $\{x_i^{S_2}\}$ in $\{x_i^{A'}\}$ is offset by $\{x_i^{S_3}\}$, ρ_{DCCA} fails in providing accurate results, as shown in (e), the black open-circle curve (denoted as ρ_{DCCA} results I). But DPCCA succeeds, as shown in (f), the black solid-circle curve.

(Yuan, et al., 2015)

$$\{x_i^{A'}\}=\{x_i^{A}\}+\{x_i^{S_1}\}+\{x_i^{S_2}\} \text{ and } \{x_i^{B'}\}=\{x_i^{B}\}+\{x_i^{S_2}\}$$

Internal Climate Forcings and TSI




Nino3 vs TSI
Correlation Coefficient
Time Scale/Years
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
0
10
20
30
40
50
60
70
80
90
100
DCCA
DPCCA-AllVar
DPCCA-AMO.PDO
DPCCA-CO2.TropAOD.StratAOD

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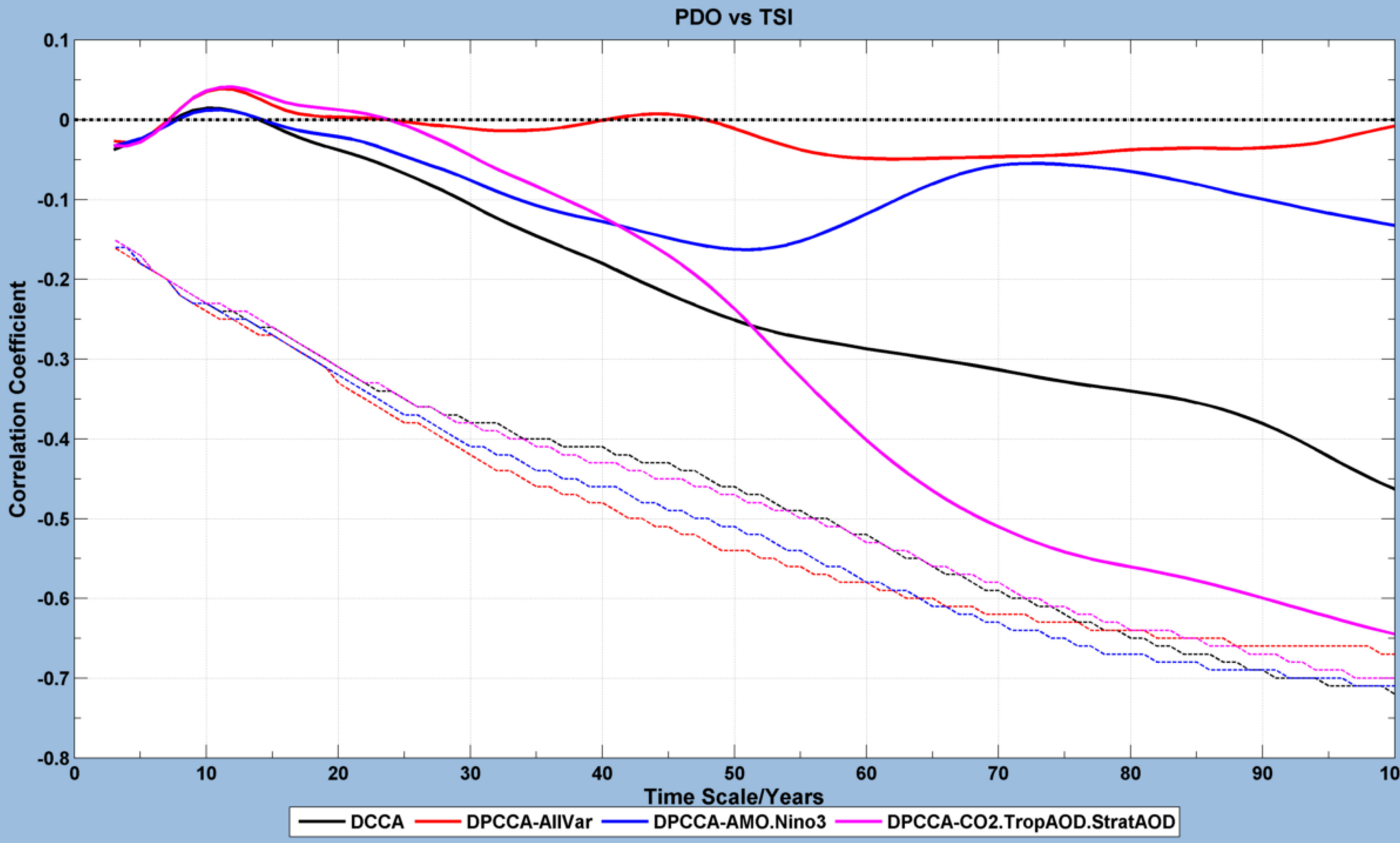
CLIMATE CHANGE RESEARCH



Internal Climate Variability

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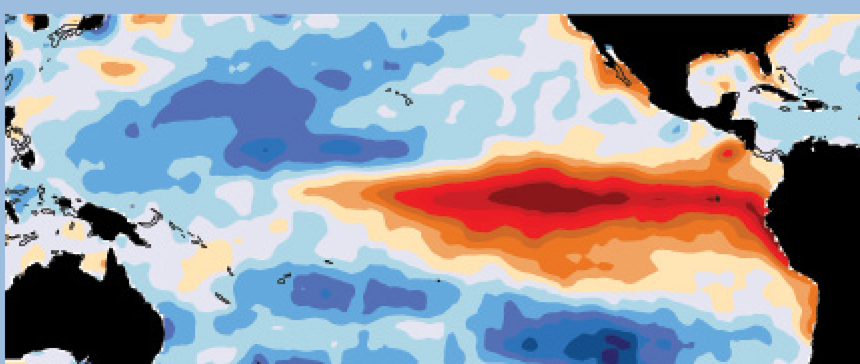
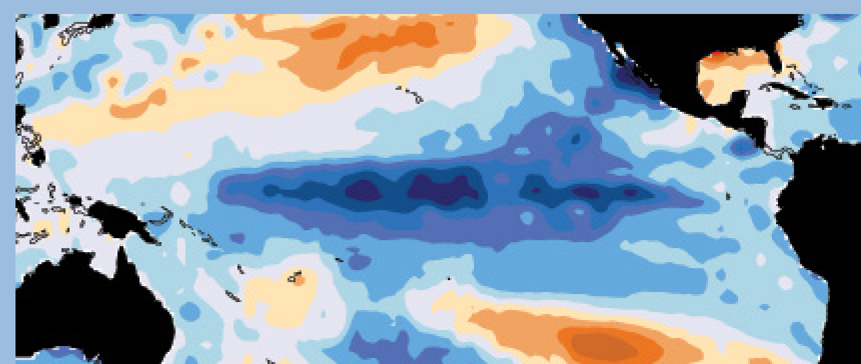
El Niño-Southern Oscillation (ENSO)

- Ocean-Atmosphere interaction in the tropical Pacific
- Irregularly periodical (~2-7-yr) variation in winds and Sea Surface Temperatures (SSTs)

El Niño



La Niña



Internal Climate Variability

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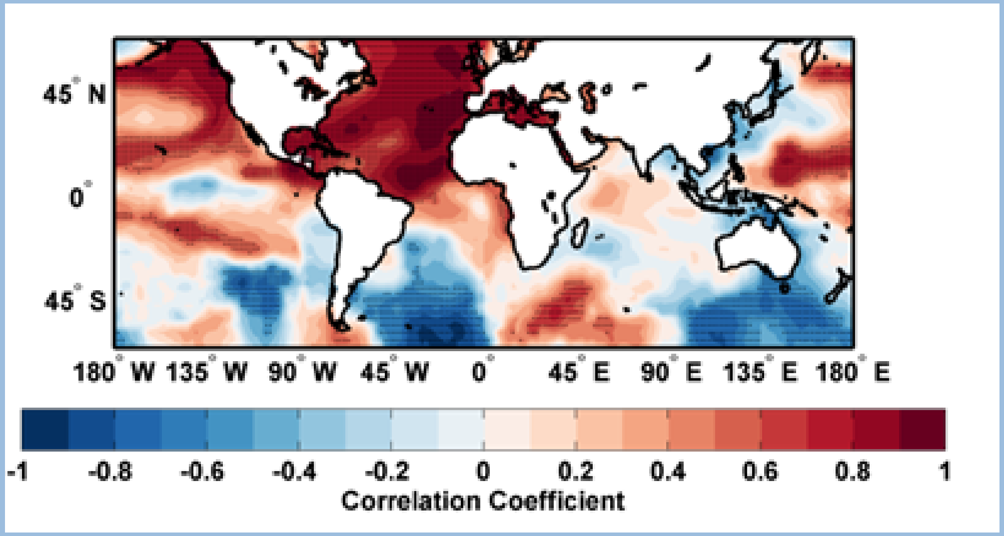
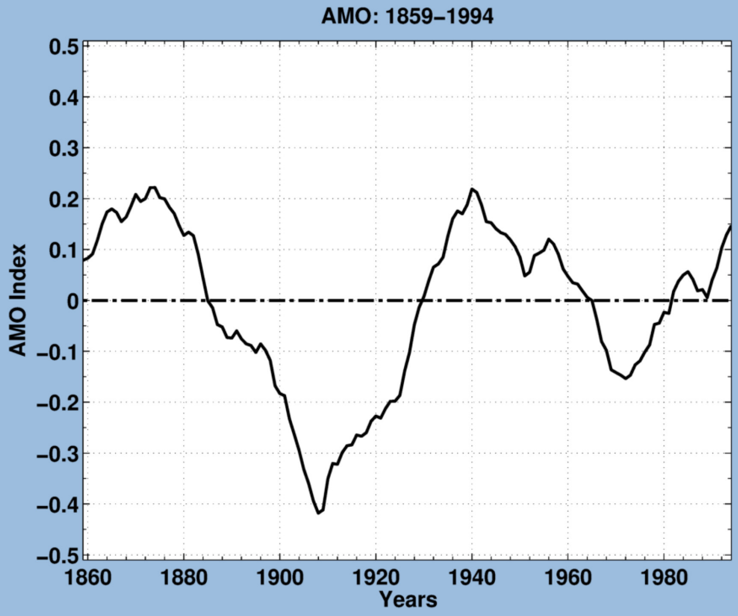
Atlantic Multi-decadal Oscillation (AMO)

> A pattern of SSTs in the North Atlantic with a period of ~55-80 years and an amplitude of 0.4°C





Internal Climate Variability

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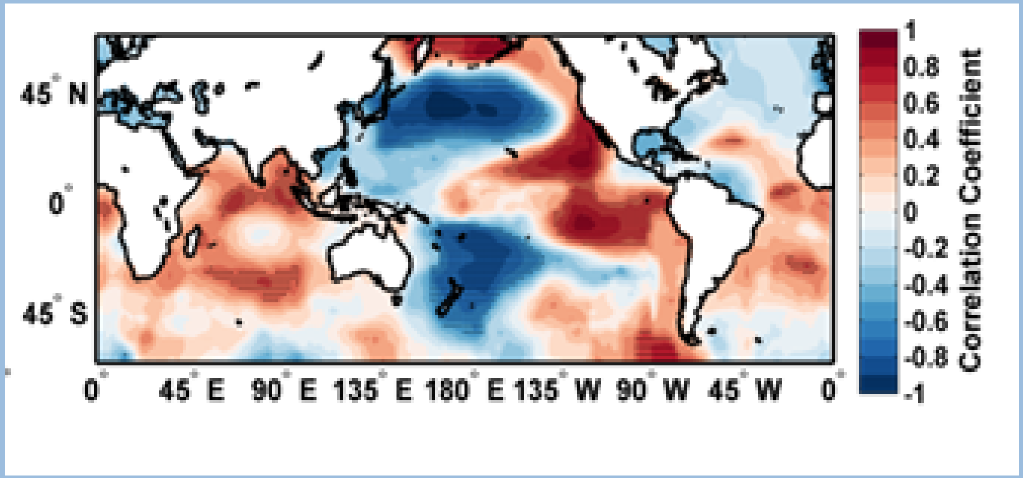
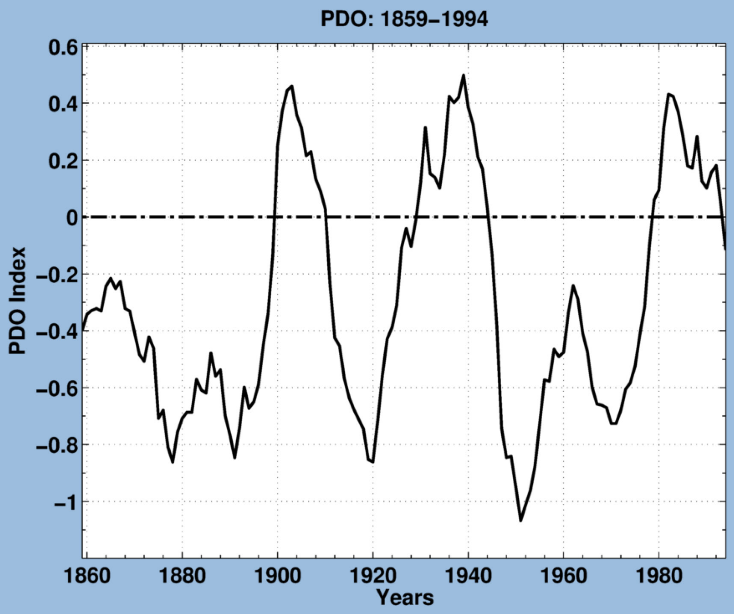
Pacific Decadal Oscillation (PDO)

> The leading mode of SSTs in the North Pacific Ocean with periodicities of 15-25 years and 50-70 years





AMO Index

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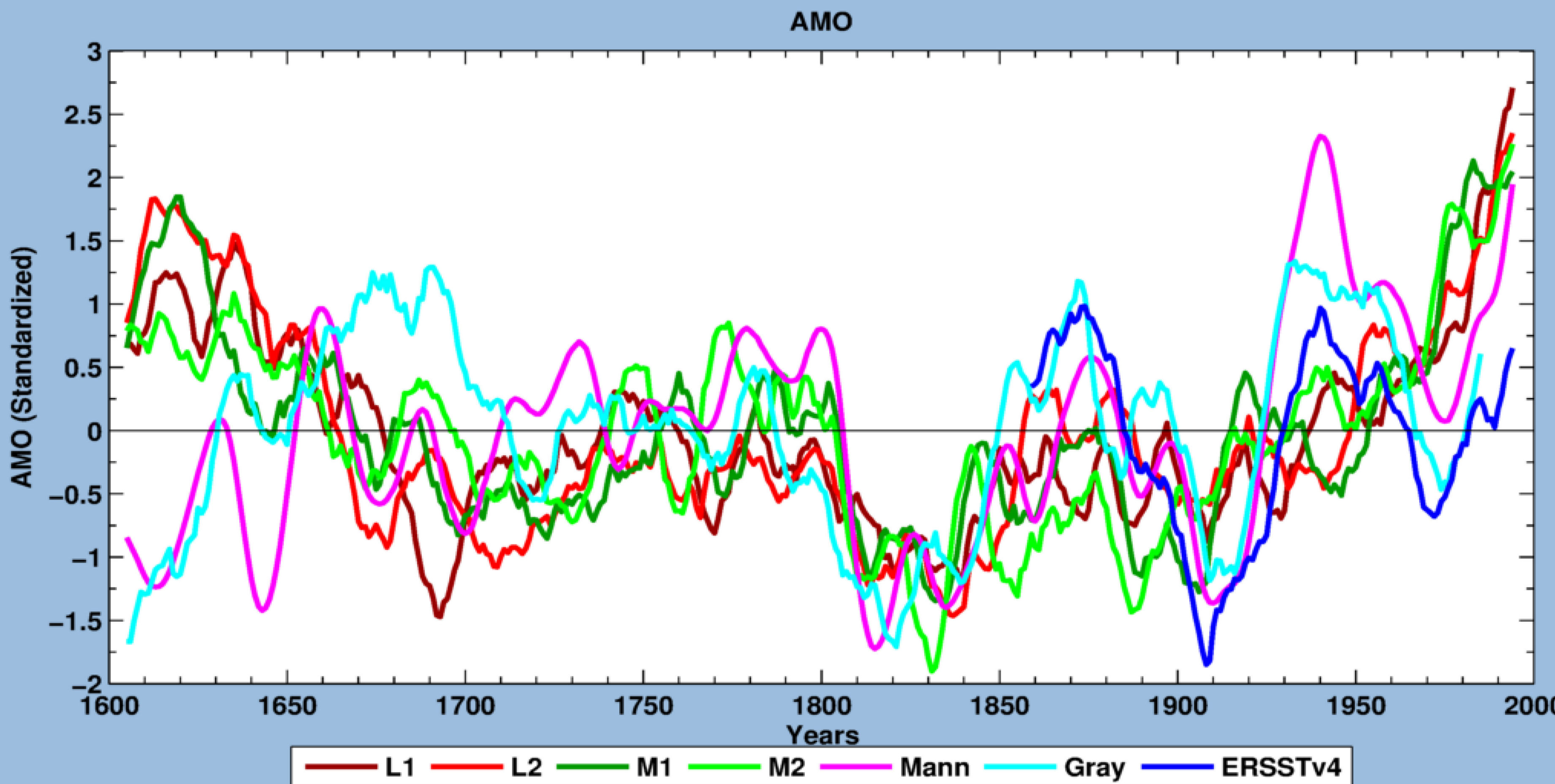

PDO Index

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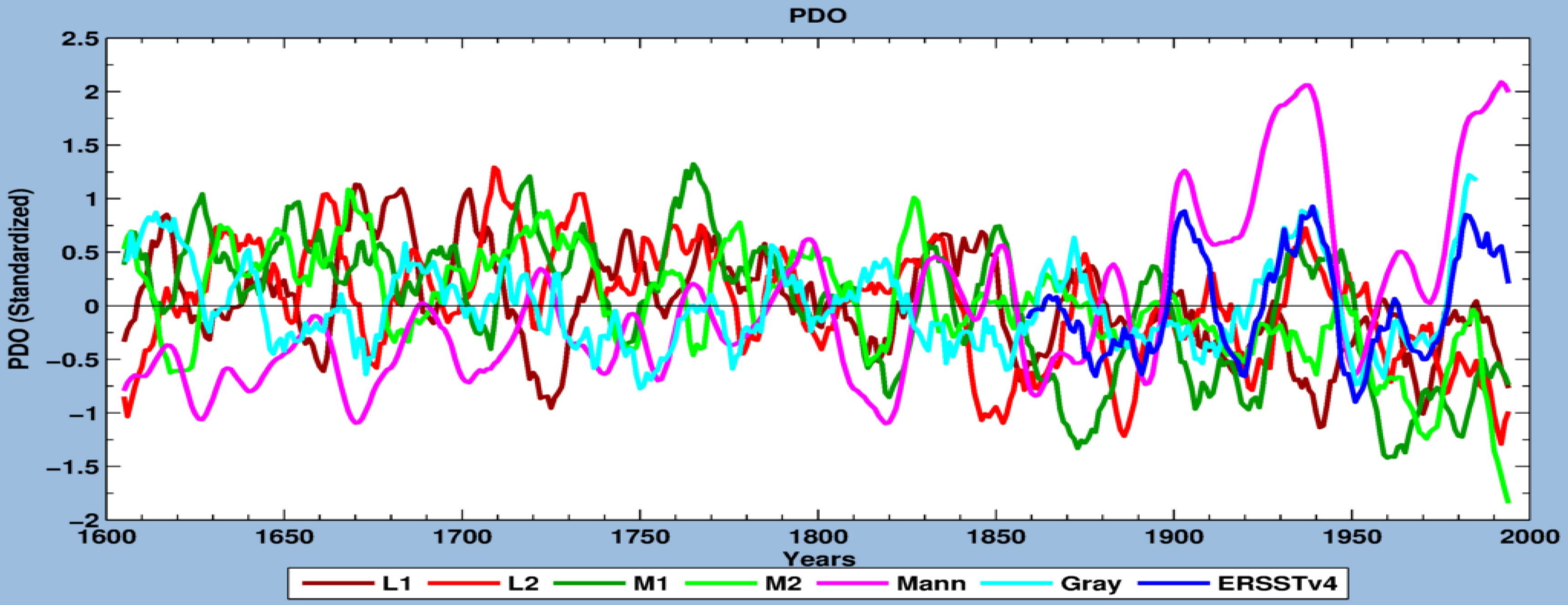

Nino3 Index

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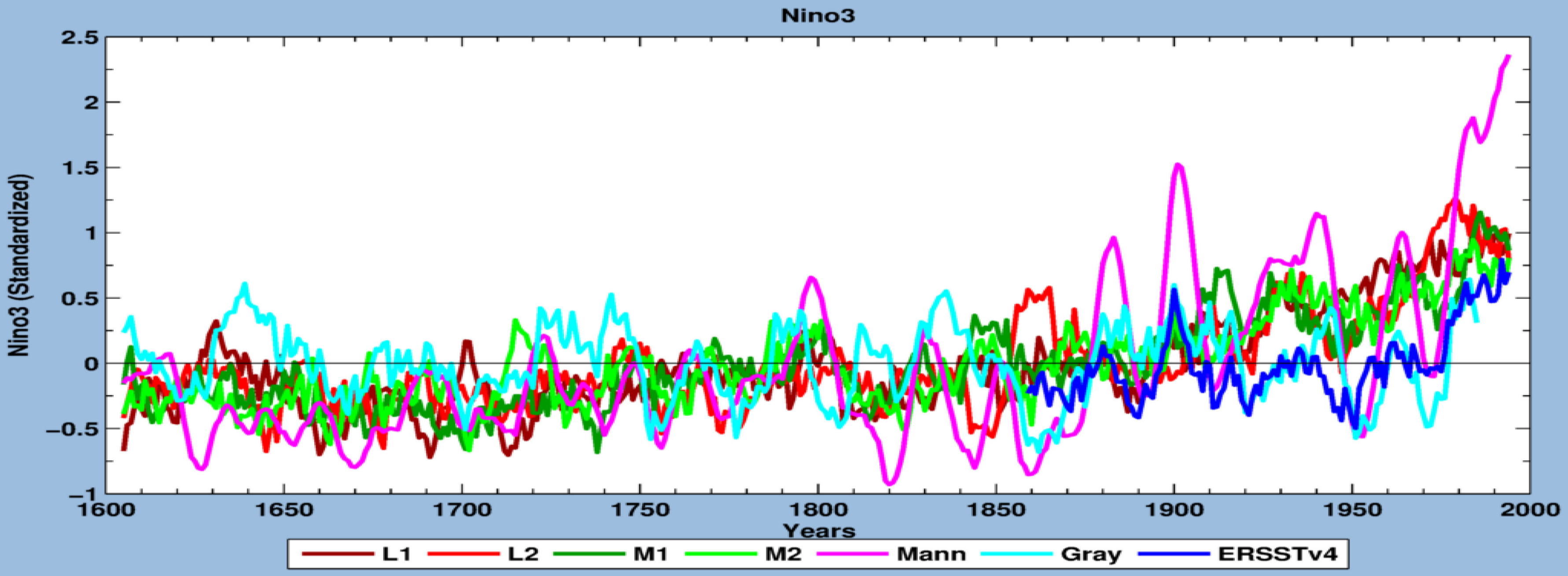

Mechanism

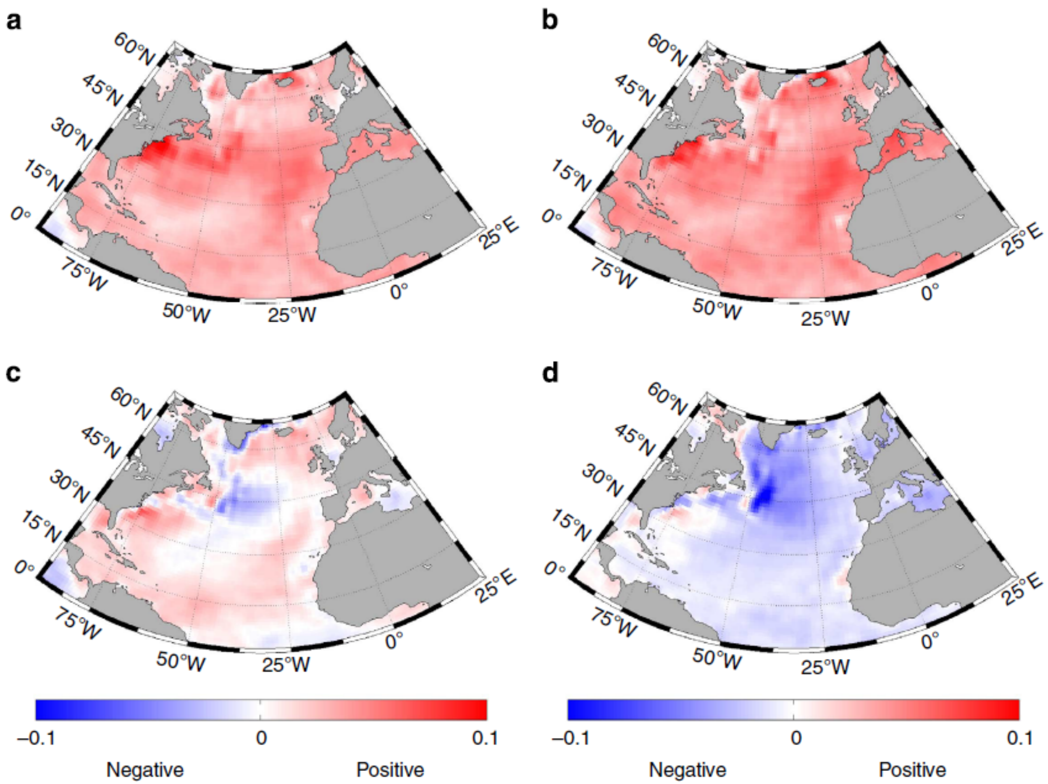

Figure 4 | Spatial relationship between external forcings and instrumental North Atlantic SSTs. Cross-covariances between instrumental North Atlantic SSTs obtained from HadISST[56] and the combined solar and volcanic forcing (Fig. 1d) between 1870 and 1982 for time lags of 0 years (**a**), 5 years (**b**), 20 years (**c**) and 30 years (**d**). The colour bar showing the covariance (in °C × W m^{-2}) is the same for all panels.